Midday Stem Water Potential Values Needed to Maintain Photosynthesis and Leaf Gas Exchange Established for Pecan

Yahia Othman

Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003

Dawn VanLeeuwen

Economics, Applied Statistics and International Business, New Mexico State University, Las Cruces, NM 88003

Richard Heerema and Rolston St. Hilaire¹

Plant and Environmental Sciences, New Mexico State University, 127 N. Skeen Hall, Las Cruces, NM 88003

ADDITIONAL INDEX WORDS. *Carya illinoensis*, drought, irrigated agriculture, water relations

ABSTRACT. Demand for New Mexico's limited water resources coupled with periodic drought has increased the necessity for tree water status monitoring to guide irrigation scheduling of pecan (*Carya illinoensis*) orchards. The objectives of this study were to assess the impact of water status developed during the flood irrigation dry-down cycles on photosynthesis (P_n), and gas exchange [stomatal conductance (g_s) to H_2O (g_{H_2O}), transpiration (E), and intercellular CO_2 (c_i)] and to establish values of midday stem water potential (Ψ_{smd}) that are needed to maintain P_n and gas exchange of pecan. We conducted the study simultaneously on two southern New Mexico mature pecan orchards from 2011 through 2013. Flood irrigation as determined by grower practice was used on both orchards and P_n , g_{H_2O} , E , and c_i were assessed at Ψ_{smd} of -0.4 to -2.0 MPa. Photosynthesis and gas exchange were higher in pecan trees shortly after irrigation than trees exhibiting water deficit near the end of a flood irrigation dry-down cycle. The decline in P_n was markedly noticeable when Ψ_{smd} dropped below -0.9 MPa. We attributed the reduction in P_n mostly to stomatal limitation. The decline in P_n and g_{H_2O} exceeded 50% when Ψ_{smd} ranged from -1.5 to -2.0 MPa. For those reasons, we recommended that pecan orchards be maintained at Ψ_{smd} higher than -0.90 MPa to prevent significant reductions in carbon assimilation and gas exchange.

With the prediction of rising global air temperatures, drought may become more frequent and severe in areas where problems with water resources already exist (Wujeska et al., 2013). New Mexico has an arid to semiarid climate. Mean annual precipitation is 200 mm and average annual temperature is 20 °C. Pecan is one of the most important agricultural crops in New Mexico. In 2012, New Mexico produced 31.3 million kilograms of pecan nuts (in-shell basis), which accounted for $\approx 23\%$ of the U.S. production [U.S. Department of Agriculture (USDA), 2012]. However, the extreme demand for water coupled with periods of drought and increasing pecan acreage has reduced the available water for irrigating pecan (Johnson, 2004; Samani et al., 2011). Because of ongoing drought in the Rio Grande Basin, irrigation districts have allocated much less water to farmers than in the past. Farmers in the region recently have been forced to rely heavily on water pumped from wells to irrigate orchards. Orchards without available well water have not been irrigated adequately and typically have died.

Pecan requires adequate water for development of the nut. Pecan nut development can be divided into two stages: nut

sizing and kernel filling (Wells et al., 2007). In nut sizing, the nut enlarges and the volume of endosperm increases (Herrera, 1990). Water deficit during nut sizing diminishes the ability of pecan roots to extract soil water and this reduces growth and nut size and increases nut split (Wells et al., 2007). Low soil moisture during this stage also reduces embryo development, resulting in poor kernel fill (Herrera, 1990; Wells et al., 2007).

Drought reduced pecan yield 5% to 24% when the applied water was reduced from 5% to 52% relative to control (Garrot et al., 1993). Root growth and number of growing roots of black walnut (*Juglans nigra*) approached zero as soil water potential ranged from -0.5 to -1.0 MPa (Kuhns et al., 1985). Yield of almond (*Prunus dulcis*) trees exposed to water deficits decreased 7.7 kg/tree for each 1-MPa decline in midday stem water potential below -1.2 MPa during the previous growing season (Esparza et al., 2001). Midday stem water potential of -0.7 to -1.4 MPa reduced fruit relative yield percentage of apple (*Malus $\times$ domestica*) trees (bearing medium cropload) by less than 15%, whereas Ψ_{smd} of -1.5 to -3.0 MPa reduced the fruit relative yield by 20% to 100% (Naor et al., 2008).

Stomatal closure is among the first processes to occur in the leaf in response to water deficit (Cifre et al., 2005). As plants transition from no or low water deficit to moderate plant water deficit, g_s generally declines into the 0.05 to $0.15 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ H_2O range, photosynthesis and intercellular CO_2 decrease slightly, and stomatal limitations to gas exchange dominate (Cifre et al., 2005). At severe water deficits (g_s less than $0.05 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ H_2O), P_n further decreases and c_i increases indicating that

Received for publication 28 Apr. 2014. Accepted for publication 30 May 2014. A contribution of the New Mexico State University Agricultural Experiment Station.

We thank Cameron Radosevich for his help with collecting field data. We also thank Caiti Steele, Sanjit Deb, Theodore Sammis, Vince Gutschick, and Salim Bawazir for their critical reviews of this manuscript. We acknowledge Mr. Midray Clark for allowing us to use his pecan orchard.

¹Corresponding author. E-mail: rsthilai@nmsu.edu.

non-stomatal limitations become significant (Cifre et al., 2005). However, the water stress study of Cifre et al. (2005) was conducted on grapevine (*Vitis vinifera*). Information on P_n and gas exchange in response to water stress of mature pecan trees is practically non-existent. When red oak (*Quercus rubra*) leaf water potential was between -1.5 and -2.0 MPa, CO_2 assimilation reduction relative to control trees was 60% (Weber and Gates, 1990). Subjecting rubber trees (*Hevea brasiliensis*) seedlings to water deficit decreased gas exchange and hydraulic conductivity parameters. However, these variables had recovered to control levels after 5 d of rewatering (Chen et al., 2010).

Irrigation scheduling is the process used to determine when to irrigate the orchard, how much water to apply, and improve orchard irrigation efficiency in agricultural areas (Food and Agriculture Organization of the United Nations, 1996). Timing of irrigation usually requires continuous monitoring of the variables that best represent moisture status of trees and applying irrigation only when such a variable drops below a certain threshold value (Cifre et al., 2005). However, most New Mexico pecan growers use the calendar and soil moisture “by feel” to schedule irrigation (Kallestad et al., 2008). Less than 3% of New Mexico growers refer to plant and soil moisture-sensing devices to schedule irrigation (Kallestad et al., 2008; USDA, 2008). This could be attributed to the inconsistent results of these instruments during the growing season. Midday stem water potential has been proposed as a precise plant water status indicator for scheduling irrigation of pecan orchards (Othman et al., 2014). Klein et al. (2001) showed that the threshold Ψ_{smd} value for leaf persistence in mature almond trees was -1.8 MPa. At this level of Ψ_{smd} , the decline in P_n and g_s was 30% and 20%, respectively. However, no report we are aware of has established water deficit thresholds for irrigating field-grown pecan while linking the irrigation threshold to precise pecan growth and development functions.

Under field conditions, water deficit develops gradually over an irrigation cycle rather than suddenly like in most studies designed to assess the impact of drought on trees (Damour et al., 2009). In fact, Poorter et al. (2012) cautioned that water deficit studies that are conducted on plants grown in small containers or pots may lead to sudden drought and plant nutrient deficiency, which are unlikely to occur under field conditions. In a previous study (Othman et al., 2014), leaf-level physiological measurements were made during the cyclic irrigation to determine which of these leaf-level parameters best represented changes in moisture status.

We concluded that of the leaf-level physiological response variables tested, Ψ_{smd} was the best for detecting moisture status in pecan. Therefore, Ψ_{smd} was used as a water deficit reference against which to test the responses of P_n and gas exchange variables. The objectives of this field study were to 1) assess the impact of water status developed during the flood irrigation dry-down cycles on P_n and gas exchange; and to 2) establish values of Ψ_{smd} that are needed to maintain P_n and gas exchange of pecan. These data could determine water deficit thresholds of Ψ_{smd} needed for irrigation scheduling in pecan orchards.

Materials and Methods

STUDY SITES. The primary study was conducted on two mature pecan orchards in the Mesilla Valley near Las Cruces, NM, from 20 May 2011 to 7 Oct. 2012. One orchard was at New Mexico State University’s Leyendecker Plant Science Research Center [Leyendecker (lat. $32^\circ 12' 01.14''$ N, long. $106^\circ 44' 30.32''$ W, elevation 1173 m)] and the other was at a commercial farm [La Mancha (lat. $32^\circ 17' 06.25''$ N, long. $106^\circ 50' 04.26''$ W, elevation 1185 m)] (Fig. 1). Photosynthesis measurements recorded in 2013 were used to validate the models derived from the primary study, which was conducted

Fig. 1. Study locations in the Mesilla Valley, NM. Pecan orchards (in 2012) appear in black and Mesilla Valley land area appears in gray.

from 2011 to 2012. Nut production (in-shell) and total irrigation (millimeters per year) data were collected from 2010 to 2012 at La Mancha and from 2009 to 2012 at the Leyendecker orchard.

Trees from the Leyendecker orchard (4 ha) were 20 to 30 years old, 7 to 9 m high, and planted at a spacing of 6 to 7 m within rows and 8 m between rows. La Mancha (7 ha) trees were ≈ 30 years old, 9 to 11 m high, and spaced at 6 to 7 m within rows and 8 to 10 m between rows. Both orchards were comprised of rows 'Western' pecan (75%) and pollenizer rows of 'Wichita' pecan (25%). All measurements were made on 'Western'.

Leyendecker trees were grown in Armijo clay loam soil (fine, montmorillonitic, thermic Typic Torrierts) (USDA, 1980). The Leyendecker orchard was flood-irrigated every 3 weeks from April to October of both years and the total water applied per irrigation was ≈ 160 mm. Urea (46N-0P-0K) at the rate of $225 \text{ kg} \cdot \text{ha}^{-1}$ and zinc sulfate (foliar spray) at the rate of $7 \text{ kg} \cdot \text{ha}^{-1}$ were applied once in May of both years. The La Mancha orchard was commercially managed. Soils at La Mancha are Brazito very fine sandy loam, thick surface (mixed, thermic Typic Torripsamments) (USDA, 1980). Urea at the rate of $250 \text{ kg} \cdot \text{ha}^{-1}$ and zinc sulfate (foliar spray) at the rate of $8 \text{ kg} \cdot \text{ha}^{-1}$ were applied once in May and July of both years (i.e., 500 and $16 \text{ kg} \cdot \text{ha}^{-1}$ per year of urea and zinc sulphate, respectively). The field was flood-irrigated every 16 to 20 d from May to October of both years and the total water applied per irrigation was ≈ 162 mm.

METEOROLOGICAL DATA. For both orchards, rainfall data were obtained from the Leyendecker Plant Science Research weather station, 90 m north of the Leyendecker orchard, and the Fabian Garcia Science Center weather station, ≈ 6 km southeast of the La Mancha orchard. Air temperature, relative humidity, wind speed, and net radiation were recorded by instruments fixed on a 7.5-m tower above the orchard floor at Leyendecker and on a 9.0-m tower at La Mancha. A detailed description of all microclimatic instruments used in both orchards can be found in Othman et al. (2014). Vapor pressure deficit was determined using the equations of Murray (1967). Meteorological data of both orchards are given in Figure 2.

PHYSIOLOGICAL MEASUREMENT TIMING AND IRRIGATION TREATMENT. Ten trees within each orchard were selected randomly for plant physiological measurements (Ψ_{smd} , P_n , E ,

Fig. 2. (A) Daily air temperature, (B) precipitation, (C) relative humidity, and (D) vapor pressure deficit of two Mesilla Valley, NM, pecan orchards, La Mancha and Leyendecker during the experimental period (Apr. 2011 to Nov. 2013).

$g_{\text{H}_2\text{O}}$, and c_i). Measurements were made during and after prescribed flood irrigations of the orchards. All measurements were taken between 1100 and 1300 HR from four fully expanded leaves. At both orchards, measurements were made weekly during an irrigation dry-down cycle to capture a range of pecan water status conditions (Table 1). We then selected the irrigation cycles during a period when leaves were fully expanded, presenescent, and weather conditions permitted consistent and uninterrupted gas exchange measurements within a complete measurement cycle. Irrigation was withheld for 2 months in 2013 (16 Aug. to 17 Oct.) at the Leyendecker orchard to ensure the imposition of severe water deficit stress.

MIDDAY STEM WATER POTENTIAL. We measured Ψ_{smd} on two fully expanded compound leaves on the lower shaded part of each tree and close to the trunk (≈ 2 m from the soil surface) with a pressure chamber (PMS Instrument Co.,

Table 1. Mean midday stem water potential ($n = 10$) and the selected field measurements dates for two southern New Mexico pecan orchards subjected to cyclic flood irrigation from May 2011 to Oct. 2013.^z

Orchard	Year	Week no.	Cycle no. and date ^y		
			Midday stem water potential (MPa)		
La Mancha	2011		I (30 June to 19 July)	II (4 Aug. to 20 Aug.)	III (21 Sept. to 7 Oct.)
		1	−0.54	−0.52	−0.45
		2	−1.30	−1.35	−1.06
	2012	3	−1.66	Irrigation	Irrigation
			I (10 May to 31 May)	II (4 June to 25 June)	III (27 July to 12 Aug.)
		1	−0.50	−0.70	−0.5
		2	−1.20	−1.15	−0.75
		3	−1.80	−1.80	−1.1
	2013		I (16 Aug. to 7 Sept.)	II (8 Sept. to 4 Oct.)	— ^x
		1	−0.66	−0.45	—
		2	−1.50	−0.72	—
		3	−1.78	−1.21	—
		4	Irrigation	−1.49	—
Leyendecker	2011		I (17 May to 9 June)	II (6 July to 27 July)	III (14 Aug. to 13 Sept.)
		1	−0.60	−0.52	−0.50
		2	−0.81	−0.90	−0.80
		3	−1.21	−1.30	−1.25
	2012	4	Irrigation	Irrigation	−1.61
			I (20 May to 11 June)	II (3 Aug. to 29 Aug.)	III (31 Aug. to 15 Sept.)
		1	−0.54	−0.45	−0.39
		2	−0.80	−0.090	−0.55
		3	−1.17	−1.10	Irrigation
	2013		I (16 Aug. to 20 Oct.)	—	—
		1	−0.55	—	—
		2	−0.70	—	—
		4	−1.20	—	—
		5	Rainfall ^w	—	—
		6	Rainfall	—	—
		7	−1.32	—	—
		8	−1.52	—	—
		9	−1.74	—	—
		10	−1.94	—	—

^zOther irrigation cycles were omitted from the data set.

^yThe first date is the first day of flood irrigation.

^xThere were no irrigation cycles.

^wTotal rainfall was 20 mm in Week 5 and 21 mm in Week 6.

Albany, OR). While on the tree, leaves were enclosed in aluminum foil bags and left 2 h for leaf transpiration to stop and Ψ_{smd} to equilibrate with trunk xylem water potential. Leaves were then excised while still enclosed in the bags and placed immediately in the chamber. The average Ψ_{smd} of the two leaves per tree was recorded. Although we did not check the impact of aluminum bags on leaf temperature, a study conducted at the same orchards (i.e., La Mancha and Leyendecker) showed that no additional leaf heating was observed while the leaf equilibrated even on sun-exposed canopy leaves (Deb et al., 2012).

PHOTOSYNTHESIS AND LEAF GAS EXCHANGE. Photosynthesis and gas exchange were examined on one leaflet of the middle pair of leaflets from each of two leaves (on fruit-bearing shoots) located in the midheight on the outer sun-exposed canopy of each tree (≈ 5 m from the soil surface) using a portable photosynthesis system (LI-6400XT; LI-COR, Lincoln, NE). The operator used 4.5-m aluminum orchard ladders to collect photosynthetic and gas exchange data from the middle part

of the tree. Chamber air CO_2 concentration was set to $390 \mu\text{mol}\cdot\text{mol}^{-1}$, irradiance to track ambient photosynthetically active radiation (1000 to $1200 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), and flow rate to $500 \mu\text{mol}\cdot\text{s}^{-1}$. Leaf temperature ranged from 30 to 33°C . The values registered for two leaflets per tree were averaged. Changes in P_n and gas exchange variables were assessed over the course of an irrigation dry-down cycle; i.e., at Ψ_{smd} of -0.40 to -0.85 MPa (well-watered), -0.90 to -1.45 MPa (moderate), and -1.5 to -2.0 MPa (severe). Stomatal conductance to CO_2 (g_{CO_2}) was derived from $g_{\text{H}_2\text{O}}$ using the equation of Tezara et al. (1999) ($g_{\text{CO}_2} = g_{\text{H}_2\text{O}}/1.6$, where 1.6 is the ratio of the diffusivities of H_2O and CO_2 in air). Photosynthesis and gas exchange of well-watered trees were compared with the same trees of moderate and severe water deficit (over the course of an irrigation dry-down cycle) to determine the decline in P_n and gas exchange.

YIELD AND WATER-DEFICIT LEVEL ESTIMATION. Because pecan are alternate bearers, 2 consecutive years of yield and water-deficit data before or after the water-deficit year are required to

determine if the impact of stress on yield is the result of stress or alternate bearing. Trees received less than the normal number of flood irrigations (based on the irrigation frequency for the orchards studied) in 2012 at La Mancha (eight vs. 11) and in 2011 at Leyendecker (six vs. seven). Thus, we needed yield and water deficit stress data (i.e., Ψ_{smd}) for the 2 consecutive years before the water-deficit year (i.e., 2010 and 2011 at La Mancha; 2009 and 2010 at Leyendecker). Midday stem water potential data were available only for 2011 and 2012. However, plant available soil water (PASW) data within a rooting depth of 0 to 60 cm were available for 2009 to 2011 for both orchards. In all cases, time domain reflectometry sensors (CS616; Campbell Scientific, Logan, UT) were used to determine the volumetric soil water content (at depth of 0 to 60 cm) from which the PASW was calculated using the equation of Ritchie (1981): $PASW = \frac{\theta_a - \theta_{wp}}{\theta_{fc} - \theta_{wp}}$, where θ_a is the actual volumetric soil water content, θ_{fc} is the soil field capacity, and θ_{wp} is the soil wilting point. The average soil field capacity at a depth of 0 to 60 cm was $0.2 \text{ cm}^3 \cdot \text{cm}^{-3}$ at La Mancha and $0.32 \text{ cm}^3 \cdot \text{cm}^{-3}$ at Leyendecker (Deb et al., 2013). The average soil wilting point at depth of 0 to 60 cm was $0.05 \text{ cm}^3 \cdot \text{cm}^{-3}$ at La Mancha and $0.16 \text{ cm}^3 \cdot \text{cm}^{-3}$ at Leyendecker (Deb et al., 2013). We used PASW data to estimate Ψ_{smd} in 2010 at La Mancha and in 2009 and 2010 at Leyendecker. To estimate Ψ_{smd} , a simple linear regression on PASW was fitted for 2011, the year when both PASW and Ψ_{smd} data were available for both orchards. Then the simple linear regression model was applied to estimate Ψ_{smd} at La Mancha in 2010 and at Leyendecker in 2009 and 2010 (Fig. 3). Pecan nut yield (in-shell) was then related to the annual water applied (millimeters per hectare) and the water-deficit stress levels (Ψ_{smd}) measured within the irrigation dry-down cycles.

GRAPHING AND STATISTICAL ANALYSIS. Statistical analyses were performed using SAS software (Version 9.3 for Windows; SAS Institute, Cary, NC). ArcMap (Version 10.2 for Windows;

ESRI, Redlands, CA) was used to generate the study map and pecan orchards shape files and to calculate the total area grown in pecan in 2012. Sigmaplot (Version 10.0 for Windows; Systat Software, San Jose, CA) was used to graph the results. A preliminary mixed model analysis (orchard as a fixed effect) showed that the relationship between Ψ_{smd} and the other variables did not depend on orchard. Fixed effect probability for P_n and gas exchange variables of orchard and the interaction of Ψ_{smd} and orchard were always higher than 0.18. Therefore, we pooled both data sets (La Mancha and Leyendecker).

Although simple regression of P_n and gas exchange variables against Ψ_{smd} was appealing, our data (2011 and 2012) clearly violated the independence assumptions required for this to be a valid approach. The influence of Ψ_{smd} on P_n and gas exchange was carried out under PROC MIXED of SAS 9.3 software. Midday stem water potential was used as the fixed effect in the model statement. The individual tree and the day of the year nested within an orchard was the random effect. The option DDFM = KR was used to provide a better estimate of denominator df and adjust the SE estimated for each test statistic. The coefficient of determination between marginal predicted and observed variables values also was reported. A photosynthesis-derived mixed model from 2011 and 2012 data was used to predict P_n in 2013.

Results

MIDDAY STEM WATER POTENTIAL. Irrigation cycle length of both orchards ranged from 2 to 4 weeks during 2011 to 2013 with the exception of the Leyendecker orchard in 2013 when irrigation was withheld for 10 weeks (Table 1). The La Mancha orchard (sandy loam soil) mean Ψ_{smd} 5 d after irrigation ranged from -0.45 to -0.70 MPa, -0.95 to -1.5 MPa after 14 d, and -1.55 to -2.0 MPa after 21 d. The Leyendecker orchard (clay loam soil) mean Ψ_{smd} ranged from -0.39 to -0.60 MPa after 5 d, -0.60 to -0.90 MPa after 14 d, and -1.10 to -1.3 MPa after 21 d.

Midday stem water potential exceeded -1.50 MPa and became more negative at Leyendecker only 24 d or more after an irrigation event.

PHOTOSYNTHESIS AND LEAF GAS EXCHANGE. Changes in P_n and gas exchange variables were assessed over three levels of Ψ_{smd} (i.e., -0.40 to -0.85 , -0.90 to -1.45 , and -1.5 to -2.0 MPa). These values of Ψ_{smd} usually are used to assess the impact of water deficit in mesophytic plants (Fitter and Hay, 2002). With Ψ_{smd} ranging from -0.40 to -0.85 MPa after 7 d of withholding irrigation, P_n was not reduced significantly (Fig. 4A). Conversely, a significant positive relationship between Ψ_{smd} and P_n occurred when Ψ_{smd} was between -0.90 and -2.0 MPa (Fig. 4A). When Ψ_{smd} of pecan trees ranged from -0.90 to -1.45 MPa, the declines in P_n , g_{H_2O} and E [compared with the same tree at well-watered level (Ψ_{smd} -0.4 to -0.85 MPa)] were 20% to 30% (Fig. 4A), 35% to 55% (Fig. 4B) and 20% to 40% (Fig. 4C), respectively. However, Ψ_{smd} of -1.5 to -2.0 MPa reduced P_n by 50% to 70% (Fig. 4A), g_{H_2O} by 60% to 90% (Fig. 4B), and E by 30% to 70% (Fig. 4C).

Fig. 3. The relationship between midday stem water potential (Ψ_{smd}) and plant-available soil water (PASW) measured in two New Mexico pecan orchards [La Mancha ($n = 12$) and Leyendecker ($n = 13$)] in 2011. Simple linear regression model was used to estimate Ψ_{smd} at La Mancha in 2010 and Leyendecker in 2009 and 2010.

Fig. 4. Relationship among (A) photosynthesis (P_n), (B) stomatal conductance (g_s ; g_{H_2O}), and (C) transpiration (E) and midday stem water potential (Ψ_{smd}) of trees at La Mancha and Leyendecker, southern New Mexico, pecan orchards. Mixed model analysis was used to derive P_n , g_{H_2O} , and E models.

Although the relationship between Ψ_{smd} and P_n under water deficit conditions was moderate ($R^2 = 0.68$) (Fig. 4A), the mixed model for the 2011 and 2012 data successfully predicted P_n in 2013 (Fig. 5). The coefficient of determination between actual and predicted P_n in 2013 was 0.84. Photosynthesis and c_i tended to decrease as Ψ_{smd} decreased to -2.0 MPa (Fig. 6A). Inter-cellular CO_2 also decreased in parallel with decreased g_{CO_2} and increased water deficit stress level (Fig. 6B).

YIELD AND MIDDAY STEM WATER POTENTIAL. Total nut production (in-shelled) was $2980 \text{ kg} \cdot \text{ha}^{-1}$ at the La Mancha orchard (Fig. 7A) and $1909 \text{ kg} \cdot \text{ha}^{-1}$ at Leyendecker in 2010 (Fig. 7B). During 2010, there were 11 flood irrigations at La Mancha and seven at Leyendecker. However, in 2010, Ψ_{smd} estimated using the linear regression on PASW, never fell below -1.5 MPa (more negative) at either orchard (Table 2). When trees received fewer than the normal number of irrigations in 2012 at La Mancha (eight vs. 11) and in 2011 at Leyendecker (six vs. seven), total

yield declined by 38% at La Mancha ($1652 \text{ kg} \cdot \text{ha}^{-1}$) and 50% at Leyendecker ($872 \text{ kg} \cdot \text{ha}^{-1}$) as compared with the previous 2 years (Table 2; Fig. 7). Meanwhile, Ψ_{smd} at the end of irrigation cycles exceeded -1.5 MPa and became more negative three times at La Mancha and once at the Leyendecker orchard (Table 2).

Discussion

MIDDAY STEM WATER POTENTIAL FOR IRRIGATION SCHEDULING OF PECAN. Plant-based measurements have been suggested as a useful tool for irrigation scheduling in pecan, apple, and olive (*Olea europaea*) orchards (Deb et al., 2012; Moriana et al., 2012; Naor et al., 2008). However, the sensitivity of the measurement to water deficit and its ability to define a precise threshold value beyond which irrigation is required dictates which plant-based measurement is adopted (Jones, 2004). Using different values of Ψ_{smd} as a water deficit reference against which to test the plant responses provided a consistent and clear pattern of the physiological changes that occur during a flood irrigation dry-down cycle (Othman et al., 2014). Our current results confirm the findings of our previous study, which revealed that the threshold Ψ_{smd} that separated well-watered trees from the same trees exhibiting moderate water deficit near the end of a flood irrigation cycle was -0.9 MPa (Othman et al., 2014). Establishing distinct classes or threshold values to trigger the need for irrigation is the most serious problem that limits transferring research developed measurements to the practical application level. Our Ψ_{smd} values in this study further support the suggestion that Ψ_{smd} can be used as a practical measurement for irrigation scheduling on a commercial scale.

Because many features of tree physiology react immediately to changes in water status in tree tissues such as root and stem rather than to changes in the bulk soil water potential, Ψ_{smd} is a better water deficit stress indicator than soil-water-based measurements (Jones, 2004). Moreover, the number of Ψ_{smd} measurements (sample size) required for a reasonable representation of orchard water status is relatively small (≈ 7) (Naor et al., 2006). This is because the tree-to-tree Ψ_{smd} variability is low compared with other plant and soil-based measurements (Fernández and Cuevas, 2010; Naor et al., 2006). Our previous study showed that 10 trees were adequate to properly represent the water status of selected pecan orchards (Othman et al., 2014). Given that the number of trees required to gather reliable data is small and clear separation in moisture status was apparent, we recommend that Ψ_{smd} , a plant-based measurement, be used for detecting moisture status in pecan orchards.

PHOTOSYNTHESIS AND LEAF GAS EXCHANGE. Photosynthesis, g_{H_2O} , and E were higher in pecan trees shortly after irrigation than trees exhibiting water deficit near the end of a flood irrigation dry-down cycle (Fig. 4A–C). The decline in P_n and gas exchange was greater when Ψ_{smd} dropped below -0.9 MPa. A report of Pilar et al. (2007) showed there was no decline in P_n at mild water deficit (predawn leaf water potential, -0.2 to -0.8 MPa). However, that paper used predawn leaf water potential as the plant-based measurements and the study was conducted on grapevine *V. vinifera* ‘Cabernet-Sauvignon’. Possible explanations of insignificant reduction in P_n is that P_n is not sensitive to moderate water deficit as Ψ_{smd} (Goldhamer et al., 1999) or Ψ_{smd} of -0.4 to -0.85 MPa did not induce stomatal closure (the main suppression of P_n) in pecan leaves. Because P_n did not decline significantly in response to Ψ_{smd} of -0.85 MPa, we do not recommend irrigation when Ψ_{smd} is above this threshold.

Fig. 5. Actual and predicted photosynthesis (P_n) under different levels of midday stem water potential (Ψ_{smd}) for trees at two southern New Mexico pecan orchards (La Mancha and Leyendecker) measured in 2013. Mixed model equation ($P_n = 4.1 \Psi_{\text{smd}} - 0.05 \Psi_{\text{smd}}^2 + 15.97$) derived from 2011 and 2012 data (Fig. 4A) was used to establish the predicted line. Actual Ψ_{smd} values in 2013 were used to predict P_n in the model. Coefficient of determination (R^2) represented actual P_n (La Mancha and Leyendecker) vs. predicted P_n .

This could possibly save water while maintaining carbon assimilation and gas exchange.

The La Mancha orchard (sandy loam soil) received 30 irrigations from 2010 to 2012 (Table 2). Approximately 17% of irrigations (five of 30) occurred when no significant reduction in P_n was noticed (Ψ_{smd} at the end of the irrigation cycle -0.85 to -1.05 MPa). Consequently, trees were re-irrigated mostly when a significant reduction in P_n and gas exchange occurred; mean P_n was $11 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \text{CO}_2$ (Fig. 4A), $g_{\text{H}_2\text{O}}$ was $0.15 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \text{H}_2\text{O}$ (Fig. 4B), and E was $4.7 \text{ mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \text{H}_2\text{O}$ (Fig. 4C). Our results support the findings of Samani et al. (2009), which showed that most pecan orchards in the Rio Grande Valley, NM, a major pecan-growing area, are frequently subjected to water deficit conditions during the growing season.

Fifty percent reduction in P_n (Fig. 4A) and $g_{\text{H}_2\text{O}}$ (Fig. 4B) only occurred when Ψ_{smd} exceeded -1.5 MPa. A strong correlation among xylem sap abscisic acid, stomatal closure, and predawn leaf water potential was found in black walnut (Loewenstein and Pallardy, 1998). Weber and Gates (1990) attributed the significant decline in P_n (greater than 50% of control) to stomatal closure. Stomatal closure reduces CO_2 availability in the leaf and could lead to photo-oxidative stress and generation of reactive oxygen species (Wujeska et al., 2013). When leaf water potential of walnut (*Juglans regia*) trees was ≈ -1.9 MPa, the percentage loss of hydraulic conductivity in the petioles was 87% (Tyree et al., 1993). In our experiment, although Ψ_{smd} of -0.4 to -0.85 MPa did not reduce P_n and gas exchange parameters significantly, Ψ_{smd} of -1.5 to -2.0 MPa markedly reduced these variables (Fig. 4). Accordingly, irrigating pecan orchards when Ψ_{smd} range from -0.8 to -0.9 MPa could be the critical threshold to prevent significant reduction in P_n and gas exchange.

Because g_{CO_2} declines with water deficit stress, P_n may be inhibited because of low c_i (Tezara et al., 1999). At moderate water deficit, g_{CO_2} , P_n , and c_i decreased slightly, and stomatal limitations seem dominant (Cifre et al., 2005). At severe water deficits ($g_{\text{H}_2\text{O}}$ less than $0.05 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \text{H}_2\text{O}$), P_n further decreases and c_i increases indicating that non-stomatal limitations become significant (Cifre et al., 2005). The P_n/c_i curve shows that increasing water deficit stress (Ψ_{smd} -0.4 to -2.0 MPa) decreased P_n from 18 to $4 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \text{CO}_2$, g_{CO_2} from 0.3 to $0.02 \text{ mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1} \text{CO}_2$, and c_i from 270 to $70 \mu\text{mol}\cdot\text{mol}^{-1} \text{CO}_2$ (i.e., 74% less than the same trees under well-watered conditions). Although g_{CO_2} was near zero at Ψ_{smd} between -1.8 and -2.0 MPa, curtailed g_{CO_2} did not completely reduce P_n . This is because the percentage decline in c_i was less than g_{CO_2} at severe water deficit (at Ψ_{smd} of -1.8 to -2.0 , the decline in $c_i \approx 74\%$, whereas $g_{\text{CO}_2} \approx 90\%$). The different percentage decline values between c_i and g_{CO_2} suggested that there were other factors beside curtailed g_{CO_2} that played a role in reducing P_n . Rosati et al. (2006) found that lower P_n in walnut was associated with stomatal closure and a direct effect of heat on leaf

biochemistry, especially in hot and dry weather. However, c_i decreased in parallel with decreased P_n and g_{CO_2} when trees exhibited water deficit. Also, no increase in c_i was noticed at severe water deficit (Ψ_{smd} -1.5 to -2.0 MPa). Therefore, we conclude that P_n of pecan trees was impaired greatly by stomatal components when trees transitioned from no or low water deficit (Ψ_{smd} -0.4 MPa) to severe water deficit (Ψ_{smd} -2.0 MPa).

YIELD. Not all water deficits are formed equally; timing, length, and severity of drought impact the temporal and spatial availability of soil moisture (Anderegg et al., 2013). Soil moisture is more critical to trees at certain times of the season than others because of seasonal variation in growth, gas exchange, and photosynthesis (Anderegg et al., 2013). This is also true for pecan. Adequate soil moisture is critical for pecan trees at budbreak to stimulate vigorous growth, at nut filling to optimize kernel percentage, and late in the season to prevent the negative impact of the drought on shuck split and energy reserves (Wells et al., 2007). As a result of shortage in surface water delivery in the last decade, La Mancha (2012) and Leyendecker (2011) orchards received less than the normal number of irrigations (Table 2). In 2012, Ψ_{smd} exceeded -1.5 MPa three times at La Mancha at the end of irrigation cycles. Based on the timing of ontogenic events in pecan (Wells et al., 2007), those three times corresponded to the pollination period (May), the beginning of the nut-sizing period (June), and the end of the kernel filling stage (September) (Table 2). Meanwhile, nut production was 38% less than the average of the previous 2 years (2010 and 2011). In both years (2010 and 2011), trees were irrigated mostly when Ψ_{smd} was between -1.1 and -1.45 MPa. Although the reduction in P_n at this level of Ψ_{smd} (-1.1 and -1.45 MPa) ranged from 30% to 45%, pecan yield in 2010 and 2011 was relatively stable during the multiple cycles of moderate water deficit

Fig. 6. Relationship between (A) intercellular CO₂ (c_i) and photosynthesis (P_n) and (B) intercellular CO₂ and stomatal conductance (g_s ; g_{CO_2}) under different level of midday stem water potential of trees at two southern New Mexico pecan orchards (La Mancha and Leyendecker) in 2011 and 2012. Mixed model analysis was used to derive P_n and g_{CO_2} models.

(Ψ_{smd} -1.1 to -1.45 MPa at the end of the irrigation cycle). Naor et al. (2008) found that Ψ_{smd} of -0.7 to -1.4 MPa reduced fruit relative yield percentage of apple trees (bearing medium cropload) by less than 15%, whereas Ψ_{smd} of -1.5 to -3.0 MPa reduced the fruit relative yield by 20% to 100%. At Leyendecker

orchards, Ψ_{smd} never fell below -1.5 MPa except once in 2011, the year when nut production was reduced when compared with the 2 previous years (Fig. 7; Table 2). Withholding water within the nut-filling stage for 1 month at Leyendecker in 2011 (Ψ_{smd} = -1.61 MPa at the end of the irrigation cycle) could possibly explain why the total yield reduction was 50% (Fig. 7; Table 2).

Herrera (1990) and Wells et al. (2007) concluded that low soil moisture during the kernel-filling stage reduces embryo development and kernels do not fill properly. However, our yield data were a case study and we had no mechanism for estimating error. We compared the yield data from water deficit trees of 1 year vs. well-watered trees of another year. These yield data are not a product of direct comparisons between well-watered vs. water deficit trees in the same year. Consequently, we had no way to confirm whether the difference was simply the result of year-to-year variability or the effect of water deficit.

In summary, the irregularity of irrigation resulting from the limited availability of surface irrigation water during the experimental period caused reduction in P_n . This lends support to the assertion of that water availability reduces pecan production in New Mexico. We recommend that Ψ_{smd} be used as a plant-based measurement to schedule irrigation in commercial pecan orchards. As Ψ_{smd} transitioned from -0.40 to -0.85 MPa, P_n of pecan trees decreased only slightly. With further increases in water deficit (Ψ_{smd} -0.9 to -2.0 MPa), P_n reduction fell from 10% to 70%. Reduction in P_n was attributable mostly to stomatal limitation. For the first time for pecan, we have shown that Ψ_{smd} of -0.8 to -0.9 MPa could be the water deficit threshold to prevent any significant reduction in P_n and gas exchange. Further research that links the decline in P_n and

Fig. 7. Nut production (in-shelled) and annual water applied for two southern New Mexico pecan orchards: (A) La Mancha and (B) Leyendecker from May 2009 to Oct. 2012.

Table 2. Midday stem water potential measured at the end of flood irrigation cycles and total number of irrigation of two New Mexico pecan orchards, La Mancha and Leyendecker, from May 2009 to Oct. 2012.

Location	Year	Midday stem water potential (MPa)			Total irrigation cycles (no.)	Dates of –1.5 to –2.0 MPa cycles ^z
		–0.85 to –1.05	–1.1 to –1.45	–1.5 to –2.0		
La Mancha	2009	NA ^y	NA	NA	NA	2011 (30 June to 19 July)
	2010	2 ^x	9	Never	11	2012 (10 May to 31 May)
	2011	2	8	1	11	(4 June to 25 June)
	2012	1	4	3	8	(16 Sept. to 6 Oct.)
Leyendecker	2009	4	3	Never	7	2011 (14 Aug. to 13 Sept.)
	2010	3	4	Never	7	
	2011	2	3	1	6	
	2012	5	2	Never	7	

^zThe first date is the first day of flood irrigation.

^yData not available.

^xNumber of irrigation cycles in 2010 at which midday stem water potential measured at the end of the irrigation dry-down cycle ranged from –0.85 to –1.05 MPa.

Ψ_{smd} to yield is required to determine the critical threshold Ψ_{smd} values that significantly reduce pecan yield.

Literature Cited

- Anderegg, L., W. Anderegg, and J. Berry. 2013. Not all droughts are created equal: Translating meteorological drought into woody plant mortality. *Tree Physiol.* 33:701–712.
- Chen, J., Q. Zhang, X. Li, and K. Cao. 2010. Gas exchange and hydraulics in seedlings of *Hevea brasiliensis* during water stress and recovery. *Tree Physiol.* 30:876–885.
- Cifre, J., J. Bota, J. Escalona, H. Medrano, and J. Flexas. 2005. Physiological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.) an open gate to improve water-use efficiency? *Agr. Ecosyst. Environ.* 106:159–170.
- Damour, G., M. Vandame, and L. Urban. 2009. Long-term drought results in a reversible decline in photosynthetic capacity in mango leaves, not just a decrease in stomatal conductance. *Tree Physiol.* 29:675–684.
- Deb, S., M. Shukla, and J. Mexal. 2012. Estimating midday leaf and stem water potentials of mature pecan trees from soil water content and climatic parameters. *HortScience* 47:907–916.
- Deb, S., M. Shukla, P. Sharma, and J. Mexal. 2013. Soil water depletion in irrigated mature pecans under contrasting soil textures for arid southern New Mexico. *Irr. Sci.* 31:69–85.
- Esparza, G., T. DeJong, S. Weinbaum, and I. Klein. 2001. Effect of irrigation deprivation during the harvest period on yield determinants in mature almond trees. *Tree Physiol.* 21:1073–1079.
- Fernández, J. and M. Cuevas. 2010. Irrigation scheduling from stem diameter variations: A review. *Agr. For. Meteorol.* 150:135–151.
- Fitter, A. and R. Hay. 2002. *Environmental physiology of plants*. 3rd Ed. Academic Press, San Diego, CA.
- Food and Agriculture Organization of the United Nations. 1996. *Irrigation scheduling: From theory to practice*. Proc. Intl. Commission Drainage/FAO Wkshp. Irr. Scheduling. FAO Press, Rome, Italy.
- Garrot, D., M. Kilby, D. Fangmeier, S. Husman, and A. Ralowicz. 1993. Production, growth, and nut quality in pecans under water stress based on the crop water stress index. *J. Amer. Soc. Hort. Sci.* 118:694–698.
- Goldhamer, D., E. Fereres, M. Mata, J. Girona, and M. Cohen. 1999. Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. *J. Amer. Soc. Hort. Sci.* 124:437–444.
- Herrera, E. 1990. Fruit growth and development of ‘Ideal’ and ‘Western’ pecan. *J. Amer. Soc. Hort. Sci.* 115:915–923.
- Johnson, D. 2004. Prediction of water deficit stress in pecans (*Carya illinoensis*) with remotely sensed hyper-spectral data. PhD diss., New Mexico State Univ., Las Cruces, NM.
- Jones, H. 2004. Irrigation scheduling: Advantages and pitfalls of plant-based methods. *J. Expt. Bot.* 55:2427–2436.
- Kallestad, J., J. Mexal, T. Sammis, and R. Heerema. 2008. Development of a simple irrigation scheduling calendar for Mesilla Valley pecan growers. *HortTechnology* 18:714–725.
- Klein, I., G. Esparza, A. Weinbaum, and T. DeJong. 2001. Effects of irrigation deprivation during the harvest period on leaf persistence and function in mature almond trees. *Tree Physiol.* 21:1063–1072.
- Kuhns, M., H. Garrett, R. Teskey, and T. Hinckley. 1985. Root growth of black walnut trees related to soil temperature, soil water potential, and leaf water potential. *For. Sci.* 31:617–629.
- Loewenstein, N. and S. Pallardy. 1998. Drought tolerance, xylem sap abscisic acid and stomatal conductance during soil drying: A comparison of young plants of four temperate deciduous angiosperms. *Tree Physiol.* 18:421–430.
- Moriana, A., D. Pérez-López, M. Prieto, M. Ramírez-Santa-Pau, and J. Pérez-Rodríguez. 2012. Midday stem water potential as a useful tool for estimating irrigation requirements in olive trees. *Agr. Water Mgt.* 112:43–54.
- Murray, F.W. 1967. On the computation of saturation vapor pressure. *J. Appl. Meteorol.* 6:203–204.
- Naor, A., Y. Gal, and M. Peres. 2006. The inherent variability of water stress indicators in apple, nectarine and pear orchards, and the validity of a leaf-selection procedure for water potential measurements. *Irrig. Sci.* 24:129–135.
- Naor, A., S. Naschitz, M. Peres, and Y. Gal. 2008. Responses of apple fruit size to tree water status and crop load. *Tree Physiol.* 28:1255–1261.
- Othman, Y., C. Steele, D. VanLeeuwen, R. Heerema, S. Bawazir, and R. St. Hilaire. 2014. Remote sensing used to detect moisture status of pecan orchards grown in a desert environment. *Intl. J. Remote Sens.* 35:949–966.
- Pilar, B., P. Sánchez-de-Miguel, A. Centeno, P. Junquera, R. Linares, and J. Lissarrague. 2007. Water relations between leaf water potential, photosynthesis and agronomic vine response as a tool for establishing thresholds in irrigation scheduling. *Sci. Hort.* 114:151–158.
- Poorter, H., J. Bühler, D. Dusschoten, J. Climent, and J. Postma. 2012. Pot size matters: A meta-analysis of the effects of rooting volume on plant growth. *Funct. Plant Biol.* 39:839–850.
- Ritchie, J. 1981. Water dynamics in the soil–plant–atmosphere system. *Plant Soil* 58:81–96.
- Rosati, A., S. Metcalf, R. Buchner, A. Fulton, and B. Lampinen. 2006. Tree water status and gas exchange in walnut under drought, high temperature and vapour pressure deficit. *J. Hort. Sci. Biotechnol.* 81:415–420.
- Samani, Z., S. Bawazir, M. Bleiweiss, R. Skaggs, J. Longworth, A. Piñon, and V. Tran. 2011. A simple irrigation scheduling approach for pecans. *Agr. Water Mgt.* 98:611–664.
- Samani, Z., S. Bawazir, M. Bleiweiss, R. Skaggs, J. Longworth, V. Tran, and A. Piñon. 2009. Using remote sensing to evaluate the spatial variability of evapotranspiration and crop coefficient in the lower Rio Grande Valley, New Mexico. *Irrig. Sci.* 28:93–100.

- Tezara, W., V. Mitchell, S. Driscoll, and D. Lawlor. 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. *Nature* 401:914–917.
- Tyree, M., H. Cochard, P. Cruiziat, B. Sinclair, and T. Ameglio. 1993. Drought-induced leaf shedding in walnut: Evidence for vulnerability segmentation. *Plant Cell Environ.* 16:879–882.
- U.S. Department of Agriculture. 1980. Soil survey of Dona Ana County Area, New Mexico. 20 Feb. 2014. <http://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/new_mexico/NM690/0/nm_dona_ana.pdf>.
- U.S. Department of Agriculture. 2008. Geographic area series, farm and ranch irrigation survey for 2008. 20 Feb. 2014. <http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/fris08.pdf>.
- U.S. Department of Agriculture. 2012. The census of agriculture report. 20 Feb. 2014. <<http://www.agcensus.usda.gov>>.
- Weber, J. and D. Gates. 1990. Gas exchange in *Quercus rubra* (northern red oak) during a drought: Analysis of relations among photosynthesis, transpiration and leaf conductance. *Tree Physiol.* 7:215–225.
- Wells, L., P. Conner, B. Goff, M. Nesbitt, B. Wood, P. Bertrand, T. Brenneman, J. Brock, M. Hotchkiss, C. Reilly, K. Stevenson, J. Dutcher, W. Hudson, H. Ellis, J. Payne, L. Tedders, K. Harrison, and P. Sumner. 2007. Southeastern pecan growers' handbook. 1st Ed. Coop. Ext. Serv., Univ. Georgia Press, Athens, GA.
- Wujeska, A., G. Bossinger, and M. Tausz. 2013. Responses of foliar antioxidative and photoprotective defence systems of trees to drought: A meta-analysis. *Tree Physiol.* 33:1018–1029.