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Crop coefficients of open-canopy pecan orchards

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ABSTRACT

Pecan [*Carya illinoinensis* (Wangehn.) K. Koch] production is an essential component of irrigated agriculture in arid southwestern USA. Pecan consumptive water use is high compared to other crops. For irrigation purposes, consumptive water use (ETc) or evapotranspiration is estimated from ETc = Kc ETr where Kc is the crop coefficient used to adjust the known reference crop evapotranspiration (ETr). The Kc of pecans, the ratio of ETc and ETr, varies according to tree age, tree spacing, growth stage within a season, and local weather conditions. The equation for Kc that is applicable to closed-canopy pecan orchards (i.e., for $\mathrm{Kc}_{\max}$) is available from the literature. However, there is a lack of a method to calculate open-canopy pecan Kc according to tree size and spacing (varying effective canopy cover, ECC). The objective of this study was to derive a regression relationship in the form $\mathrm{Kc} = \mathrm{Kc}_{\max} \times f(\mathrm{ECC})$ or $\mathrm{Kc}/\mathrm{Kc}_{\max} = f(\mathrm{ECC})$ for open-canopy pecan orchards assuming that $\mathrm{Kc}/\mathrm{K}_{\max}$ is affected mainly by ECC. ECC was measured for orchards with different canopy covers using image analysis. Images were taken from a balloon and by satellite. Corresponding ETc values from the various pecan orchards were measured or estimated using four methods: (1) one propeller eddy covariance (OPEC) technique, (2) eddy covariance (EC) system, (3) remote sensing technique, and (4) simulations from a climate-based physiological tree model. $\mathrm{Kc}/\mathrm{Kc}_{\max}$ was calculated for different ECC values as $\mathrm{ETc}/\mathrm{ETc}_{\max}$, where $\mathrm{ETc}_{\max}$ is the closed-canopy ETc. A regression equation for open-canopy pecan orchards was obtained using data from OPEC, EC, and remote sensing techniques ($\mathrm{Kc}/\mathrm{Kc}_{\max} = 1.33\mathrm{ECC}$, i.e., $\mathrm{Kc} = \mathrm{Kc}_{\max} \times 1.33\mathrm{ECC}$) and was found to be statistically significant ($R^2 = 0.96$, $F = 2487$, $P < 0.001$). The equation is consistent with the results from the physiological model and related literature. The Kc equation from this study can help pecan farmers and researchers get more accurate estimates of pecan irrigation requirements for open-canopy orchards.

1. Introduction

Pecan production is an essential component of irrigated agriculture in arid southwestern USA. Seasonally, pecan consumptive water use is high compared to most crops, and was estimated to vary between 1260 and 1310 mm for mature trees (Miyamoto, 1983; Sammis et al., 2004). In the arid southwest water is a limited resource. Thus, farmers need to

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maximize irrigation water use efficiency (IWUE), defined as the ratio of crop yield to seasonal irrigation water applied, including rain (Howell, 1994).

The consumptive water use of pecans is a combination of evaporation from the soil and transpiration through the leaves. The two processes occur simultaneously and are usually measured together as evapotranspiration (ET). Estimation of crop ET under local weather conditions is based on potential ET of a reference crop (well-watered grass or alfalfa), ETr. The ETr is then multiplied by a crop coefficient (Kc) to obtain crop ET (ETc) under standard conditions. Standard conditions are defined as large fields under optimum soil water, excellent management and environmental conditions that allow the crop to achieve full production under the given climatic conditions (Allen et al., 1998). The Kc of pecans, the ratio of ETc and ETr, varies according to tree age, tree spacing, growth stage within a season, and local weather conditions. The effect of tree age and spacing is manifested in the amount of canopy cover (influences solar energy partitioning between soil evaporation and tree transpiration) and the rooting extent. Thus, there is a need for a method to adjust Kc values according to tree size and spacing.

When pecan trees are young the water use is proportional to the amount of solar radiation intercepted by the canopy. Miyamoto (1983) developed Kc values for pecan orchards based on the diameter of the trunk and the tree spacing. However, canopy cover (and ETc) varies largely even among trees with the same trunk diameter and tree spacing. For example, with the same trunk diameter and tree spacing, transplanted pecan has much smaller canopy cover (ETc) than regularly planted pecan.

Allen et al. (1998) suggested adjusting Kc by effective canopy cover (ECC) where ECC is defined as the proportion of the soil surface shaded by a crop at solar noon. Theoretically, the maximum ECC is 0.785 assuming the projection of a closed canopy on the ground is circular,

$$\mathrm{ECC}_{\max} = \frac{\pi r^2}{2r \times 2r} = 0.785 \tag{1}$$

where $\mathrm{ECC}_{\max}$ is the maximum ECC, r the canopy radius, the numerator is the area of the projection, and the denominator is the ground square area each tree occupies.

Johnson et al. (2000 and 2002) found a linear relationship between the Kc and ECC for peach tree transpiration where Kc = 1.5ECC, which might include partial soil evaporation. In another study, Goodwin et al. (2004) determined that Kc = 1.4ECC for peach tree transpiration. Consequently, the daily water use (transpiration only) of a peach tree (ETc) is proportional to the light interception and reference evapotranspiration (ETr) where:

$$\mathrm{ETc} = 1.4\,\mathrm{ECC}\,\mathrm{ETr} \tag{2}$$

Another method to determine Kc for young orchards throughout the growing season is by adjusting the closed-canopy crop coefficient ($\mathrm{Kc}_{\max}$) by the ECC ($\mathrm{Kc}_{\max}$ is a known variable calculated from a known equation from inputs of weather data, Sammis et al., 2004) where:

$$\frac{\mathrm{Kc}}{\mathrm{Kc}_{\max}} = a\mathrm{ECC}^b \tag{3}$$

where a and b are empirical coefficients.

Snyder (personal communication, 2003) determined that a sine function instead of a power function described $\mathrm{Kc}/\mathrm{Kc}_{\max}$ better based on almond ETc data from Fereres (1980):

$$\frac{\mathrm{Kc}}{\mathrm{Kc}_{\max}} = \sin\left(\frac{\mathrm{ECC}}{70} \times \frac{\pi}{2}\right) \tag{4}$$

where π is in radians.

Evapotranspiration is then obtained by:

$$\mathrm{ETc} = \mathrm{Kc}\,\mathrm{ETr} \tag{5}$$

$\mathrm{Kc}_{\max}$ for a closed-canopy pecan orchard can be calculated from the equation given by Sammis et al. (2004), according to weather data and stages of a season. However, there is a need for another equation that is applicable to open-canopy pecan orchards of varying ECC. The objective of this study was to derive a regression equation for Kc using empirical and simulated data in a form of Eq. (3) that is applicable to pecan orchards of varying ECC.

2. Materials and methods

In this study we deduced a regression equation for $\mathrm{Kc}/\mathrm{Kc}_{\max}$ according to ECC. The assumption is that $\mathrm{Kc}/\mathrm{Kc}_{\max}$ is mainly affected by ECC. This assumption is supported by the peach Kc studies of Johnson et al. (2000 and 2002).

ECC was measured for different pecan fields (ECC from 3 to 78.5%) using digital images taken from a balloon and by a satellite (Quickbird-2, DigitalGlobe Corporate, Longmont, CO, USA) in July 2005. The pecan fields are located in Las Cruces, New Mexico. The climate is semi-arid with an average annual rainfall of 234 mm, with half of the rainfall occurring during the winter months and the other half occurring during the summer monsoon season. The pecan trees are cultivar Western Schley. The soil is Harkey loam (coarse-silty, mixed, calcareous, thermic typic Torrifluvents). Each orchard dimension was larger than 300 m × 400 m. The trees ranged from 2 to 35 years old, from 1.5 to 13 m height, and from 6 to 10 m square spacing. The orchards were flood irrigated about once every 2 weeks in the growing season and the irrigation dates were recorded, and were supplied enough nitrogen through the irrigation system throughout the growing season. Therefore, the orchards were always non-stressed. The corresponding ETc in the 2005 growing season was measured using OPEC and EC systems, and also estimated by satellite remote sensing and using a physiological model. Then the regression equation for $\mathrm{Kc}/K_{\max}$ from ECC was obtained.

2.1. ECC measurements

ECC was measured for pecan orchards of different canopy cover using digital images taken over Las Cruces, New Mexico in July of 2005 from a balloon and a satellite. Balloon aerial photography was used to determine the ECC for six orchards.

The image locations are shown in Table 1 and partially (four locations) in Fig. 1. The sites at Holy Cross Road, Snow Road,

Table 1 – ECC measurements using balloon images compared with the measurements from the satellite image

Site name (closest road)	Location (latitude, longitude)	ECC measured from balloon image	ECC measured from the satellite image
Holy Cross Road	32°15′12.43″N, 106°44′58.35″W	0.31	0.27
Snow Road	32°13′30.49″N, 106°45′20.7″W	0.70	N/A[a]
Rocky Acres Trail	32°23′57.95″N, 106°51′57.48″W	0.03	N/A
Las Alturas Drive (site 1)	32°14′23.58″N, 106°42′45.61″W	0.05	0.05
Las Alturas Drive (site 2)	32°14′19.53″N, 106°42′43.46″W	0.37	0.40
Las Alturas Drive (site 3)	32°14′16.24″N, 106°42′51.52″W	0.54	0.55

[a] N/A: not available.

and Rocky Acres Trail were set up with ETc measurement instruments (EC and OPEC).

A lightweight digital camera (Cybershot 7.2 Mega pixels, Sony DSC-P200) was attached to a radio controlled, basic aerial photography kit (Pacific Grove, CA, www.brooxes.com) that hung from a standard 2.43 m (8 ft) spherical helium balloon (Arizona Balloon Company, Glendale, Arizona, www.arizona-balloon.com). The balloon was filled with helium and tethered to several ground points. The balloon was raised approximately 30 m above the pecan canopies to take pictures of several crowns at a time (Fig. 2). It was not possible to take an image of the entire orchard from just one setting of the balloon. Therefore, five pictures of different sampling areas (randomly chosen) in each orchard were taken. Five pictures were considered representative of an orchard because the ECC was very uniform within each orchard. These photos were then imported into an image analysis software package (Adobe Photoshop 8.0, Adobe Systems Incorporated, San Jose, CA, USA) that can distinguish and count the number of pixels that were covered by the tree crowns (Bernhardt and Griffing, 2001). The "Magic Wand" and "Select Similar" functions in Photoshop 8.0 were used to select pecan canopy-cover pixels. Then, the "Histogram" function gave the pixel number of the canopy cover. The pixel number of the whole picture was obtained using the "Image Size" function in the Image menu. ECC is the ratio of canopy pixel number and the whole image pixel number. The average of the ECC values for the five pictures of each orchard was used as the ECC for the corresponding orchard.

Because image acquisition using the balloon was time-consuming, satellite imagery was used for most of the orchards. A satellite image (Fig. 1) taken at 12:00 noon on July 4, 2005 was bought from DigitalGlobe Corporation (Longmont, CO, USA). The image was a natural color image and had a resolution of 0.6 m. Different ECC orchards on the images were magnified in Arcview 3.2 (ESRI GIS and Mapping, Redlands, CA), and then imported into Adobe Photoshop 8.0 for processing. ECC values were obtained using the same method

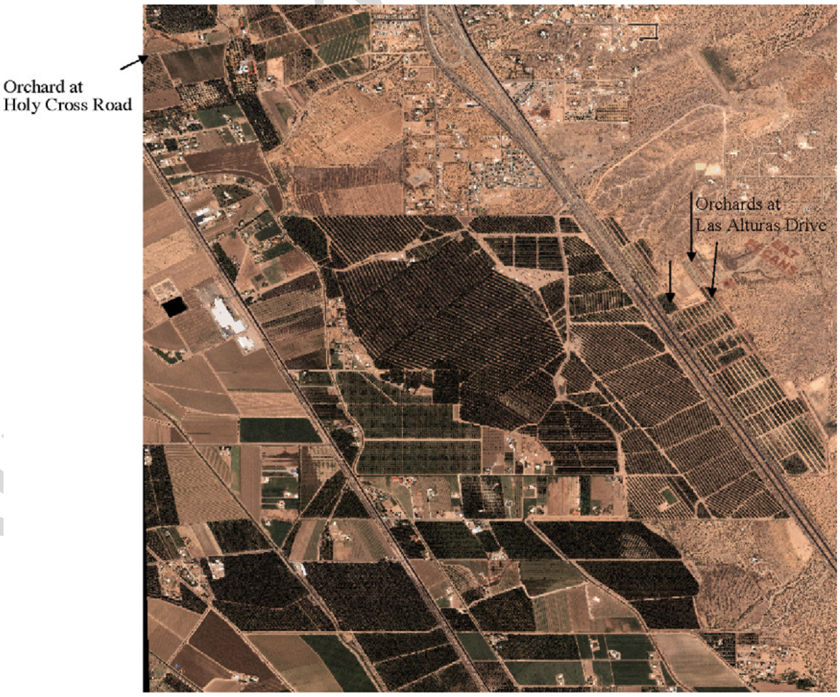

Fig. 1 – A satellite image covering different open- and closed-canopy orchards taken by the Quickbird-2 satellite from DigitalGlobe Corporation at 12:00 noon on July 4, 2005. The center of the image is at 32°13′54.69″ latitude, −106°43′45.77″ longitude, east of Las Cruces, New Mexico. The coverage is 5 km × 5 km with a resolution of 0.6 m. The orchards marked by arrows were the locations where the ECC values were measured from this image and images taken from the balloon.

Fig. 2 – A sample image taken from a balloon over a pecan orchard at Holy Cross Road (32°15′12.43″ latitude, −106°44′58.35″ longitude).

as for the images taken from the balloon. For each orchard, five sampling areas were processed and the average ECC was used for the corresponding orchard. A total of 17 sites were processed for ECC. There were four locations on the satellite image where ECC were calculated from the balloon pictures. Using regression analysis, the ECC from the balloon images were compared with the values obtained from the satellite image to check consistency between the two imaging methods. The dependent variable was ECC from the satellite ($\text{ECC}_{\text{stellite}}$) and the predictor variable was the ECC from the balloon ($\text{ECC}_{\text{balloon}}$).

2.2. *ETc field measurements*

The ETc of three orchards were measured using OPEC and EC systems during the growing season of 2005. Two of the orchards used EC technology. The other one used the OPEC technique. A fourth site was originally included but had grass growing between the pecans. This site was excluded from the analysis because crop coefficients were influenced by ETc from both trees and grass.

In the EC measurements, one orchard at Snow Road had an ECC of 70% (Table 1). The orchard at Rocky Acres Trail had an ECC of 3%. In the orchard at Snow Road, the EC system measured ETc from April 27 to October 31. The orchard was 35 years old, had a square spacing of 10 m, and average tree height of about 12.8 m. A 3-axis sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT) was used in conjunction with an open path, infrared water vapor analyzer (Li-Cor 7500, Li-cor Inc., Lincoln, NE) to measure ETc following Swinbank (1951):

$$\text{LE}_{\text{EC}} = L_v(\overline{w'q'}) \tag{6}$$

where LE_{EC} is the latent heat flux from EC measurements ($\text{J m}^{-2}\,\text{s}^{-1}$), L_v the latent heat of vaporization (J kg^{-1}), and $(\overline{w'q'})$ is the covariance between the vertical wind velocity (w, m s^{-1}) measured by the anemometer and the water vapor density (q, kg m^{-3}) measured by the vapor analyzer. The measurement tower was located in the center of the orchard and the measurement height (z) was 16.5 m. The measurement frequency was 10 Hz. The 30-min average of LE was calculated and stored in a CR23X datalogger (Campbell Scientific Inc., Logan, UT). These measurements were corrected for different density and sonic temperature effects (Webb et al., 1980).

In the orchard at Rocky Acres Trail, an identical EC system was used to measure LE from May 6 to September 30. This orchard consisted of 2-year-old saplings that were approximately 1.5 m in height and had a square spacing of 6 m. The EC system was mounted at 2 m height in the center of the orchard.

An OPEC system was used to measure ETc in an orchard with ECC value of 31% at Holy Cross Road (from April 19 to August 13). This orchard had a square spacing of 6 m. The average tree height was about 8 m. The OPEC system uses a simplified surface energy balance equation:

$$\text{Rn} - G = \text{LE}_{\text{OPEC}} + H \tag{7}$$

where LE_{OPEC} is the latent heat flux from OPEC measurements ($\text{J m}^{-2}\,\text{s}^{-1}$), Rn the net radiation ($\text{J m}^{-2}\,\text{s}^{-1}$), G the soil heat flux ($\text{J m}^{-2}\,\text{s}^{-1}$), and H is the sensible heat flux ($\text{J m}^{-2}\,\text{s}^{-1}$). The OPEC technique measures the Rn, G, and H components of Eq. (7) and calculates the LE_{OPEC} as a residual ($\text{J m}^{-2}\,\text{s}^{-1}$). OPEC systems have been found to be reliable predictors of LE in long-term studies (Blanford and Gay, 1992; Sammis et al., 2004; Simmons et al., in press). A Q7.1 net radiometer (Radiation and Energy Balance Systems, Bellevue, Washington) was used to measure Rn and three soil heat flux plates (HFT3, Radiation Energy Balance System, Seattle, Washington) were buried at 2 cm depth to measure G. A fast response thermocouple (TC-BR-

3, Campbell Scientific Inc., Logan, UT) and a propeller anemometer oriented vertically (#27106, RM Young, Traverse City, MI) measured H:

$$H_{\mathrm{EC}} = \rho c_p(\overline{w'T'}) \tag{8}$$

where ρ is the density of air (kg m^{-3}), c_p the specific heat of air (J kg^{-1} K^{-1}), and $(\overline{w'T'})$ is the covariance between the vertical wind velocity and the temperature (T, K). The systems were mounted in the center of the orchards and at least 6 m above the zero plane displacement height to minimize errors in measuring H (Blanford and Gay, 1992), i.e., at 11.5 m height at Holy Cross Road. The data were measured at a frequency of 1 Hz, averaged over 30 min and stored in a CR23X datalogger.

The $\mathrm{LE_{EC}}$ and $\mathrm{LE_{OPEC}}$ were in flux units (J m^{-2} s^{-1}) and were converted to evapotranspiration depth, $\mathrm{ET_{depth}}$ (mm s^{-1}),

$$\mathrm{ET_{depth}} = 1000\frac{\mathrm{LE}}{L_v\rho} \tag{9}$$

where ρ is water density (1000 kg m^{-3}).

The daily ETc (mm day^{-1}) was obtained by integrating the $\mathrm{ET_{depth}}$ over 24 h.

The siting of EC and OPEC systems in open-canopy orchards may affect the ETc measurements. If the instruments were close to the rows, the flux measurements may have measured larger values than the average flux. In addition to the siting, the wind speed and direction also can affect the flux measurements. To better represent the average flux, the EC and OPEC systems were placed in-between rows (midpoint). At this location, the ETc flux from pecans was well mixed with the flux from soil and the measured flux represented the average flux.

2.3. ETc from remote sensing

The ETc measurements by EC or OPEC systems were limited to three orchards and the data were not enough to deduce a regression equation for Kc/K_{max}. Therefore, remote sensing technology was used to estimate more ETc at more sites (13 different ECC sites). There were 11 sites in the area of Fig. 1, which included the site at Holy Cross Road (Table 1). The other two sites were at Snow Road and Rocky Acres Trail (Table 1). This remote sensing technology used the ground surface reflectance and temperature data obtained from the ASTER satellite (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (Abrams et al., 2002), and wind speed, solar radiation, and humidity from the local weather station to estimate ETc based on the energy balance principle (Eq. (7)) (Morse et al., 2000; Wang et al., 2005). H is calculated as a function of the difference between air and surface temperature. The difference is calculated as a function of surface temperature and surface cover type (e.g., vegetation, bare soil), which is determined by the normalized difference vegetation index (NDVI). NDVI can be calculated from the satellite reflectance data. G is calculated as a function of NDVI and solar radiation. Rn is calculated as a function of solar radiation and albedo, which is calculated from satellite reflectance data. The details of the method are described by Wang et al. (2005). The typical accuracy of this technique at field scale is 85% for 1 day and it increases to 95% on a seasonal basis (Bastiaanssen et al., 2005).

The ASTER satellite provided data sets on April 21 and June 8, 2005 for Las Cruces. Wind speed, solar radiation, and humidity came from a Campbell weather station that recorded the hourly climate parameters needed by the model at the New Mexico State University Plant Science Research Farm (32°12′3.89″N, 106°44′33.0″W) located 15 km south of Las Cruces, NM. The weather station was within 7 km of most sites, except the Rock Areas Road site (Table 1) that was about 25 km from the weather station. The weather station data were deemed to represent the weather conditions at the study sites. The weather data is available from the New Mexico Climate Center Web page (http://weather.nmsu.edu/data/data.htm). We used the remote sensing model by Wang et al. (2005) to calculate the ETc for Las Cruces. The satellite-estimated ETc values ($\mathrm{ETc_{satellite}}$) were compared with measurements from the OPEC and EC systems ($\mathrm{ETc_{EC\text{–}OPEC}}$) to check the accuracy. A regression analysis was used for this check.

2.4. ETc from physiological model

A physiological model developed by Gutschick (2006) was used to estimate ETc for orchards with different ECC values. The model estimates were compared to ETc values estimated from remote sensing, OPEC, and EC systems. The following section gives an overview of the physiological model. A more detailed description is given by Gutschick (2006). The full Fortran program, incorporating copious explanatory comments, is posted on the Website http://biology-web.nmsu.edu/vince. Also posted are sample data sets and lists of program variables with their units and purposes.

The physiological model estimates microenvironments for leaves throughout the canopy and then solves for $\mathrm{CO_2}$ assimilation (A_{L}) and transpiration (E_{L}) for each leaf environment. The mean leaf dimension crosswise to wind was set to 0.05 m. A_{L} and E_{L} are summed over all environments with weighting by frequency of occurrence. The microenvironment is specified as quantum irradiances in the photosynthetically active radiation (I_{L}), energy irradiances in the near infrared and thermal infrared, air temperature (T_{a}) and water vapor partial pressure (e_{a}), wind speed (u), and $\mathrm{CO_2}$ mixing ratio (C_{a}).

Light interception is computed from the geometry of canopies and of solar radiation. Tree placements are specified on an arbitrary grid, taken in the current case as a square array with 9-m spacing. Each tree has an ellipsoidal crown with semi-axes a_{tree} and b_{tree}. The major axis can be tilted at specified zenith and azimuth angles, θ_{tree}, φ_{tree}; these are irrelevant for spherical crowns. Computations of light interception are performed on tree number 1. Light is traced through its own crown and all other crowns.

Photosynthetically active radiation is resolved into the direct solar beam and diffuse skylight. Flux density (direct beam) and intensity (diffuse skylight) are given in quantum units (mol m^{-2} s^{-1}) for use in photosynthesis calculations. They are readily converted to energy units for calculations of energy balance. The solar elevation, and thus the beam direction, is computed from latitude, longitude, date, and time from standard formulae (e.g., Pearcy, 1989). Diffuse skylight is approximated as uniform. The penetration of both components is calculated at a sampling of points within crown number 1. The step size for tracing optical paths inside the canopy was set to 0.1 m. The maximum path length at which tracing is terminated was set to 10 m. Radii are sampled at n_r locations, chosen to give equal shell volumes for each point. The number of radii sampled in tree crown was set to 5. Zenith and azimuthal angles, relative to the crown coordinates, are sampled at n_θ and n_φ locations, respectively, and locations are chosen to resolved equal solid angles. The number of zenith angles and azimuthal angles were set to 5 separately. Therefore, total sectors sampled in crown was $5^3 = 125$.

Leaf irradiance is calculated from the quantum flux densities of the direct solar beam (I_0) and diffuse skylight (D_0):

$$I_L = I_0 \cos\theta_{Ls} + D_0 \tag{10}$$

where θ_{Ls} is the angle between leaf normal and the direct beam, calculated for a given leaf angular orientation.

Approximating leaves as randomly oriented (Ross, 1981), the $\cos\theta_{Ls}$ is distributed uniformly from 0 to 1 (Gutschick and Wiegel, 1984). Consequently in the model at a given location 10 values are sampled with values between 0 and 1.

Diffuse skylight arrives nearly deterministically, over a small range of flux densities centered at D_0, with probability nearly unity, independent of leaf orientation (Gutschick and Wiegel, 1984). The direct beam arrives at a 3-D location $\mathbf{r}$ probabilistically, with probability $P_{pen}(\mathbf{r})$. Thus, in its statistical distribution, I_L magnitude at D_0 with a probability $1 - P_{pen}(\mathbf{r})$ and a uniform probability over magnitudes D_0 to $D_0 + I_0$ that integrates to $P_{pen}(\mathbf{r})$. For practical computations, we resolve I_L in a limited number, n_{bins}, of intervals between zero and the maximum, $D_0 + I_0$. The n_{bins}, bin number, was set to 10. Computations of leaf photosynthesis and transpiration are performed for each discrete I_L value (bin central value) and summed by weighting with the total bin probability.

In a turbulent-medium approximation (Gutschick, 1991):

$$P_{pen}(\mathbf{r}) = \exp(-0.5 f_d S) \tag{11}$$

where f_d is foliage density (taken as uniform within a tree crown as a first approximation) and S is the total path length through tree crowns. The factor 0.5 is the average of $|\cos\theta_{Ls}|$ for randomly oriented leaves.

The canopy can be modeled as a collection of discrete tree crowns. The model generalizes the method of Norman and Welles (1983) to crowns that are ellipsoids of revolution that can be canted off vertical and that are not necessarily spaced regularly. The model solves for path length through crowns by a numerical search along the solar ray direction, from a chosen internal canopy location to a point above any crown. The model samples a range of in-crown locations of a specified tree, at selected radii and angles that represent equal canopy volumes. Second- and higher-order scattered radiation is ignored in the approximation.

Direct and diffuse flux densities are estimated from total irradiance on weather-station sensors by comparing the latter to expected clear-sky values and assigning deficits to overcast conditions (only D_0 occurs). Downwelling thermal infrared (TIR) flux densities are estimated as diffuse sky radiation (using the same algorithms), using an effective radiative temperature that can be specified as an offset from screen-height air temperature; computations based on air humidity and pressure can be accommodated. Upwelling TIR flux is described with sufficient accuracy as diffuse blackbody radiation at air temperature. The TIR absorptivity and emissivity were set to 0.95. The fraction of photosynthetically active radiation absorbed by leaf was set to 0.85.

Transport of water vapor (E) and sensible heat (H) within the canopy is described simply with one layer with a canopy resistance following Sellers et al. (1996). Canopy resistance ($r_{b,can}$) is a linear function of canopy structure and wind speed:

$$r_{b,can} = \frac{C}{u} \tag{12}$$

where C is a constant dependent on canopy structure.

In-canopy magnitudes of e_a and T_a are computed iteratively from a resistance model using free-air values and the total E and H flux densities per unit ground area. Convergence of E and H within 1% is enforced and is typically achieved in three iterations. Soil evaporation and heat flux is omitted. These numbers integrated over a day under a tree canopy are small. Wind speed is exponentially attenuated (Sellers et al., 1996) in the layered pecan canopy.

For any total leaf environment, the model iteratively solves three simultaneous nonlinear equations: leaf energy balance, the Ball–Berry equation for assimilation rate (g_s) (Ball et al., 1987), and the enzyme-kinetic equations for CO_2 assimilation in terms of photosynthetic capacities and internal CO_2 partial pressure (C_i).

A binary search is initiated in g_s from robustly estimated upper and lower limits. At a given g_s, one solves the energy-balance equation for leaf temperature, which then allows computation of T-dependent enzyme parameters and leaf respiration rate per unit area. The model then solves for a consistent magnitude of C_i by a hobbled Newton–Raphson search. For this, the model expresses light-limited and light-saturated rates in terms of C_i and the model expresses net assimilation rate (A_n) as $g'_{tot}(C_a - C_i)/P$, with g'_{tot} as the total conductance for CO_2 through stomata and leaf boundary layer and P as the total air pressure. We obtain an estimated A_n, which is used in the outer loop binary search for g_s consistent with the Ball–Berry equation, that is, seeking to drive the function $F = g_s - (\text{Ball–Berry value}) = g_s - (mA_n h_s/C_s + b)$ to zero, where h_s is the humidity at the leaf surface, C_s the CO_2 concentration at the leaf surface, m and b are constants derived from gas exchange studies. At convergence, the maximum absolute error in g_s for each leaf was enforced to within 0.0001 mol m^{-2} s^{-1}. Then, the model has consistent estimates for A_n and E per leaf area, as well as auxiliary estimates of leaf temperature and C_i.

The model was run for the month of July 2005 using 9-m spacing of trees on a square grid, and five different canopy diameters of individual trees: 9, 7.5, 6, 4.5, and 3 m. The simulation interval was 10 min. The corresponding ECC varied from 0.785 to 0.112. In the simulations, f_d was set to 0.7 m^2 m^{-3}. Then, the total leaf area varied from 267 to 9.9 m^2 for tree crown diameter from 9 to 3 m, which corresponded to a leaf area index (LAI) of 3.2 down to 0.12 m^2 m^{-2}, based on the tree

Table 2 – Input parameters and assumptions for the physiological model

Weather data taken from July 1 to 31, 2005 at the NMSU horticultural farm
Mean air pressure: 88,500 Pa
Mean CO_2 partial pressure: 34 Pa
Canopy resistance constant $C = 1.5$; from Sellers et al. (1996)
Foliage density: 0.7 $m^2\ m^{-3}$, as simple but good approximation, taken as uniform throughout the canopy (non-uniformity does not change light interception dynamics)
Random leaf orientations assumed
Neighboring trees sampled for light interception to four rows and four columns away

Leaf physiology and morphology—consensus of measurements by three research groups
  Maximal photosynthetic (carboxylation) capacity: 150 $\mu mol\ m^{-2}\ s^{-1}$
  Dark respiration: 0.08 of maximal achieved photosynthetic rate, at mean photoperiod temperature (26.6 °C) of previous 2 weeks
  Curvature parameter (transition from light-limited to light-saturated PS): 0.8 (standard value for many C_3 plants) (Leverenz, 1994).
  Ball–Berry slope for stomatal control: 10 (Ball et al., 1987)
  Ball–Berry intercept (minimal stomatal conductance): 0.05 $mol\ m^{-2}\ s^{-1}$ (Ball et al., 1987)
  Fraction of photosynthetically active radiation absorbed by leaf: 0.85
  Thermal infrared absorptivity and emissivity: 0.95
  Mean leaf dimension crosswise to wind: 0.05 m

Error control parameters
  Number of leaf-irradiance bins: 10
  Fractional error in whole-tree transpiration accepted as converged: 0.01
  Maximal absolute error in stomatal conductance for each leaf: 0.0001 $mol\ m^{-2}\ s^{-1}$
  Step size for tracing optical paths inside the canopy: 0.1 m
  Maximal path length at which tracing is terminated: 10 m
  Number of radii sampled in tree crown: 5
  Number of zenith angles sampled in tree crown: 5
  Number of azimuthal angles sampled in tree crown: 5 (total number of sectors sampled in crown = 5 × 5 × 5 = 125)
  Simulation interval: 10 min, all day and night

spacing of 81 m^2. The LAI range is reasonable compared with Qi et al. (1995) who measured LAI for different ECC pecan orchards with a range from 2.48 down to 0.87 $m^2\ m^{-2}$. Simulated conditions specified in Table 2 represented a pecan orchard at Las Cruces, NM. The climate data to drive the model came from the weather station at New Mexico State University Plant Science Research Farm.

2.5. *Regression analysis for Kc/Kc$_{max}$*

The ETc measured by the EC and OPEC systems in July 2005 (leaves were fully developed) were used to calculate Kc/Kc_{max} ($=ETc/ETc_{max}$). Daily ETc_{max} is the ETc of a closed-canopy pecan orchard, which was calculated using the equation by Sammis et al. (2004). Then daily Kc/Kc_{max} was calculated and its average in the whole month of July was used as the field Kc/Kc_{max} for the regression analysis.

The ETc on June 8, 2005, for different ECC values estimated from remote sensing, were divided by the corresponding ETc_{max} values obtained from Sammis et al. (2004) and the resulting values were used as Kc/Kc_{max}.

Then, regression analysis was conducted for the dependent variable Kc/K_{max} from OPEC, sonic, and remote sensing and the predictor variable ECC. The ETc data during irrigation or rainy days and 5 days after the events were excluded from the data analysis. Therefore, the ETc was mainly from pecan transpiration.

The regression results were compared with the simulated results from the physiological model. The ETc for different ECC values from the physiological model was divided by the ETc_{max}, which was the ETc for the orchard of ECC = 0.785 (full canopy cover) simulated by this model. Then the resultant variable was Kc/Kc_{max} and its average in the whole month was used for regression analysis.

3. Results and discussion

3.1. *ECC and ETc measurements*

ECC measured from balloon and satellite images were consistent for different open-canopy orchards (Table 1). The regression analysis showed $ECC_{satellite} = 1.01 \times ECC_{balloon}$ ($T = 25.01$, $P < 0.001$, $R^2 = 0.98$). The ECC measurements from both images were deemed accurate based on the regression equation and the high R^2 value between the two methods.

The ETc can be obtained for a large area by remote sensing (Fig. 3). The ETc estimated from the satellite remote sensing compared well to the measured daily ETc values from the experimental orchards (Table 3) for the orchards of ECC from 3 to 70%. The regression analysis showed that $ETc_{satellite} = 0.994 \times ETc_{EC–OPEC}$ ($T = 101.64$, $P < 0.001$, $R^2 = 0.99$). Consequently, the satellite ETc estimates were validated by the OPEC and EC data.

3.2. *Physiological model*

The physiological model predicted an average ETc of 8.4 mm day^{-1} (Table 4) for the closed-canopy orchard (crown diameter = 9 m, ECC = 0.785) for the month of July 2005 compared to a calculated value of 8.4 mm day^{-1} based on a published crop coefficient for pecans and reference ET for alfalfa (Sammis et al., 2004). Simulated photosynthetic biomass produced for the month (PB), including respiratory losses, varied from 34.28 to 4.18 kg per tree that resulted in a water use efficiency of 0.00162 to 0.00304 kg L^{-1} (Table 4). Compared to measured data by Wang et al. (submitted for publication), the model simulation was reasonable. For example, when ECC = 0.7, the measured biomass growth and water use efficiency during July 2005 were 34 kg per tree and 0.0016 kg L^{-1}, respectively (Wang et al., submitted for publication) versus the simulated values of about 32 kg per tree (from linear interpolation based on the simulations of ECC = 0.785 and ECC = 0.5468) and 0.0017 kg L^{-1}.

3.3. *Regression equations*

From the combined data from remote sensing, EC, and OPEC measurements, a linear equation for ETc was obtained (Fig. 4),

$$\frac{Kc}{K_{max}} = 1.33ECC \tag{13}$$

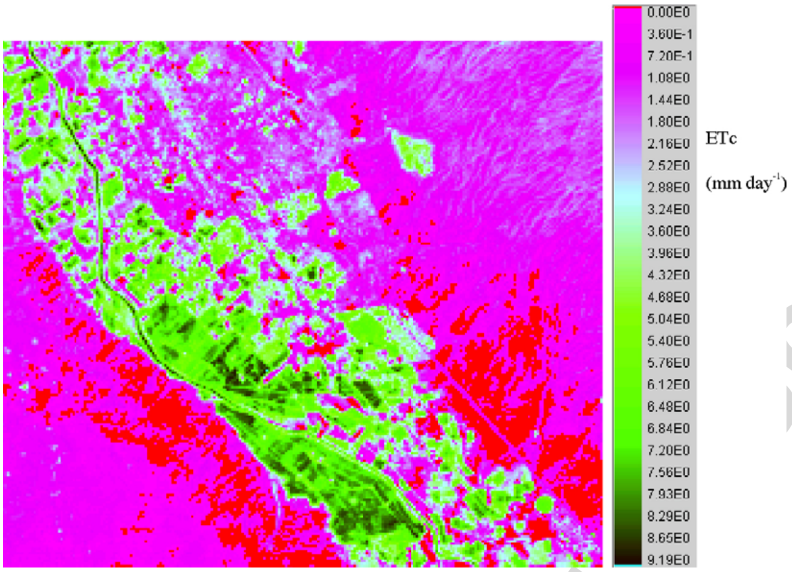

Fig. 3 – An ET map on June 8, 2005 at Las Cruces estimated from remote sensing. The coverage of the map is 22 km × 18 km. The center is at 32°15′48.94″ latitude, −106°45′28.92″ longitude.

It was found to be statistically significant ($R^2 = 0.96$, $F = 2487$, $P < 0.001$).

The functions reach a maximum closed canopy when ECC equals 0.785, which is close to what a tree with a spherical canopy that is perfectly opaque and has very dense leaf area would represent. The area of a sphere takes up 0.785 of a square area based on the projected area.

In the regression, we excluded the data during irrigation and rain events, including the 5 days after each event. Therefore, the ETc data were mainly from plant transpiration. Eq. (13) is close to the regression Eq. (14) obtained from the physiological model ($R^2 = 0.99$, $F = 158968.32$, $P < 0.001$) that simulated plant transpiration only,

$$\frac{\mathrm{Kc}}{\mathrm{K}_{\max}} = 1.24\mathrm{ECC} \tag{14}$$

The difference between Eqs. (13) and (14) was partially caused by the lack of an advection term in the physiological model. The model did not account for any local advection that supplies energy for the evapotranspiration process from the dry interspaces between trees. In addition, the physiological

Table 3 – ETc estimated by remote sensing compared with the values measured by OPEC and EC systems

Site name (closest road)	Date in 2005	ETc measured by OPEC or EC (mm day^{-1})	ETc measured by remote sensing (mm day^{-1})
Holy Cross Road	April 21	1.84	1.95
	June 8	4.87	4.83
Snow Road	April 21	5.55	5.7
	June 8	8.82	8.64
Rocky Acres Trail	June 8	5.74	5.70

ETc measurements were not available at Rocky Acres Trail on April 21.

Table 4 – Physiological model simulation run for pecan trees grown in Las Cruces, NM with different ECC values

Crown Diameter (m)	Leaf area (m^2)	I_{Lavg}[a] (moles of photons)	Mcrown (moles of photons)	ECC	T (L month^{-1})	ETc (mm day^{-1})	PB (kg month^{-1})	WUE (kg L^{-1})
9.0	267.2	153.0	108,702	0.7850	21,109	8.40	34.28	0.00162
7.5	154.6	187.4	77,056	0.5468	14,172	5.64	28.42	0.00201
6.0	79.2	228.8	48,187	0.3419	8,391	3.34	19.73	0.00235
4.5	33.4	281.1	24,969	0.1772	4,096	1.63	11.06	0.00270
3.0	9.9	339.4	8,932	0.0634	1,373	0.55	4.18	0.00304

[a] I_{Lavg}, average leaf irradiance; Mcrown, quanta of light intercepted by all leaves in each tree, over duration of simulation; ECC, effective canopy cover; T, monthly transpiration; Etc, daily transpiration; PB, total photosynthetic biomass produced for the month; WUE, water use efficiency.

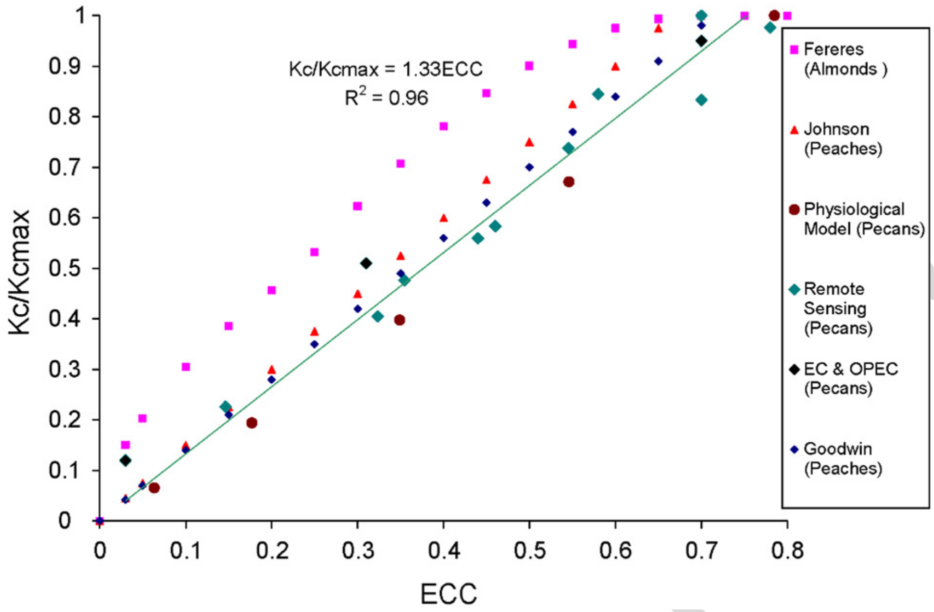

Fig. 4 – Open–canopy crop coefficient (Kc)/closed-canopy crop coefficient (Kc_{max}) vs. ECC. Kc_{max} from Johnson et al. (2000 and 2002) and Goodwin et al. (2004) was set to 1, which represents a closed-canopy orchard.

model did not include any soil evaporation. Consequently, the model slightly under-estimated the ETc.

The slope (1.33) of regression Eq. (13) is also close to the slope (1.4) found for peaches (Eq. (2)), assuming peach $Kc_{max} = 1$ (Goodwin et al., 2004). The difference between the slopes might be caused by the differences of measurement methods and species. Goodwin et al. (2004) measured trunk sap flow velocity to estimate plant transpiration ETc. We estimated ETc using EC, OPEC, and remote sensing techniques.

The slope (1.33) of regression Eq. (13) is slightly less than the slope (1.5) for peaches given by Johnson et al. (2000 and 2002) (assuming peach $Kc_{max} = 1$). The difference between the slopes might also be caused by the differences of measurement methods and species. Johnson et al. (2000 and 2002) used a lysimeter to measure ETc and it included soil evaporation.

The slope of regression Eq. (13) is lower than that for almonds (Fereres, 1980) (Fig. 4). Fereres (1980) used the total irrigation depth as the ETc. However, this is valid only if drainage is negligible. Otherwise, ETc is overestimated.

The regression data were measured and estimated for June and July when the leaves were fully developed. During the vegetative stages (April and May), the maximum ECC will be smaller than 0.785 (not a closed-canopy). If Eq. (13) is used to calculate Kc during this time, underestimation may occur. To get reasonable ETc values from Eq. (13) during vegetative stage, we may assume $Kc_{max} = 1$, i.e., assuming there is a virtual closed-canopy pecan orchard having the same ETc as the reference ETc for a grass or an alfalfa field (i.e., ETr).

The regression Eq. (13) does not work for open-canopy when the soil surface is wet because the equation was regressed using data when the soil surface was dry. When the soil surface is wet, the ET will be the sum of the canopy transpiration plus the soil evaporation. Under this condition the canopy transpiration can be obtained using our regression Eq. (13) and the soil evaporation can be obtained using the soil evaporation equations in literature (e.g., Ventura et al., 2001).

4. Conclusion

Based on OPEC, EC, and remote sensing estimates, a regression equation for calculating open-canopy pecan Kc was obtained. The equation ($Kc = Kc_{max} \times 1.33ECC$) was statistically significant ($R^2 = 0.96$, $F = 2487$, $P < 0.001$), where Kc_{max} is given by the closed-canopy Kc equation (Sammis et al., 2004). The regression equation was validated using a physiological model, which gave an equation of $Kc = K_{max} \times 1.24ECC$. The Kc equations from this study can help pecan farmers and researchers in getting more accurate estimates of pecan irrigation requirements for open-canopy orchards.

Differences were found between the equations derived through different methods. The physiological model by Gutschick (2006) should be improved by adding advection effects. The ETc data for almonds (Fereres, 1980) may have been overestimated because the ETc estimates may have included drainage and soil evaporation. The ETc data from Johnson et al. (2000 and 2002) may have also been overestimated because their measurements may have included partial soil evaporation.

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