

HEAT PULSE NEEDLES TO MEASURE PECAN TREE TRANSPIRATION

R. B. Sorensen, T. L. Jones, G. S. Campbell, M. Montes-Helu

ABSTRACT. Heat pulse needles (HPN), three thermocouple (TC) junctions per needle, were inserted into pecan (*Carya illinoensis* K. Koch) tree trunks to evaluate their effectiveness in measuring transpiration. Two terraces were selected and irrigated at 50% and 11% depletion of available water. A maximum of four pairs of HPN were inserted into the tree at a 1.5-m (5-ft) trunk height. A datalogger was used to control an 8.0-s heat pulse and to collect temperature data at each TC junction at 2.0-s intervals for 60 s starting midway through the heat pulse. A nonlinear least-square (Marquardt) method was used to analyze each TC junction temperature trace to estimate sap velocity and transpiration. Sap velocity was variable between needles and TC junctions and ranged from 0.05 mm·s⁻¹ (0.002 in./s) to 0.27 mm·s⁻¹ (0.01 in./s). Daily tree transpiration calculated from sap velocity and other tree characteristics measured about 20% of estimated ET_o (Penman equation referenced to grass) during peak water use and about 25% during the spring and autumn of the year. HPN transpiration was constant at 1.5 to 2.0 mm·day⁻¹ (0.06 to 0.08 in./day) throughout the growing season. Consistently low HPN transpiration rate was attributed to the ring-porous structure of the pecan tree and not to tree wounding. Hourly calculated HPN transpiration rates did not decrease when water stress occurred and stomatal resistance increased to 5.3 s·cm⁻¹ (13.5 s/in.) compared with non water stress conditions at 1.6 s·cm⁻¹ (4.1 s/in.). HPN with three TC junctions/needle does not appear to provide a practical measure of pecan tree transpiration or indicate water stress.

Keywords. Heat pulse needles, Pecan, *Carya illinoensis*, Water stress, Irrigation.

Heat tracer techniques have been used to measure transpiration in trees. A pulse of heat is injected into a tree trunk via a needle and the rise in downstream temperature is measured to determine the sap flow velocity and ultimately the transpiration rate (Marshall, 1958; Swanson, 1972; Cohen et al., 1981).

Green and Clothier (1988) showed that the heat pulse technique was within 7% of actual transpiration for apple, but underestimated transpiration in kiwifruit by 62%. Swanson and Whitfield (1981) noted that heat pulse needles underestimated transpiration due to heterogeneous thermal properties of tree wood and the interruption of sap flow by needle insertion. This technique assumes homogeneity within the stem and that heat moves uniformly throughout the plant material. Zimmermann et al. (1971) stated that ring-porous trees (oaks, ashes, hickories, etc.) have rings that are very distinct, with a

narrow band of large early-wood vessels followed by the production of more compact and smaller vessels in the late-wood. Such a ring-porous pattern could affect thermal homogeneity and thus influence the transmission and measurement of heat pulse velocity and tree transpiration.

Direct measurement of tree transpiration using heat pulse needles would allow better estimation of crop coefficients, and more efficient scheduling of irrigation events, and estimation of deep drainage. This direct technique could also be used to indicate plant water stress, thereby requiring less instrumentation and labor than when using other tree physiology measurements. This research assesses the effectiveness of heat pulse needles for measuring sap velocity, estimating transpiration, and indicating water stress in pecan.

MATERIAL AND METHODS

Marshall (1958) and Cohen et al. (1981) used the following equation to describe the temperature rise resulting from an application of heat at a specified distance from a heat source:

$$T = \frac{H}{4\pi K_q t} \text{Exp} \left[-\frac{(r - vt)^2}{4D_q t} \right] \quad (1)$$

where

- T = temperature (°C)
- H = heat supplied per unit length of heater needle (J·m⁻¹)
- t = time (s)
- r = distance between heater and thermocouple (m)

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K_q = thermal conductivity ($J \cdot m^{-1} \cdot ^\circ C^{-1} \cdot s^{-1}$)
 v = convective heat velocity ($m \cdot s^{-1}$)
 D_q = thermal diffusivity ($m^2 \cdot s^{-1}$)

A complete heat pulse trace was used to solve equation 1 for the sap velocity (v) and thermal diffusivity (D_q) using a nonlinear least squares method (Marquardt, 1963). The sap velocity for each thermocouple (TC) junction was integrated to determine the sap flux for each needle. Tree transpiration was then estimated from the average sap flux of all the needles installed per tree.

Heat pulse needles used in this study were manufactured by Soiltronics, Inc. (1111 Myrtle Drive, Burlington, Wash.). The downstream temperature sensing needle has three thermocouple (TC) junctions at specific distances (10, 20, and 30 mm) from the needle housing. The sap velocities determined for each TC junction are used to calculate the volume flux at each junction. Equation 2 describes the volume flux for each needle (Cohen et al., 1981).

$$J = \frac{\rho_{tw} C_{tw}}{\rho_w C_w} \sum v_i A_i \quad (2)$$

where

J = flux ($m^3 \cdot s^{-1}$)
 ρ_{tw} = density of green tree wood ($kg \cdot m^{-3}$)
 C_{tw} = mass specific heat of green tree wood ($J \cdot kg^{-1} \cdot ^\circ C^{-1}$)
 ρ_w = density of water ($1000 \text{ kg} \cdot m^{-3}$)
 C_w = mass specific heat of water ($4185 \text{ J} \cdot kg^{-1} \cdot ^\circ C^{-1}$)
 v_i = convective heat velocity for each TC junction ($m \cdot s^{-1}$)
 A_i = annular area associated with each TC junction (m^2)

Tree wood density, ρ_{tw} , was measured from actual tree samples. The green wood mass specific heat (average of all samples $2379 \text{ J} \cdot kg^{-1} \cdot ^\circ C^{-1}$) was determined following the procedure described by Marshall (1958) using the wood moisture content, the tree wood density, ρ_{tw} , and the oven dry wood mass specific heat of $1381 \text{ J} \cdot kg^{-1} \cdot ^\circ C^{-1}$ described

by Dunlap (1912) (see table 1). The annular area, A_i , associated with each TC junction was determined using equations 3, 4, and 5:

$$A_1 = \pi [R_x^2 - (R_x - T_1)^2] \quad (3)$$

$$A_2 = \pi [(R_x - T_1)^2 - (R_x - T_2)^2] \quad (4)$$

$$A_3 = \pi [(R_x - T_2)^2 - (R_x - R_h)^2] \quad (5)$$

where

$A_{1,2,3}$ = areas associated with TC junction 1, 2, and 3 (m^2)
 R_x = radius of the tree with bark removed (m)
 $T_{1,2}$ = length associated with TC junctions 1 and 2 (m)
 R_h = length of needle or where sap flow is assumed negligible (m) for TC junction 3 (fig. 1)

Tree transpiration ($mm \cdot d^{-1}$; in./day) was estimated by dividing the volume flux (J) by the shaded area of the tree canopy measured at solar noon.

This study was conducted in a commercial pecan orchard about 6.5 km (4 mi) south of Las Cruces, New Mexico on a mesa overlooking the Rio Grand River Valley. Pecan trees that were 15 to 20 yr had been transplanted from established orchards on the valley floor (spring of 1986) to coarse alluvium soils above the valley floor. These trees were transplanted on a $10.6 \times 18.3 \text{ m}$ ($35 \times 60 \text{ ft}$) grid pattern with a terrace between each row of trees. The trees were about 13 m (42 ft) tall, have a canopy diameter of 10.0 m (33 ft), and trunk diameter of 0.27 m (10.6 in.). Irrigation water was pumped from a 30 m (100 ft) deep water table into an underground irrigation system. An outlet valve was opened manually to flood irrigate each basin between the berms of adjacent terraces. Two terraces were selected (Terrace 5 and 6) with T5 being irrigated when 50% of the available water (AW) was depleted and T6 at 11% AW depletion. Soil characteristics, irrigation frequency, and root depth for water uptake are described by Sorensen and Jones (1999). Available water is that portion

Table 1. Tree wood characteristics of tree circumference, mass and volumetric water content, dry and green wood bulk density, and green wood mass specific heat for T5 and T6*

Tree Characteristic	Terrace 5	Terrace 6	Avg. †
Circumference (m ‡)	0.879	0.868	0.874
Shaded area at solar noon (m ²)	78.90	81.30	80.10
Mass water content (kg kg ⁻¹)	0.553	0.581	0.567
Dry wood bulk density (Mg m ⁻³)	0.604	0.597	0.601
Volume water content (m ³ m ⁻³)	0.334	0.347	0.340
Green wood bulk density (Mg m ⁻³)	0.937	0.944	0.941
Green wood water content (m ³ m ⁻³)	0.519	0.549	0.534
Green wood specific heat (J kg ⁻¹ °C ⁻¹)	2362.2	2394.1	2379.0

* T5 irrigated at 50% depletion and T6 at 11% depletion.
 † t-test analysis showed no significance at the 0.05 probability level.
 ‡ Metric to English conversions:
 1 m = 39.37 in.
 1 kg = 2.2046 lb
 1 Mg m⁻³ = 62.4 lb/ft³
 1 m³ m⁻³ = 35.1 ft³/35.1 ft³
 1 J kg⁻¹ °C⁻¹ = 0.239 Btu/(lb·°F)

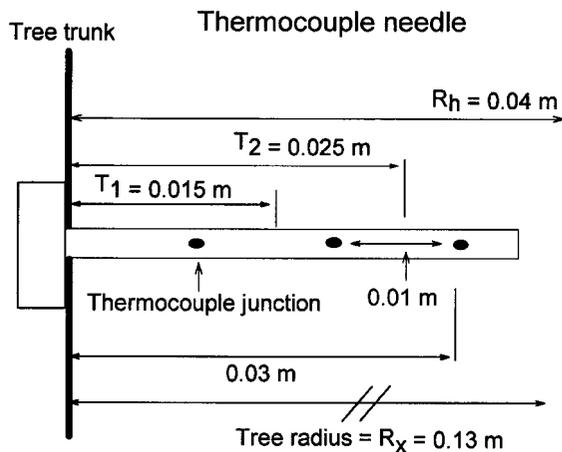


Figure 1—Diagram of installed thermocouple needle and dimensions used for annular area calculations (1.0 m = 39.37 in.).

of water that plants can absorb between field capacity and permanent wilting point. The water content at field capacity was measured in the field after a winter irrigation when evaporation and transpiration were minimal using the neutron probe moderation technique. Water content at permanent wilting point (-1500 kPa; -15 bar soil water potential) was estimated from water retention curve data collected using pressure plate and thermocouple psychrometer techniques. Both T5 and T6 had 16 trees per terrace and each irrigated basin covered about 2290 m² (0.56 ac).

The dry wood bulk density was determined by taking core samples of four trees in each terrace using a Suunto wood coring tool, 30-cm (12-in.) length. Core samples were not taken from the tree where HPN needles were installed. A 20-cm (8-in.) wood core was taken to determine tree bulk density and water content. Only sapwood was kept and measured while the cambium and heartwood samples were discarded. The wood samples' diameter and length were measured using calipers. Mass and volumetric water content and dry wood bulk density were determined for each sample.

TC needles were tubular stainless steel, 35 mm long and 1.3 mm diameter (1.38 in. \times 0.051 in.), with three copper-constantan TC junctions inserted into the tube with epoxy. The heater needle (44 ohms resistance) was identical to the TC needle (fig. 1).

Heat pulse needles were installed in the middle tree of each terrace. The trees' outer dead bark was removed and a hardened steel drill guide, 1.3 cm (0.5 in.) wide \times 1.3 cm (0.5 in.) thick \times 10 cm (4 in.) long with pre-drilled holes 6 mm (0.24 in.) apart was strapped flush against the cambium layer. Holes were drilled 1.32 mm diameter (0.052 in.) \times 35 mm (1.38 in. long), into the tree. Each needle, TC and heater, was lubricated (grafting paste or nontoxic lubricant) and inserted into the tree with the TC needle downstream of the heater needle.

Thermocouple and heater needles were connected to a datalogger (CR-21X or CR-10 and AM416 multiplexer, Campbell Scientific, Inc., Logan, Utah) and a relay to collect temperature data and control the current from the battery to the heater needles, respectively.

The pecan tree trunk radius was 13.0 cm (5.1 in.) for both T5 and T6 with the outside bark removed. The bark thickness was about 0.5 cm (0.2 in.). The area calculated for each thermocouple was 115.7 (A_1 , $T_1 = 0.015$ m), 69.3 (A_2 , $T_2 = 0.025$ m) and 92.17 (A_3 , $R_x - R_h = 0.04$ m) cm² (24, 10.7 and 14.3 in.²) for the outer, middle, and center TC junctions, respectively (fig. 1).

A sap flow measurement cycle consisted of an application of a heat pulse followed by measurement of the downstream temperature at the three TC junction points. The datalogger was programmed to apply 12V to the heater needle for eight seconds to create the heat pulse. Temperature was recorded at each TC junction every 2.0 s for 60 s starting midway through the heat pulse (4 s). Sap flow measurements were taken hourly.

In 1994, three pair of HPN needles were installed in one tree on T5 while two pair were installed on one tree in T6. All needles were installed at about 1.5 m (5 ft) height. HPN data were downloaded daily to a laptop computer and transferred to an office computer for data analysis and archival. Each pair of needles were covered with insulation

consisting of about 225 cm² (36 in.²), 5 cm (2 in.) thick foam rubber. The foam rubber was covered by aluminum foil to reflect solar radiation covering about 0.5 m (1.6 ft) of the tree trunk with the needles approximately in the center. The needles were removed prior to nut harvest.

In 1995, a total of eight pair of needles were installed, four pair in each terrace on the same tree and at the same height but at 5- to 6.0-cm (2- to 2.5-in.) horizontal circumference distance from the 1994 insertion sites. The needles were checked periodically to keep sap and insects from collecting around the needle housing. HPN needles were removed prior to nut harvest.

A steady state porometer was used to monitor the stomatal resistance of the pecan leaves. A leaf water status console (pressure bomb) was used to measure leaf water potential. Leaf samples were taken to determine the leaf osmotic potential.

In 1994, porometer and leaf water potential measurements were taken five times in August. Data were recorded from each terrace starting one day after an irrigation event, then every other day until the next irrigation event. Five trees were sampled at each outing. Two opposing main branches were selected on each tree. A total of 20 leaves per terrace were sampled with two leaves selected from each branch (four leaves per tree). The selected leaves were in full sunlight between 1300 to 1500 h, full grown (spring growth) without blemish, terminal leaflets, and 3.0 to 5.0 m (10 to 16 ft) above the soil surface. On irrigation day, porometer and leaf water potential measurements were taken hourly.

This same procedure was followed in 1995 except two leaves per tree were sampled for a total of 10 leaves per terrace. When the apical leaf was excised for leaf water potential, the next two adjacent leaves were also excised and inserted into a 3.0 cm³ (0.183 in.³) syringe, frozen, sealed in plastic bags, and stored in a freezer for subsequent osmotic potential analysis.

Meteorological data were collected using a CR-21X datalogger (Campbell Scientific, Inc., Logan, Utah) located about 6.5 km (4 mi) from the orchard. Potential evapotranspiration (ET_o) was estimated using Penman's equation referenced to grass.

RESULTS AND DISCUSSION

TREE CHARACTERISTICS

Table 1 shows the average tree circumference, mass water content, and wood bulk density of samples taken from four trees in each terrace. The dry wood bulk densities were essentially the same at 0.604 and 0.597 g/cm³ (37.7 and 37.3 lb/ft³) for T5 and T6, respectively. These dry wood densities are lower than reported values of 0.72 (Vine, 1960) and 0.84 g cm⁻³ (44.95 and 52.4 lb/ft³) (hickory species, Dunlap, 1912). Overall, there was no statistical difference between trees sampled in T5 with trees in T6. Therefore, average tree characteristics were used in calculations to estimate sap velocity, sap flux, and transpiration.

SAP FLOW VARIABILITY

The ring-porous structure affects measurement of sap velocity and tree transpiration when point samples of sap velocity are taken. This type of ring structure promotes

different sap velocities across each ring (large, high conductive vessels) and between rings (smaller, low conductive vessels). Sap flow velocities are expected to show discrete peaks and valleys corresponding to the large and small conductive tissue with increased depth into the tree. Temperature measurements were collected at discrete "in-tree" depths, so measurements could vary greatly depending on whether the TC junction bisected high or low conductive tissue. If a TC junction was positioned precisely to measure flow in the high conductive ring areas, sap flow could still vary because flow in these rings can vary radially within the tree.

Variability in sap velocities measured by HPN was observed with depth and position on the tree circumference. Each needle was a precise length, such that each thermocouple records temperatures at precise 'in-tree' depths of 10, 20, and 30 mm (0.39, 0.79, and 1.18 in.). If ring growth was perfectly concentric and the flow in the ring and inter-ring areas were uniform, then the sap velocity should be the same for each TC junction at each discrete 'in-tree' depth implying low variability between needles.

Figures 2 and 3 show the diurnal mean sap velocities for the installed needles in T5 and T6 during 1994 and 1995, respectively. These data show cyclic day/night patterns with high sap velocities during the day and lower sap velocities at night. Individual needle sap velocities ranged between 0.05 and 0.27 mm·s⁻¹ (1.97×10^{-2} and 1.06×10^{-2} in./s).

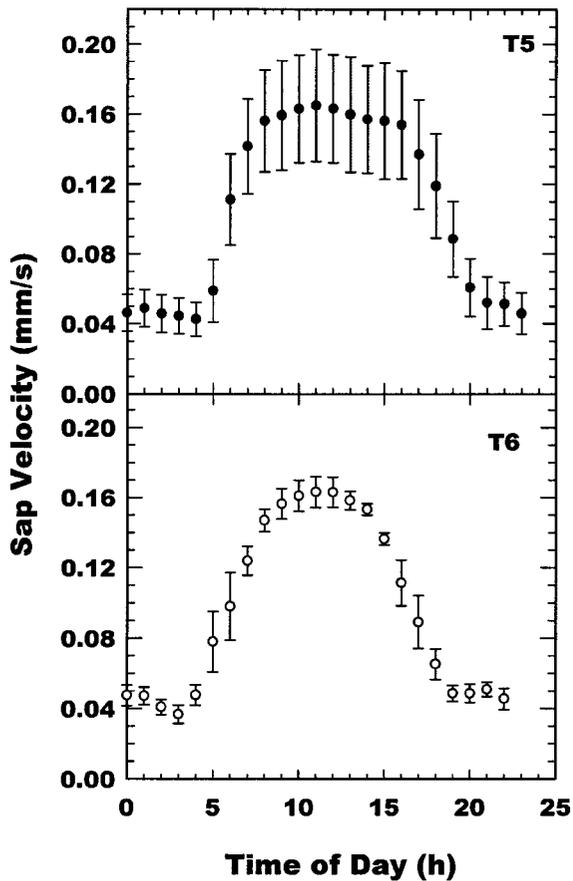


Figure 2—Average diurnal sap velocity for T5 and T6 in 1994. T5 irrigated at 50% depletion and T6 irrigated at 11% depletion (25.4 mm = 1 in.). Bars indicate the SE (n = 3).

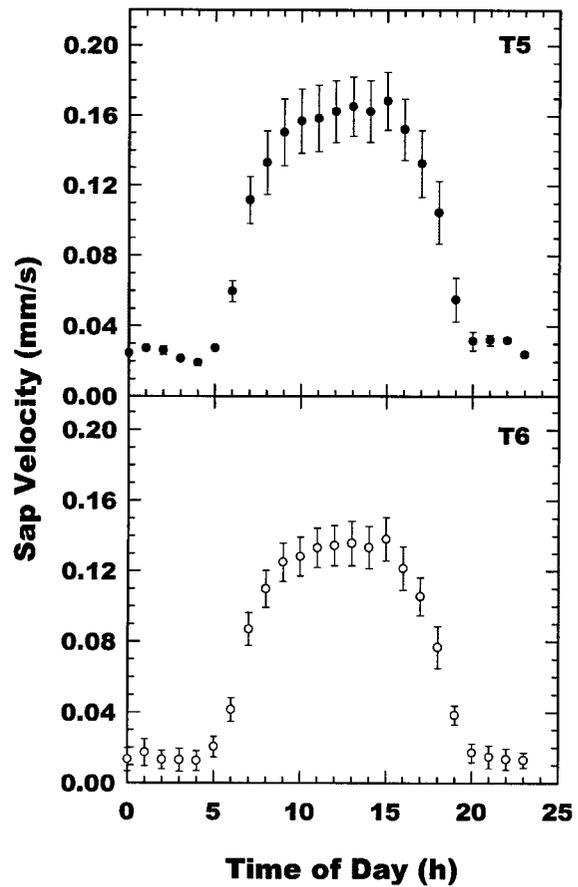


Figure 3—Average diurnal sap velocity for T5 and T6 in 1995. T5 irrigated at 50% depletion and T6 irrigated at 11% depletion (25.4 mm = 1 in.). Bars indicate the SE (n = 3).

T5 shows much higher variability (high standard error about the mean) during 1994 when compared to the same tree in 1995. This was caused by one pair of needle positioned beneath a limb scar in 1994. Sap velocities for this needle (1994) were measured at or below 0.1 mm s^{-1} (3.94×10^{-3} in./s) during daylight hours. In 1995, needles were not positioned below visible limb scars. Sap velocities were higher ranging between 0.12 and 0.22 mm s^{-1} (4.72×10^{-3} and 8.66×10^{-3} in./s) respectively during daylight hours. These data imply that old tree injuries may affect sap movement in areas directly below old tree injuries. Humphries and Gifford (1984) suggested not placing sensors in areas where surface blemishes could indicate internal tissue disturbance. However, tree cuttings made by Humphries and Gifford (1984) showed tissue disruption in the tree interior even when the surface bark was uniform.

Large standard error (SE) bars (fig. 2 and 3) indicate that tree rings are not perfectly concentric or flow within the rings and inter-ring areas were not uniform. The SE did decrease from 1994 to 1995 for T5 by placing needles in locations away from old injuries. However, there was still large errors between needles in 1995. Variability of measured sap flow with depth for a given needle position could represent flow variability in different age rings. However, it could also result from a TC junction at one depth being closer to a high-conductive area of a ring and the other TC junction being centered in the low or nonconductive tissue of the ring. Dye et al. (1991) showed

that ring growth, ring width, and type of wood within a ring could affect heat pulse velocity measurements.

During the night when sap flow is negligible, the calculated thermal conductivity (thermal diffusivity) should be the actual value. Between 2000 to 0400 h, the thermal conductivity averaged $0.65 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ($0.37 \text{ Btu}\cdot\text{h}^{-1}\cdot\text{ft}^{-2}\cdot^{\circ}\text{F}^{-1}$). Steinberg et al. (1990), using the heat balance method, showed that pecan wood from small, young branches of a five-year old pecan tree, had a thermal conductivity of $0.47 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ($0.27 \text{ Btu}\cdot\text{h}^{-1}\cdot\text{ft}^{-2}\cdot^{\circ}\text{F}^{-1}$). The heat balance method supplies heat to the outer surface of the pecan tree, while the HPN method supply heat from the surface to 35 mm (1.4 in.) deep and take temperature measurements at discrete tree depths. This implies that new tree wood (surface wood) may have different thermal properties than older, internal wood.

NEEDLE TRANSPIRATION VERSUS ET_0

Figure 4 shows the average daily tree transpiration measured by HPN for T5 and T6 compared with daily grass reference evapotranspiration, ET_0 (modified Penman equation). HPN transpiration rate shows the same cyclic pattern as ET_0 with the rise and fall during the spring and autumn, and peaking in the summer. In 1994 when the needles were installed, both T5 and T6 showed about the same transpiration rate at about 2.0 mm d^{-1} (0.08 in./day). This transpiration rate was consistent throughout the season until the middle of October when strong winds (DOY 287) blew many leaves and nuts off the trees. The average transpiration (measured by HPN) rate for both trees decreased to below 1.0 mm d^{-1} (0.04 in./day). In 1995, HPN transpiration peaked in late May (1.5 mm d^{-1} ; 0.06 in./day), day 520 (time since 01 January 1994), and remained constant until about day 630 (September 1995).

ET_0 peaked at about 10.0 mm d^{-1} (0.4 in./day) in June and July (both years). During peak ET_0 , HPN measured about 15 to 20% of ET_0 and only about 25% of ET_0 during the spring and fall (ET_0 decreased while HPN transpiration remained constant).

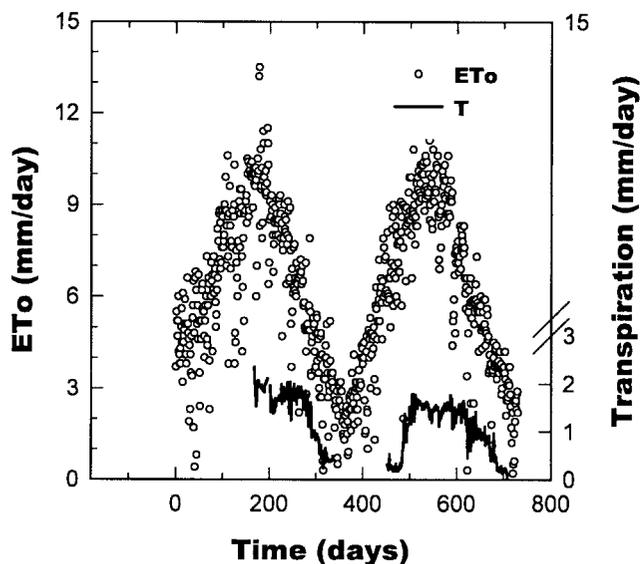


Figure 4—Estimated daily ET_0 and average HPN transpiration (T5 and T6) during 1994 and 1995. T5 irrigated at 50% depletion and T6 irrigated at 11% depletion (25.4 mm = 1 in.).

Measured tree transpiration of 2.0 mm d^{-1} (0.08 in./day) was always considerably lower than estimated ET_0 and literature transpiration values. Steinberg et al. (1990) using the heat balance technique and associated lysimeter data on young pecan trees, measured transpiration at 8.8 mm d^{-1} (0.35 in./day).

Possible reasons why HPN does not measure a higher transpiration rate can be explained by possible wounding, heat pulse needle length, or ring characteristics. Swanson and Whitfield (1981), using a three-probe heat pulse technique, showed that wounds from needle insertion can affect tree transpiration measurements due to flow interruption (drilling into the tree) and resin deposition (tree repair). Figure 4 shows that once HPN peak transpiration was reached, the transpiration rate was constant thereafter. This implies that once the needles were installed, transpiration was not affected by the trees normal functions to repair damaged areas. If wounding affected tree transpiration then the transpiration rate would decrease with time as resins would be deposited at the wounded area disrupting transpiration flow. Since the transpiration rate was constant throughout the growing season needle installation must not of affected the transpiration rate unless it occurred instantly during needle installation and cannot be measured.

The radius of the both trees was about 130 mm (5 in.) while heat pulse needles were only 35 mm (1.38 in.) long. The HPN needles only measured sap flow in a small portion (27%) of the tree trunk. It is unknown if the sap velocity in the wood past the end of the needle is the same, increases, or decreases. Both Dye et al. (1991) and Caspari et al. (1993) showed that sap velocity decreased as depth increased below the cambium layer. Longer needles could be installed to measure the sap velocity in sap wood deeper than the 35 mm (1.38 in.). As a test, the tree transpiration was estimated by increasing the area of A_3 (eq. 5) to include the unmeasured tree area and also assumed the sap flux to be the same as that of the TC at 30 mm “in-tree depth”. Estimated transpiration increased between 10 and 20% (data not shown) depending on needle position and time of year. Thus, the use of longer needles may help estimate total transpiration, but total values of transpiration were still lower than ET_0 .

Another possible explanation of the underestimation of actual transpiration by the heat pulse needles could be the variability of the sap flow between the high-conductive tissue and the low or nonconductive tissue within a yearly growth ring. Zimmermann et al. (1971) documented that climatic and management conditions such as limb removal or disease and insect damage can affect tree ring characteristics. Heat pulse needles measure sap velocity at three discrete, evenly spaced points along each needle. With the ring-porous pecan, the probability of these three discrete points coinciding with three “high-conductive” rings is small. Most TC junctions are in zones of low sap flow with a zone of high sap flow nearby.

The establishment of TC junctions in the low flow regions would also explain the flat peak of measured transpiration (fig. 4). If TC junctions bisect low conductive areas of the ring then the peak transpiration rate of 2.0 mm d^{-1} (0.078 in./day) may reflect the maximum flow through this low-conductive zone. This may indicate that higher

flow rates are only possible through the visibly larger, presumably higher-conductive zones.

HPN TRANSPARATION BETWEEN IRRIGATIONS

Although heat pulse needles do not appear to accurately monitor actual transpiration rates, they still could possibly be used as an indicator for water stress by monitoring relative sap flow rates. When soil moisture is limiting, stomatal resistance should increase and sap flow should decrease. Stomatal resistance measurements were taken from 0600 to 1300 h (DOY 165, 1995) just before an irrigation (irrigation started at 1420 h). T5 had not been irrigated for 15 days and T6 had not been irrigated for eight days. Neutron probe data taken in T5 before an irrigation showed that 45% of the available soil (AW) water was depleted throughout the 260-cm (8.5-ft) soil profile (data not shown) and 65% AW was depleted in the 0- to 140-cm (4.6-ft) soil depth. Figure 5 shows the diurnal stomatal resistance values for T5 and T6 compared with the average HPN transpiration rate. Porometry measurements show that from about 1000 to 1300 h the stomatal resistance in T5 was about 2.5 times greater (4.3 s·cm⁻¹, 11.0 s/in.) than those measured in T6 (1.6 s·cm⁻¹; 4.0 s/in.). This implies that transpiration and possibly sap flow should be lower in T5 than in T6. HPN transpiration rates did not decrease in T5 when compared with T6 during this time. Calculated HPN transpiration rates in T5 and T6 were not statistically different while stomatal resistance values were statistically different between T5 and T6 between 0800 to 1300 h.

Figure 6 shows the cumulative mass sap flux before and after the irrigation event described above (DOY 163 to 167). T5 and T6 show about the same cumulative mass sap flux before and after the irrigation and were not statistically different. While both trees showed the same magnitude and shape of curve for each needle T5 showed a higher cumulative value than T6.

A possible explanation for the lack of response of measured sap flow to stomatal closure is that sap flow may not immediately respond to stomatal closure. It seems

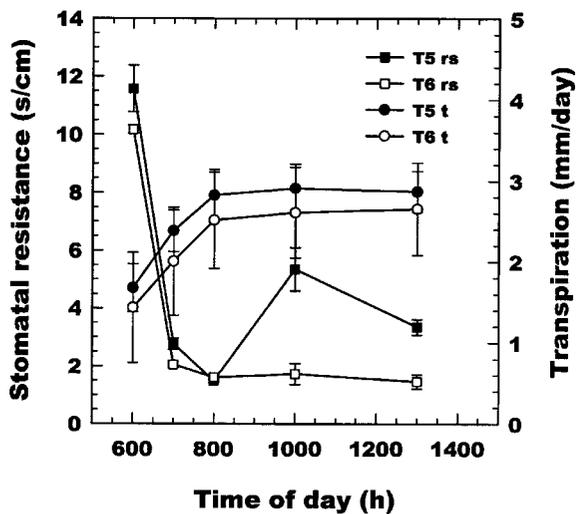


Figure 5—Average calculated HPN transpiration (circles) compared to diurnal stomatal resistance (squares) for T5 (14 days after irrigation) and T6 (8 days after irrigation). T5 irrigated at 50% depletion and T6 at 11% depletion. Bars indicate the SE (n = 10 for stomatal resistance and n = 3 for HPN transpiration) (25.4 mm = 1 in.; 2.54 cm = 1 in.).

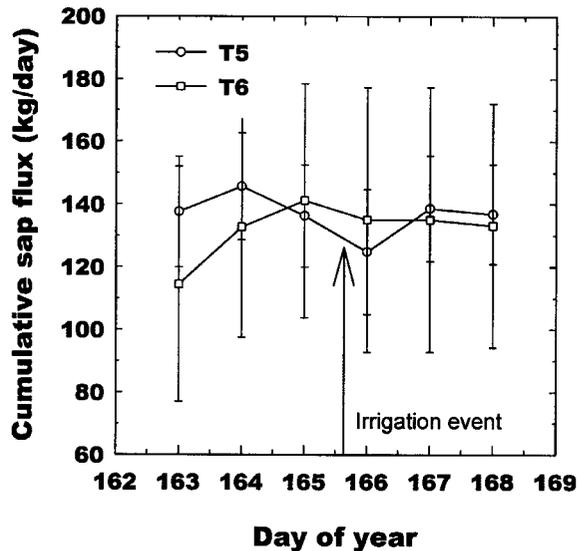


Figure 6—Cumulative HPN mass sap flux before and after an irrigation event for T5 and T6, 1995. T5 irrigated at 50% depletion and T6 at 11% depletion. Bars indicate the SE (n = 3; 1 kg = 2.2046 lb).

reasonable that during the initial time after stomatal closure (during mid day water stress or night) sap flow would continue as the plant “recharges” water lost to transpiration and leaf water potential recovers. However, Steinberg et al. (1990) showed that at night transpiration ceased rapidly after sundown, while sap flow continued at a decreasing rate until early morning. During the day on well watered pecan trees (assumed no water stress, T6) there was not pronounced lag between trunk sap flow and canopy transpiration. Therefore, plant water “recharge” does not explain low flow rates measured by HPN.

If HPN are measuring a low amount of flow through the low conductive region of the xylem, this area may not be affected by stomatal closure. Initial reductions in the sap flow would be seen first in the high conductive flow regions of the xylem. This implies that sap flow velocities in this low conductive area do not dramatically change in response to short-term stomatal closures.

CONCLUSIONS

Overall, heat pulse needles (HPN) used in this study did not precisely measure transpiration or indicate water stress. Sap velocity was variable between TC junctions and HPN needles within the same tree. Sap velocities ranged between 0.05 and 0.27 mm·s⁻¹ (1.97 × 10⁻² and 1.06 × 10⁻² in./s) and varied 1.5 to 3.0 times the lowest sap flow rate.

Calculated HPN transpiration described about 20% of ET_o during peak water use. This percentage increased in the spring and fall because of the change in ET_o not due to an increase in measured sap flow. Transpiration measurements could theoretically be improved if TC needles could be inserted at precise tree depths to place TC junctions within the high flow area of each yearly ring. However, each tree would need to be characterized for ring width, number of rings, and possibly vessel characteristics per ring. Tree sampling is destructive and would prohibit the placement of a needle at characterization sites.

Sap flow velocities did not respond to short term water stress conditions, i.e., stomatal closure. The major cause of low transpiration rates and sap flow rates measured by the heat pulse needles can be attributed to the ring-porous nature or the non-homogeneous structure of pecan. HPN does not appear to progressively damage trees and can be installed and maintained in a pecan tree for prolonged time periods.

Heat pulse needles with thermocouple junctions at discrete depths do not appear to provide a practical measure of pecan tree transpiration or indicate short term water stress. Therefore, the use of this type of needle design to estimate pecan tree transpiration or to schedule irrigations may not be feasible.

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