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

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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 illinoinensis) orchards. The objectives of this study were to assess the impact of water status developed during the flood irrigation dry-down cycles on photosynthesis (Pn) and gas exchange [stomatal conductance (gs) to H2O (gsH2O%), transpiration (E), and intercellular CO2 (ci)] and to establish values of midday stem water potential (Ψsmd) that are needed to maintain Pn 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 Pn, gsH2O%, E, and ci were assessed at Ψsmd 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 Pn was markedly noticeable when Ψsmd dropped below –0.9 MPa. We attributed the reduction in Pn mostly to stomatal limitation. The decline in Pn and gsH2O% exceeded 50% when Ψsmd ranged from –1.5 to –2.0 MPa. For those reasons, we recommended that pecan orchards be maintained at Ψsmd 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 ≈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 ×domestica) trees (bearing medium cropload) by less than 15%, whereas Ψsmd 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, gs generally declines into the 0.05 to 0.15 mol·m⁻²·s⁻¹ H2O range, photosynthesis and intercellular CO2 decrease slightly, and stomatal limitations to gas exchange dominate (Cifre et al., 2005). At severe water deficits (gs less than 0.05 mol·m⁻²·s⁻¹ H2O), Pn further decreases and ci increases indicating that
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 $\Psi_{smd}$ value for leaf persistence in mature almond trees was −1.8 MPa. At this level of $\Psi_{smd}$, 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, $\Psi_{smd}$ was the best for detecting moisture status in pecan. Therefore, $\Psi_{smd}$ 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 $\Psi_{smd}$ that are needed to maintain $P_n$ and gas exchange of pecan. These data could determine water deficit thresholds of $\Psi_{smd}$ 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°12′01.14″ N, long. 106°44′30.32″ W, elevation 1173 m)] and the other was at a commercial farm [La Mancha (lat. 32°17′06.25″ N, long. 106°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...
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 of ‘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 Torrerts) (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 kg ha⁻¹ and zinc sulfate (foliar spray) at the rate of 7 kg 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 kg ha⁻¹ and zinc sulfate (foliar spray) at the rate of 8 kg ha⁻¹ were applied once in May and July of both years (i.e., 500 and 16 kg 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 ($\Psi_{smd}$, $P_{tr}$, $E$, $g_{H2O}$, 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 $\Psi_{smd}$ 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.,...
While on the tree, leaves were enclosed in aluminum foil bags and left 2 h for leaf transpiration to stop and $\Psi_{smd}$ 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 $\Psi_{smd}$ 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 ($\approx$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 µmol-mol$^{-1}$, irradiance to track ambient photosynthetically active radiation (1000 to 1200 µmol-m$^{-2}$-s$^{-1}$), and flow rate to 500 µmol-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 $\Psi_{smd}$ 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 $CO_2$ ($g_{CO2}$) was derived from $g_{H2O}$ using the equation of Tezara et al. (1999) ($g_{CO2} = g_{H2O}/1.6$, 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 used yield and water deficit stress data (i.e., $\Psi_{\text{smd}}$) 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):

$$\text{PASW} = \frac{\theta \mu - \theta \wp}{\theta \fc - \theta \wp},$$

where $\theta \mu$ is the actual volumetric soil water content, $\theta \fc$ is the soil field capacity, and $\theta \wp$ is the soil wilting point. The average soil field capacity at a depth of 0 to 60 cm was 0.2 cm$^3$ cm$^{-3}$ at La Mancha and 0.32 cm$^3$ cm$^{-3}$ at Leyendecker (Deb et al., 2013). The average soil wilting point at depth of 0 to 60 cm was 0.05 cm$^3$ cm$^{-3}$ at La Mancha and 0.16 cm$^3$ cm$^{-3}$ at Leyendecker (Deb et al., 2013). We used PASW data to estimate $\Psi_{\text{smd}}$ in 2010 at La Mancha and in 2009 and 2010 at Leyendecker.

To estimate $\Psi_{\text{smd}}$, a simple linear regression on PASW was fitted for 2011, the year when both PASW and $\Psi_{\text{smd}}$ data were available for both orchards. Then the simple linear regression model was used to estimate $\Psi_{\text{smd}}$ 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 ($\Psi_{\text{smd}}$) measured within the irrigation dry-down cycles.

**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 $\Psi_{\text{smd}}$ 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 $\Psi_{\text{smd}}$ 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 $\Psi_{\text{smd}}$ (i.e., $-0.40$ to $-0.85$, $-0.90$ to $-1.45$, and $-1.5$ to $-2.0$ MPa). These values of $\Psi_{\text{smd}}$ usually are used to assess the impact of water deficit in mesophytic plants (Fitter and Hay, 2002). With $\Psi_{\text{smd}}$ 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 $\Psi_{\text{smd}}$ and $P_n$ occurred when $\Psi_{\text{smd}}$ was between $-0.90$ and $-2.0$ MPa (Fig. 4A). When $\Psi_{\text{smd}}$ of pecan trees ranged from $-0.90$ to $-1.45$ MPa, the declines in $P_n$, $g_{\text{stom}}$, and $E$ (compared with the same tree at well-watered level ($\Psi_{\text{smd}} = 0.4$ to $-0.85$ MPa) were $20\%$ to $30\%$ (Fig. 4A), $35\%$ to $55\%$ (Fig. 4B) and $20\%$ to $40\%$ (Fig. 4C), respectively. However, $\Psi_{\text{smd}}$ of $-1.5$ to $-2.0$ MPa reduced $P_n$ by $50\%$ to $70\%$ (Fig. 4A), $g_{\text{stom}}$ by $60\%$ to $90\%$ (Fig. 4B), and $E$ by $30\%$ to $70\%$ (Fig. 4C).
Although the relationship between \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \) decreased to −2.0 MPa (Fig. 6A). Intercellular CO\(_2\) also decreased in parallel with decreased \( g_{\text{CO2}} \) and increased water deficit stress level (Fig. 6B).

**Yield and midday stem water potential.** Total nut production (in-shell) was 2980 kg ha\(^{-1}\) at the La Mancha orchard (Fig. 7A) and 1909 kg 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, \( \Psi_{\text{smd}} \) 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 kg ha\(^{-1}\)) and 50% at Leyendecker (872 kg ha\(^{-1}\)) as compared with the previous 2 years (Table 2; Fig. 7). Meanwhile, \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \) values in this study further support the suggestion that \( \Psi_{\text{smd}} \) 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, \( \Psi_{\text{smd}} \) is a better water deficit stress indicator than soil-water-based measurements (Jones, 2004). Moreover, the number of \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \), a plant-based measurement, be used for detecting moisture status in pecan orchards.

**Photosynthesis and leaf gas exchange.** Photosynthesis, \( g_{\text{H2O}} \), 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 \( \Psi_{\text{smd}} \) 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 rather than to changes in water status in tree tissues such as root and stem, rather than to changes in the bulk soil water potential, \( \Psi_{\text{smd}} \) is a better water deficit stress indicator than soil-water-based measurements (Jones, 2004). Moreover, the number of \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \) 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 \( \Psi_{\text{smd}} \), a plant-based measurement, be used for detecting moisture status in pecan orchards.
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 (\( \Psi_{smd} \) 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 \( \mu \)mol m\(^{-2}\) s\(^{-1}\) CO\(_2\) (Fig. 4A), \( g_{H2O} \) was 0.15 \( \mu \)mol m\(^{-2}\) s\(^{-1}\) H\(_2\)O (Fig. 4B), and \( E \) was 4.7 mmol m\(^{-2}\) s\(^{-1}\) H\(_2\)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 \( g_{H2O} \) (Fig. 4B) only occurred when \( \Psi_{smd} \) 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 (\( J. \) regia) trees was \( \approx -1.9 \) MPa, the percentage loss of hydraulic conductivity in the petioles was 87% (Tyree et al., 1993). In our experiment, although \( \Psi_{smd} \) of –0.4 to –0.85 MPa did not reduce \( P_n \) and gas exchange parameters significantly, \( \Psi_{smd} \) of –1.5 to –2.0 MPa markedly reduced these variables (Fig. 4). Accordingly, irrigating pecan orchards when \( \Psi_{smd} \) range from –0.8 to –0.9 MPa could be the critical threshold to prevent significant reduction in \( P_n \) and gas exchange.

Because \( g_{CO2} \) declines with water deficit stress, \( P_n \) may be inhibited because of low \( c_i \) (Tezara et al., 1999). At moderate water deficit, \( g_{CO2} \), \( P_n \), and \( c_i \) decreased slightly, and stomatal limitations seem dominant (Cifre et al., 2005). At severe water deficits (\( g_{H2O} \) less than 0.05 \( \mu \)mol m\(^{-2}\) s\(^{-1}\) H\(_2\)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 (\( \Psi_{smd} \) –0.4 to –2.0 MPa) decreased \( P_n \) from 18 to 4 \( \mu \)mol m\(^{-2}\) s\(^{-1}\) CO\(_2\), \( g_{CO2} \) from 0.3 to 0.02 \( \mu \)mol m\(^{-2}\) s\(^{-1}\) CO\(_2\), and \( c_i \) from 270 to 70 \( \mu \)mol mol\(^{-1}\) CO\(_2\) (i.e., 74% less than the same trees under well-watered conditions). Although \( g_{CO2} \) was near zero at \( \Psi_{smd} \) between –1.8 and –2.0 MPa, curtailed \( g_{CO2} \) did not completely reduce \( P_n \). This is because the percentage decline in \( c_i \) was less than \( g_{CO2} \) at severe water deficit (at \( \Psi_{smd} \) of –1.8 to –2.0, the decline in \( c_i \) \( \approx 74\% \), whereas \( g_{CO2} \approx 90\% \)). The different percentage decline values between \( c_i \) and \( g_{CO2} \) suggested that there were other factors beside curtailed \( g_{CO2} \) 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 \( g_{CO2} \) when trees exhibited water deficit. Also, no increase in \( c_i \) was noticed at severe water deficit (\( \Psi_{smd} \) –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 (\( \Psi_{smd} \) –0.4 MPa) to severe water deficit (\( \Psi_{smd} \) –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, \( \Psi_{smd} \) 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 \( \Psi_{smd} \) was between –1.1 and –1.45 MPa. Although the reduction in \( P_n \) at this level of \( \Psi_{smd} \) (–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.
(Ψsmd –1.1 to –1.45 MPa at the end of the irrigation cycle). Naor et al. (2008) found that Ψsmd of –0.7 to –1.4 MPa reduced fruit relative yield percentage of apple trees (bearing medium cropload) by less than 15%, whereas Ψsmd of –1.5 to –3.0 MPa reduced the fruit relative yield by 20% to 100%. At Leyendecker orchards, Ψsmd 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 (Ψsmd = –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 Ψsmd be used as a plant-based measurement to schedule irrigation in commercial pecan orchards. As Ψsmd transitioned from –0.40 to –0.85 MPa, \( P_n \) of pecan trees decreased only slightly. With further increases in water deficit (Ψsmd –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 Ψsmd 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. 6. Relationship between (A) intercellular CO₂ (\( c_\text{i} \)) and photosynthesis (\( P_n \)) and (B) intercellular CO₂ and stomatal conductance (\( g_\text{CO}_2 \)) 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 \( g_\text{CO}_2 \) models.

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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 | Location Year | Midday stem water potential (MPa) | Total irrigation cycles (no.) | Dates of –1.5 to –2.0 MPa cycles |
|------------|------|---------------|----------------------------------|-----------------------------|----------------------------------|
| La Mancha  | 2009 | NA            | –0.85 to –1.05                   | NA                          | 2011 (30 June to 19 July)       |
|            | 2010 | 2*            | –1.1 to –1.45                    | 11                          | 2012 (10 May to 31 May)         |
|            | 2011 | 3             | –1.5 to –2.0                     | 11                          | (4 June to 25 June)             |
|            | 2012 | 4             |                                   | 8                           | (16 Sept to 6 Oct.)             |
| Leyendecker| 2009 | 4             | –0.85 to –1.05                   | 7                           | 2011 (14 Aug to 13 Sept.)       |
|            | 2010 | 3             | –1.1 to –1.45                    | 7                           |                                  |
|            | 2011 | 2             | –1.5 to –2.0                     | 6                           |                                  |
|            | 2012 | 5             |                                   | 7                           |                                  |

*The first date is the first day of flood irrigation.

*Data not available.

*Number 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.

\( \Psi_{smd} \) to yield is required to determine the critical threshold \( \Psi_{smd} \) values that significantly reduce pecan yield.

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