Estimating Midday Leaf and Stem Water Potentials of Mature Pecan Trees from Soil Water Content and Climatic Parameters

Sanjit K. Deb¹, Manoj K. Shukla, and John G. Mexal

Department of Plant and Environmental Sciences, New Mexico State University, MSC 3Q, P.O. Box 30003, Las Cruces, NM 88003

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Abstract. Diurnal and temporal patterns of stem water potential (ψ_{stem}) and leaf water potential (ψ_{leaf}) were determined during June to Sept. 2010 and 2011 at lower (2.5 m tree height), mid- (4.6 m), and upper (7.6 m) canopy positions for two flood-irrigated, mature pecan [*Carya illinoensis* (Wangenh.) K. Koch] orchards near Las Cruces, NM. Diurnal measurements of ψ_{stem} and ψ_{leaf} at three canopy heights were correlated under both dry and wet soil conditions. However, although soil water contents at Site 2 (silty clay loam texture) remained higher compared with Site 1 (sandy loam), ψ_{stem} and ψ_{leaf} values, particularly under dry soil conditions at Site 2, were consistently lower, showing the effect of clayey soil texture on pecan water stress. Diurnal patterns of ψ_{stem} and ψ_{leaf} indicated that measurements of ψ_{stem} and ψ_{leaf} should be made close to early afternoon (between 1400 and 1500 HR Mountain Standard Time) to evaluate mature pecan water stress, which also corresponded to maximum climatic stress conditions. Midday ψ_{stem} and ψ_{leaf} measured at three canopy heights over several irrigation cycles during the 2010 season were correlated with one another, midday soil water content at different depths, and atmospheric vapor pressure deficit (VPD). Multiple regression analysis [between midday ψ_{stem} or ψ_{leaf} and midday θ_{avg} (soil water content at 0 to 40 cm), air temperature (T_{md}), and relative humidity (RH_{md})] during the 2010 season revealed that two-parameter regression models [ψ_{stem} or $\psi_{\text{leaf}} = f(\text{midday } \theta_{\text{avg}} \text{ and } T_{\text{md}})$] were the most significant for the interpretation of midday ψ_{stem} or ψ_{leaf} at both sites. Using the two-parameter model, predictions of ψ_{stem} and ψ_{leaf} measured on the both shaded and sunlit sides of trees at three canopy heights for 2011 showed good agreement between measured and predicted ψ_{stem} and ψ_{leaf} (R^2 ranged from 0.70 to 0.98). Two-parameter models derived in an earlier study generally underpredicted ψ_{stem} both in 2010 and 2011, which further supported the importance of the time of midday ψ_{stem} and ψ_{leaf} measurements suggested in this study.

Irrigation application in orchards should be timed so that tree water status is maintained at a level sufficient for optimum production. Irrigation scheduling decisions based on plant responses rather than measurements of soil

water status have gained wide acceptance because many features of the plant's physiology respond directly to changes in water status in the plant tissues rather than to changes in the bulk soil water content (or potential) (Jones, 2004). Direct physiological methods including ψ_{leaf} (Jones, 1990; Meyer and Green, 1980; Scholander et al., 1965) and ψ_{stem} (Garnier and Berger, 1985; McCutchan and Shackel, 1992) have greater relevance to plant functioning than soil-based measures because these measurements integrate both the effects of soil water available to the plant and the climatic conditions with physiological processes (Jones, 2004; Naor et al., 2006; van Zyl, 1987; Williams et al., 1994), which impact crop productivity directly (Grimes and Williams, 1990; Marsal et al., 2008).

Predawn and midday ψ_{leaf} are common plant water status parameters for irrigation scheduling in orchards (Intrigliolo and Castel, 2006a; Loveys et al., 2008; Williams and Baeza, 2007). However, studies suggest that midday ψ_{stem} is a significant and reliable indicator of plant water status for scheduling the irrigation of various crops (e.g., Deb et al., 2011a; Goldhamer and Fereres, 2001;

McCutchan and Shackel, 1992; Naor et al., 2001; Olivo et al., 2009; Shackel et al., 1997; Williams and Baeza, 2007). Williams and Araujo (2002) compared predawn ψ_{leaf} , midday ψ_{leaf} , and midday ψ_{stem} in grapevines and found that all represented equally viable assessments of the water status of grapevines and were all correlated similarly with the amount of water in the soil profile and leaf gas exchange as well as with one another. Remorini and Massai (2003) confirmed the ψ_{stem} throughout the day (hourly, from predawn to sunset) and predawn ψ_{leaf} to be better water status indicators than midday ψ_{leaf} for young peach trees. Williams and Trout (2005) found measurements of predawn ψ_{leaf} could not distinguish among higher irrigation regimes, whereas midday ψ_{stem} measurements provided discrimination because of a closer relationship to soil water potential and transpiration. In contrast, Intrigliolo and Castel (2006a) reported that midday ψ_{stem} values could not discriminate between irrigation treatments, which were shown to differ based on predawn ψ_{leaf} . However, in another study, Intrigliolo and Castel (2006b) recommended both predawn ψ_{leaf} and midday ψ_{stem} as water stress indicators in plum. Conversely, the ψ_{leaf} has been shown unreliable as an estimate of plant water status in many studies as a result of lack of its correlation with physiological parameters, measures of growth, and amounts of applied water (e.g., Choné et al., 2001; Garnier and Berger, 1985; Naor, 1998).

Little is reported about the midday ψ_{stem} and midday ψ_{leaf} for irrigated pecans [*Carya illinoensis* (Wangenh.) K. Koch] of southern New Mexico grown under different soil textures (Deb et al., 2011a). Water availability is frequently the most limiting factor for pecan productivity in the lower Rio Grande Valley of southern New Mexico. The shortage of water for irrigation is leading to an emphasis on improving methods of irrigation scheduling. Plant water stress indicators, ψ_{stem} and ψ_{leaf} , are tools that can help pecan growers to determine the timing of peak water demand by pecans and to make decisions for efficient use of irrigation water. In addition to the lack of general agreement on the most suitable plant water stress indicator, none of the plant-based ψ_{leaf} and ψ_{stem} measurements are well adapted for automation of irrigation scheduling or control (Jones, 2004). It is also difficult to sample multiple trees regularly, especially in a commercial pecan orchard. Although it may be possible to use automated stem or leaf psychrometers (Dixon and Tyree, 1984), these instruments are unreliable (Jones, 2004). Consequently, because the pecan response to soil water content varies as a function of evaporative demand, interpretation of ψ_{stem} and ψ_{leaf} data in pecans and their subsequent use in irrigation scheduling requires empirical relationships that take into account plant water status, variations in root-zone soil water content, distribution of plant roots, plant growth characteristics in addition to atmospheric conditions, specifically atmospheric evaporative demand.

In a previous study, Deb et al. (2011a) derived empirical relationships among direct

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¹To whom reprint requests should be addressed; e-mail sanjit@nmsu.edu.

physiological measurement of pecan water status (midday ψ_{stem}), soil water content at shallow depth (0 to 40 cm), and midday conditions of atmospheric VPD parameters, especially the climatic parameter T_{md} . Deb et al. (2011a) also assessed these empirical relationships based on temporal and spatial variations in soil water depletion and root length densities. However, it still remains unclear whether both midday ψ_{stem} and ψ_{leaf} can be used equally well to take account of the effects of soil water status and climatic factors. In particular, there is a need to evaluate to what extent these relationships can be used to interpret both midday ψ_{stem} and midday ψ_{leaf} in flood-irrigated, mature pecan orchards under contrasting soil types. Furthermore, there is a paucity of quantitative observations on variations in both midday ψ_{stem} and midday ψ_{leaf} at different tree heights or different leaf layers of the tree canopy, particularly on both shaded and sunlit sides of the pecan canopy. To our knowledge, literature provides no quantitative data on the diurnal patterns of ψ_{stem} and ψ_{leaf} in irrigated mature pecans under different soil textures, when root-zone soil water content and atmospheric conditions are evaluated simultaneously. There is still a question regarding the suitable time for both ψ_{stem} and ψ_{leaf} measurements to evaluate pecan water stress under different soil water conditions. Quantifying the effect of climatic conditions on diurnal ψ_{stem} and ψ_{leaf} changes at different tree heights in irrigated mature pecan orchards under different soil textures is lacking. Therefore, the objectives of this study were to: 1) evaluate diurnal and temporal patterns of both ψ_{stem} and ψ_{leaf} under different soil water status and climatic conditions in flood-irrigated, mature pecan orchards with contrasting soil textures; and 2) evaluate the validity of empirical relationships between both midday ψ_{stem} and midday ψ_{leaf} as dependent variables and soil water content and midday climatic parameters as independent variables in these pecan orchards.

Materials and Methods

Experimental site. Measurements of ψ_{stem} and ψ_{leaf} in 25- to 30-year-old 'Western Schley' pecan trees were carried out during June to Sept. 2010 and 2011 growing seasons at two orchards near Las Cruces, NM. A detailed description of these orchards can be found in Deb et al. (2011a, 2011b). Site 1 (0.9 ha) consisted of five rows of pecan trees in a diamond pattern with 15 trees in each row, 8 m between-row spacing, and 15 m in-row spacing. Site 2 (1 ha), located at New Mexico State University Leyendecker Plant Science Research Center (LPSRC), comprised seven rows of pecan trees in a rectangular pattern (7 m $\times$ 8 m) with 29 trees in each row. Root-zone soil water content and ψ_{stem} and ψ_{leaf} were monitored in three representative trees for each site (denoted as east, south, and north tree for Site 1 and north, south, and southwest tree for Site 2, respectively). Both orchards were flood-irrigated with a combination of surface water and groundwater. The climate

of the study areas is semiarid, and average annual temperature and precipitation are 17.7 °C and 297 mm, respectively.

Soil physical properties at Sites 1 and 2 were reported in Deb et al. (2011a, 2011b). Soil texture at Site 1 is sandy loam, and the soil texture is silty clay loam at Site 2. In accordance with the soil texture, the saturated hydraulic conductivity (K_s) for Site 1 was generally higher, and field capacity (FC) and wilting point (WP) water contents at 30 kPa and 1500 kPa, respectively, were lower for Site 1 than Site 2. The K_s for Site 1 ranged from 0.78 to 1.87 cm·h⁻¹ above 40 cm soil depth and 3.72 to 3.84 cm·h⁻¹ below 40 cm. The ranges of K_s values at Site 2 were between 0.01 and 1.7 cm·h⁻¹ above 60 cm and 0.75 and 3.72 cm·h⁻¹ below 60-cm soil depth. The average FC and WP water contents were 0.25 and 0.10 cm³·cm⁻³ above 40 cm and 0.15 and 0.05 cm³·cm⁻³ below 40 cm at Site 1, whereas these parameter values were 0.38 and 0.20 cm³·cm⁻³ above 60 cm and 0.28 and 0.12 cm³·cm⁻³ below 60 cm at Site 2.

Measurement of stem water potential and leaf water potential. Midday ψ_{stem} and ψ_{leaf} (between 1400 and 1500 HR Mountain Standard Time) were determined simultaneously using a pressure chamber (Model 1000 with digital gauge; PMS Instrument Company, Albany, OR) for each of the selected trees at both sites on a weekly basis over several irrigation cycles (i.e., every third and sixth day after irrigation) from June to Sept. 2010 and 2011. In 2010, for determining diurnal patterns, measurements of ψ_{stem} and ψ_{leaf} were carried out at each site throughout the day under typical dry and wet soil conditions. At each site, the diurnal ψ_{stem} and ψ_{leaf} measurements were made at 1-h intervals from 0800 to 1900 HR and thereafter measurements were made at 2100, 0000, 0300, 0600, and 0900 HR. For ψ_{stem} determinations during 2010, on each tree, shoot tips with several leaves on the sunlit sides of the canopy at tree heights of 2.5 m, 4.6 m, and 7.6 m above the soil surface, denoted as lower canopy, midcanopy, and upper canopy, respectively, were enclosed with foil-laminated plastic bags (Deb et al., 2011a). The effect of these bags on leaf temperature was also checked at both sites during a midday ψ_{stem} and ψ_{leaf} measurement day (between 1400 and 1500 HR). Test leaves together with HOBO H8 temperature sensors (Onset Computer Corp., Bourne, MA) were enclosed with bags at lower canopy, midcanopy, and upper canopy positions and temperature inside the bags were recorded at 1-s intervals, which showed no additional leaf heating even on sunlit side leaves (data not presented).

During ψ_{stem} measurements, the leaves were bagged for 30 min, which effectively stopped the natural transpiration from the leaves, allowing ψ_{leaf} to equilibrate with the ψ_{stem} (Fulton et al., 2001). Each shoot tip sealed in foil-laminated plastic bag was excised and then quickly placed into the pressure chamber. The exposed edge of the shoot was carefully observed for the appearance of a drop of water (sap). The rate of pressure increase in

the chamber was kept low to avoid errors during each measurement. The time between bagged leaves excision and chamber pressurization was generally less than 30 s. As soon as the water appeared, the corresponding pressure (ψ_{stem}) was read from the chamber digital gauge.

On each tree, leaves, chosen for ψ_{leaf} determinations at lower, mid-, and upper canopy were fully expanded, mature leaves exposed to direct sunlight. For non-bagged leaves, both leaf transpiration effects on water potential values and desiccation of transpiring leaves after excision from the plant have been reported in previous studies (e.g., Fulton et al., 2001; Turner and Long, 1980). Therefore, the targeted leaves were covered with foil-laminated plastic bags and sealed immediately after excision to avoid any further transpiration, and within 5 to 10 s, midday ψ_{leaf} was determined using the same pressure chamber. During the period of June to Sept. 2011, midday ψ_{stem} and ψ_{leaf} at the lower, mid-, and upper canopy were determined simultaneously for each of the selected trees at both sites on both shaded and sunlit side leaves of the tree.

Measurement of soil water content. At each site, time domain reflectometry (TDR) CS616 sensors (Campbell Scientific, Inc., Logan, UT) were installed horizontally at depths of 5, 10, 20, 40, 60, and 80 cm to continuously record volumetric water content (θ) once every 10 min at under- and outside-canopy locations of selected three trees during the 2010 and 2011 growing seasons. Sensor data were calibrated in situ using gravimetric water content data (Deb et al., 2011a). During the 2009 season, soil cores (11.4 cm in diameter) near the middle of the canopy and just inside the tree dripline were collected up to 100-cm depth for each tree and site to determine rooting depth and root length density (RLD) (Deb et al., 2011a, 2011b). At both sites, according to Deb et al. (2011a, 2011b), total RLD was much higher in the shallow depths (0 to 40 cm) than in the deeper depths (40 to 80 cm). Deb et al. (2011a) also reported that soil water depletion within the root zone (0 to 80 cm) was higher in the shallow depths (0 to 40 cm). As suggested by Deb et al. (2011a), soil water contents within the shallow depths (i.e., TDR data at depths of 5, 10, 20, and 40 cm), where RLD was also higher than in the deeper depths, were used to evaluate correlations with the midday ψ_{stem} and ψ_{leaf} at each tree and site. At each site, soil water content at shallow depth (0 to 40 cm) (θ_{avg}) was obtained by averaging θ at soil depths of 5, 10, 20, and 40 cm among selected trees at the time of midday ψ_{stem} and ψ_{leaf} measurements.

Estimation of atmospheric vapor pressure deficit. Air temperature, wind speed, relative humidity, and solar radiation at 2 m height above the ground were continuously recorded by a HOBO U30-NRC weather station (Onset Computer Corporation, Bourne, MA) at Site 1. Rainfall was measured at Site 1 using a tipping bucket measuring at 10-min intervals. Hourly meteorological variables were also obtained from the New Mexico State University

Fabian Garcia Science Center (FGSC) weather station, ≈ 6 km southeast of Site 1, to facilitate weather data comparison with the HOBO weather station. For Site 2, hourly rainfall, air temperature, solar radiation, wind speed, and relative humidity measured at 2-m height were collected from the LPSRC weather station, which is located ≈ 0.1 km from Site 2. To account for diurnal changes in evaporative demand at both sites, atmospheric VPD values were calculated using Murray's (1967) equations separately for Sites 1 and 2 using the average hourly air temperature and average hourly relative humidity data. For each measurement of midday ψ_{stem} and midday ψ_{leaf} , midday conditions of VPD at both sites were calculated using T_{md} and RH_{md} values between 1400 HR and 1500 HR. The diurnal and midday VPD were used to evaluate correlations with the diurnal variations of ψ_{stem} and ψ_{leaf} and midday ψ_{stem} and ψ_{leaf} respectively.

Data analysis. Linear regression analysis was used to explore relationships between

dependent and independent variables at both sites, namely, diurnal and midday ψ_{stem} and ψ_{leaf} values at lower, mid-, and upper canopy; midday VPD; T_{md} ; RH_{md} ; midday θ at different soil depths; and midday θ_{avg} . The effect that midday soil water content at shallow depth (θ_{avg}) and midday VPD parameters (climatic parameters T_{md} and RH_{md}) had on midday ψ_{stem} and ψ_{leaf} was evaluated through multiple regression analysis for the 2010 season. For each tree, one-parameter (dependent variables ψ_{stem} or ψ_{leaf} were regressed against independent variables θ_{avg} or T_{md}), two-parameter (against independent variables θ_{avg} and T_{md} or RH_{md} and T_{md}), and three-parameter (against independent variables θ_{avg} , T_{md} and RH_{md}) regression models were derived at both sites. *F*-test was performed to determine whether a regression model with more parameters provided a significant improvement over the regression models with a smaller number of independent parameters (Deb et al., 2011a). The null hypothesis was that a model with higher number of independent

parameters did not provide a significantly better fit than models with fewer parameters, and the null hypothesis was rejected if the *F* calculated from the data was greater than the critical value of the *F* distribution at 0.05 significant level.

Results and Discussion

Diurnal pattern of stem water potential and leaf water potential in pecan trees. The diurnal variations of ψ_{stem} and ψ_{leaf} of lower canopy, midcanopy, and upper canopy, θ at soil depths of 10, 20, and 40 cm, and microclimate variables at both Sites 1 and 2 are plotted for dry and wet soil conditions (Figs. 1 and 2). The ψ_{stem} and ψ_{leaf} of the both wet and relatively dry soil conditions at both sites decreased rapidly at sunrise (from 0600 HR), reached a minimum in early afternoon (between 1400 and 1500 HR), and rapidly increased in late afternoon (after 1800 HR).

The differences of both ψ_{stem} and ψ_{leaf} values between wet and relatively dry soil

Fig. 1. Diurnal variation of average air temperature, solar radiation, and relative humidity (A and D), volumetric water content (θ) at soil depths of 10, 20, and 40 cm (B and E), and measured stem water potential (ψ_{stem}) and leaf water potential (ψ_{leaf}) at tree heights of 2.5 m (lower canopy), 4.6 m (midcanopy), and 7.6 m (upper canopy) above the soil surface and atmospheric vapor pressure deficit (VPD) (C and F) for pecan trees at Site 1 after an irrigation event on 4 Aug. 2010: under wet soil conditions during 5 to 6 Aug. 2010 (left; A through C), and under relatively dry soil conditions during 9 to 10 Aug. 2010 (right; D through F). The ψ_{stem} and ψ_{leaf} values at each tree height represent the averages of three measurements on the selected east, south, and north pecan trees of Site 1.

Fig. 2. Diurnal variation of average air temperature, solar radiation, and relative humidity (A and D), volumetric water content (θ) at soil depths of 10, 20, and 40 cm (B and E), and measured stem water potential (ψ_{stem}) and leaf water potential (ψ_{leaf}) at tree heights of 2.5 m (lower canopy), 4.6 m (midcanopy), and 7.6 m (upper canopy) above the soil surface and atmospheric vapor pressure deficit (VPD) (C and F) for pecan trees at Site 2: under wet soil conditions during 28 to 29 Aug. 2010 after an irrigation event on 25 Aug. 2010 (left; A through C), and under dry soil conditions during 7 to 8 Aug. 2010 after the previous irrigation applied on 19 July 2010 (right; D through F). The ψ_{stem} and ψ_{leaf} values at each tree height represent the averages of three measurements on the selected north, south, and southwest pecan trees of Site 2.

conditions at both Sites 1 and 2 were straightforward, i.e., under dry soil conditions, ψ_{stem} and ψ_{leaf} values were more negative, particularly at early afternoon (between 1400 and 1500 HR) for both sites. For example, for 5 to 6 Aug. 2010 (Fig. 1C), after an irrigation event on 4 Aug. at Site 1, ψ_{stem} measured at midcanopy ranged from -0.76 (at 1500 HR) to -0.23 MPa (at 0300 HR) under wet soil conditions, whereas ψ_{leaf} at midcanopy varied from -1.03 (1500 HR) to -0.25 MPa (0300 HR). In contrast, for 9 to 10 Aug. 2010 (Fig. 1F) 5 d after the irrigation event on 4 Aug. at Site 1, the values of ψ_{stem} and ψ_{leaf} at midcanopy under relatively dry conditions ranged from -1.12 (1400 to 1500 HR) to -0.31 (0300 HR) and -1.46 (1300 to 1500 HR) to -0.32 MPa (0300 HR), respectively. Similar diurnal trends in ψ_{stem} and ψ_{leaf} under soil wet and dry conditions (Figs. 2C and Fig. 2F, respectively) were observed at Site 2. However, an important aspect to be noted in Figures 1F and 2F is that ψ_{stem} and ψ_{leaf} values under dry soil conditions exhibited relatively larger amplitude in the

silty clay loam Site 2 compared with the sandy loam Site 1 with diurnal variations in ψ_{stem} and ψ_{leaf} values at midcanopy ranging from -1.31 to -0.39 MPa and -1.72 to -0.41 MPa, respectively, under dry soil conditions at Site 2 (Fig. 2F). On the other hand, soil water content at Site 2 remained higher than Site 1 (Figs. 1B, 1E, 2B, and 2E), which could be explained by higher clay content and therefore higher field capacity and water-holding capacity within the root zone at Site 2. Obviously, the relatively lower ψ_{stem} and ψ_{leaf} values at Site 2 indicated that soil texture has an important effect on pecan water stress because capillary conductivity of soil influences flow of water from soil to roots. Previous work reported that root-zone soil water depletion at silty clay loam Site 2 was much lower than Site 1 (Deb et al., 2011a), indicating that reduced water adsorption rate by the root system might be related in part to the clayey soil type at Site 2.

The ψ_{stem} and ψ_{leaf} values of both the wet and relatively dry soil conditions at both sites

responded to diurnal variations in incoming solar radiation, VPD, air temperature, and relative humidity (Figs. 1 and 2). The rapid decrease in ψ_{stem} and ψ_{leaf} values was closely associated with the increase in solar radiation. For example, under the peak solar radiation at 1400 HR, the values of ψ_{stem} and ψ_{leaf} at Site 1 decreased to -0.74 and -0.98 and to -1.12 and -1.46 MPa under wet and dry soil conditions, respectively (Fig. 1). At Site 2, the values of ψ_{stem} and ψ_{leaf} during peak solar radiation at 1200 HR decreased to -0.62 and -0.85 and to -1.29 and -1.70 MPa for wet and dry soil conditions, respectively (Fig. 2). The diurnal trends of ψ_{stem} , ψ_{leaf} , and VPD under dry and wet soil conditions were also similar at both sites with increases in the evaporative demand (expressed as atmospheric VPD, a function of the air temperature and relative humidity) inducing more negative ψ_{stem} and ψ_{leaf} (Figs. 1 and 2). Accordingly, increases in air temperature and decreases in relative humidity during the day induced more negative ψ_{stem} and ψ_{leaf} at both

sites. Because air temperature and relative humidity are easy to determine and usually recorded at weather stations, air temperature or relative humidity might be directly used to interpret diurnal changes of ψ_{stem} and ψ_{leaf} in mature pecans under wet and dry soil conditions rather than estimating atmospheric VPD. The diurnal changes of ψ_{stem} and ψ_{leaf} and weather data for dry and wet soil conditions at both sites clearly suggest that, to evaluate water stress in mature pecans, measurements of ψ_{stem} and ψ_{leaf} should be made close to early afternoon (between 1400 and 1500 HR Mountain Standard Time) when the ψ_{stem} and ψ_{leaf} were minimum and responded to prevailing weather conditions that could impact water deficit on a given day. Although site-specific conditions including weather, soil, soil water depletion pattern, management conditions as well as plant properties affect daily dynamics of plant water status, there has been no general consensus regarding the most suitable time to measure midday ψ_{stem} and ψ_{leaf} , particularly for mature pecan. Time periods of midday ψ_{stem} measurements have been from 1100 to 1400 HR for grapevines (e.g., Choné et al., 2001), 1200 to 1500 HR for prunes (e.g., McCutchan and Shackel, 1992), and 1300 to 1500 HR for almonds, walnuts, and prunes (e.g., Fulton et al., 2001). Midday ψ_{stem} and ψ_{leaf} measurements were also taken only 0.5 h on either side of solar noon (from 1230 to 1330 HR) (Williams and Araujo, 2002).

Vertical differences in ψ_{stem} and ψ_{leaf} values among different tree heights, i.e., at lower, mid-, and upper canopy, developed soon after sunrise, indicating that a straightforward interpretation of ψ_{stem} and ψ_{leaf} determined at a single tree height within the canopy might not be representative. Both ψ_{stem} and ψ_{leaf} in the upper canopy were lower during the day at both sites than those in the lower canopy, suggesting that there was relatively more plant water stress at the upper canopy compared with the lower canopy at both sites. Consistently, the lower values of ψ_{stem} and ψ_{leaf} associated with tree heights within the canopy were most likely the result of resistances to liquid water flow in the longer pathway to the uppermost leaves (Begg and Turner, 1970; Hellkvist et al., 1974), differences in plant physiology, and flow against gravity. These vertical differences of ψ_{stem} and ψ_{leaf} values at lower, mid-, and upper canopy might also be related to the absorption and partitioning of radiation within the canopy, particularly the ψ_{leaf} might appear to reflect the degree of exposure of the leaves to solar radiation rather than its vertical position in the canopy above the soil surface. The differences in ψ_{stem} and ψ_{leaf} between the lower and upper canopy at Site 1 ranged from -0.01 to -0.2 MPa (Figs. 1C and 1F), whereas the differences were between -0.01 and -0.1 MPa at Site 2 (Figs. 2C and 2F). At both sites, under both wet and dry soil conditions (Figs. 1 and 2), although leaves were bagged just before excision, the ψ_{leaf} values were consistently more negative as compared with ψ_{stem} . This observation is

consistent with studies of other crops (e.g., Williams and Araujo, 2002). However, diurnal measurements of ψ_{stem} and ψ_{leaf} of both the dry and wet soil conditions at three canopy heights (Figs. 1 and 2) were highly correlated with one another at Site 1 ($R^2 > 0.94$, $P < 0.05$) and Site 2 ($R^2 > 0.95$, $P < 0.05$).

Temporal pattern of midday stem water potential and leaf water potential in pecan trees. The midday ψ_{stem} at three canopy heights and volumetric water content (θ) at soil depths of 10, 20, and 40 cm corresponding to midday ψ_{stem} measurements during June through Sept. 2010 for all trees at both sites are demonstrated in Figures 3 and 4, respectively. Simultaneous measurements of midday ψ_{leaf} at three canopy heights for each tree and site made throughout June to Sept. 2010 are not shown. The relationship between midday ψ_{stem} and midday ψ_{leaf} determined at midcanopy for selected trees at both sites are shown in Figure 5. As observed in diurnal trends of ψ_{stem} and ψ_{leaf} (Figs. 1 and 2), midday ψ_{leaf} exhibited relatively larger amplitude, i.e., more negative as compared with midday ψ_{stem} , because the midday ψ_{leaf} values depend partially on water loss from leaves or leaf transpiration rate at the time of measurement (Jones, 2004). Overall,

the values of R^2 between midday ψ_{stem} and midday ψ_{leaf} ranged from 0.81 to 0.90 at the lower canopy ($P < 0.05$), 0.83 to 0.85 at midcanopy ($P < 0.05$), and 0.84 to 0.85 at the upper canopy ($P < 0.05$) at Site 1 (data not presented). At Site 2, the values of R^2 between midday ψ_{stem} and midday ψ_{leaf} were between 0.86 and 0.90 at the lower canopy ($P < 0.05$), 0.90 at midcanopy ($P < 0.05$), and between 0.90 and 0.91 at the upper canopy ($P < 0.05$) (data not presented).

Evaluation of the relationship between midday ψ_{stem} and midday ψ_{leaf} has yielded contrasting results in studies for other tree crops. For example, although midday ψ_{stem} and midday ψ_{leaf} were highly correlated with one another in grapevines (Stevens et al., 1995; Williams and Araujo, 2002) and peach (Selles and Berger, 1990), Naor et al. (1995) reported a weak correlation between ψ_{stem} and ψ_{leaf} for apple trees (R^2 of 0.35). The high correlation of the comparisons between midday ψ_{stem} and midday ψ_{leaf} at sandy loam Site 1 and silty clay loam Site 2 indicated that either measurement of midday ψ_{stem} and ψ_{leaf} could be a good indicator of the water status of mature pecans regardless of soil type. Moreover, both ψ_{stem} and ψ_{leaf} at lower, mid-, and upper canopy did not exhibit significant

Fig. 3. Midday stem water potential (ψ_{stem}) at tree heights of 2.5 m (lower canopy), 4.6 m (midcanopy), and 7.6 m (upper canopy) above the soil surface, and volumetric soil water content (θ) at soil depths of 10, 20, and 40 cm corresponding to ψ_{stem} measurements taken at identical times during the period from June to Sept. 2010 for the selected east (top), south (middle), and north (bottom) pecan trees of Site 1. The predicted ψ_{stem} using two-parameter [Deb et al. (2011a); relationships between ψ_{stem} and measured midday θ within the 0- to 40-cm soil depth (θ_{avg}) and midday air temperature (T_{md}) data during 2010] regression models for each tree are also presented. Estimated midday atmospheric vapor pressure deficit (midday VPD) for Site 1 is depicted in the east pecan's (top) plot. Irrigation and rain events during the period of June to Sept. 2010 are shown in the east pecan's (top) plot.

Fig. 4. Midday stem water potential (Ψ_{stem}) at tree heights of 2.5 m (lower canopy), 4.6 m (midcanopy), and 7.6 m (upper canopy) above the soil surface, and volumetric soil water content (θ) at soil depths of 10, 20, and 40 cm corresponding to Ψ_{stem} measurements taken at identical times during the period from June to Sept. 2010 for the selected north (top), south (middle), and southwest (bottom) pecan trees of Site 2. The predicted Ψ_{stem} using two-parameter [Deb et al. (2011a); relationships between Ψ_{stem} and measured midday θ within the 0- to 40-cm soil depth (θ_{avg}) and midday air temperature (T_{md}) data during 2010] regression models for each tree are also presented. Estimated midday atmospheric vapor pressure deficit (midday VPD) for Site 2 is depicted in the north pecan's (top) plot. Irrigation and rain events during the period of June to Sept. 2010 are shown in the north pecan's (top) plot.

Fig. 5. Relationship between midday leaf water potential (Ψ_{leaf}) and stem water potential (Ψ_{stem}) measured at midcanopy (at 4.6 m tree height above the soil surface) at both Sites 1 and 2 during the period from June to Sept. 2010: (A) for east pecan tree at Site 1 and (B) for north pecan tree at Site 2. *Significant at $P < 0.05$.

differences in magnitudes among trees, even under dry soil conditions at both sites. In a previous study, Deb et al. (2011a) found that root-zone soil water depletion within and outside the canopy locations of pecan trees for both sites did not vary spatially. In contrast, for other crops, Ψ_{stem} has been shown to be

better related to tree-to-tree differences in water status, particularly in drier soils (Choné et al., 2001; Shackel et al., 1997).

For both sites, because midday Ψ_{stem} and midday Ψ_{leaf} values at lower, mid-, and upper canopy showed similar temporal trends between irrigation events, for ease of interpretation

as well as comparison with the predictions of Ψ_{stem} using the regression model (Deb et al., 2011a), temporal variations in midday Ψ_{stem} for selected trees at both sites during the season 2010 are only presented (Figs. 3 and 4). As demonstrated in Figures 3 and 4, similar to diurnal trends (Figs. 1 and 2), temporal patterns of vertical differences in midday Ψ_{stem} values from lower to upper canopy indicated that there was always relatively more plant water stress at the upper canopy compared with the lower canopy at both sites. In contrast, Deb et al. (2011a) reported that midday Ψ_{stem} values at both Sites 1 and 2 during the growing season in 2009 were nearly the same at different heights after irrigation and a decrease in midday Ψ_{stem} with canopy height was observed 10 to 14 d after the irrigation. Temporal trends of midday Ψ_{stem} and midday Ψ_{leaf} (data not shown) over several irrigation cycles in mature pecans at Sites 1 and 2 suggested that the differences in midday Ψ_{stem} or midday Ψ_{leaf} between measurements at different tree heights were not negligible.

Volumetric soil water content and midday stem water potential and leaf water potential. At both sites, the midday Ψ_{stem} followed the cyclic pattern of the θ between irrigations, and Ψ_{stem} at different canopy heights decreased with decreasing θ at soil depths of 10, 20, and 40 cm (Figs. 3 and 4). For example, during the period of 26 June through 11 July 2010 at Site 1 (Fig. 3), after the irrigation on June 26, the θ at the time of midday Ψ_{stem} measurements, on average, decreased from 0.40 to 0.23 $\text{cm}^3 \cdot \text{cm}^{-3}$ at 10 cm, 0.33 to 0.27 $\text{cm}^3 \cdot \text{cm}^{-3}$ at 20, and 0.33 to 0.25 $\text{cm}^3 \cdot \text{cm}^{-3}$ at 40 cm soil depth for the east, south, and north tree. These decreases in θ corresponded to the decreases in midday Ψ_{stem} during the period of 26 June to 11 July 2010 with midday Ψ_{stem} values measured at lower canopy decreasing from -0.63 to -1.25 MPa, -0.62 to -1.26 MPa, and -0.62 to -1.25 MPa for the east, south, and north trees of Site 1, respectively (Fig. 3). The respective decreases in midday Ψ_{stem} values at midcanopy and upper canopy were from -0.68 to -1.31 MPa and -0.71 to -1.36 MPa, from -0.67 to -1.32 MPa and -0.72 to -1.40 MPa, and from -0.66 to -1.31 MPa and -0.69 to -1.35 MPa for the east, south, and north trees at Site 1, respectively (Fig. 3).

The volumetric soil water contents (θ) at soil depths of 5, 10, 20, 40, and 60 cm were compared with midday Ψ_{stem} measurements taken at the same times for all trees. Regression analysis was used to evaluate correlations between midday Ψ_{stem} at three canopy heights and θ at depths of 5, 10, 20, 40 and 60 cm for each tree at both sites. Soil water contents (θ) at depths of 5, 10, 20, 40 cm, and 60 cm as well as average values of θ at the soil depth of 0 to 40 cm (θ_{avg}) were significantly correlated with midday Ψ_{stem} at three canopy heights for each tree at both sites (Deb et al., 2011a). Overall, the values of R^2 between θ and midday Ψ_{stem} at different canopies ranged from 0.66 (at 60-cm depth) to 0.78 (at 20 cm) ($P < 0.05$) and from 0.72 (at 40 cm) to 0.80 (at 5 cm) ($P < 0.05$) among trees at Sites 1 and 2, respectively. The relationship between θ_{avg}

and midday ψ_{stem} at different canopy heights provided the R^2 ranges of 0.73 to 0.78 ($P < 0.05$) and 0.80 to 0.82 ($P < 0.05$) among trees at Sites 1 and 2, respectively (data not presented).

The midday ψ_{stem} values were lower in trees at the silty clay loam Site 2 than at the sandy loam Site 1, particularly in dry soil conditions (Figs. 3 and 4), in accordance with previously reported data during the 2009 growing season (Deb et al., 2011a). For example, during the period from June to Sept. 2010, midday ψ_{stem} values of trees under wet soil conditions measured at midcanopy for both sites converged near -0.60 MPa, whereas under dry soil conditions, midday ψ_{stem} values at midcanopy were -1.88 MPa and -1.66 MPa for trees on silty clay loam (Site 2) and sandy loam soils (Site 1), respectively (Figs. 3 and 4). As shown in Figures 3 and 4, the decrease in midday ψ_{stem} was because of the increase in midday atmospheric VPD. When the midday ψ_{stem} and ψ_{leaf} at three canopy heights were regressed against midday atmospheric VPD, the values of R^2 ranged from 0.51 to 0.68 ($P < 0.05$) and 0.67 to 0.85 ($P < 0.05$) among trees at Sites 1 and 2, respectively (data not presented). The midday ψ_{stem} and/or ψ_{leaf} have also been reported to have a linear relationship with the VPD for various crops (Goldhamer and Fereres, 2001; McCutchan and Shackel, 1992; Stern et al., 1998; Stevens et al., 1995; Williams and Baeza, 2007), including mature pecans (Deb et al., 2011a).

Relationship between midday stem water potential and leaf water potential and soil water content and atmospheric vapor pressure deficit parameters. For each tree at both sites

during the 2010 season, one-parameter [ψ_{stem} or $\psi_{\text{leaf}} = f(\theta_{\text{avg}}$ or $T_{\text{md}})$], two-parameter [ψ_{stem} or $\psi_{\text{leaf}} = f(\theta_{\text{avg}}$ and T_{md} or RH_{md} and $T_{\text{md}})$], and three-parameter [ψ_{stem} or $\psi_{\text{leaf}} = f(\theta_{\text{avg}}$, T_{md} , and $\text{RH}_{\text{md}})$] regression models derived using the multiple regression analysis are presented in Tables 1 and 2. Introducing more independent variables to explain the variability of ψ_{stem} or ψ_{leaf} improved R^2 ($P < 0.05$) (Tables 1 and 2). F -test showed that in general the two-parameter regression model (between ψ_{stem} or ψ_{leaf} and θ_{avg} and T_{md}) provided a significantly better fit to the data than one- (θ_{avg} or T_{md}), two- (RH_{md} and T_{md}), and three-parameter (θ_{avg} , T_{md} , and RH_{md}) models for most of the trees at both sites, suggesting that θ_{avg} and T_{md} had an important influence on both midday ψ_{stem} and midday ψ_{leaf} variation at both sites. Therefore, measurements of θ_{avg} and T_{md} could be made as an adjunct for the simple interpretation of midday ψ_{stem} or midday ψ_{leaf} to help refine irrigation scheduling in mature pecan orchards.

In an earlier study on the same pecan orchards, two-parameter regression models similar to the models proposed in this study were developed only for ψ_{stem} using the measured ψ_{stem} data for 2009. Except for north and south pecan trees at Site 2 under dry soil conditions (Fig. 4), the predicted ψ_{stem} values using these two-parameter models [in Table 6 of Deb et al. (2011a)] for 2010 and 2011 were consistently higher than the measured ψ_{stem} values (Figs. 3, 4, 6A, and 7A). The most plausible explanation for this underprediction is that measurements in the previous study (Deb et al., 2011a) were made between 1200 and 1400 HR Mountain Standard Time,

and ψ_{stem} was more variable and not minimum. In contrast, using two-parameter regression models [ψ_{stem} or $\psi_{\text{leaf}} = f(\text{midday } \theta_{\text{avg}} \text{ and } T_{\text{md}})$] developed in this study from 2010 data for both sites (Tables 1 and 2) showed better agreement between the measured and predicted ψ_{stem} as well as ψ_{leaf} measured on the both shaded and sunlit sides of pecan trees (Figs. 6 and 7). The values of R^2 ranged from 0.70 to 0.98 ($P < 0.05$) among trees at Site 1, whereas the values of R^2 were in the range of 0.85 to 0.98 ($P < 0.05$) among trees at Site 2. These empirical relationships [ψ_{stem} or $\psi_{\text{leaf}} = f(\text{midday } \theta_{\text{avg}} \text{ and } T_{\text{md}})$] were evaluated at each of the two pecan orchards, where irrigation scheduling and other management practices, and midday conditions of microclimate variables, particularly air temperature and relative humidity during the period from June to September (Fig. 8), were similar during the 2010 and 2011 seasons. Therefore, the further evaluation of these empirical relationships under different climatic conditions, irrigation, and other pecan management practices may improve their reliability to estimate the water status of mature pecans.

Another aspect to be pointed out from Figures 6 and 7 is that the values of ψ_{stem} measured at different heights on both shaded and sunlit sides of the tree over several irrigation cycles during the 2011 season were almost the same (Fig. 6A and 7A), whereas the lower values of ψ_{leaf} of sunlit side leaves in comparison with their shaded counterparts were observed (Fig. 6B and 7B). From this perspective, it could be argued that when the midday parameters θ_{avg} and T_{md} were used as complementary factors for the interpretation

Table 1. Multiple regression analysis with midday stem water potential (ψ_{stem} , MPa) at midcanopy (i.e., at 4.6 m tree height above the soil surface) as the dependent variable and average values of volumetric water content at the shallow soil depth of 0 to 40 cm (θ_{avg} , $\text{cm}^3 \cdot \text{cm}^{-3}$), midday air temperature (T_{md} , $^{\circ}\text{C}$), and midday relative humidity (RH_{md} , %) as the independent variables.

Site 1 (2010)			Site 2 (2010)		
Regression model ^z	R^{2y}	Adjusted R^2 (P value; SEE)*	Regression model ^z	R^{2y}	Adjusted R^2 (P value; SEE)*
East tree:			North tree:		
$\psi_{\text{stem}} = -2.37 + 4.70 \times \theta_{\text{avg}}$	0.78	0.77 (0.00000; 0.14)	$\psi_{\text{stem}} = -3.34 + 5.80 \times \theta_{\text{avg}}$	0.79	0.78 (0.00000; 0.162)
$\psi_{\text{stem}} = 0.652 - 0.054 \times T_{\text{md}}$	0.79	0.78 (0.00000; 0.14)	$\psi_{\text{stem}} = 1.81 - 0.094 \times T_{\text{md}}$	0.75	0.75 (0.00000; 0.176)
$\psi_{\text{stem}} = 0.625 - 0.052 \times T_{\text{md}} - 0.001 \times \text{RH}_{\text{md}}$	0.79	0.77 (0.00000; 0.141)	$\psi_{\text{stem}} = 1.49 - 0.068 \times T_{\text{md}} - 0.013 \times \text{RH}_{\text{md}}$	0.86	0.85 (0.00000; 0.134)
$\psi_{\text{stem}} = -0.66 + 2.20 \times \theta_{\text{avg}} - 0.0324 \times T_{\text{md}}$	0.84	0.83 (0.00000; 0.12)	$\psi_{\text{stem}} = -0.94 + 3.55 \times \theta_{\text{avg}} - 0.05 \times T_{\text{md}}$	0.88	0.87 (0.00000; 0.13)
$\psi_{\text{stem}} = -0.76 + 2.29 \times \theta_{\text{avg}} - 0.026 \times T_{\text{md}} - 0.0036 \times \text{RH}_{\text{md}}$	0.84	0.82 (0.00000; 0.13)	$\psi_{\text{stem}} = -0.297 + 2.49 \times \theta_{\text{avg}} - 0.048 \times T_{\text{md}} - 0.0072 \times \text{RH}_{\text{md}}$	0.90	0.89 (0.00000; 0.11)
South tree:			South tree:		
$\psi_{\text{stem}} = -2.33 + 4.57 \times \theta_{\text{avg}}$	0.76	0.75 (0.00000; 0.15)	$\psi_{\text{stem}} = -3.34 + 5.80 \times \theta_{\text{avg}}$	0.79	0.78 (0.00000; 0.162)
$\psi_{\text{stem}} = 0.65 - 0.054 \times T_{\text{md}}$	0.79	0.78 (0.00000; 0.14)	$\psi_{\text{stem}} = 1.81 - 0.094 \times T_{\text{md}}$	0.75	0.75 (0.00000; 0.177)
$\psi_{\text{stem}} = 0.637 - 0.053 \times T_{\text{md}} - 0.001 \times \text{RH}_{\text{md}}$	0.79	0.77 (0.00000; 0.141)	$\psi_{\text{stem}} = 1.487 - 0.068 \times T_{\text{md}} - 0.013 \times \text{RH}_{\text{md}}$	0.86	0.85 (0.00000; 0.134)
$\psi_{\text{stem}} = -0.684 + 2.26 \times \theta_{\text{avg}} - 0.032 \times T_{\text{md}}$	0.84	0.83 (0.00000; 0.12)	$\psi_{\text{stem}} = -0.94 + 3.55 \times \theta_{\text{avg}} - 0.005 \times T_{\text{md}}$	0.88	0.87 (0.00000; 0.13)
$\psi_{\text{stem}} = -0.78 + 2.35 \times \theta_{\text{avg}} - 0.026 \times T_{\text{md}} - 0.0035 \times \text{RH}_{\text{md}}$	0.85	0.83 (0.00000; 0.12)	$\psi_{\text{stem}} = -0.297 + 2.49 \times \theta_{\text{avg}} - 0.048 \times T_{\text{md}} - 0.0072 \times \text{RH}_{\text{md}}$	0.90	0.89 (0.00000; 0.11)
North tree:			Southwest tree:		
$\psi_{\text{stem}} = -2.32 + 4.52 \times \theta_{\text{avg}}$	0.75	0.74 (0.00000; 0.15)	$\psi_{\text{stem}} = -3.79 + 6.80 \times \theta_{\text{avg}}$	0.81	0.80 (0.00000; 0.16)
$\psi_{\text{stem}} = 0.64 - 0.054 \times T_{\text{md}}$	0.79	0.78 (0.00000; 0.14)	$\psi_{\text{stem}} = 1.83 - 0.094 \times T_{\text{md}}$	0.75	0.75 (0.00000; 0.177)
$\psi_{\text{stem}} = 0.625 - 0.052 \times T_{\text{md}} - 0.001 \times \text{RH}_{\text{md}}$	0.79	0.77 (0.00000; 0.141)	$\psi_{\text{stem}} = 1.501 - 0.068 \times T_{\text{md}} - 0.013 \times \text{RH}_{\text{md}}$	0.86	0.853 (0.00000; 0.135)
$\psi_{\text{stem}} = -0.66 + 2.20 \times \theta_{\text{avg}} - 0.032 \times T_{\text{md}}$	0.84	0.83 (0.00000; 0.123)	$\psi_{\text{stem}} = -1.33 + 4.27 \times \theta_{\text{avg}} - 0.047 \times T_{\text{md}}$	0.89	0.88 (0.00000; 0.123)
$\psi_{\text{stem}} = -0.76 + 2.29 \times \theta_{\text{avg}} - 0.026 \times T_{\text{md}} - 0.0036 \times \text{RH}_{\text{md}}$	0.84	0.82 (0.00000; 0.124)	$\psi_{\text{stem}} = -0.62 + 3.07 \times \theta_{\text{avg}} - 0.046 \times T_{\text{md}} + 0.007 \times \text{RH}_{\text{md}}$	0.91	0.90 (0.00000; 0.11)

^zFor each tree, one-parameter regression model (regression between ψ_{stem} and θ_{avg} and between ψ_{stem} and T_{md}), two-parameter regression model (multiple regression between ψ_{stem} and θ_{avg} and T_{md} ; between ψ_{stem} and RH_{md} and T_{md}), and three-parameter regression model (multiple regression between ψ_{stem} and θ_{avg} , T_{md} , and RH_{md}).

^y R^2 = the coefficient of determination.

* P value from analysis of variance section of the regression (significant at $P < 0.05$).

SEE = SE of estimate.

Table 2. Multiple regression analysis with midday leaf water potential (ψ_{leaf} , MPa) at midcanopy (i.e., at 4.6 m tree height above the soil surface) as the dependent variable and average values of volumetric water content at the shallow soil depth of 0 to 40 cm (θ_{avg} , $\text{cm}^3 \cdot \text{cm}^{-3}$), midday air temperature (T_{md} , $^{\circ}\text{C}$), and midday relative humidity (RH_{md} , %) as the independent variables.

Site 1 (2010)			Site 2 (2010)		
Regression model ^z	R^2 ^y	Adjusted R^2 (P value; SEE)*	Regression model ^z	R^2 ^y	Adjusted R^2 (P value; SEE)*
East tree:			North tree:		
$\psi_{\text{leaf}} = -2.77 + 5.0 \times \theta_{\text{avg}}$	0.76	0.75 (0.00000; 0.16)	$\psi_{\text{leaf}} = -3.46 + 5.38 \times \theta_{\text{avg}}$	0.67	0.65 (0.00000; 0.21)
$\psi_{\text{leaf}} = 0.46 - 0.058 \times T_{\text{md}}$	0.78	0.77 (0.00000; 0.15)	$\psi_{\text{leaf}} = 1.60 - 0.096 \times T_{\text{md}}$	0.772	0.77 (0.00000; 0.172)
$\psi_{\text{leaf}} = 0.578 - 0.076 \times T_{\text{md}} - 0.011 \times \text{RH}_{\text{md}}$	0.80	0.79 (0.00000; 0.145)	$\psi_{\text{leaf}} = 1.37 - 0.08 \times T_{\text{md}} - 0.009 \times \text{RH}_{\text{md}}$	0.83	0.81 (0.00000; 0.151)
$\psi_{\text{leaf}} = -0.97 + 2.37 \times \theta_{\text{avg}} - 0.034 \times T_{\text{md}}$	0.83	0.82 (0.00000; 0.135)	$\psi_{\text{leaf}} = -0.194 + 2.321 \times \theta_{\text{avg}} - 0.07 \times T_{\text{md}}$	0.83	0.81 (0.00000; 0.152)
$\psi_{\text{leaf}} = -0.73 + 2.16 \times \theta_{\text{avg}} - 0.051 \times T_{\text{md}} + 0.009 \times \text{RH}_{\text{md}}$	0.84	0.83 (0.00000; 0.13)	$\psi_{\text{leaf}} = 0.354 + 1.411 \times \theta_{\text{avg}} - 0.066 \times T_{\text{md}} - 0.006 \times \text{RH}_{\text{md}}$	0.84	0.83 (0.00000; 0.15)
South tree:			South tree:		
$\psi_{\text{leaf}} = -2.74 + 4.90 \times \theta_{\text{avg}}$	0.75	0.74 (0.00000; 0.163)	$\psi_{\text{leaf}} = -3.46 + 5.38 \times \theta_{\text{avg}}$	0.67	0.65 (0.00000; 0.21)
$\psi_{\text{leaf}} = 0.45 - 0.058 \times T_{\text{md}}$	0.77	0.76 (0.00000; 0.155)	$\psi_{\text{leaf}} = 1.60 - 0.096 \times T_{\text{md}}$	0.772	0.77 (0.00016; 0.172)
$\psi_{\text{leaf}} = 0.602 - 0.077 \times T_{\text{md}} - 0.011 \times \text{RH}_{\text{md}}$	0.80	0.78 (0.00000; 0.149)	$\psi_{\text{leaf}} = 1.37 - 0.08 \times T_{\text{md}} - 0.009 \times \text{RH}_{\text{md}}$	0.83	0.81 (0.00000; 0.151)
$\psi_{\text{leaf}} = -0.99 + 2.44 \times \theta_{\text{avg}} - 0.034 \times T_{\text{md}}$	0.83	0.81 (0.00000; 0.14)	$\psi_{\text{leaf}} = -0.194 + 2.321 \times \theta_{\text{avg}} - 0.066 \times T_{\text{md}}$	0.83	0.81 (0.00000; 0.153)
$\psi_{\text{leaf}} = -0.74 + 2.23 \times \theta_{\text{avg}} - 0.051 \times T_{\text{md}} + 0.009 \times \text{RH}_{\text{md}}$	0.84	0.82 (0.00000; 0.134)	$\psi_{\text{leaf}} = 0.354 + 1.411 \times \theta_{\text{avg}} - 0.066 \times T_{\text{md}} - 0.006 \times \text{RH}_{\text{md}}$	0.84	0.83 (0.00000; 0.15)
North tree:			Southwest tree:		
$\psi_{\text{leaf}} = -2.71 + 4.81 \times \theta_{\text{avg}}$	0.75	0.74 (0.00000; 0.161)	$\psi_{\text{leaf}} = -3.87 + 6.26 \times \theta_{\text{avg}}$	0.68	0.67 (0.00002; 0.21)
$\psi_{\text{leaf}} = 0.43 - 0.0572 \times T_{\text{md}}$	0.78	0.77 (0.00000; 0.152)	$\psi_{\text{leaf}} = 1.62 - 0.096 \times T_{\text{md}}$	0.78	0.77 (0.00000; 0.17)
$\psi_{\text{leaf}} = 0.578 - 0.076 \times T_{\text{md}} - 0.011 \times \text{RH}_{\text{md}}$	0.80	0.79 (0.00000; 0.145)	$\psi_{\text{leaf}} = 1.384 - 0.08 \times T_{\text{md}} - 0.009 \times \text{RH}_{\text{md}}$	0.83	0.82 (0.00000; 0.151)
$\psi_{\text{leaf}} = -0.97 + 2.37 \times \theta_{\text{avg}} - 0.034 \times T_{\text{md}}$	0.83	0.82 (0.00000; 0.135)	$\psi_{\text{leaf}} = -0.401 + 2.73 \times \theta_{\text{avg}} - 0.066 \times T_{\text{md}}$	0.83	0.82 (0.00000; 0.15)
$\psi_{\text{leaf}} = -0.72 + 2.16 \times \theta_{\text{avg}} - 0.051 \times T_{\text{md}} + 0.009 \times \text{RH}_{\text{md}}$	0.84	0.83 (0.00000; 0.13)	$\psi_{\text{leaf}} = 0.194 + 1.722 \times \theta_{\text{avg}} - 0.066 \times T_{\text{md}} - 0.006 \times \text{RH}_{\text{md}}$	0.84	0.83 (0.00000; 0.15)

^zFor each tree, one-parameter regression model (regression between ψ_{leaf} and θ_{avg} and between ψ_{leaf} and T_{md}), two-parameter regression model (multiple regression between ψ_{leaf} and θ_{avg} and T_{md} ; between ψ_{leaf} and RH_{md} and T_{md}), and three-parameter regression model (multiple regression between ψ_{leaf} and θ_{avg} , T_{md} , and RH_{md}).

^y R^2 = the coefficient of determination.

* P value from analysis of variance section of the regression (significant at $P < 0.05$).

SEE = SE of estimate.

Fig. 6. Midday stem water potential (ψ_{stem}) and midday leaf water potential (ψ_{leaf}) measured on the both shaded and sunlit sides of the tree at heights of 2.5 m (lower canopy), 4.6 m (midcanopy), and 7.6 m (upper canopy) above the soil surface, and the predicted ψ_{stem} using the two-parameter regression models at Site 1 during the period from June to Sept. 2011: (A) measured midday ψ_{stem} vs. predicted ψ_{stem} using two-parameter [multiple regression between ψ_{stem} and θ_{avg} and T_{md} (Table 1); and Deb et al. (2011a)] regression models, and (B) measured midday ψ_{leaf} vs. predicted ψ_{leaf} using the two-parameter (multiple regression between ψ_{leaf} and θ_{avg} and T_{md} ; Table 2) regression models. The measured ψ_{stem} and ψ_{leaf} values at each tree height represent the averages of six measurements on each of shaded and sunlit sides of the selected east, south, and north pecan trees at Site 1.

of either midday ψ_{stem} or midday ψ_{leaf} at both sandy loam and silty clay loam sites, it might be more favorable to choose midday ψ_{stem} because it provided a relatively stable indicator of mature pecan water status on both shaded and sunlit sides of the pecan canopy.

Conclusions

Diurnal patterns of ψ_{stem} and ψ_{leaf} of both the dry and wet soil conditions measured at

three canopy heights for flood-irrigated mature pecan orchards with sandy loam (Site 1) and silty clay loam (Site 2) soil textures suggested that midday measurements of ψ_{stem} and ψ_{leaf} should be made in midafternoon (between 1400 and 1500 HR Mountain Standard Time) to determine water stress in mature pecans that responded to potential climatic conditions. Diurnal measurements of ψ_{stem} and ψ_{leaf} at three canopy heights were significantly correlated under both the dry and wet

soil conditions. However, although soil water contents at Site 2 remained higher as compared with Site 1, ψ_{stem} and ψ_{leaf} values, particularly under dry soil conditions at Site 2 in contrast to Site 1, were consistently more negative, indicating that soil texture has an important effect on pecan water stress, and the flow of water from soil to roots might be influenced in part by more clayey soil at this Site 2. Midday ψ_{stem} and midday ψ_{leaf} at three canopy heights over several irrigation cycles

Fig. 7. Midday stem water potential (ψ_{stem}) and midday leaf water potential (ψ_{leaf}) measured on the both shaded and sunlit sides of the tree at heights of 2.5 m (lower canopy), 4.6 m (midcanopy), and 7.6 m (upper canopy) above the soil surface, and the predicted ψ_{stem} using the two-parameter regression models at Site 2 during the period from June to Sept. 2011: (A) measured midday ψ_{stem} vs. predicted ψ_{stem} using three-parameter [multiple regression between ψ_{stem} and θ_{avg} and T_{md} (Table 1); and Deb et al. (2011a)] regression models, and (B) measured midday ψ_{leaf} vs. predicted ψ_{leaf} using two-parameter (multiple regression between ψ_{leaf} and θ_{avg} and T_{md} ; Table 2) regression models. The measured ψ_{stem} and ψ_{leaf} values at each tree height represent the averages of six measurements on each of shaded and sunlit sides of the selected north, south, and southwest pecan trees at Site 2.

Fig. 8. Midday air temperature (T_{md}) and relative humidity (RH_{md}) (1400 to 1500 HR Mountain Standard Time) at both Sites 1 and 2 during the 2010 and 2011 seasons.

during the 2010 season were correlated with one another, midday soil water content at different soil depths and within the shallow depths (θ_{avg}), and midday atmospheric VPD at each tree and site. To evaluate the effect that soil water status and climatic parameters had on both midday ψ_{stem} and ψ_{leaf} during the 2010 season, multiple regression analysis (between midday ψ_{stem} or ψ_{leaf} and midday θ_{avg} , T_{md} , and RH_{md}) revealed that two-parameter multiple regression models (relationships between midday ψ_{stem} or ψ_{leaf} and midday θ_{avg} and T_{md}) were the most significant for the interpretation of midday ψ_{stem} or ψ_{leaf} at both sites. The predictions of average ψ_{stem} and ψ_{leaf} using these two-parameter models were correlated with midday ψ_{stem} and midday ψ_{leaf} measured on the both shaded and sunlit sides of trees at three canopy heights during 2011. Midday measurements of ψ_{stem} and ψ_{leaf} on both shaded and sunlit sides of the pecan canopy during the 2011 season suggested that midday ψ_{stem} in contrast to midday ψ_{leaf} provided a relatively stable indicator of mature pecan water status.

Measurements of ψ_{stem} or ψ_{leaf} using the pressure chamber method are expensive, time-consuming, and destructive sampling of stems is required. It is easier to monitor soil water content and air temperature continuously, and these two-parameter models (relationships between midday ψ_{stem} or ψ_{leaf} and midday θ_{avg} and T_{md}) could be useful for the simple interpretation of midday ψ_{stem} and ψ_{leaf} to help refine irrigation scheduling of pecans. However, the further evaluation of relationships between midday ψ_{stem} or ψ_{leaf} and midday θ_{avg} , T_{md} , and RH_{md} under different irrigation and other pecan management practices, soils, and climatic conditions is recommended to improve the reliability of these empirical relationships to estimate the water status of mature pecans.

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