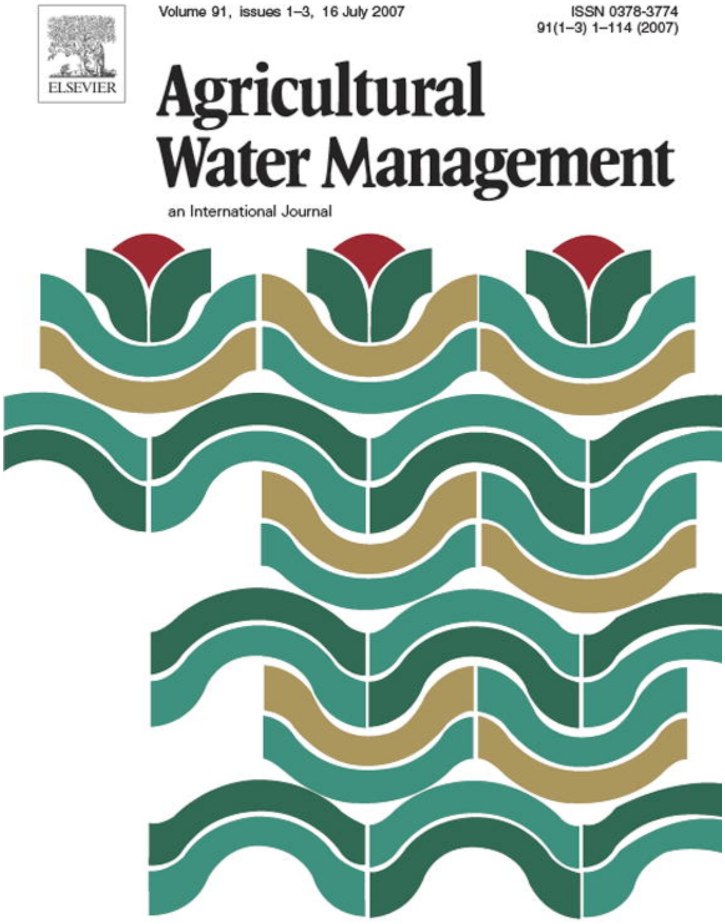
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Energy balance measurements and a simple model for estimating pecan water use efficiency

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ABSTRACT

Plant water use efficiency (WUE) is defined as the net dry matter production (DM) per unit of consumptive water use. It is a vital variable for plant growth, yield, and irrigation-management models. Pecan [Carya illinoinensis (Wangenh.) C. Koch] WUE has been estimated for above ground biomass growth using evapotranspiration (ET) and DM data measured separately in different experiments. The WUE for whole pecan trees (including above and below ground parts), a direct measurement (ET and DM measured in one experiment), and a simple model for WUE based on weather conditions, are currently lacking. A 16.5 m walk-up tower in a flood irrigated pecan orchard, located in the Mesilla Valley of NM, was instrumented with energy budget and eddy flux sensors. Continuous, above canopy measurements of vertical fluxes of sensible heat, H_2O vapor, and CO_2 were made by the eddy covariance technique in growing seasons from 2002 to 2005. ET was calculated from vapor flux. DM production was calculated from CO_2 flux assuming that dry matter of pecan trees was 46.4% carbon.

During the growing seasons (May through November), the mean ET was 122.7 cm (48 inch) per season; the mean dry matter production for the whole trees was 22082.3 kg ha^{-1} (19684.4 lb $acre^{-1}$) per season. The average seasonal water use efficiency for the whole trees was 179.7 kg ha^{-1} cm^{-1} (406.5 lbs $acre^{-1}$ $inch^{-1}$). In 'on' years (high-yield years) 13.8% of the dry matter produced was allocated to the harvested nut crop, while in 'off' years only 8.0% was so allocated. Similarly, the nut WUE as nut yield per unit water used (as cm depth) was higher in 'on' years, at 26.2 kg nuts ha^{-1} cm^{-1} versus 14.9 kg nuts ha^{-1} cm^{-1}. A simple model for monthly WUE (kg ha^{-1} cm^{-1}) as a function of vapor pressure deficit (VPD) and relative humidity (RH) was obtained. It is anticipated that the measured WUE, the simple WUE model, and other data obtained in this study will be useful in developing and validating pecan growth, yield, and irrigation-management models.

1. Introduction

WUE has generally been defined as units of plant growth per unit of evapotranspiration (ET) or consumptive water use. It has been expressed as units of dry matter produced (DM) per unit of water used (Jensen et al., 1981; Begg and Turner, 1976) and as photosynthesis per unit of water transpired (Fischer and Turner, 1978; Sinclair et al., 1984). The term WUE has also been used to

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describe harvested yield per unit of water used (Evans and Wardlaw, 1976). WUE is a vital parameter for plant growth, yield and irrigation-management models. For example, Al-Jamal et al. (2002) developed a Eucalyptus tree irrigation model in which the total tree growth (DM production) was a product of WUE and ET.

In New Mexico, the site of the study reported here, annual WUE has been reported as ranging from 14 kg ha^{-1} cm^{-1} for cotton fiber (Sammis, 1981) to 90 to 140 kg ha^{-1} cm^{-1} for dry alfalfa forage (Abdul-Jabbar et al., 1983). Consequently, reported estimates of WUE can vary by a factor of 10, depending on the definition of WUE used, the type of crop, and what portion of the crop is harvested. WUE can also be affected by weather conditions. For example, Law et al. (2002) found that WUE for forest trees, crops, and grasslands are strongly affected by vapor pressure deficit. Thus the current literature cannot be used to quantify the basic consumptive use - productivity interactions between different fields, crops, and weather.

Pecan water use is greater than that of most row crops. In the arid southwest USA, the portion of irrigation water allocated to pecans is increasing as pecan acreage increases compared to other crops. Using total above ground biomass (including nuts) measured by Kraimer (1998) and ET measured by Miyamoto (1983), a WUE estimate for pecans is 150 kg ha^{-1} cm^{-1}. Based on lower values of seasonal ET measured by Sammis et al. (2004) combined with Kraimer's (1998) data, the WUE estimate is 160 kg ha^{-1} cm^{-1}. But these estimates are based on separate ET and biomass (DM) measured in different experiments, and do not include below ground biomass.

Dry matter production of a plant can be directly measured by drying and weighing the biomass such as in the above-mentioned studies. However, the direct measurements are time and labor intensive and the daily DM production cannot be easily measured. Eddy covariance technology can measure CO_2 assimilation (CO_2 flux) such as in the international network FLUXNET (e.g., Law et al., 2002). Then, the DM production can be estimated from the CO_2 assimilation based on the percentage carbon weight in the plants.

Complex physiological models can be used to calculate WUE by simulating leaf photosynthesis, CO_2 assimilation, DM production, and water use. For example, Gutschick (2007) calculated WUE using CO_2, N, solar radiation, and VPD estimates. The model solves a series of equations describing a combination of carboxylation kinetics, the Ball-Berry model of stomatal control (Ball et al., 1987), the energy balance, and the functional balance for N and carbon gains. However, this model is too complex to be easily built and operated. A simple model for WUE is needed for pecan trees.

The objective of this research was to establish the WUE of flood irrigated pecans, and develop a simple model for WUE based on weather conditions. The WUE was for the whole tree, including above (crown, shoots, and nuts) and below ground parts (roots).

2. Methods

2.1. Site description

The experimental site was located within a pecan orchard (cultivar Western Schley) on a farm south of Las Cruces, NM (latitude: 32.2 N; longitude: 106.8 W; elevation, 1180 m). The orchard consisted of mature pecan trees with an average tree height (h) of 12 m with branches occasionally reaching 15 m. The zero plane displacement, d (m), was estimated as $d = 0.7$ h following the methods reported by Baldocchi and Hutchison (1987) for an almond orchard. The roughness length, z_o (m), was estimated as $z_o = 0.1$ h. The trees were squarely spaced 9.7 m (32 ft) from one another. Wet pecan yields were obtained by weighing the harvested nuts and dry yield was calculated by assuming 12% moisture content. There was little weed cover on the floor of the orchard during the experiments.

The orchard was flood-irrigated at intervals varying from 8 to 21 days, averaging about every 14 days. Irrigations were frequent enough that the soil water potential in the top 20 cm was never below −65 kPa. This practice ensured the plants were never water stressed. Irrigation amounts were measured by calibrated floodgate openings using Hobo^{TM} automated data loggers and sensors (Onset Computer Corporation, Bourne, MA). Table 1 lists the dates and amounts of flood irrigation applied during the four seasons. The farmer applied 320 kg ha^{-1} of actual nitrogen through the irrigation system throughout each growing season.

2.2. Measurements

A 16.5 m (54 ft) tower was constructed within the orchard and instrumented with micrometeorological sensors (Fig. 1). Table 2 lists the sensor information including mounting height, model, manufacturer and parameter measured. The sonic anemometers were carefully leveled and oriented south. Wind statistics were rotated into the mean wind stream for 30 min averaging periods following traditional rotational techniques developed by Tanner and Thurtell (1969) and detailed by Kaimal and Finnigan (1994). Soil heat flux disks were buried 1 cm beneath the soil surface to minimize heat flux divergence (Mayocchi and Bristow, 1995). The soil temperature profile was not measured in this study. The eddy covariance instruments were sampled continuously at 10 hz and 30-min averages were saved in the data logger. A CS500 temperature and relative humidity sensor (Campbell Sci., Inc., Logan, Utah) was placed on top of the tower to collect data for correcting the latent heat, sensible heat, and CO_2 fluxes. The temperature profile of the pecan canopy was measured by placing four thermocouples at four different heights (3, 6, 9, and 13 m).

A Campbell Scientific 23× data logger was used to control the instruments and record the data. A Campbell Scientific 21× data logger was used to control and record the slow response sensors that were sampled at 1-min intervals and averaged for 15 and 30 min periods. All sensors and data loggers were powered by three deep-cycle marine 12 V batteries, and were recharged by solar panels.

Data were continuously acquired from May 1 to November 30, 2002, from April 1 to November 30, 2003, from May 1 to November 30, 2004, and from April 1 to October 30, 2005 with only a few missing periods. Missing data points were estimated by linear interpolation between surrounding data for periods less than 1 h. For periods greater than 1 h and less than three days, data were estimated from values taken at the same time the previous and following days with similar

Table 1 – Flood irrigations to the pecan orchard from 2002 through 2005

2002 Date	Depth (mm)	2003 Date	Depth (mm)	2004 Date	Depth (mm)	2005 Date	Depth (mm)
3/14	115.0	3/24	120.4	3/22	116.8	4/6	146.3
4/17	114.4	4/28	135.4	4/25	111.8	5/2	111.7
5/5	203.6	5/14	139.8	5/16	134.6	5/22	119.8
5/21	122.1	5/20	151.8	5/30	109.2	6/5	118.1
6/3	114.3	5/28	124.3	6/10	160.0	6/18	148.3
6/14	125.2	6/10	124.2	6/21	152.4	6/28	155.1
6/23	115.0	6/16	147.0	7/6	139.7	7/6	115.5
7/4	111.3	6/22	195.9	7/14	127.0	7/15	116.3
7/15	96.8	7/1	119.5	7/23	127.0	7/25	111.7
7/25	95.0	7/9	93.0	8/2	111.8	8/2	110.9
8/5	94.0	7/17	88.0	8/11	111.8	8/10	119.1
8/14	87.9	7/25	93.2	8/24	99.1	8/22	116.7
8/23	81.3	8/2	87.6	9/2	101.6	9/1	N/A[a]
8/30	94.3	8/14	94.2	9/9	96.5	9/14	N/A
9/14	107.2	8/21	92.0	9/17	101.6	9/22	127.2
9/23	80.4	8/28	49.7	9/28	101.6	10/4	73.4
10/4	112.8	9/5	107.1	10/14	88.9	10/24	73.4
10/22	83.6	9/13	101.0	10/27	68.6		
		9/23	75.6				
		10/6	95.4				
		10/22	94.2				
Total	1954.2		2329.5		2059.9		1997.3

[a] N/A: not available.

meteorological conditions. The longest data gap was three days.

A local weather station, Leyendecker Plant Science Research Center Weather Station, NM (weather.nmsu.edu), 3 km southeast of the orchard, measured hourly weather data, including: wind speed ($m\,s^{-1}$) and direction (degree), precipitation (cm), solar radiation ($MJ\,m^{-2}$), humidity (%), air temperature (°C), and soil temperature (°C).

2.3. *Energy budget*

The energy budget of the pecan orchard was considered using the traditional approach:

$$Rn - G = H + LE \quad (1)$$

Fig. 1 – Eddy-covariance instrument tower in the pecan orchard in January 2003.

Here Rn is the net radiation, G is the soil heat flux, H is the sensible heat flux, and LE is the latent heat flux ($W\,m^{-2}$ or $J\,m^{-2}\,s^{-1}$). H and LE fluxes were estimated by eddy covariance using the vertical velocity and the sonic temperature from the CSAT3 along with the H_2O fluctuations from the LI-COR 7500. The signs of H, LE and G were positive away from the orchard floor and Rn was positive toward the surface (net downward flux). We did not count the diurnal storage term in the energy budget. The storage term, when integrated over a diurnal cycle in a forest, can be negligible according to the measurements by Gay et al. (1996). We assumed that this was also the case in the pecan orchard.

2.4. *Sensible heat, evapotranspiration, carbon flux, and energy residual*

Eddy covariance (EC) techniques (Swinbank, 1951; Dyer, 1961) were used to derive H, LE and F_{CO_2} (Garratt, 1992):

$$H = \rho c_p(\overline{w'T_v'}) \quad (2)$$

$$LE = L(\overline{w'r_w'}) \quad (3)$$

$$F_{CO_2} = (\overline{w'[CO_2]'}) \quad (4)$$

where ρ is the density of air ($kg\,m^{-3}$), c_p is the specific heat of air ($J\,kg^{-1}\,K^{-1}$), T_v is the sonic anemometer virtual temperature (Kaimal and Gaynor, 1991) (K), L is the latent heat of vaporization ($J\,kg^{-1}$), r_w is the concentration of water vapor in the air ($kg\,m^{-3}$), $[CO_2]$ is the CO_2 concentration in air ($mg\,m^{-3}$), and F_{CO2} is the net flux of CO_2 ($mg\,m^{-2}\,s^{-1}$). In this paper, a component prime (ʹ) indicates a deviation from the mean

Table 2 – Eddy covariance instrumentation in the pecan orchard

Height above ground (m)	Instrument/Manufacturer	Variable measured	Sampling frequency	Comment
16.5	CSAT3, 3-axis sonic anemometer (Campbell Sci., Inc., Logan, Utah)	Component wind speeds u, v, w ($m\,s^{-1}$)	10 hz	
16.5	LI-COR 7500, open path H_2O-CO_2 sensor (LI-COR Corporate, Lincoln, Nebraska)	CO_2 concentration ($mg\,m^{-3}$) H_2O concentration ($kg\,m^{-3}$)	10 hz	Mounted below CSAT3
16.5	IRTP-P, Infrared thermocouple (Apogee Instruments, Inc., Logan, UT)	Canopy surface temperature (K)	1 min^{-1}	
16	Q 7, net radiometer (Radiation Energy Balance System, Seattle, Washington)	Net radiation ($W\,m^{-2}$)	1 min^{-1}	
16	LI-COR Silicon Pyranometer, (LI-COR Corporate, Lincoln, Nebraska)	Solar radiation ($W\,m^{-2}$)	1 min^{-1}	
−.01	HFT3, 3 Soil heat flux disks (Radiation Energy Balance System, Seattle, Washington)	Soil heat flux ($W\,m^{-2}$)	1 min^{-1}	

and the overbar denotes a time average. Energy residual is calculated as the difference between the LE measured using Eq. (3) and the energy balance using Eq. (1) ($J\,m^{-2}\,s^{-1}$ or $W\,m^{-2}$).

Daily/monthly energy terms Rn, H, G, and LE and the residual (all in $J\,m^{-2}\,d^{-1}$ or $J\,m^{-2}\,month^{-1}$) were calculated by integrating the corresponding measured term ($J\,m^{-2}\,s^{-1}$) over each day /month.

LE was converted to ET ($cm\,s^{-1}$).

$$ET = 100\frac{LE}{L\rho} \tag{5}$$

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

Monthly ET ($cm\,month^{-1}$) was calculated by integrating ET ($cm\,s^{-1}$) throughout each month. Growing season total ET ($cm\,season^{-1}$) was calculated by summing monthly ET from May through November for each year.

Net flux of CO_2 was converted to net dry matter production ($mg\,m^{-2}\,s^{-1}$) by multiplying with 0.593, which was derived from the following:

$$\frac{12\,gC}{44\,gCO_2}\left(\frac{2.17\,gDM}{1\,gC}\right) = \frac{26.1\,gDM}{44\,gCO_2} = 0.593\frac{gDM}{gCO_2}\quad (mg\,m^{-2}\,s^{-1}) \tag{6}$$

where there are 12 g C in 44 g of CO_2 (per mole) and the plant dry matter (DM) is, on average, composed of 46.4% C (i.e. 2.17 g DM per g C,). Shafizadeh (1984) reported the average C weight composition (46.4% C) for tree woody parts. Negi et al. (2003) reported trees in Australia having an average of 45% C (weight) in leaves. Stewart and Silcox (1999) reported that pecan shells are 47.74% C. There are little information in the literature for the C percent composition for fine roots and nutmeat, and new shoots. The average C composition in annual dry matter growth was assumed to be 46.4%.

Consequently, 1 mg $CO_2\,m^{-2}\,s^{-1}$ can produce 0.593 mg DM $m^{-2}\,s^{-1}$. This DM is total DM production including pecans root, tree trunk, leaves, branches and pecan nuts, along with any biomass in the soil other than roots.

Hourly/daily/monthly net DM production ($mg\,m^{-2}\,hour^{-1}$, $kg\,ha^{-2}\,day^{-1}$, $kg\,ha^{-2}\,month^{-1}$) was calculated by integrating DM production ($mg\,m^{-2}\,s^{-1}$) over each hour/day/month. The yearly DM production was calculated from May 1 to November 30. In 2005, because the November ET and DM data were not available, 2004 November data was used for the 2005 yearly ET and DM production calculations.

Daily average night CO_2 flux (net respiration flux) was calculated from 20:00 h to 4:00 h every day. Average daily net respiration flux was obtained by multiplying 1.66 to the corresponding average night CO_2 flux. The parameter 1.66 was derived as the ratio of the whole-day to night-only integrals of exp(0.085Tsoil), which is the soil-temperature (Tsoil) response of respiration, in the short term (Fang and Moncrieff, 2001). This response was, in turn, derived by fitting this exponential form of soil temperature (°C) against the nighttime flux data. Then, average daily net respiration flux was multiplied by 0.593 to convert to a flux representing DM consumption ($mg\,m^{-2}\,s^{-1}$). Monthly DM consumption (R_d) from respiration ($kg\,ha^{-2}\,month^{-1}$) was calculated by integrating the corresponding daily average DM consumption over each month. The monthly total DM production (A) ($kg\,ha^{-2}\,month^{-1}$) was calculated as the summation of net DM production and the DM consumption. The ratio (R_d/A) was calculated for each month to estimate the seasonal variation.

2.5. *Corrections to LE, H, and CO_2 fluxes*

The H was calculated using the sonic virtual temperature (Tv), which is affected by moisture in the air. A CS500 air temperature and humidity sensor (Campbell Sci., Inc., Logan, Utah) was mounted next to the eddy covariance system in order to obtain the vapor pressure in the air, which was used to make moisture corrections to H (Schotanus et al., 1983). In addition to this correction, when the turbulent flux of any constituent is measured by the eddy covariance system, the simultaneous flux of any other entity needs to be taken into account. In particular, heat or water vapor can cause expansion of the air and thus affects the constituent's density and flux. Corrections were done for LE and CO_2 fluxes based on the vapor and heat fluxes' effects on the densities of moist air (Webb et al., 1980).

2.6. *Measured WUE and VPD*

Monthly/yearly WUE ($kg\,ha^{-1}\,cm^{-1}$) was calculated using monthly/yearly net DM production divided by corresponding ET.

At the experimental orchard, the daily VPD was calculated using local weather data from Leyendecker Plant Science Research Center Weather Station, NM (weather.nmsu.edu). The daily VPD was calculated as the average of hourly VPD. Hourly VPD was calculated as the following.

$$\mathrm{VPD} = 0.6108 \times 2.718^{\frac{17.269\times T}{T+237.3}} \times (1 - \mathrm{RH}) \qquad (7)$$

where *T* is the mean air temperature (°C), and RH is the hourly relative humidity (%/%). Monthly average of VPD was calculated for future WUE regression analysis.

2.7. *Complex model simulation*

To obtain a simple model for WUE, the input weather variables and the mathematical form of the equation (exponential, linear, etc.) should be determined. A physiological model by Gutschick (2007) was used to deduce the framework of the mathematical form for WUE. The following simply describes the physiological model structure. The details are described by Gutschick (2007).

This physiological model can calculate WUE by simulating leaf photosynthesis, CO_2 assimilation and water use. The model solves a series of equations describing combination of carboxylation kinetics, the Ball-Berry model of stomatal control (Ball et al., 1987), the energy balance, and the functional balance for N and carbon gains. Standard values of the physiological parameters were used.

(A) Photosynthetic capacity of leaves: 100 μ mol CO_2 m^{-2} s^{-1}.
(B) PAR (Photosynthetic active radiation) absorptivity of leaves: 0.85.
(C) Ball-Berry slope: 10.
(D) Ball-Berry intercept: 0.03 mol m^{-2} s^{-1}.
(E) "Convexity" factor in the shift from light-limited to light-saturated
(F) photosynthetic rate: 0.8.
(G) PPFD (photosynthetic photon flux density): 1000 μ mol
(H) photons m^{-2} s^{-1}.
(I) Ca (CO_2 partial pressure in the canopy), on average: 34 Pa.

2.8. *Simple model*

The input weather variables and mathematical form for the WUE simple model was derived according to the theory presented by Gutschick (2007). The procedure is as follows.

$$\mathrm{WUE} = \frac{\mathrm{A} - \mathrm{R_d}}{\mathrm{E}} = \frac{\mathrm{A}}{\mathrm{E}}\left(1 - \frac{\mathrm{R_d}}{\mathrm{A}}\right) \qquad (8)$$

where A is plant CO_2 assimilation, R_d is plant and soil respiration, and E is plant transpiration (we ignore the soil evaporation here and it is generally small because of the large attenuation of both Rn and u near the ground under canopies).

$$\frac{\mathrm{A}}{\mathrm{E}} = \frac{g_s'(\mathrm{C_a} - \mathrm{C_i})}{g_s(e_i - e_a)} = \frac{0.62\mathrm{C_a}(1 - \mathrm{C_i}/\mathrm{C_a})}{\mathrm{VPD_{Leaf}}} \qquad (9)$$

g_s is stomatal conductance per unit leaf area for water vapor, g_s' is stomatal conductance per unit leaf area, for CO_2 (=0.62 × g_s), C_i and C_a are leaf-interior and exterior partial pressures of CO_2, e_i and e_a are leaf-interior and exterior partial pressures of water vapor. We set $\mathrm{VPD_{Leaf}} = e_i - e_a$, where $\mathrm{VPD_{Leaf}}$ is the vapor pressure deficit between the leaf interior and the air.

$$VPD_{Leaf} - VPD = e_i - e_a - (e_s(T) - e_a) = e_i - e_s(T) \qquad (10)$$

$e_s(T)$ is saturation vapor pressure when air temperature is *T*.

$$e_i - e_s(T) = [T_{leaf} - T] \times \frac{d(e_s(T))}{dT} \qquad (11)$$

From our measured canopy temperature compared to air temperature, T_{Leaf}–*T* is close to 0. This is similar to the finding of Campbell and Norman (1998) where T_{Leaf}–*T* ranges from 0 to 1.2 °C if leaf characteristic dimension is 5 cm, air temperature is 30 °C, *u* = 1 m s^{-1}, and RH = 0.2.

Then Eq. (9) can be written as:

$$\frac{\mathrm{A}}{\mathrm{E}} = \frac{0.62\mathrm{C_a}(1 - \mathrm{C_i}/\mathrm{C_a})}{VPD} \qquad (12)$$

There is a normal response of C_i/C_a to the environment, particularly to relative humidity or VPD (Ball et al., 1987). High VPD (low humidity) tends to close stomata. To find the relationship between C_i/C_a and VPD and humidity, Gutschick's model was run using our monthly weather data (air temperature, relative humidity, wind speed, and solar radiation) (total 26 cases). C_i/C_a in the model is highly correlated to relative humidity (R^2 = 0.84, Fig. 2) and not strongly related to VPD (R^2 = 0.25, Fig. 3).

Then, we derive a new equation.

$$\frac{\mathrm{A}}{\mathrm{E}} = \frac{0.62\mathrm{C_a}(1 - 0.86RH - 0.3)}{VPD} = \frac{0.62\mathrm{C_a}(0.7 - 0.86RH)}{VPD} \qquad (13)$$

Now, R_d/A in Eq. (8) needs to be determined. We found R_d/A (average = 0.67) did not vary much over the study period (Fig. 4).

Eq. (8) can be written as:

$$\mathrm{WUE} = \frac{\mathrm{A}}{\mathrm{E}}\left(1 - \frac{\mathrm{R_d}}{\mathrm{A}}\right) = a\frac{\mathrm{C_a}(0.7 - 0.85RH)}{VPD}0.33 \qquad (14)$$

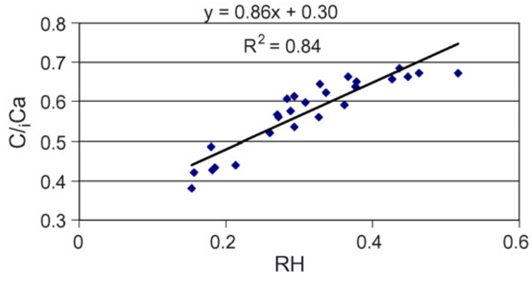

Fig. 2 – The relationship between C_i/C_a and relative humidity (RH) for pecan trees simulated by the physiological model in Gutschick (2007). C_i and C_a are leaf-interior and exterior partial pressures of CO_2.

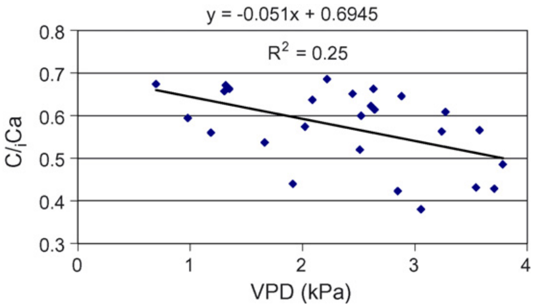

Fig. 3 – The relationship between C_i/C_a and vapor pressure deficit (VPD) for pecan trees simulated by the physiological model in Gutschick (2007). C_i and C_a are leaf-interior and exterior partial pressures of CO_2.

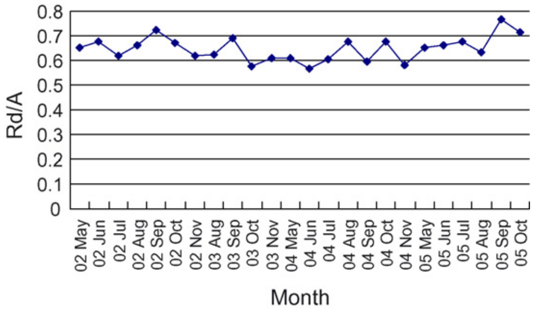

Fig. 4 – R_d/A variation with month from 2002 through 2005 in the pecan orchard. Monthly dry-matter consumption (R_d) from respiration (kg ha^{-2} month^{-1}) was calculated by integrating the corresponding daily dry-matter consumption (calculated from CO_2 flux) over each month. The monthly total dry-matter production (A) (kg ha^{-2} month^{-1}) was calculated as the summation of net dry-matter production (calculated from CO_2 flux) and the dry-matter consumption. Data during April to July 2003 were not included because of CO_2 sensor calibration problems.

where a is a constant. Assuming monthly C_a (CO_2 partial pressure in the canopy) is similar during a growing season, we set (0.7–0.85RH)/(*VPD*) as the independent variable and the intercept as 0 and then a regression equation for WUE was determined. All the data from May to November (excluding May to July of 2003) were used for the regression analysis. Residual analysis and F test were conducted for this equation to check if it was statistically significant. All the statistical analyses were conducted using MINITAB (2000).

3. Results and discussion

3.1. Energy budgets

Typical seasonal energy budgets presented in Fig. 5 show that ET (LE in the figure) increased sharply from April to June and peaked in June in response to the available radiation and increasing leaf area. Fig. 6 also gives monthly ET totals in the four experimental years and supports the above statement.

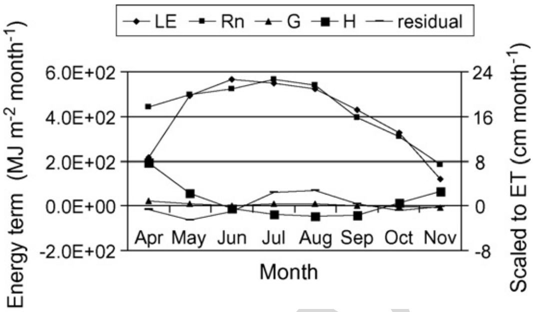

Fig. 5 – Typical seasonal energy budgets of the pecan orchard (2003 growing season). LE: latent heat flux, Rn: net solar radiation, G: soil heat flux, H: sensible heat flux, and residual = Rn-G-H-LE.

Energy budgets from this orchard for 2001 and 2002 were reported by Sammis et al. (2004), where LE was estimated as the residual of the energy budget (Eq. (1)) and an one-propeller eddy covariance (OPEC) system (Blanford and Gay, 1992) was used to measure sensible heat flux. The LE fluxes measured in this study during 2002 were 8% higher in June, 10% higher in July, 2% higher in August, and 15% higher in September than LE in the same orchard in the same year (Sammis et al., 2004).

The differences may be explained by several possible causes. One cause may be that the OPEC system may have produced erroneous estimates of H, which then led to erroneous LE. In order for the OPEC system to work correctly, the conditions have to be right: larger eddies of medium to low frequency, which typically precludes nighttime data. Another cause may be error in the flux measurements by the eddy covariance technique, especially at night when stable conditions result in eddies smaller than the path lengths of the sonic anemometer and the LI-COR 7500.

We also compared our monthly LE fluxes (ET) to those reported by Miyamoto (1983). Our data were slightly lower than those reported by Miyamoto (1983), who used soil moisture depletion measurements. Based on the comparisons, our measured ET seemed reasonable.

Fig. 5 demonstrates a positive residual (error) in the energy budget closure during the summer months. The soil heat flux plates were buried 1 cm beneath the ground in this study. It may have had errors in measuring the soil surface heat flux

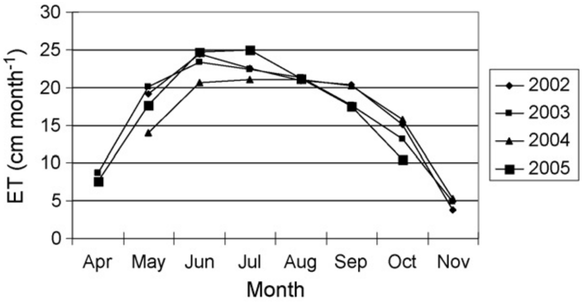

Fig. 6 – Monthly values of evapotranspiration (ET) of pecan trees during 2002–2005 growing seasons measured by eddy covariance technology.

Table 3 – The total amount (mm) of precipitation and irrigation in the pecan orchard in selected months during 2002–2005

	2002	2003	2004	2005
May	327.7	415.9	135.9	243.2
June	354.5	492.1	321.0	421.5
September	286.2	283.7	436.1	N/A[a]
October	218.2	189.6	282.0	183.6

[a] N/A: not available.

and partially contributed to the non-zero residual. Wilson et al. (2002) showed that at 22 FLUXNET sites, there was a general lack of closure at most sites, with a mean imbalance in the order of 25%. The closure in this study was improved because LI-COR 7500 was calibrated relative to a Krypton Hygrometer (KH20, Campbell Sci., Inc., Logan, Utah).

Fig. 6 shows that 2004 ET estimates in May and June were lower than in the other three years; and 2002 and 2004 ET estimates in September and October were higher than in 2003 and 2005. These can be partially explained by the irrigation and precipitation amounts. In 2004 May and June, the irrigation and precipitation amounts were lower than in the other three years (Table 3). This may have caused 2004 May and June ET to be lower than the other three years. In 2002 and 2004 September and October, the irrigation and precipitation amounts were higher than in 2003 and 2005 (September data was missing from 2005). This may have caused the ET to be higher in September and October of 2002 and 2004 than in the months of 2003 and 2005.

An example of the daily course of the energy budget terms can be seen in Fig. 7, which shows four clear sky days from June 21^{-2}4, 2002. Note that the net radiation (R_n) approaches 790 W m^{-2} (J m^{-2} s^{-1}) at midday and −100 W m^{-2} immediately after sunset. The average latent heat flux (LE) at midday is about 700 to 790 W m^{-2} and the latent heat curve lags the net radiation by about an hour. Small amounts of soil evaporation (well irrigated orchard) occur every night with maximum values approaching 100 W m^{-2} (LE) when the air is moving. Stoughton et al. (2002) showed that H is generally a much smaller term than LE when water for evapotranspiration is plentiful in a pecan orchard, and this orchard is no exception.

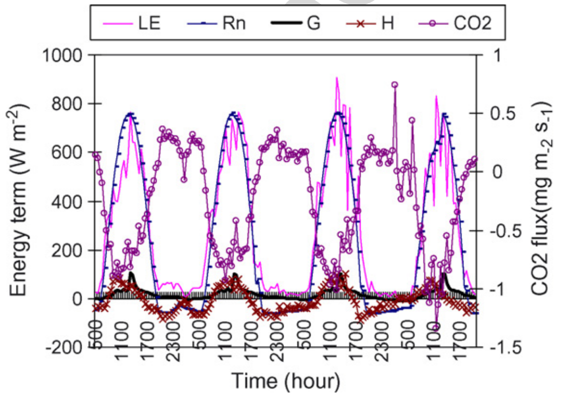

Fig. 7 – Diurnal energy budgets and CO_2 flux of the pecan orchard for June 21–24, 2002. LE: latent heat flux, Rn: net solar radiation, G: soil heat flux, and H: sensible heat flux.

Sensible heat is produced in the mornings and fluxes are out of the orchard (positive, upward flux). It is absorbed by the orchard in the afternoons and nights (negative, downward flux). Downward sensible heat flux in this situation is often called ‘‘oasis advection of sensible heat’’. The temperature profile measurements for the pecan orchard showed that the temperature increased with height at nighttime. The wind speed was high (3–4 m s^{-1} during nighttime periods shown in Fig. 7), giving a high aerodynamic conductance. The combination of the vertical temperature gradient and the conductance (high wind speed) generated a negative H. During nighttime, leaves did not transpire; the downward sensible heat flux was larger than LE (Fig. 7) and may have provided some energy for soil surface evaporation (the orchard was well irrigated).

The soil heat flux is a significant value in this orchard with values approaching 100 W m^{-2} of energy absorbed by the soil during midday (G positive) and ~30 W m^{-2} released most nights. When integrated over the entire day the three soil heat flux plate measurements were similar, indicating spatial variation in soil heat flux is averaged out in the 24 h totals.

3.2. *Orchard gas exchange*

Both ET and CO_2 assimilation are dependent on stomata activity in the pecans. Fig. 7 shows the diurnal course of CO_2 assimilation (DM production) by the orchard during the four days. The sign convention used herein makes CO_2 flux negative during the day (downward flux) and generally positive at night (upward flux). Unlike the latent heat flux which is driven by the available energy through the day, the daytime rates of CO_2 assimilation by the orchard increase from 0 at sunrise to a maximum 3–5 h later and then decreases steadily to zero at sunset on every clear day.

The daytime net absorption of CO_2 was much larger than the nighttime emissions (Fig. 7), as expected, thus resulting in net absorption over 24 h periods. Gross assimilation was 1.5 times respiration ($R_d/A = 0.67$). It is of interest that the long-term trend of R_d/A is near-constancy across months; respiration shows acclimation to mean temperature (Fig. 4, Wythers et al., 2005).

Fig. 8 shows the typical daily LE and DM production during a growing season. The DM production was not the directly measured weight of the biomass; instead it was calculated based on the CO_2 flux and the percentage carbon weight in pecan trees. Fig. 8 shows considerably more scatter in the daily total DM data than in the latent heat flux data, even though both are partially dependent on the same stomata activity in the pecan trees. Fluctuating atmospheric concentrations of CO_2 and continuous soil and plant respiration are factors affecting the CO_2 flux that are independent of the stomata (Buchmann et al., 1996; Kondo et al., 2005). The factors affecting the latent heat flux are those that supply energy for evapotranspiration. Radiant energy is the primary energy source that is independent of the stomata. In this desert environment the R_n is consistent, compared to other locations, and the orchard was well irrigated (no stress variations), therefore LE is considerably less variable day to day than the CO_2 flux.

Figs. 6 and 9 show the monthly totals of LE and DM in the four experimental years (DM data in April to July 2003 were not included because the CO_2 sensor had calibration problems). In

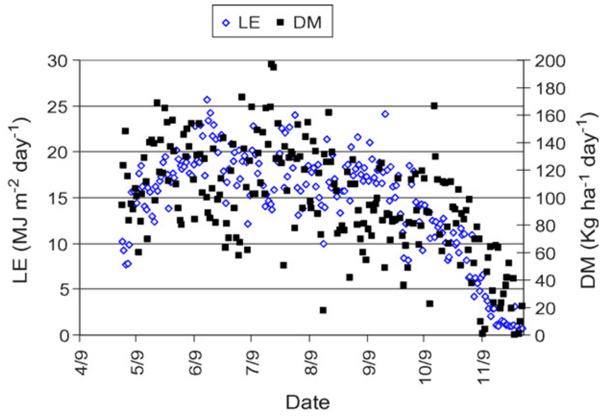

Fig. 8 – Typical daily values of latent heat flux (LE) and dry matter (DM) production of pecan trees in 2002 growing season. DM production was calculated from CO_2 flux assuming that dry matter of pecan trees was 46.4% carbon. LE and CO_2 flux was measured by eddy covariance technology.

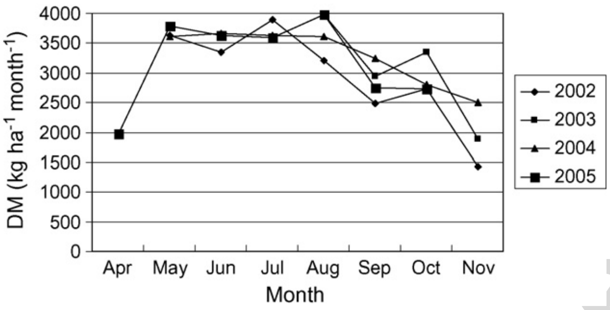

Fig. 9 – Monthly values of dry matter (DM) production of pecan trees during 2002–2005 growing seasons. Data in months of April to July in 2003 were not included. DM production was calculated from CO_2 flux assuming that dry matter of pecan trees was 46.4% carbon. CO_2 flux was measured by eddy covariance technology.

April, pecan trees were in the leaf out stage and ET rates and DM production were low. During May to August, leaves were fully developed and there was high radiation, consequently, the DM and ET were high during these months. From September to November, solar radiation decreased, as did ET and DM. During the growing seasons in the four years (May to November), the mean ET was 122.7 cm per season and the standard deviation was 3.0 cm per season; the mean dry matter production was 22082.3 kg ha^{-1} (19684.4 lb $acre^{-1}$) and the standard deviation was 1190.1 kg ha^{-1} (1060.9 lb $acre^{-1}$).

3.3. *Water use efficiency*

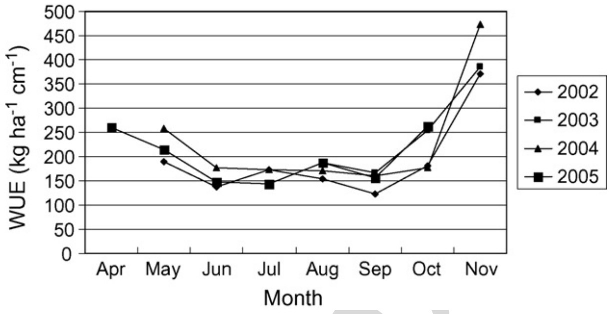

Fig. 10 – Monthly values of Water Use Efficiency (WUE) of pecan trees measured by eddy covariance technology during 2002–2005 growing seasons. Data in months of April to July in 2003 were not included because of CO_2 sensor calibration problems.

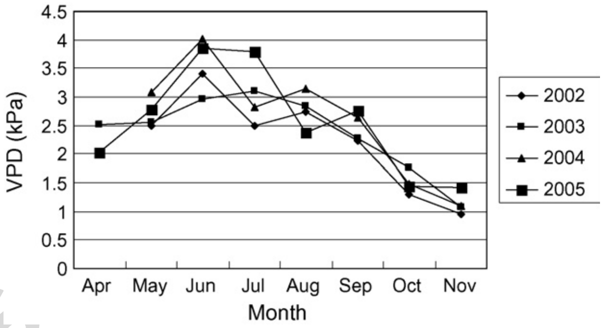

Fig. 11 – Monthly values of Vapor Pressure Deficit (VPD) in the pecan orchard during 2002–2005 growing seasons.

Fig. 10 shows the monthly average of WUE was about 260 kg ha^{-1} cm^{-1} at the beginning of the growing seasons, decreasing to ~120 to 200 during the growing season and returning to high values, 360–470 kg ha^{-1} cm^{-1} at the end of the season. The higher water use efficiency at the beginning and end of the seasons is partially due to lower water flux at the leaf-level in response to lower vapor pressure deficits (VPD) (Figs. 10 and 11). The international network FLUXNET measured the net CO_2 flux and LE flux at different sites during the day and then calculated a WUE as the difference between the net CO_2 flux and the daytime ecosystem respiration divided by the water flux (gross ecosystem production, GEP). These studies showed a decrease in WUE with an increase in VPD (Law et al., 2002). Gutschick (2007) model simulations also supported the above remark (Fig. 12) and proved our measured WUE was reasonable.

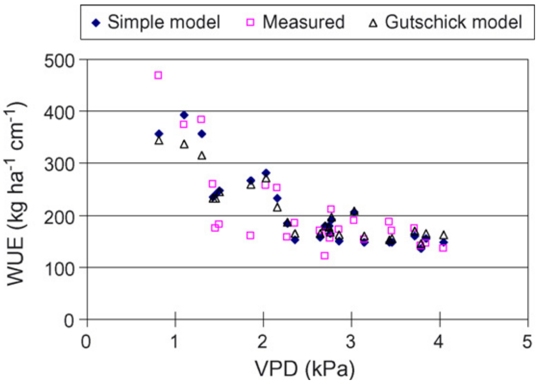

Fig. 12 – Measured and predicted monthly mean water use efficiency (WUE) of pecan trees against vapor pressure deficit (VPD). Predicted values are from the simple regression model and Gutschick (2007) complex physiological model.

The eddy covariance measurements in this study were used to estimate the combined above and below ground biomass production, which was used in calculating WUE. The average seasonal water use efficiency (May to November) was 179.7 kg ha^{-1} cm^{-1} (406.5 lbs acre^{-1} inch^{-1}) and the standard deviation was 22.5 kg ha^{-1} cm^{-1} (50.8 lbs acre^{-1} inch^{-1}). Consequently these are 25–35% higher than previous WUE estimates (150–160 kg ha^{-1} cm^{-1}), which included only above ground biomass. Thus, it appears that about 25–35% of the total seasonal tree growth was in the roots.

The pecan nut yield (dry weight) was 2106, 3239, 1557, and 3256 kg ha^{-1} in 2002, 2003, 2004, and 2005, respectively. In 'on' years (2003 and 2005), 13.8% (standard deviation = 4.2%) was allocated to the harvested nut crop and in 'off' years (2002 and 2004) 8.0% (standard deviation = 1.7%) was allocated to the harvested nut crop. The 2005 ('on' year) DM production data from May to July was used for the same period in 2003 ('on' year), in lieu of outliers in 2003 caused by faulty calibration of CO_2 sensors.

The average water use efficiency based on nut yield was 14.9 kg nut yield ha^{-1} cm^{-1} (standard deviation = 2.6 kg nut yield ha^{-1} cm $^{-1}$) in 'off' years and 26.2 kg nut yield ha^{-1} cm^{-1} water (standard deviation = 0.4 kg nut yield ha^{-1} cm^{-1}) in 'on' years.

3.4. Simple model for WUE

Given below is the derived form of the simple model for WUE.

$$\mathrm{WUE} = 1095 \times \frac{(0.7 - 0.86RH)}{\mathrm{VPD}} \tag{15}$$

The residual analysis and F test ($F = 634.34$, $P < 0.001$, $R^2 = 0.74$) show that the equation is significant. Using our VPD and RH data inputs, predictions from the equation are shown in Fig. 12 (because VPD was calculated from and correlated to RH, only the plot of WUE vs VPD is shown). This figure shows that when VPD is high (RH is low), WUE is low. Higher VPD can result in stomatal closure and decreased WUE (Law et al., 2002; Gutschick, 2007).

WUE for pecan DM and pecan nut yield would be greater in southeastern states such as Georgia where the VPD would be lower during the growing season compared to southern New Mexico. One hypothesis is that the simple model presented in Fig. 12 can be used to estimate WUE of pecans at other locations, such as Georgia. However, the hypothesis needs to be evaluated in future studies.

In the derivation of the simple model, C_i/C_a (the ratio of leaf-interior and external partial pressures of CO_2) was found to be highly correlated with relative humidity ($R^2 = 0.84$, Fig. 2) but was not strongly related to VPD ($R^2 = 0.25$, Fig. 3). This agrees with the conclusions of Gutschick and Simonneau (2002) and Gutschick (2007), that the Ball-Berry model (using leaf surface humidity) is generally better than the Leuning (1995) or Dewar (1995) models that use VPD.

We attempted to exclude November data (at the end of the growing seasons) in our regression. However, the R^2 decreased to 0.4. Nevertheless, this is still better than what Law et al. (2002) obtained across one type of ecosystem (e.g. grassland). Considering that significant DM production occurred in November, we included the data in the final regression analysis (Eq. (15)). Leaf stomatal control and carboxylation capacity may be different in these months than the months before. We have only partial data on these months and, in the future, a better model that includes degree days to distinguish different growth phases will be needed.

A non-mechanistic regression equation for WUE was also obtained with a high $R^2 = 0.82$ and $P < 0.01$ (F test).

$$\mathrm{WUE} = 146 + \frac{839}{\mathrm{VPD}} \exp(-0.09T) \tag{16}$$

Although the R^2 of the equation is higher than the mechanistic one, the mechanistic equation is recommended. Although the non-mechanistic equation fits the experimental data better, it may not fit other experimental data well. The mechanistic model was derived based on physiological principles and should be more robust (i.e. applicable at different locations) than the non-mechanistic model.

4. Conclusions

During the 2002 to 2005 growing seasons, mean pecan ET was 122.7 cm (48 inch) per season; mean dry matter production for the whole pecan trees was 22082.3 kg ha^{-1} (19684.4 lb acre^{-1}) per season. The average seasonal water use efficiency for the whole trees was 179.7 kg ha^{-1} cm^{-1} (406.5 lbs acre^{-1} inch^{-1}). Dry matter allocation to nuts averaged 13.8% in the high-yielding 'on' years (2003 and 2005) and 8.0% in the lower-yielding 'off' years (2002 and 2004). Corresponding nut yield WUE values were 26.3 kg nut yield ha^{-1} cm $^{-1}$ in the 'on' years and 14.9 kg nut yield ha^{-1} cm^{-1} in the 'off' years.

A simple model for monthly pecan WUE (kg ha^{-1} cm^{-1}) as a function of VPD and RH was obtained (WUE = 1095 × ((0.7–0.86RH)/(VPD)), $R^2 = 0.74$, $F = 23.39$, $P < 0.001$). This model, derived from data measured at the Mesilla Valley in New Mexico, may possibly be used at other locations. However, this hypothesis must be tested with data from other locations. We anticipate that the measured WUE, the simple WUE model, and other data obtained in this study will be useful in developing and validating pecan growth, yield, and irrigation-management models.

Finally, it appears that energy budget estimates of ET using the OPEC system should be calibrated against an eddy covariance system over the crop canopy under consideration to avoid underestimates of ET.

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