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Use of Thermal Dissipation Probes to Estimate Water Loss of Containerized Landscape Trees[1]

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Abstract

Granier style thermal dissipation probes (TDPs) have been used to estimate whole plant water use on a variety of tree and vine species. However, studies using TDPs and load cells (gravimetric water loss) to estimate water use of landscape tree species are rare. This research compared gravimetric water loss (estimated with load cells) of four containerized landscape tree species with water loss estimated with TDPs. Over a 66 day period, an experiment compared water loss of three established, 5.0 cm (2 in) caliper poplar (*Populus nigra* 'Italica') trees in 75-liter (20 gal) containers on load cells to TDP estimated water loss. Each tree had a single 30 mm (1.2 inch) TDP inserted into the trunk at four heights above soil level (15, 30, 45, and 60 cm (6, 12, 18, and 24 in, respectively)). Data revealed TDP estimated water loss was less than load cell estimated water loss regardless of TDP height, but TDP estimated water loss at the 30 cm height was closest to actual load cell estimated tree water loss. Over the next three years, similar sized Bradford pear (*Pyrus calleryana* 'Bradford'), English oak (*Quercus robur* x *Q. bicolor* 'Asjes'), poplar (*Populus deltoides* 'Siouxland'), and sweetgum (*Liquidambar styraciflua* 'Rotundiloba') trees in containers were placed on load cells and one 30 mm TDP was placed into the trunk of each tree 30 cm above soil level. Over an extended time period, tree water loss was estimated using load cells and TDPs. Hourly TDP water loss estimates for each species over a three day period indicate TDP estimated water loss followed similar trends as load cell estimated water loss. However, TDP estimates were generally less than load cell estimates, especially during peak transpiration periods. For each species, mean total daily water loss estimates were less for TDP estimated water loss when compared to load cell estimated water loss. Although TDP estimated water loss has been correlated with actual tree water loss for many species, these data suggest errors may arise when using TDPs to estimate water loss of small, containerized landscape tree species.

Index words: irrigation, container production, tree water use, poplar, Bradford pear, English oak, sweetgum.

Species used in this study: 'Rotundiloba' sweetgum (*Liquidambar styraciflua* L. 'Rotundiloba'); 'Siouxland' poplar (*Populus deltoides* Bartr. 'Siouxland'); 'Italica' poplar (*Populus nigra* L. 'Italica'); 'Bradford' pear (*Pyrus calleryana* Decne. 'Bradford'); 'Asjes' English oak (*Quercus robur* L. x *Q. bicolor* Willd. 'Asjes').

Significance to the Nursery Industry

Because water quality and quantity are concerns in many regions of the United States, conserving water in nurseries and landscapes is essential. However, little research has been conducted into estimating tree water use in nurseries or landscape settings. We investigated methods to estimate water loss of four containerized landscape tree species ('Rotundiloba' sweetgum, 'Siouxland' poplar, 'Italica' poplar, 'Bradford' pear, and 'Asjes' English oak) using thermal dissipations probes (TDPs) and load cells. For each species examined, diurnal trends of TDP and load cell estimated water loss were similar, but total daily water loss estimates for TDPs were less when compared to daily water loss estimates provided by load cells. If water conservation in nurseries and landscapes is to become a reality, estimating water requirements of trees will be necessary. Using TDPs appears to be a procedure that can estimate water requirements of containerized trees. However, additional research will be needed to calibrate tree species with TDP estimates.

Introduction

Isolated trees are an important component of urban landscapes, and represent a substantial monetary investment sustained by maintaining proper tree health (25). Even though landscape trees are frequently grown in landscapes requiring irrigation, a challenge confronting irrigation managers is to conserve water while meeting plant irrigation requirements (37). Production nurseries also face water restrictions and increased pressure to improve water management practices (26). Water conservation research in production nurseries is ongoing (2). An ideal method to schedule plant irrigation would be to estimate water requirements and replenish the root system with the required volume (26). However, because irrigation requirements of many landscape tree species are not well known, and are likely to vary with climate, nursery and landscape irrigation managers are often unsure of the amount of water required by landscape trees (3, 29). In fact, because of the lack of information available regarding tree irrigation requirements, landscape and nursery trees are frequently exposed to unnecessarily high irrigation rates (20, 26).

Numerous studies have been conducted on whole-plant water use of trees (40). However, most of this research has focused on individual forest tree species and was scaled from individual tree transpiration rates to ecosystem water use estimates. Irrigation requirements of individual landscape trees have been estimated using several approaches. Indirect measurement of water loss from isolated trees has been attempted using energy-balance (22) and standard flux equations (27). Lindsey and Bassuk (23) used a comparable model to estimate water needs of mature urban street trees. The most direct means to estimate whole-tree water loss is gravimetrically, with the use of load cells. In a semi-arid climate, Montague et al. (28) used in-ground load cells to estimate daily water loss of five, newly transplanted, balled and burlaped landscape tree species. Several authors also report

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individual landscape plant water loss estimates using containerized plants and load cells (22, 31). Despite precision and accuracy, whole-tree water loss estimates using load cells has restrictions. Concerns include load cell expense, root-zone limitations, and constraints due to tree size (1).

If measured over a sufficient period of time, and excluding the small amount of water utilized during photosynthesis (33), the volume of sap moving upward through the stem of a tree must equal the volume of water lost by transpiration (38). As an in-situ alternative to gravimetric methods, transpiration of individual trees have been estimated using various configurations of thermal sensors placed in tree trunks (38). Thermal sap flow methods provide direct and continuous measurement of whole-plant water use with excellent time resolution (40). Granier's (15) thermal dissipation probe (TDP) method is reported to be an accurate method of measuring xylem sap flow and estimate whole-tree transpiration (16). Granier's method is based upon a thermal sensor composed of two probes inserted radially into the sapwood of the trunk. The upper probe is heated with a constant power supply and the unheated lower probe is considered a temperature reference. An empirical equation enables users to calculate whole-tree transpiration as a function of the temperature difference between probes and functional sapwood area of the trunk (15). Because of simplicity and low energy requirements (10), Granier's method has been used to estimate whole-tree water loss of numerous large forest tree species (14, 16), and TDP estimates have generally compared favorably with other sap flow (21) and energy balance/micrometeorological (8) estimates.

To date, research using TDPs to investigate water loss of horticultural species has been limited to grapevines (*Vitis vinifera*) (4, 34), bananas (*Musa* 'Cavendish') (24), mesquite (*Prosopis alba*), desert willow (*Chilopsis linearis*), live oak (*Quercus virginiana*) (9), and hybrid poplars (*Populus deltoides* x *P. nigra*) (13). In particular, comparisons of TDP and load cell estimated water loss of containerized species is limited, and has produced variable results. Ferro et al. (13) reports daily, TDP estimated water loss of containerized hybrid poplar was substantially underestimated when compared to water loss estimated by load cells. However, Braun and Schmid (4) report daily containerized grapevine water loss measured by TDPs was well correlated with containerized grapevine water loss measured by load cells. Devitt et al. report similar results for daily water loss estimates of containerized live oak, mesquite, and desert willow (9).

Because there is a lack of scientific information regarding irrigation requirements of landscape and nursery tree species, nursery and landscape trees are frequently irrigated in excess (which may result in water logged soil, poor plant growth, increased runoff, leached nutrients, increased water bills, and misuse of irrigation water) or deficit (which may result in poor plant growth, poor plant aesthetics, and plant death) amounts. In either case, performance of ornamental trees species will not meet grower or landscape expectations. Thermal dissipation probes offer a relatively low cost method for estimating landscape tree water use in situ and in a nursery setting. Therefore, if used properly, TDPs could provide valuable information for nursery producers and landscape irrigators. This research investigated methodology for using TDPs to estimate water loss of containerized landscape tree species. In addition, water loss of four containerized, landscape tree species was compared using TDPs and load cells.

Materials and Methods

Sap flow measurements were made using commercially available Granier-type TDPs (Model TDP-30, Dynamax, Inc., Houston, TX). Probes were installed and operated according to manufacture's specifications and probe set up and tree water loss calculations were similar for all experiments in this study. Two cylindrical probes, each 30 mm (1.2 in) in length and 1.3 mm (0.0013 in) in diameter, were fully inserted (flush with bark) into trunks of selected trees. Probes were placed in a vertical line spaced 4.0 cm (1.6 in) apart. To provide thermal insulation, silicon gel was applied to all excess space in drilled holes and over sensor housings (30). Sapwood temperature fluctuations were minimized by installing TDPs on the north side of trees, and once installed, TDPs and tree trunks were covered with reflective bubble wrap from soil surface to slightly above TDP level. The upper probe was heated with a constant energy source (0.2 W) and the differential voltage measurement across thermocouple leads were converted to a temperature difference (ΔT) between heated and unheated (reference) probes. Under no flow conditions, temperature around the heated probe increases to a point where heat conduction through the wood is in equilibrium with the energy supplied by the heater (4). At this point ΔT is at a maximum (ΔT_m). As xylem flow increases, ΔT decreases such that ΔT is at a minimum when transpiration is at a maximum. The ΔT between probes is influenced by the sap flux density in the vicinity of the heated probe. Granier (15) found, and Clearwater et al. (7) validated, that:

$$v = 0.0119k^{1.231} \quad [1]$$

where v is sap velocity (cm/s) and k is related to the temperature difference between the two probes such that:

$$k = (\Delta T_m - \Delta T) / (\Delta T) \quad [2]$$

Grainer (15) determined coefficients in equations 1 and 2 by fitting a nonlinear regression to the measured relationship between v and k (7). Sap flow rate can be calculated as:

$$F = (v) * (A) * (3600 \text{ seconds/hour}) \quad [3]$$

where F is sap flow rate (cm^3/hour) and A is cross sectional area of sapwood (cm^2) between the upper and lower probes. Loads cells (Model 6400, Pennsylvania Scale Co., Lancaster, PA.) and TDPs were connected to a data logger (Model 21X; Campbell Scientific Inc., Logan, UT). Data loggers scanned load cell mass and ΔT every 10 seconds and recorded TDP and load cell means every hour (4).

Because methodology for use of TDPs on landscape trees is unknown, a preliminary experiment was design to investigate at which height above soil level TDP estimated water loss most closely correlated with load cell estimated water loss. This experiment was conducted in a greenhouse at Utah State University, (Logan, UT) and utilized containerized poplar (*Populus nigra* 'Italica') trees. Prior to experiment initiation, three established trees in 75 liter (20 gal) containers with a minimum 5.1 cm (2 in) caliper (at 15 cm (6 in)) were selected from a nursery and allowed to acclimate to greenhouse conditions. Each tree was placed on a load cell and had a TDP fully inserted into the trunk 15, 30, 45, and 60 cm (6, 12, 18, and 24 in, respectively) above soil level (distance was measured from soil level to mid-point between probes).

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A single probe was inserted in each cardinal direction (north, south, east, and west side of trunk). Each night irrigation replaced soil water lost via tree transpiration (estimated by load cell) and soil water evaporation was prevented by covering the soil surface of each container with black plastic. Trees were grown under full sun conditions.

For a 66 day period beginning June 1, 2000 (post bud-set and shoot elongation), total daily tree water loss (midnight to midnight) was estimated using TDPs and load cells. Total leaf area for each tree was measured at the conclusion of the experiment. Daily load cell and TDP estimated tree water loss was calculated as:

tree water loss =
(estimated tree water loss (g or cm^3)) / (leaf area (cm^2)) [Eq. 4]

and converted to mm.

Hourly load cell and TDP estimated water loss data (mean of three trees) were plotted against time of day for a representative 72 hour period. Daily tree water loss estimates at each TDP height were analyzed by analysis of variance suitable for a randomized block design. If differences were found, means were separated by Fisher's Least Significance Difference Procedure ($\alpha = 0.05$) (32). The correlation of load cell estimated tree water loss to TDP estimated tree water loss for each TDP height was also examined. Daily load cell estimated tree water loss (dependent variable) and daily TDP estimated tree water loss (independent variable) data for each TDP height were analyzed by regression analysis. Linear curves were selected according to significance of the equation and R^2 value (32). In addition, analysis of variance was used to determine regression line differences for each TDP height ($P \leq 0.05$) (32).

Based upon results of the preliminary experiment, follow-up experiments were designed to compare water loss of four containerized, landscape tree species using TDP and load cell estimates. These experiments were conducted in a greenhouse and outdoors at Texas Tech University (Lubbock, TX). Experiment organization, data logger, load cell and TDP setup, and tree and container sizes for these experiments were similar as for trees in the preliminary experiment. However, in Lubbock all TDPs were inserted 30 cm (12.0 in) above soil level. Beginning mid-August 2000, TDP and load cell water loss estimates were made on two greenhouse grown, containerized Bradford pear (*Pyrus calleryana* 'Bradford') trees for 50 consecutive days. In 2001, TDP and load cell estimated water loss was measured on two greenhouse grown Siouxland poplar (*Populus deltoides* 'Siouxland') and two English oak (*Quercus robur* x *Q. bicolor* 'Asjes') trees. Daily water loss was estimated from mid-July until late August. In 2002 water loss was estimated with load cells and TDPs on two, outdoor grown containerized sweetgum (*Liquidambar styraciflua* 'Rotundiloba') trees. Trees were placed on load cells in late-June and water loss estimates continued through early-August. Greenhouse and outdoor grown trees were under full sun conditions. However, inside the greenhouse tree canopies shaded containers from direct sun. To avoid direct sunlight outdoors, containers were placed below soil level and wood sheeting was used to provide shade. For each species, mean, maximum, and minimum daily load cell estimated tree water loss (mm and liters) was calculated for the experiment period. In addition to TDP and load cell measurements, in follow-up experiments incoming shortwave radiation was measured with a pyranometer (Model LI-200SA, LI-COR, Inc., Lincoln, NE). A data logger (Model 21X; Campbell Scientific Inc.) scanned each sensor every 10 seconds and recorded hourly means. Depending upon tree location, pyranometer location was either inside the greenhouse or outdoors.

For each species, hourly incoming shortwave radiation, load cell, and TDP estimated water loss data were plotted against time of day for a representative 72 hour period (hourly data presented is the mean of two trees of each species). Total daily load cell estimated tree water loss (dependent variable) and total daily TDP estimated tree water loss (independent variable) data were analyzed by regression analysis for each species and linear curves were selected according to significance of the equation and R^2 value (32). In addition, analysis of variance was used to determine differences between regression lines for each tree species ($P \leq 0.05$) (32).

Because TDP estimated water loss is based upon functional sapwood area (15), correct estimation of functional sapwood area is critical for accurate TDP estimates. If sap velocity varies along the length of the probe, heat dissipation and probe surface temperature will also vary (7). If a portion of the probe is inserted into non-conducting xylem tissue while the remainder of the probe is in conducting xylem tissue, then ΔT measured by the thermocouple is the weighted mean of ΔT in the conducting sapwood (ΔT_{SW}) and ΔT of the inactive xylem tissue (which would be equal to no flow conditions or ΔT_M) such that:

$$\Delta T = a(\Delta T_{SW}) + b(\Delta T_M) \quad \text{[Eq. 5]}$$

where a and b are the proportions of the probe in sapwood and inactive xylem ($b = 1 - a$), respectively (7). Equation 5 can be arranged to find the actual temperature and sap velocity in the conducting sapwood:

$$\Delta T_{SW} = [(\Delta T) - b(\Delta T_M)] / (a) \quad \text{[Eq. 6]}$$

Equation 6 was used to compare TDP estimated tree water loss with load cell estimated tree water loss at varying percentages of active xylem along the 30 mm probe length. For each species, mean total daily water loss was estimated with equation 6 beginning with 100% active xylem along the probe length and compared to load cell estimated tree water loss. Means were analyzed using analysis of variance suitable for a randomized block design. If differences were found, means were separated by Fisher's Least Significance Difference Procedure ($\alpha = 0.05$) (32). If means differed, active xylem along the length of the probe was decreased by 10% and means were again compared to load cell estimated tree water loss. Once load cell and TDP estimated water loss means were similar, analysis ceased for the species.

Results and Discussion

During a representative 72 hour measurement period of the preliminary experiment, TDP and load cell water loss estimates for containerized 'Italica' poplar trees followed similar diurnal cycles (Fig. 1). However, hourly TDP water loss estimates at each height above soil level were generally less than load cell water loss estimates, especially during peak periods of sap flow (10:00 am to 6:00 pm, local standard time) (Fig. 1). In addition, analysis of variance results indi-

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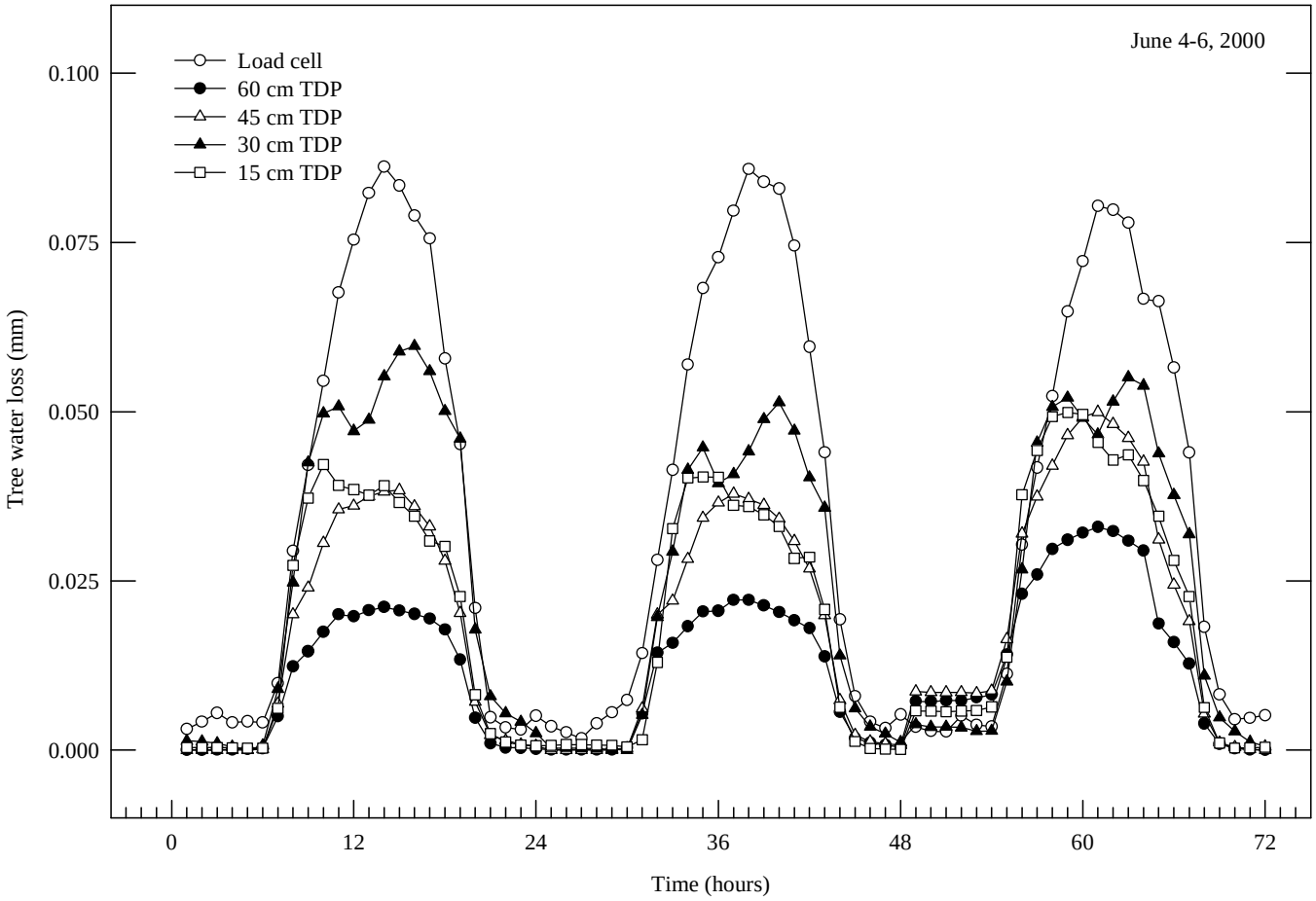

Fig. 1. Mean hourly load cell and thermal dissipation probe (TDP) estimated water loss (mm/hour) over a representative three day period for three greenhouse grown, containerized 'Italica' poplar (*Populus nigra* 'Italica') trees. Each tree was placed on a load cell and had a single TDP placed at four heights above soil level (15, 30, 45, and 60 cm). Each symbol is the mean of three measurements.

cate estimated mean daily water loss by TDPs for containerized 'Italica' poplar trees was less than load cell estimated daily water loss at each height above soil level (Fig. 2). Thermal dissipation probe estimated water loss was 65% of load cell estimated water loss at the 30 cm height, 50% of load cell estimated water loss at the 15 and 45 cm heights, and 30% of load cell estimated water loss at the 60 cm height. Regression equation R^2 values ranged from 0.03 (45 cm height) to 0.31 (30 cm height) and regression equations for TDP estimated water loss at each height were different (Fig. 2).

Load cell and TDP estimates also indicate water loss during non-daylight hours. Water uptake during non-daylight hours is not uncommon and has been reported by others (5, 30). Non-daylight water uptake was likely caused by transpiration due to high vapor pressure deficit (VPD) conditions prevailing at night in the greenhouse and stomatal response to VPD (6, 23), or recharge of stem water storage (30).

As previously reported (4, 34), TDP estimated water loss may be offset from load cell estimated water loss. This is visible with 30 and 15 cm TDP estimates (Fig. 1). Each day water loss estimated by TDPs 30 cm above soil level dropped slightly around 12:00 pm and increased around 4:00 pm. A different trend was observed with TDP estimated water loss 15 cm above soil level. Water loss estimates at 15 cm above soil level peaked around 10:00 am and decreased throughout the remainder of the day (Fig. 1). Longitudinal thermal gradients in tree trunks often occur during the course of the day and may not be eliminated by thermal insulation (14). When using TDPs to estimate plant water loss, Kostner et al. (21) and Braun and Schmid (4) indicate difficulties may arise when TDPs estimating sap flow are located near the soil surface. They indicate when soil water (with a temperature lower than ambient air) reaches the lower reference sensor thermal gradient is induced. This thermal gradient increases ΔT and therefore artificially increases sap flow estimates. As ambient and soil temperature increase during the day (and therefore soil water temperature) TDP estimated water loss becomes more consistent with actual tree water loss. Although less than load cell estimated water loss, water loss estimated by TDPs at 15 and 30 cm above soil level in our study exhibit such a trend. A possible method to avoid problems associated with cool soil water temperatures and thermal gradients is to leave a portion of the stem below the TDP gauge uninsulated (5). Theoretically, this would allow water in the stem sufficient time to warm prior to reaching the lower, reference TDP.

Dynamax suggests TDPs be inserted into trunks 1.0 to 2.0 m (3.2 to 6.4 ft) above soil level (11). For large forest trees, TDPs have been inserted at heights varying from 1.3 m (4.3 ft) to 4 m (13.1 ft) (10, 19). Due to reductions of trunk caliper, in this research it was not possible to insert 30 mm TDPs

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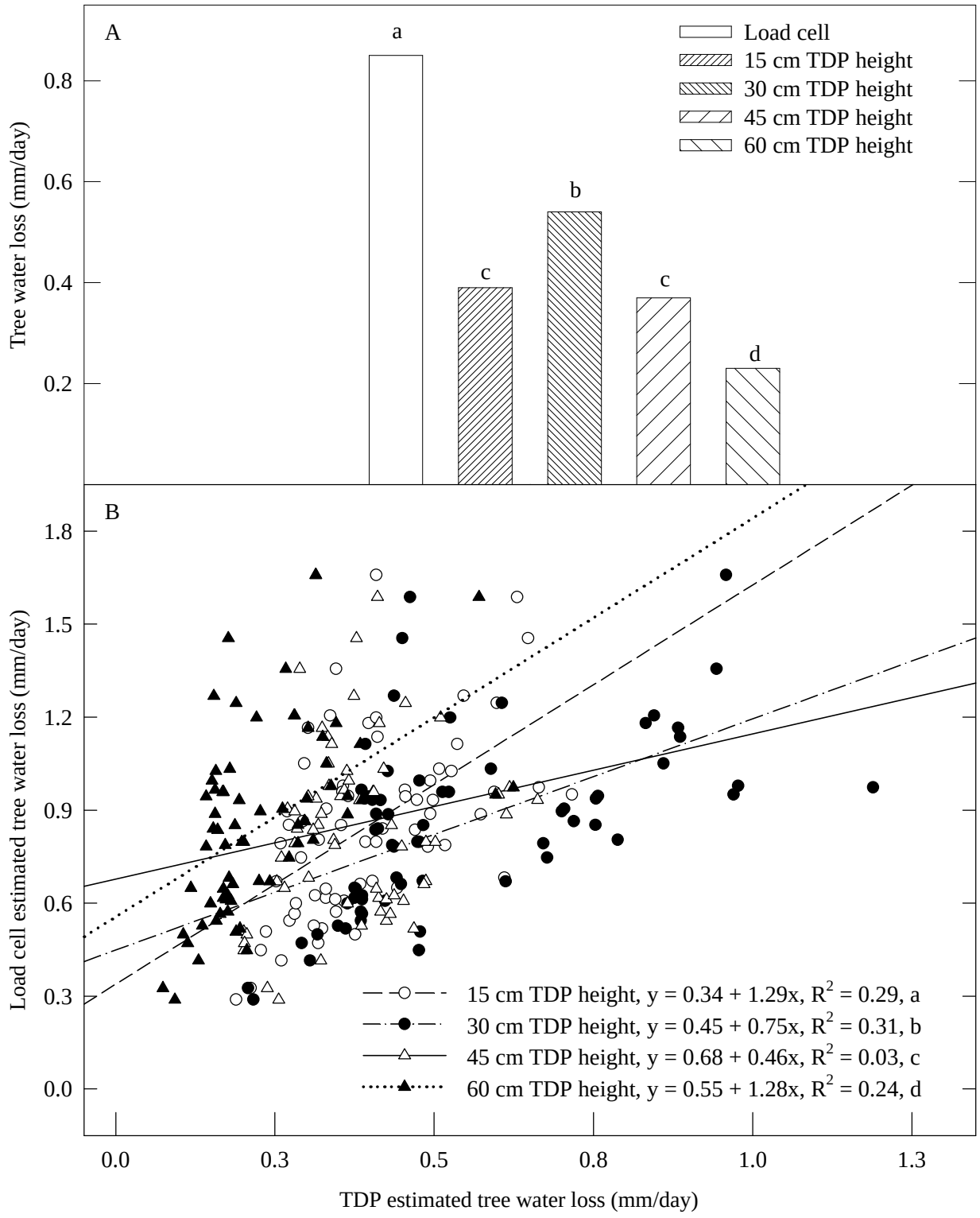

Fig. 2. Mean total daily water loss (mm/day) for three greenhouse grown, containerized 'Italica' poplar (*Populus nigra* 'Italica') trees (A). Each tree was placed on a load cell and had a single thermal dissipation probe (TDP) placed in the trunk at four heights above soil level (15, 30, 45, and 60 cm). Different letters indicate differences between water loss estimates (LSD, $\alpha = 0.05$). In addition, actual and predicted values for estimating load cell measured water loss (mm/day) using TDPs at four heights above soil level (B). Different letters indicate differences between regression equations (analysis of variance, $P \leq 0.05$).

into containerized trees at suggested distances above the soil. Therefore, in this experiment heights above soil level were selected which would accommodate 30 mm TDPs. Height above soil level for insertion of TDPs in horticulture plants has varied. Lu et al. (24) inserted TDPs into banana corms (underground, bulb-like portion of the stem plant consisting of fleshy tissues (18)) and had excellent agreement between load cell and TDP estimated water loss. Details are not given

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Table 1. Stem caliper[z], total leaf area, load cell estimated mean daily water loss, daily maximum tree water loss, and daily minimum tree water loss for containerized Bradford pear (*Pyrus calleryana* 'Bradford'), poplar (*Populus deltoides* 'Siouxland'), English oak (*Quercus robur* x 'Asjes'), and sweetgum (*Liquidambar styraciflua* 'Rotundiloba') trees grown in Lubbock, Texas.

Variable	Species			
	Pyrus[y]	*Populus*[y]	*Quercus*[y]	*Liquidambar*[x]
Caliper (cm)	6.6	5.6	5.7	5.3
Leaf area (m^2)	4.5	3.0	3.3	2.9
Daily mean water loss (liters)	3.14	3.71	3.29	3.45
Daily mean water loss (mm)[w]	0.69	1.23	1.01	1.19
Maximum daily water loss (liters)	8.10	6.11	5.66	4.84
Minimum daily water loss (liters)	1.04	1.24	0.68	2.21

[z]Measured 15 cm above soil level.

[y]Measured in greenhouse.

[x]Measured outdoors.

[w][Tree water loss (g or cm^3)] / [Total leaf area (cm^2)] and converted from cm to mm.

as to the height above soil level TDPs were inserted into grapevines (4, 34). However, due to growth patterns of grapevines, it is likely TDPs were inserted less than 1.0 m from the soil surface. Nevertheless, Braun and Schmid (4) and Schmid and Bettner (34) report good agreement between load cell and TDP estimated water loss. Regardless of TDP height, for these containerized trees, we did not find good agreement between TDP and load cell estimated daily tree water loss (Fig. 2). Similar results with containerized poplar trees are reported (13).

For follow up experiments, tree size and leaf area varied with species (Table 1). Trunk caliper ranged from 5.3 cm (2.0 in) (sweetgum) to 6.6 cm (2.6 in) (Bradford pear), and total leaf area ranged from 2.9 m^2 (31.2 ft^2) (sweetgum) to 6.6 m^2 (71.0 ft^2) (Bradford pear). Load cell estimated tree water loss also varied with species. On a volumetric basis, poplar transpired the greatest amount of water each day and Bradford pear transpired the least (Table 1). Transpirational water loss normalized on a depth basis (millimeters) takes into account volumetric water loss (cm^3) and leaf area (cm^2) of each tree. Total daily water loss (mm) of poplar was greatest followed by sweetgum. Total daily water loss was least for Bradford pear (Table 1).

During select 72 hour measurement periods, peak hourly shortwave radiation ranged from 600 (poplar) to nearly 1000 W/m^2 (sweetgum) (Fig. 3). For each species, TDP and load cell water loss estimates followed similar diurnal cycles. However, hourly TDP water loss estimates were generally less than load cell water loss estimates, especially during peak periods of sap flow (Fig. 3). Regression analysis of total daily TDP and load cell estimated water loss revealed significant equations and R^2 values which ranged from 0.48 (Bradford pear) to 0.87 (English oak) and regression equations for each species were different (Fig. 4). Percent active xylem tissue along the 30 mm TDP appears to be species specific (Fig. 5). Using equation 6 to estimate active xylem along TDP length, active xylem tissue in contact with the TDP ranged from 70% in Bradford pear to 40% in English oak (Fig. 5).

Diurnal trends of TDP and load cell estimated water loss for containerized trees closely followed that of incoming solar radiation (Fig. 3) and stomatal response to incoming shortwave radiation is well-documented (36). Also, as seen in the preliminary experiment, load cell and TDP water loss estimates in follow up experiments indicate water loss during non-daylight hours (Fig. 3), and was likely due to stomatal response to high VPD conditions prevailing at night (6, 23), and recharge of stem water storage (30). Water loss estimates by TDPs in follow up experiments were also offset from load cell estimated water loss (Fig. 3). Devitt, et al. (9) also report a delayed morning transpiration response for containerized live oak, desert willow, and mesquite trees when TDP estimated water loss was compared to lysimeter estimated water loss. As described in the preliminary experiment, this was likely due to formation of temperature gradients (4, 21) or a possible capacitance effect (35). Experimental setup for preliminary and follow-up experiments was similar, except that for the follow-up experiment, sweetgum trees were not located in a greenhouse. However, for TDPs 30 cm above soil level, regression data from follow-up experiments revealed daily TDP and load cell estimated water loss equations (Fig. 4) with greater R^2 values than were found in the preliminary experiment (Fig. 1). Because this discovery is common across all species examined in the follow-up experiments, results are encouraging, however the cause is unknown.

Environmental conditions inside a greenhouse vary from environmental conditions found outdoors. Therefore, tree transpiration differs for plants grown inside a greenhouse compared to plants grown outdoors (31). Because three of the four follow up experiments were conducted inside a greenhouse, estimated tree water loss data from these experiments should be used with caution. However, our data give insight into water loss characteristics for these containerized tree species. Based upon load cell water loss estimates, we found great variability in daily water use rates between and within species (Table 1). Montague reports similar results for load cell estimated water loss of five transplanted landscape tree species (28).

Our results indicate that for small caliper trees used in this study, the amount of active xylem tissue (sapwood) along the 30 mm TDP appears to differ between species. Although TDPs have not been previously used to estimate tree water loss of young landscape trees (and information regarding depth of active sapwood in young trees is lacking), others indicate depth of active sapwood in older woody plant species is variable. Braun and Schmid (4) used mobile dyes and visually inspected grapevine stems. They found heartwood had not developed in 20 year old grapevines, and estimated grapevine water loss with TDPs using the entire stem cross sectional area. Edwards and Booker (12) used similar methods and report xylem to be most active in poplars trees (trees

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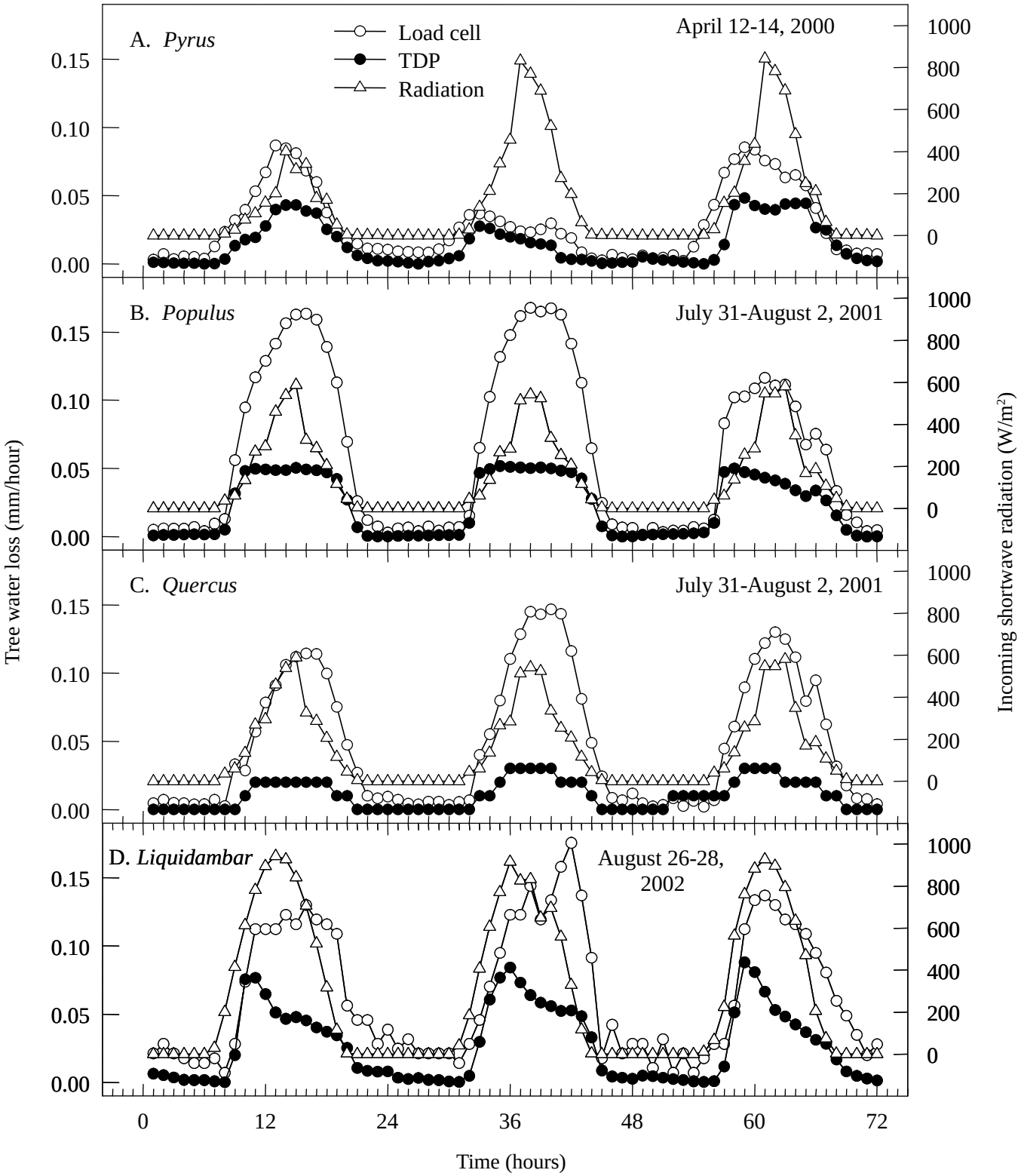

Fig. 3. Mean hourly incoming shortwave radiation, load cell, and thermal dissipation probe (TDP) estimated water loss over select three day periods for greenhouse grown, containerized Bradford pear (*Pyrus calleryana* 'Bradford') (A), poplar (*Populus deltoides* 'Siouxland') (B), English oak (*Quercus robur* x 'Asjes') (C), and outdoor grown sweetgum (*Liquidambar styraciflua* 'Rotundiloba') (D) trees.

measured 23 to 39 cm in diameter (9 to 15 inches) 1.3 m (4.2 feet) above soil level) in the second, third, and first growth rings, respectively. Phillips et al. (30) used TDPs and investigated radial patterns of sap flow at two xylem depths (0 to 2 cm and 2 to 4 cm) in mature white oak (*Q. alba*) and sweetgum (*Liquidambar styraciflua*) trees. In each species, they report sap flow differences were found between depth intervals and report differences became more distinct at low

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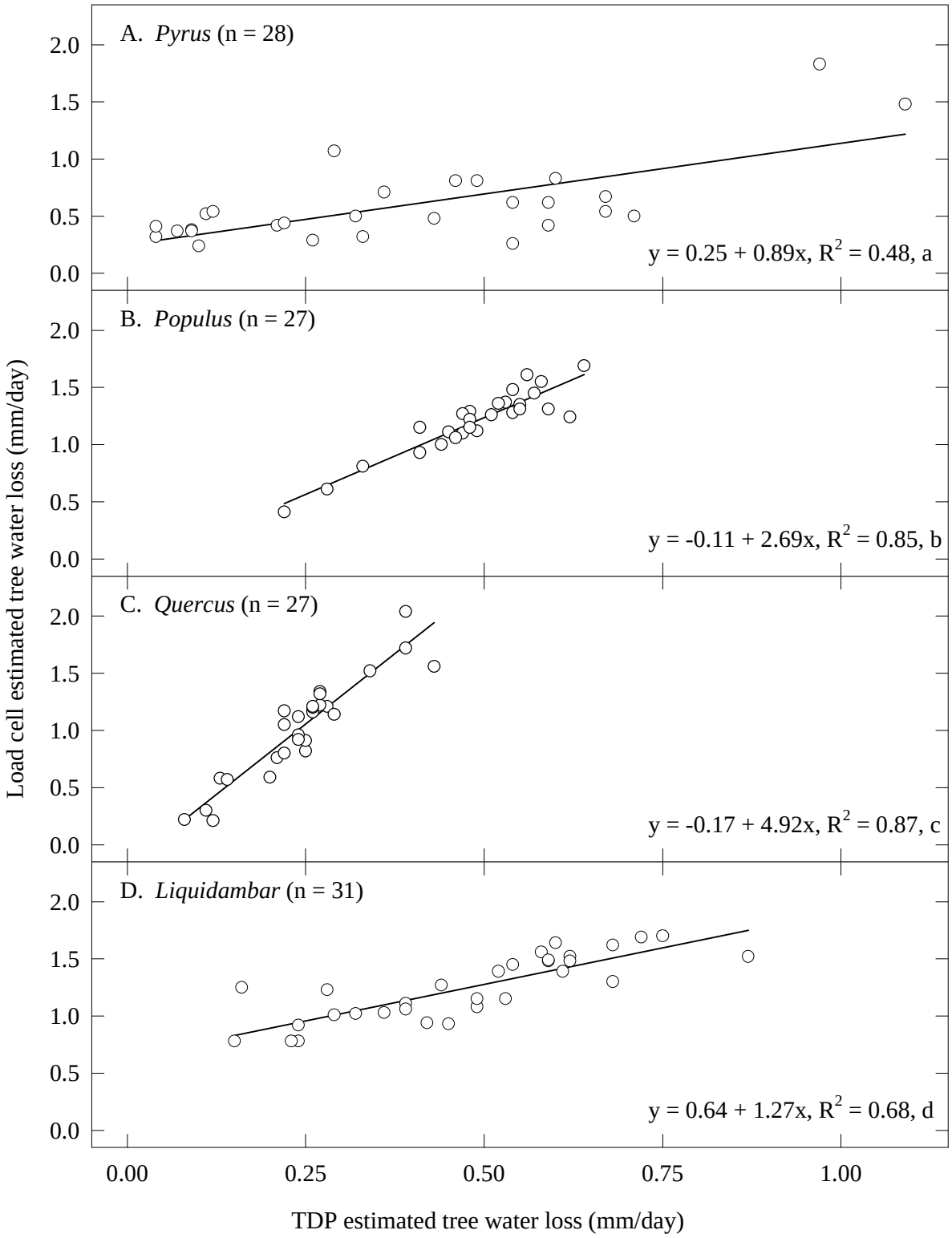

Fig. 4. Actual and predicted values for estimating daily tree water loss (mm/day) using thermal dissipation probes (TDP). Each symbol represents total daily water loss from containerized, greenhouse grown Bradford pear (*Pyrus calleryana* 'Bradford') (A), poplar (*Populus deltoides* 'Siouxland') (B), English oak (*Quercus robur* x 'Asjes') (C), and outdoor grown sweetgum (*Liquidambar styraciflua* 'Rotundiloba') (D) trees. Different letters indicate differences between regression equations (analysis of variance, P = 0.05).

sap flows. Also using TDPs, Granier (17) found that for two mature oak species (*Q. petraea* and *Q. robur*), 80% of sap flow occurred in the outer 1 cm of xylem vessels. Others (7, 8, 19) report xylem tissue nearest the cambium of mature trees to be the most active for water transport. For many tree species, it appears the region of most active sapwood becomes progressively smaller and variable as the tree ages (39). In this research, sapwood estimates are possible indi-

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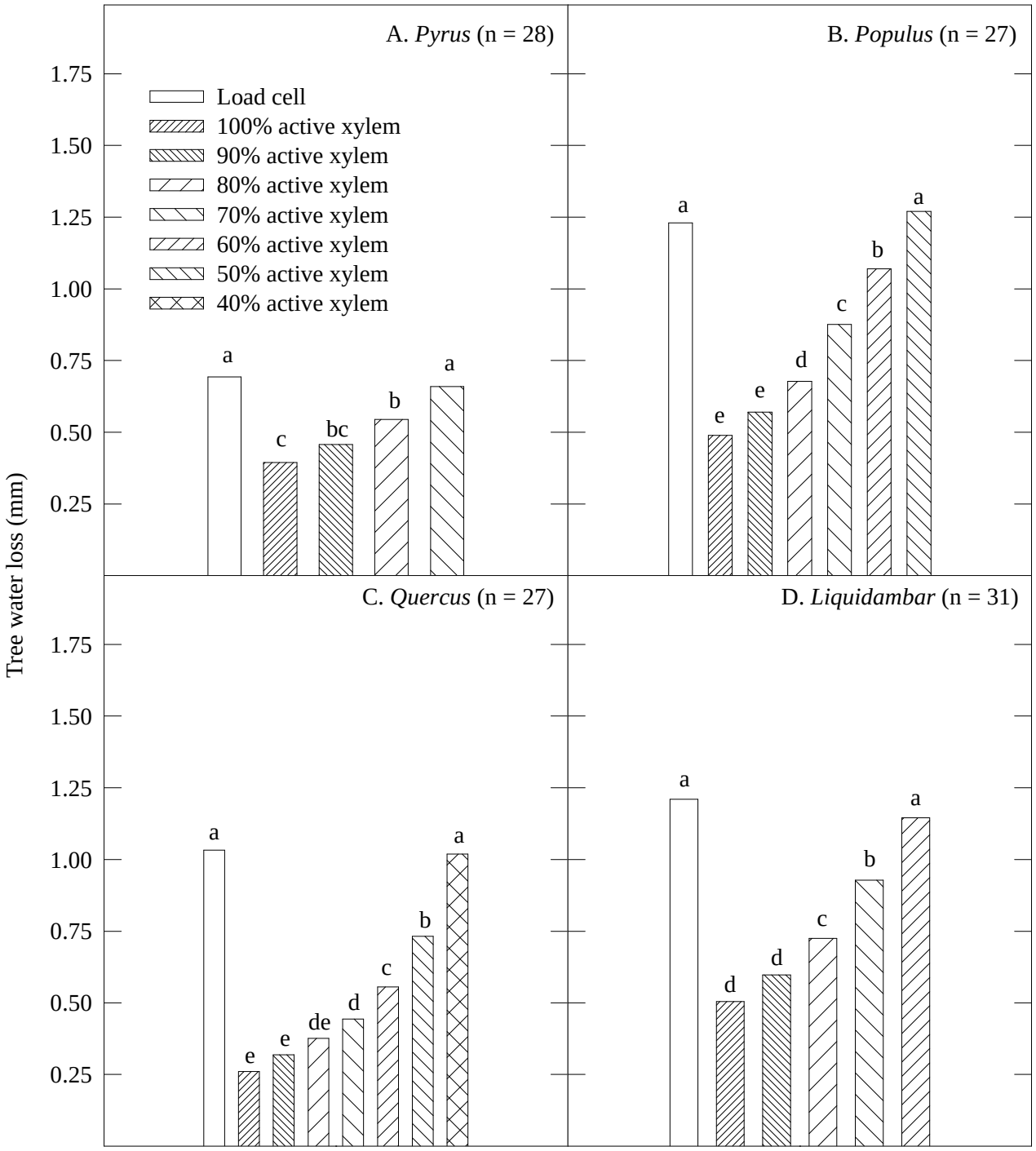

Fig. 5. Mean daily load cell and thermal dissipation probe (TDP) estimated water loss (mm/day) using percent of the TDP in contact with active xylem (100% active xylem = TDP estimate) for greenhouse grown, containerized Bradford pear (*Pyrus calleryana* 'Bradford') (A), poplar (*Populus deltoides* 'Siouxland') (B), English oak (*Quercus robur* x 'Asjes') (C), and outdoor grown, containerized sweetgum (*Liquidambar styraciflua* 'Rotundiloba') (D). Different letters indicate differences between means (LSD, α = 0.05).

cations older sapwood may be functional, but have greater resistance to water movement than younger sapwood, and therefore transport less water (12). Consequently, active xylem estimates (Fig. 5.) are likely indications of sapwood areas with high water transport, with the remaining portion of the probe having little or no water transport.

Proper irrigation management is essential for production, growth, aesthetics, and survival of nursery and landscape plants. Estimating the volume of water required by a plant, and applying that volume in a timely manner helps insure proper growth in nursery and landscape settings (2, 37). By comparing load cell and TDP estimated water loss, this research concluded TDPs can be a valid means to determine water requirements of four containerized, landscape tree species if correct precautions (avoiding thermal gradients in the trunk, correctly estimating sapwood area, etc.) are implemented. Several techniques are available to estimate tree water requirements in nursery and landscape settings (2, 27,

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28), however these methods can be cost prohibitive. Although correct use of TDPs requires plant physiology and technical expertise, water loss estimates using correctly calibrated and installed TDPs appears to be an additional method which can assist nursery and landscape personnel estimate water requirements of small landscape tree species.

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