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Cover photo:
The Narrows on the Blanco River.

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Differences in the Hydration State of Riparian Pecan Trees Between Rural and Urban Settings

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Abstract: Urbanization causes changes in near-surface meteorology and rainfall-runoff relationships that threaten to place hydraulic stress on vegetation. The goal of this study was to investigate the differences in riparian zone tree hydration state, as indicated by leaf water potential, between an urban and a rural stream site, and to understand how the trees respond differently to precipitation events. At the rural stream site, the streambed was dry due to persistent drought conditions, whereas the urban stream site had established flow due to urban water inputs. The trees at the urban site were found to suffer less hydraulic stress than the trees at the rural site, as indicated by predawn leaf water potential measurements. Additionally, trees at the rural site were found to regulate stomatal openness to reduce transpiration on the day before rain, but not after, due to the presence of near-surface moisture introduced by the rain event. Trees at the urban site did not have to regulate stomatal openness before or after the rain, as the established flow in the stream provided consistent water access. These findings support the viability of protecting and preserving riparian ecosystems in urban settings.

Keywords: urbanization, riparian vegetation, leaf water potential, transpiration

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Terms used in paper

Acronym/Initialism	Descriptive Name
cfs	cubic feet per second
CoCoRaHS	Community Collaborative Rain, Hail & Snow Network
ET	evapotranspiration
ft	feet
kPa	kilopascal
LWP	leaf water potential
MPa	megapascal
RH	relative humidity
SR	short-wave solar radiation
T	air temperature
USDM	U.S. Drought Monitor
USGS	U.S. Geological Survey
UT	University of Texas at Austin
VPD	vapor pressure deficit
WOLC	White Outdoor Learning Center

INTRODUCTION

Riparian zones serve an important ecological role as a habitat for many different species of plants, insects, and animals and as a site for numerous important biogeochemical processes and the exchange of energy and moisture between the land surface and atmosphere. Transpiration, which is the evaporation of water from plants and is one of the governing processes of this exchange, is of particular interest to earth scientists. Depending on the land cover, transpiration accounts for most total terrestrial evapotranspiration (ET; processes including transpiration and the evaporation of water from soil and other bodies of water) at the ecosystem scale and can return up to half of incident precipitation to the atmosphere (Schlesinger & Jasechko, 2014), making it a major component of the hydrologic cycle. Riparian vegetation is unique in its interactions with the bodies of water it surrounds. Riparian zones are often a major part of urban green space, offering space for leisure and recreation and providing shade and transpirative cooling to surrounding areas. Urbanization causes changes in local-scale meteorology and rainfall-runoff relationships that are exacerbated by the warming climate (Oke, 1982; Hernandez et al., 2000; Arnfield, 2003; Chen et al., 2019). These effects may be felt especially strongly in an already hot and dry environment, such as Central Texas. Therefore, understanding the relationships between urban and rural (in this study, rural is defined as streams without adjacent urban development) hydrology and the adjacent riparian vegetation hydration and function will improve the ability of city and state actors to make informed decisions about managing waterways and preserving these ecosystems.

One driving link between the land and the atmosphere—and in this case, stream channels and the atmosphere—is transpiration from riparian vegetation. Transpiration is governed by demand in the form of atmospheric vapor pressure deficit (VPD) and supply in the form of moisture availability in the root zone. VPD creates a pressure gradient that pulls water vapor from the moist plant interior into the drier atmosphere. During favorable environmental conditions, plants open stomata, microscopic pores on leaves, to maximize CO_2 uptake for photosynthesis (Medlyn, 2013). However, when VPD is overly high or water is absent from the root zone, plants restrict stomatal openness to conserve water (Running, 1976; Sperry & Tyree, 1988; Franks et al., 1997; Matheny et al., 2014). Continuing to transpire during times of high VPD or low moisture availability may result in hydraulic stress or cavitation (Maherali, 2006). Cavitation or embolism results in an air pocket forming within one or more xylem vessels, causing the plant to be unable to transmit water through its conductive tissue. A common response of plants to hydraulic stress is to close or partially close stomata in the middle of the day when it is usually hottest and driest (Running, 1976, Sperry & Tyree, 1988; Horton et al., 2001; Gazal et al., 2006).

VPD changes quickly (e.g., minutes to hours) in response to atmospheric temperature and humidity. But the second limiting factor for transpiration, water supply in the root zone, changes more slowly (e.g., days to weeks). Water can be supplied to plants' roots in the form of soil moisture or direct access to the water table (Horton et al., 2001; Potts & Williams, 2004; Gazal et al., 2006). Many riparian tree species use a combination of soil or bank water storage, while other riparian species are phreatophytic, meaning they rely on access to the water table or at the capillary fringe for a significant portion of the water required for transpiration (Rood et al., 2011; Pettit & Froend, 2018; Phelan et al., 2022). Phreatophytes exist on a spectrum from obligate to facultative, where obligate phreatophytes require continuous access to the water table and facultative do not. The Texas pecan trees (*Carya illinoinensis*) sampled in this study are facultative phreatophytes and use shallow roots to access water in the vadose zone to in addition to stream-water supplements (Sparks, 2005; Pettit & Froend, 2018).

Urbanization affects both atmospheric and subsurface conditions and therefore has the potential to impact transpiration and plant health. One climate phenomenon brought on by urban development is the urban heat island effect, wherein urban areas experience higher near-surface air temperatures than surrounding unurbanized areas because of increased dark, impervious cover (Oke, 1982; Arnfield et al., 2003; Meehl et al., 2007; Wei et al., 2021). Pielke et al., (2011) demonstrated an increase in surface albedo—the fraction of sunlight reflected by the Earth's surface—associated with urban development for numerous urban centers across every continent. This increase in albedo, when coupled with the reduction in green space associated with urban development, results in increased reflection of solar radiation by the land surface rather than absorption into the ground. Less absorption of incoming radiation results in a higher sensible heat flux and lower latent heat flux (Oke, 1982). Sensible heat flux describes energy that contributes to raising the air temperature, whereas latent heat flux describes the energy that contributes to water changing phase from liquid to gas through ET. This change in the partitioning of the surface energy balance has been shown to increase VPD (higher air temperatures, less moisture in the air) on a global scale and has been predicted to rise continuously over the next century according to several general circulation models (Park Williams et al., 2013; Zhang et al., 2015; Ficklin & Novick, 2017; Yuan et al., 2019).

In addition to increased land surface temperatures, increased impervious cover associated with urbanization alters rainfall-runoff relationships (Hernandez et al., 2000; Chen et al., 2019; Tamaddun et al., 2019). This increase in impervious cover leads to decreased infiltration and, therefore, decreased groundwater recharge (Hernandez et al., 2000; Poudel et al., 2020). Reduced infiltration can result in less available moisture in the vadose zone, in addition to increases in runoff (Hernandez et al., 2000; Poudel et al., 2020). Whether in isolation or combined, these changes can also result in changes in stream intermittency. Both Hopkins et al. (2015) and Poudel et al. (2020) showed that increased runoff and decreased infiltration contribute to lower baseflow in urban streams, especially if runoff is diverted into other water-capture systems. However, in some situations, a large portion of urban streamflow is supplemented by other water contributions from urban infrastructure leakage (Christian et al., 2011; Passarello et al., 2012). Sources of this infrastructure leakage can be cracked or broken water and sewer lines, swimming pools, irrigation systems, and other human-use-related waters (Christian et al., 2011; Passarello et al., 2012).

We conducted this study to explore the relationship between urban and rural streams and how their baseflow conditions influenced riparian tree hydration and function. Our goal was to understand if diurnal cycles of riparian pecan tree hydration differ between urban and rural settings. We hypothesized that access to root-zone moisture ultimately governs tree hydration more strongly than atmospheric conditions and therefore trees able to access continuous baseflow in the form of urban leakage will experience less hydraulic stress than those near intermittent streams, in this case, streams in rural settings. Understanding how tree hydration is controlled in an urbanized riparian setting will allow scientists, conservationists, and city and state officials to better manage these streams and ecosystems as cities continue to grow and the climate continues to warm.

DESCRIPTION OF STUDY AREAS

We selected two similar Central Texas streams and accompanying riparian ecosystems as comparison sites at which to conduct the study. The first site selected was a bedrock-lined reach of South Onion Creek that flows through the White Outdoor Learning Center (WOLC), a property owned by the University of Texas at Austin (UT). South Onion Creek is a branch of Onion Creek that has its headwaters in Hays County, Texas (30°07' N, 98°14' W) and joins the main fork of Onion Creek (~15 miles east) just south of the town of Dripping Springs, Texas (30°09' N, 98°05' W). This creek flows through Cretaceous-age limestones from the Glen Rose Formation. The adjacent soils along the creek banks are thin (~0–30 centimeters), as is common throughout the Texas Hill Country, such that the carbonate bedrock outcrops along both the banks and creek bottom (Hunt et al., 2016). Dominant tree species in South Onion Creek's riparian zone include Ashe juniper *(Juniperus ashei)*, American sycamore *(Platanus occidentalis)*, pecan *(Carya illinoinensis)*, and Texas live oak *(Quercus fusiformis).* For this study, we assessed the hydration states from three pecan trees on the south bank of the creek, which will hereafter be referred to as P1, P2, and P3. Trees were selected to be of similar size and age, but due to sampling limitations, P3 was slightly younger and smaller than P1 and P2. Both P1 and P3 were ~5–7 meters from the streambank. P2 was positioned furthest from the creek, ~10 meters from the top of bank. None of the three trees had visible roots that could be directly exposed to stream water.

This study was conducted during the summer of 2022, at a time of persistent drought conditions throughout Central Texas. Sampling at the South Onion Creek site was conducted on October 8, 2022, and November 6, 2022, with multiple small rain events between the 2 sampling days. South Onion Creek is naturally intermittent, which when coupled with the drought conditions, resulted in a dry streambed during both sampling days. On the second sampling day, we observed some minor ponding in the creek bed, but it was insufficient to allow any discharge measurements. In this area of South Onion Creek, the depth to water table is about 190 feet (ft). By the second day of sampling, the appearance of P1 and P2 reflected the prolonged drought conditions. Both trees lost a considerable number of leaves, and many in the lower canopy were yellowing and starting to become brittle. This observed leaf senescence is more likely attributable to dry conditions (Tyree et al., 1993) than to the end of growing season, as P3 and other adjacent pecan trees retained their leaves.

The second site selected for this study was the extent of Waller Creek that flows through UT's campus. Waller Creek is a tributary of the Colorado River, with headwaters in Austin's Highland neighborhood (30°20' N, 97°42' W). It discharges into the Colorado River at Town Lake (30°15' N, 97°44' W) in downtown Austin, approximately 6 miles south of the observation location. This stream flows through a Cretaceous limestone unit known as the Austin Chalk, and the extent of the stream on UT's campus has been channelized due to the surrounding urban development. Sampling at this site was conducted on October 22, 2022, and October 26, 2022, with a rainfall event of 0.89 inches occurring in the intervening days. Streamflow data taken from a U.S. Geological Survey (USGS) monitoring gage ~1 mile downstream from the sampling site showed an average discharge of 20.1 ft^3/s on the first day of sampling. Peak discharge after the rain event was measured to be 127 ft^3/s, and on the second day of sampling, the average discharge was 10.7 ft^3/s. The depth to water table of this reach of Waller Creek is ~200 ft. Although not as thin as at the South Onion Creek location, the soil layer around Waller Creek is thin enough to expose bedrock on both the creek banks and bottom. Dominant tree species in Waller Creek's riparian community, which are more numerous than at South Onion Creek, include bald cypress *(Taxodium distichum),* green ash *(Fraxinus pennsylvanica)*, boxelder *(Acer negundo)*, and pecan. Other species, such as Ashe juniper and Texas live oak, are present but not abundant. In parallel to the sampling at the South Onion Creek site, we took samples from three pecan trees on the west bank of Waller Creek, which will be hereafter referred to as P4, P5, and P6. The three trees selected for sampling were approximately the same age and size as those at the South Onion Creek location. Although P4 had a slightly shorter canopy than P5 and P6, it was a canopy-dominant tree receiving full sun exposure. Both P4 and P6 were situated ~5–8 meters from the streambank and elevated along the bank such that no visible roots made direct contact with the water. P5, on the other hand, was positioned ~2 meters from the bank and had roots visibly exposed to the water. P4 and P5 sat upstream of a small (~1 ft) low-head dam in the stream, while P6 was positioned on the downstream reach.

METHODS

To characterize tree hydration, we collected leaf water potential (LWP) measurements. LWP is the pressure at which water is held inside the leaf and is a measure of tree hydration and proxy for transpiration. A more negative LWP value indicates that water in the plant is being held in greater tension, indicating greater hydraulic stress. A less negative LWP value represents a lower level of hydraulic stress. LWP is useful because it can be measured quickly, making it possible to capture the dynamic nature of tree water-regulation at fast (e.g., hourly) timescales. We took LWP measurements using a Scholander-style pressure chamber (PMS Instruments, Albany, OR, USA) at four different times of day: predawn (6:00 a.m.), early-morning (8:00 a.m.), mid-morning (11:00 a.m.), and solar noon (about 1:30 p.m. during October and November). For each tree, we sampled a minimum of three replicate leaves receiving full sun to obtain a representative average hydration state for each tree at each time point. Tables 1-4, which can be found in the Appendix, detail all LWP measurements. All LWP values were recorded in megapascals (MPa). Measurements for each leaf were made immediately after harvest to ensure that LWP was representative of the plant's undisturbed condition. All measurements on the 4 days of sampling were conducted in the same manner. For the early-morning, mid-morning, and solar noon measurements, we took care to select leaves receiving full sunlight to accurately capture the hydration state at the site of maximum transpiration.

At South Onion Creek, measurements for air temperature *(T)*, relative humidity *(RH)*, and short-wave solar radiation *(SR)* were taken at a 12-minute interval by a meteorological station located ~20 meters from the streambank where LWP measurements were made. VPD was calculated as follows using measurements from the station:

$$e_{sat} = 0.6109 * \exp\left(\frac{17.27T}{237.3 + T}\right)$$

$$VPD = \left(1 - \left(\frac{RH}{100}\right)\right) * e_{sat}$$

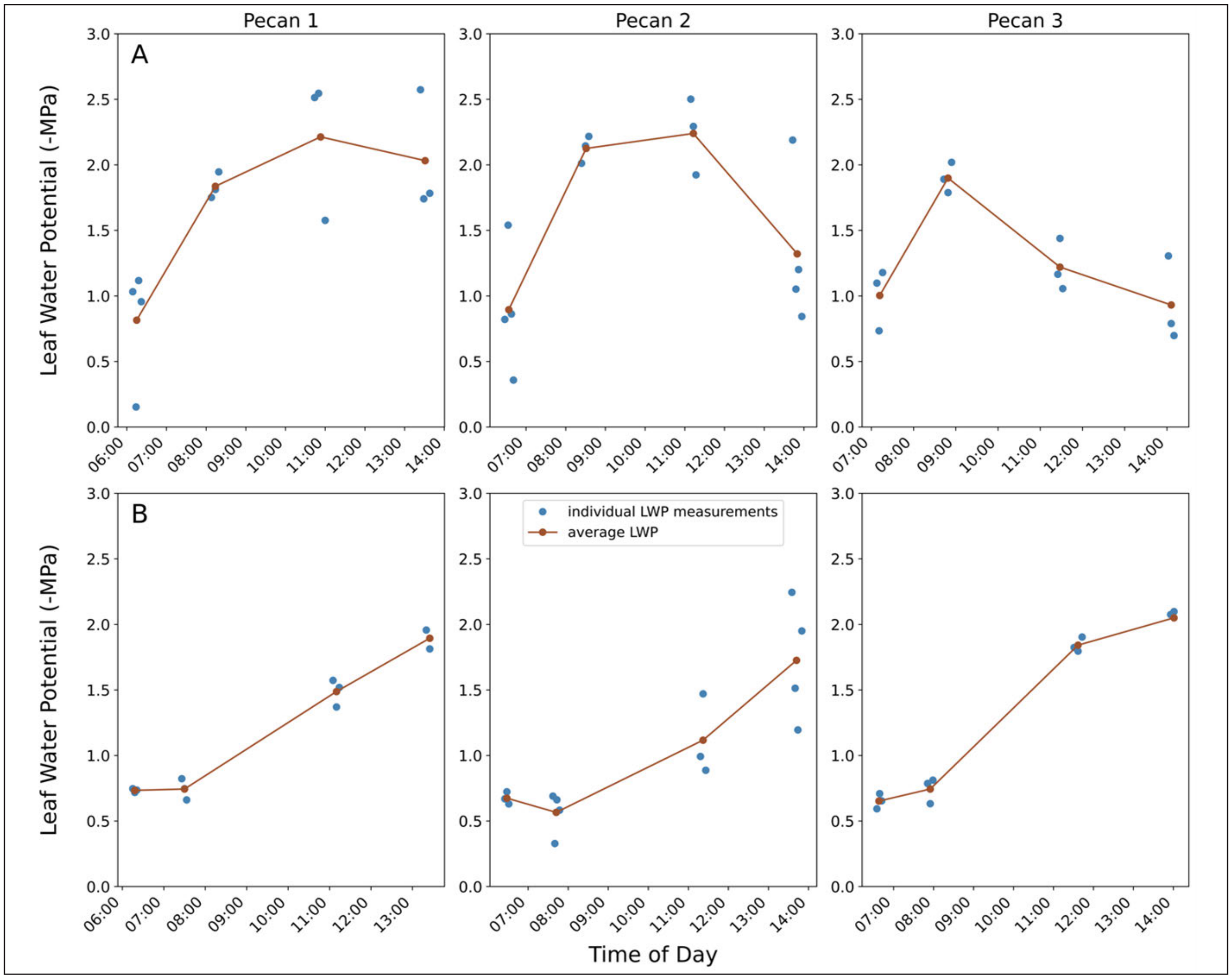

Figure 1. The top row (A) shows leaf water potential (LWP) timeseries for the first day of sampling at the White Outdoor Learning Center before the rain. All three pecan trees were most stressed (i.e., had the most negative LWP values) in the mid-morning. The bottom row (B) shows LWP timeseries for the second day of sampling after the rain event. All three pecan trees were most stressed at solar noon. LWP measurements are given in negative megapascals (-MPa).

At Waller Creek on the UT campus, these data were recorded at a 5-minute interval by a weather station ~380 meters from the data collection site. Data for precipitation were sourced from the Community Collaborative Rain, Hail & Snow Network (CoCoRaHS), and streamflow data were sourced from the USGS stream gage network (CoCoRaHS 2023a; USGS 2023). Maps of drought severity were taken from the U.S. Drought Monitor (USDM; USDM 2023). Figures 6-9, which can be found on pages 95-98, show timeseries of *T, RH, SR,* and VPD on each day of sampling.

RESULTS

The goal of this study was to determine if diurnal cycles of riparian pecan tree hydration differ between urban and rural settings. We evaluated this difference by sampling on a day before and a day after a precipitation event at both sites. This allowed us to capture tree response, in terms of LWP, to the input of near-surface moisture and compare between the urban stream, which had sustained baseflow, and the rural stream, which did not.

For P1, the least negative LWP value of –0.815 megapascal (MPa) was observed predawn at 6:15 a.m. LWP values became increasingly negative (i.e., the tree became more stressed) over the course of the morning until reaching the most negative value of –2.21 MPa at 10:53 a.m., after which time LWP became less negative again, reaching a value of –2.03 MPa at 1:31 p.m. when sampling concluded. P2 followed a similar trend, with the least negative LWP of –0.90 observed at 6:34 a.m. and the most negative LWP of –2.23 MPa observed at 11:13 p.m. LWP rose to –1.32 MPa at 1:50 p.m. when sampling concluded. P3, however, did not follow the same trend as P1 and P2. The least negative LWP value of –0.93 MPa was observed at 2:06 p.m. when sampling concluded, and the most negative value of –1.90 MPa was observed in the early morning at 8:49 a.m. (Figure 1A). The full range of LWP values were observed

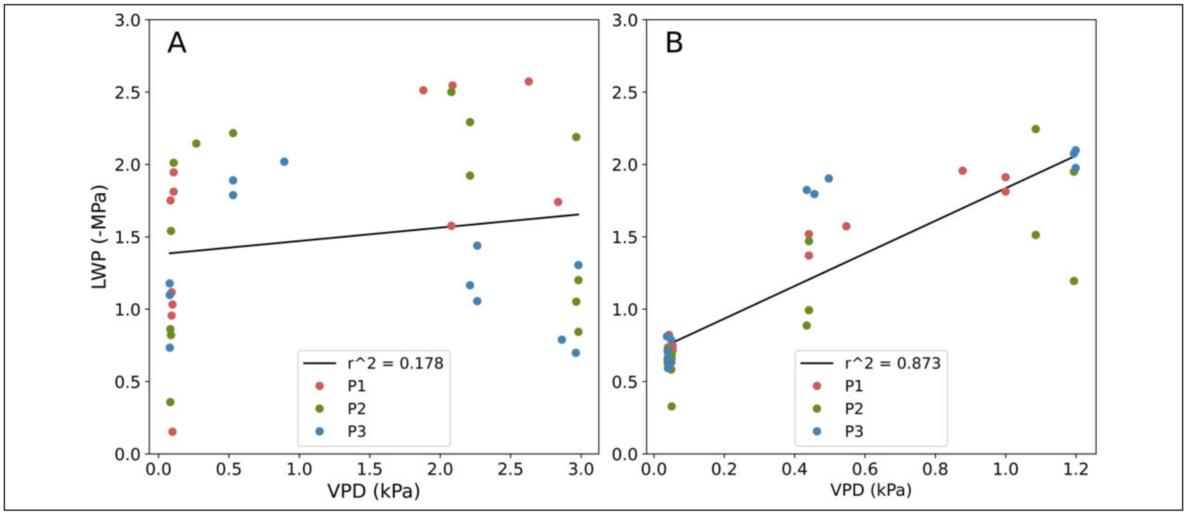

Figure 2. (A) shows the linear relationship of leaf water potential (LWP) and vapor pressure deficit (VPD) for the first day of sampling at the White Outdoor Learning Center. The relationship is not significant (p = 0.279). (B) shows the linear relationship of LWP with VPD for the second day of sampling. After rehydration of the shallow soil layers by rainfall, LWP and VPD show a very strong correlation (R^2 = 0.87, p = 9.20 x 10^{-13}). LWP values are shown in negative megapascals (-MPa), and VPD values are given in kilopascals (kPa).

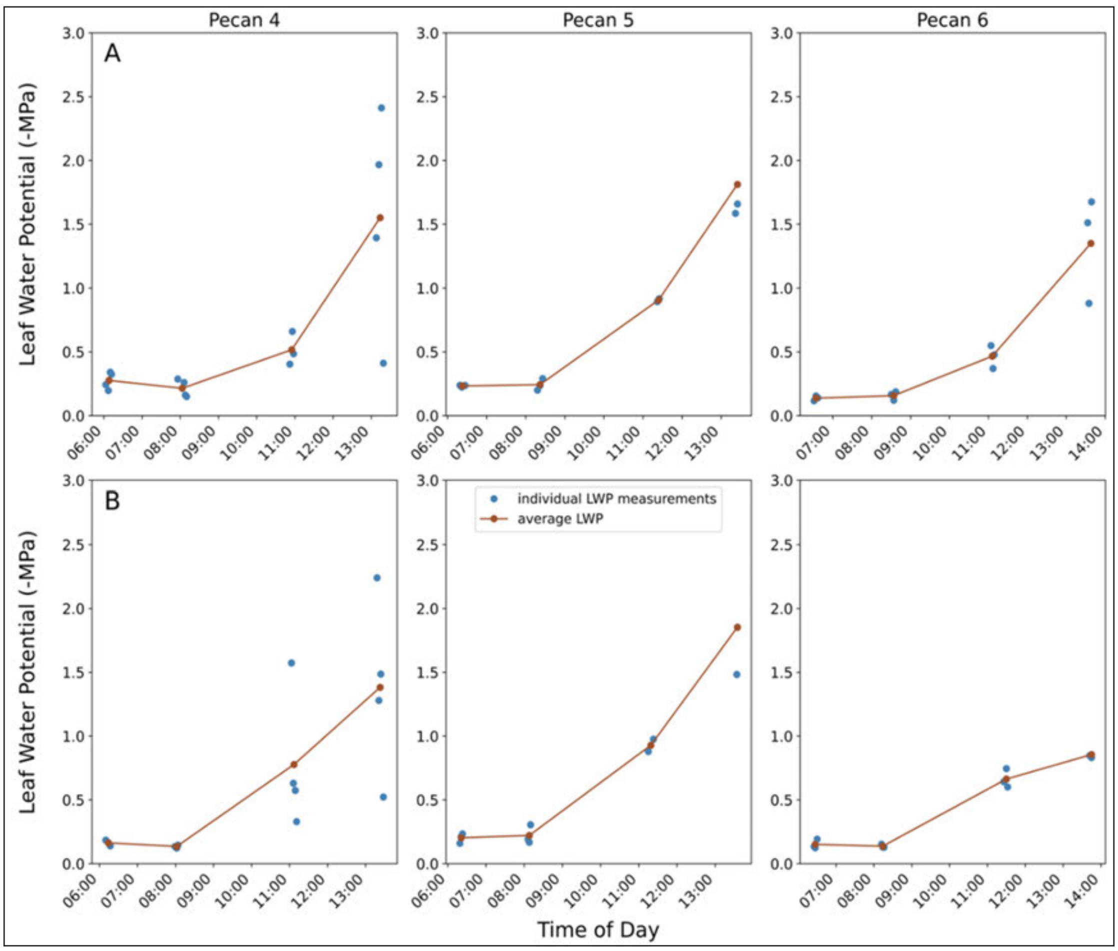

Figure 3. The top row (A) shows leaf water potential (LWP) timeseries for the first day of sampling at Waller Creek before the rain. The bottom row (B) shows LWP timeseries for the second day of sampling after the rain event at the Waller Creek site. All three pecan trees were most stressed at solar noon on both days of sampling. LWP values are given in negative megapascals (-MPa).

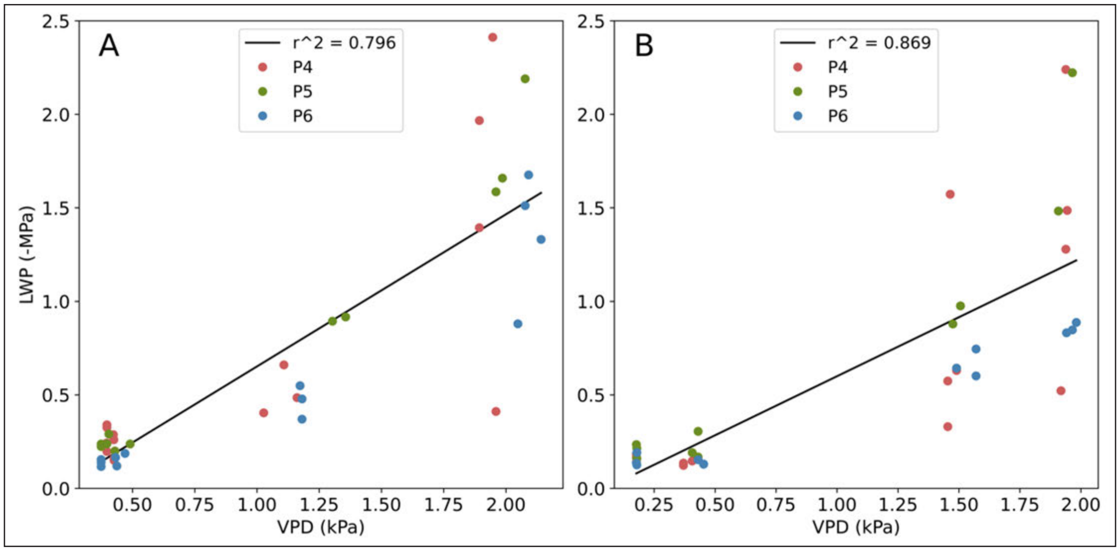

Figure 4. (A) shows the linear regression of leaf water potential (LWP) with vapor pressure deficit (VPD) for the first day of sampling at Waller Creek. (B) shows the linear regression of LWP with VPD for the second day of sampling. LWP and VPD show a very strong correlation on both days of sampling (R^2 = 0.80, p = 7.83 x 10^{-13}, and R^2 = 0.87, p = 6.38 x 10^{-9}, respectively). LWP values are shown in negative megapascals (-MPa), and VPD values are given in kilopascals (kPa).

across all measured VPD values. This high degree of variation in LWP independent of VPD is reflected in the low coefficient of determination of 0.18 and insignificant p value (Figure 2A).

Between the 2 sampling days at South Onion Creek, there were five small precipitation events totaling 2.96 inches (CoCoRaHS 2023b). These events were insufficient to restore streamflow, but some minor ponding was observed in the creek bed. Compared to the first day of sampling, there was much less variation in LWP between the trees on the second sampling day. The least negative values were observed during predawn (P1 and P3) or early morning (P2), and the most negative values were observed at solar noon when sampling concluded for all three. For P1, the predawn LWP value was –0.73 MPa, and the solar noon value was –1.89 MPa. For P2, the least negative value of –0.57 MPa was observed in the early morning, and the most negative value of –1.73 MPa was observed at solar noon. Finally, for P3, the predawn value was –0.65 MPa, and the solar noon value was –2.05 MPa (Figure 1B). A substantially stronger correlation between VPD and LWP was found on the second day of sampling (R^2 = 0.87, p = 9.20 x 10^{-13}). This value suggests that LWP is responding strongly to the atmospheric demand for water vapor. Little variation in LWP was observed at VPD values below 0.1 kilopascal (kPa), and as VPD increased, variation in LWP also increased (Figure 2B).

On October 17, between the sampling days at the WOLC and Waller Creek, there was a large rain event totaling 0.99 inches of precipitation (CoCoRaHS 2023c). Because soil moisture in this area was not monitored, it is not clear how this may have influenced subsurface dynamics prior to initial sampling at the Waller Creek site. All three of the trees had similar trends in LWP over the course of the day, with the least negative values observed either predawn (P5 and P6) or in the early morning (P4) and the most negative values observed at solar noon. For P4, the least negative value of –0.22 MPa was observed in the early morning, and the most negative value of –1.55 MPa was observed at solar noon. For P5, the least negative value of –0.23 MPa was observed predawn, and the most negative value of –1.81 MPa was observed at solar noon. Finally, for P6, the least negative value of –0.14 MPa was observed predawn, and the most negative value of –1.35 MPa was observed at solar noon. For the predawn, early morning, and mid-morning measurements, variation between individual leaf measurements was relatively small, and there was more variation between individual measurements made at solar noon (Figure 3A). At Waller Creek, LWP had a very strong positive correlation with VPD on both sampling days (R^2 = 0.80, p = 7.83 x 10^{-13}, and R^2 = 0.87, p = 6.38 x 10^{-9}, respectively; Figure 4). There was very little variation in LWP at VPD values less than 0.5 kPa and extreme variation in LWP values above 1.50 kPa (Figure 4A).

Between the 2 sampling days at Waller Creek, there were two rain events totaling 0.89 inches of precipitation. On the first day of sampling, streamflow was 20.3 cubic feet per second (cfs). In response to these events, Waller Creek streamflow reached a maximum storm flow of 128 cfs and decreased to 10.8 cfs by the second day of sampling (USGS 2023). The trees all followed the same trend on the second sampling day as on the first, with the least negative LWP values observed either predawn or in the early morning and the most negative values observed at solar noon. For P4, the least negative LWP value of –0.14 MPa was observed in the early morning, and the most negative value of –1.38 MPa was observed at solar noon. For P5, the least negative value of –0.20 MPa was observed predawn, and the most negative value of –1.85 MPa was observed at solar noon. Finally, for P6, similarly to P4, the least negative value of –0.137 MPa was observed in the early morning, and the most negative value of –0.86 was observed at solar noon. In general, these values are less negative than the LWP measured on the first sampling day, but they are not sufficiently different to suggest that the rainfall contributed significantly to the difference. As was observed on the first day of sampling, there was little variation in LWP values measured predawn and in the early morning. However, only P4 showed greater variation in LWP values measured mid-morning and at solar noon (Figure 3B). At the low end of the range in VPD values (i.e., the most humid conditions), there was very little variation in LWP, with variation only increasing slightly in the middle ranges of VPD values. At VPD values above 1.75 kPa, LWP became highly variable and nearly the full range in measured values were observed (Figure 4B).

DISCUSSION

South Onion Creek

Between the first and second sampling days at the WOLC on South Onion Creek, there was a pronounced difference in the progression of tree hydration over the course of the day. The decline in LWP by midday on the first sampling day was likely due to the trees closing the stomata on their leaves to reduce transpiration and moisture loss to the atmosphere to protect themselves against hydraulic failure or embolism (Figure 1A). Reducing stomatal conductance is a common water-regulation strategy utilized by vegetation in both mesic and arid environments to prevent excessive moisture loss to the atmosphere and reduce cavitation risk during the hottest and driest parts of the day (Horton et al., 2001; Gazal et al., 2006; Matheny et al., 2014). Cottonwood trees situated in the riparian zones of intermittent streams, such as South Onion Creek, have similarly demonstrated reduced stomatal conductance and transpiration in the middle of the day during peak dry periods (Gazal et al., 2006).

In contrast, instead of being most stressed in the morning, all three trees at South Onion Creek were the most stressed at solar noon after rainfall on the second sampling day (Figure 1B). This follows the more expected response of maximum transpiration coinciding with times of highest VPD and insolation (i.e., the maximum environmental and photosynthetic demand; Grossiord et al., 2020). An important difference in the meteorological conditions between the 2 sampling days is that the weather remained more humid on the second day compared to the first. By midday on the second sampling day, *RH* remained at 60–65%, whereas on the first sampling day it was just below 30%. This resulted in a VPD just above 1.4 kPa at midday on day two, whereas on the first day it reached over 3.0 kPa. While this difference in VPD is significant on its own, the increase in available shallow soil moisture likely also played a governing role in tree hydration, as maximum (i.e., least negative) LWP was very similar on both days (Figure 1). Likewise, the increase in soil moisture and consequently soil evaporation helped keep evaporative demand (i.e., VPD) low on the second sampling day.

Although there was not enough precipitation in the region from the rain events between sampling days to restore streamflow, this precipitation infiltrated into the streambanks, creating a near-surface reservoir of water for the trees to utilize (Sala et al., 1982; Schwinning & Ehleringer, 2001). This was reflected in the less negative predawn LWP on the second sampling day compared to on the first sampling day, suggesting that the trees were less stressed on the second day before transpiration began (Figure 1). Predawn LWP is generally interpreted as an indicator of soil water potential because trees typically do not transpire or photosynthesize at night and are therefore able to reach a hydrostatic equilibrium with the root-zone soil water pool (Thomsen et al., 2013; Martínez-Vilalta et al., 2014). The combination of a more abundant root-water source and lower VPD than on the first day enabled the pecan trees to continue transpiration throughout the middle of the day without reducing stomatal conductance (Gazal et al., 2006).

LWP was more strongly correlated with VPD on the second day of sampling than the first: 87.3% of the variation in LWP could be explained by VPD on the second day, while only 17.8% could be explained on the first (Figure 2). This finding is similar to the study by Gazal et al. (2006), which found that transpiration was not correlated to changes in VPD at the intermittent stream site before seasonal rain and was more correlated on the day after the rain. This relationship is likely due to the dual controls on transpiration: supply in the soil and demand in the atmosphere. During periods of adequate soil water availability, as on the second sampling day, demand strongly governs transpiration and LWP (Figure 2B). However, when soil water is too limiting to supply adequate LWP, stomata close, preventing the LWP–VPD relationship from developing (Figure 2A). Additionally, there was less variation between individual timepoint LWP measurements on the second day than on the first, except for P2 (Figure 1). P2 was located about 10 meters from the streambank, whereas P1 and P3 were only 5–7 meters from the bank. Even at this scale, spatial heterogeneities in soil moisture in the root zone along the bank slope may exist and could help to explain variation in LWP between trees and between individual measurements. Cottonwoods, like pecan trees, are facultative phreatophytes and therefore

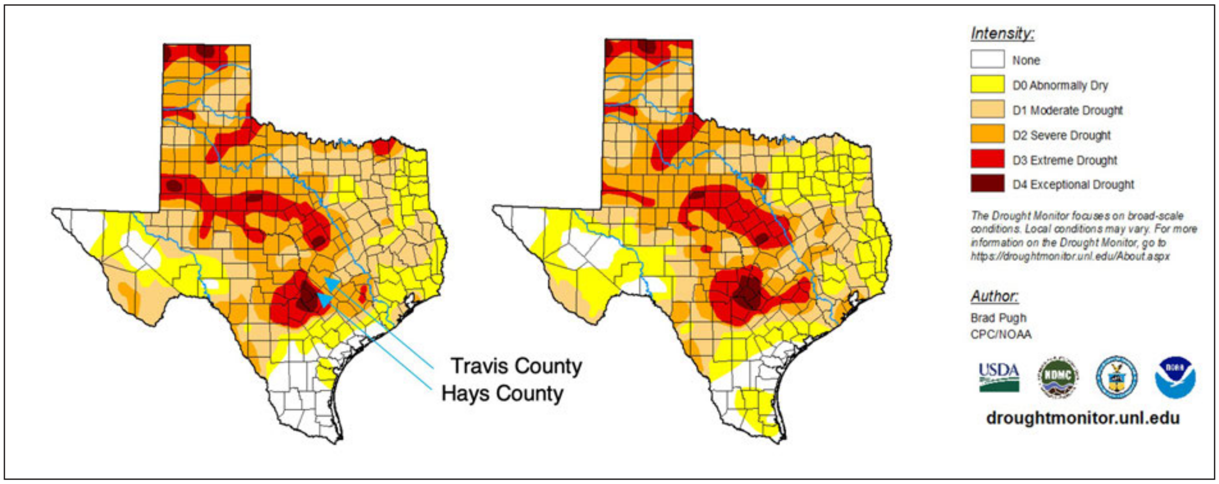

Figure 5. Maps comparing drought severity at the beginning of October 2022 (left) to the beginning of November 2022 (right), during which sampling was conducted at both sites. Hays County, where the South Onion Creek site is located, and Travis County, where the Waller Creek site is located, are highlighted in the map on the left.

can take advantage of shallow moisture when groundwater is depleted and/or difficult to reach (Sparks, 2005; Rood et al., 2011; Phelan et al., 2022). This makes them a useful analog to the water-use strategies of pecan trees, as there is a lack of research regarding the function of pecan trees in riparian zones.

Waller Creek

Between the first and second sampling days at Waller Creek, there was no major difference in the progression of tree hydration state over the course of the day, and predawn LWP was very similar for all three trees between the two sampling days (Figure 3). The similarity in response between the two days suggests that the intervening rain did not contribute to improving tree hydration, and all trees were able to adequately recharge internal hydration each night. Gazal et al. (2006) also investigated trees along a perennial stream and found significant positive and linear correlations between VPD and transpiration (also using LWP as a proxy for transpiration) both before and after the monsoon rains in Arizona. Although the precipitation received at Waller Creek was not of monsoon proportion, that the response was observed at a perennial stream suggests that the constant flow of water from the stream plays a more direct role in reducing hydraulic stress than intermittent precipitation (Solins & Cadenasso, 2020). In fact, the low (near zero) predawn LWP values observed indicates a high soil-water availability adjacent to Waller Creek, likely due to bank storage (Bigelow et al., 2020). Williams & Cooper (2005) found a similar result in cottonwood trees in the riparian zone of a regulated perennial stream, where the addition of soil water did little to reduce hydraulic stress and change overall water regulation.

Inter-site Comparison

It is worth noting that at the South Onion Creek site, the second day of sampling was conducted nearly a month (29 days) after the first, whereas at Waller Creek, the second day of sampling was conducted only 4 days after the first. Given the rather sparse rain between the sampling days (less than 3 inches at South Onion Creek and less than 1 inch at Waller Creek), the time gap likely did not have a significant impact on the results. According to the National Drought Mitigation Center, the severity of drought in both Hays (Onion Creek) and Travis (Waller Creek) counties increased from the beginning of October to the beginning of November (Figure 5). USGS groundwater well data revealed no significant change in the depth to the water table at either site (still greater than 190 feet at both) over this time, suggesting that the precipitation events were insufficient to recharge groundwater during the study period.

We initially hypothesized that the urban heat island effect may negatively influence tree hydration and function at the Waller Creek site in the urban setting, but there was relatively low meteorological variability between the two sites on sampling days. VPD was largely the same across both sites. Apart from the second day of sampling at South Onion Creek, VPD ranged from about 0.5 kPa in the morning to 2.0–2.5 kPa in the middle of the day (Figures 6–9). The overall similarity in atmospheric conditions between the two sites combined with the broad differences in tree hydration (e.g., LWP) suggests that soil water availability differences between the two riparian settings is the primary determinant of inter-site variation.

Thus, differences in tree hydration state and ensuing function (e.g., transpiration and photosynthetic rate) that persisted between the sites despite overall similar atmospheric and deep groundwater conditions indicate that near-surface moisture is

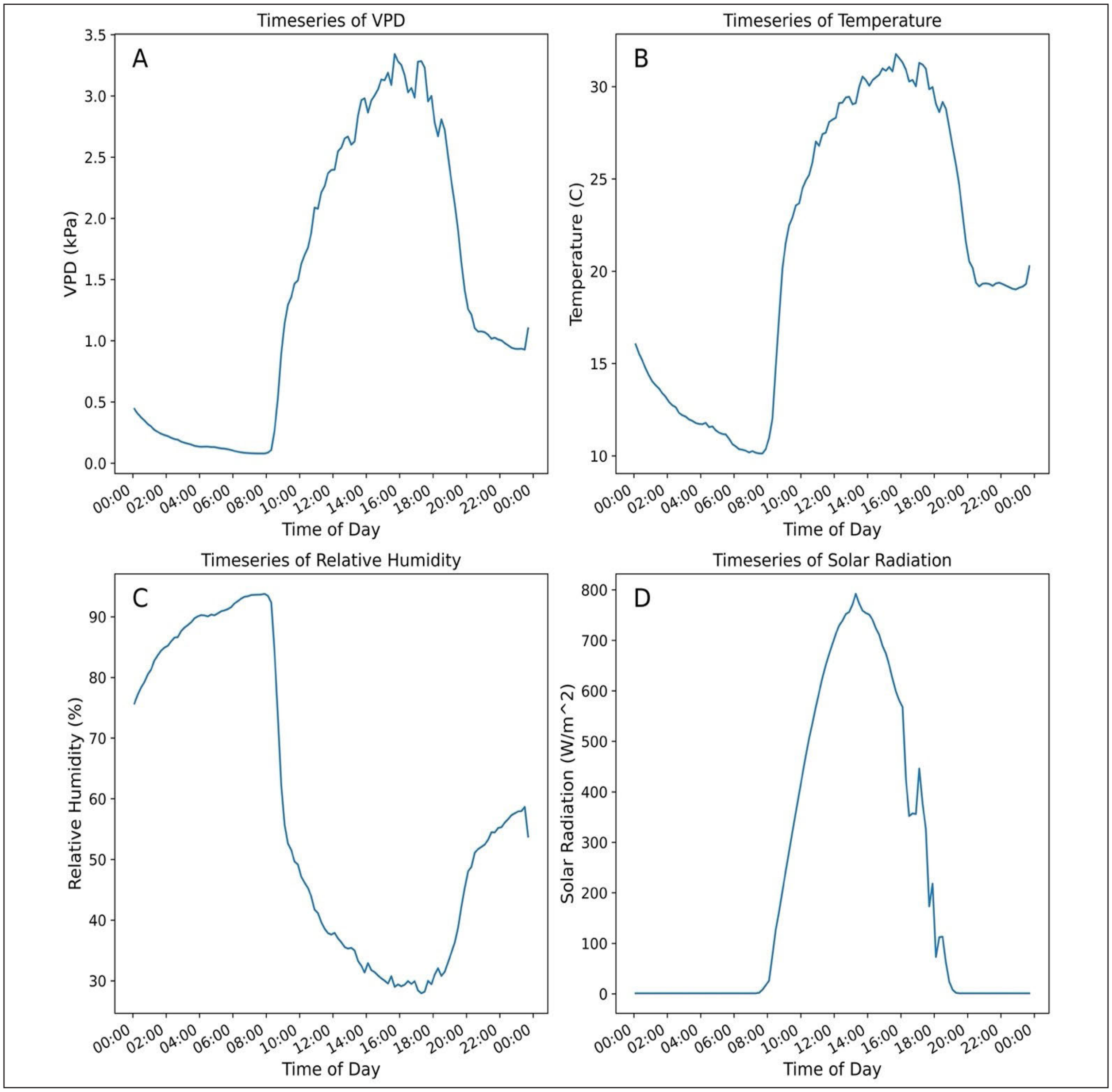

Figure 6. (A) shows the vapor pressure deficit (VPD) timeseries on the first day of sampling at the White Outdoor Learning Center, beginning just after midnight on October 8, 2022, and ending just before midnight on October 9, 2022. (B) shows the temperature timeseries; (C) shows the relative humidity timeseries; and (D) shows the short-wave solar radiation (SR) timeseries, all for the same time span. VPD is given in kilopascals (kPa), temperature is given in Celsius, and SR is given in Watts per square meter (W/m^2).

likely the most controlling factor of tree hydration. At South Onion Creek, there were only 2.96 inches of rain over 29 days, with only 1.05 inches falling in the week before the second sampling day. This was likely sufficient to temporarily elevate shallow soil moisture, which the pecan trees were able to utilize. At Waller Creek, however, the reservoir of near-surface moisture, and specifically bank storage, was likely of a different nature, given the lack of response to the rainfall event. In stream reaches both up- and downstream of the studied reach along UT's campus, Waller Creek is functionally an intermittent stream and only flows seasonally in response to large rain events, similarly to Onion Creek. Along UT's campus, however, continuous baseflow is supported by urban leakage from pipes carrying wastewater or treated municipal water, irrigation return flows, and runoff from storm sewer systems (Christian et al., 2011). A case study within the same Waller Creek sampling reach found

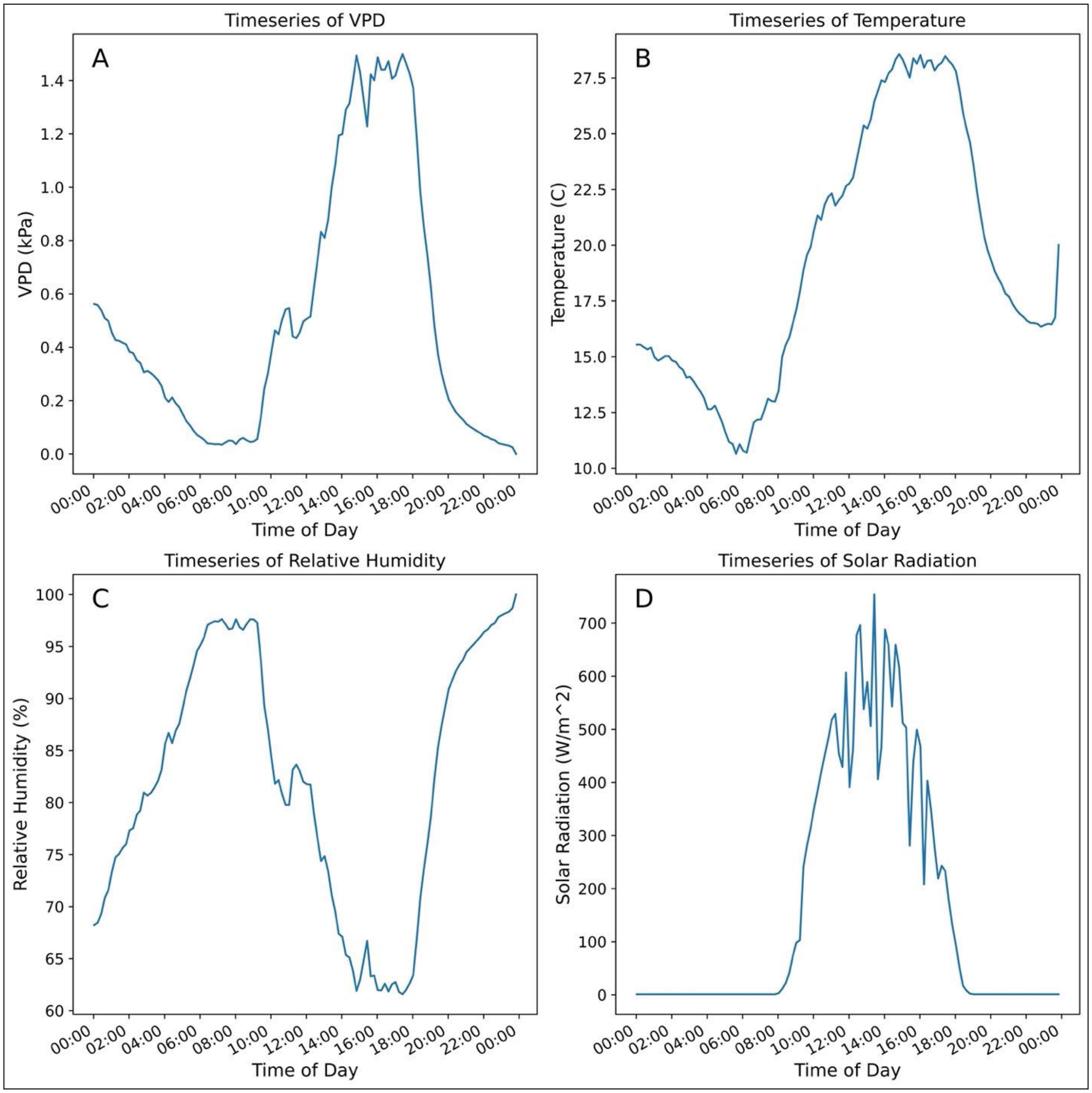

Figure 7. (A) shows the vapor pressure deficit (VPD) timeseries on the second day of sampling at the White Outdoor Learning Center, beginning just after midnight on November 6, 2022, and ending just before midnight on November 7, 2022. (B) shows the temperature timeseries; (C) shows the relative humidity timeseries; and (D) shows the short-wave solar radiation (SR) timeseries, all for the same time span. VPD is given in kilopascals (kPa), temperature is given in Celsius, and SR is given in Watts per square meter (W/m^2).

that, monthly, these sources can account for up to 100% of total recharge (Passarello et al., 2012). Although soil moisture was not measured, we used predawn water potentials as a proxy for root-zone soil hydration. Many studies use predawn LWP as a proxy for soil water potential, under the assumption that plant and soil water potentials equilibrate overnight (Thomsen et al., 2013; Martínez-Vilalta et al., 2014). Less negative soil water potentials (i.e., less negative LWP) suggest greater saturation at the root-soil interface, supporting the idea that soil moisture is higher at the Waller Creek site than at the South Onion Creek site (Figures 1 and 3).

Site-specific differences in soil and maximum tree hydration states are strongly reflected by predawn LWP measured before the onset of transpiration at sunrise. At South Onion

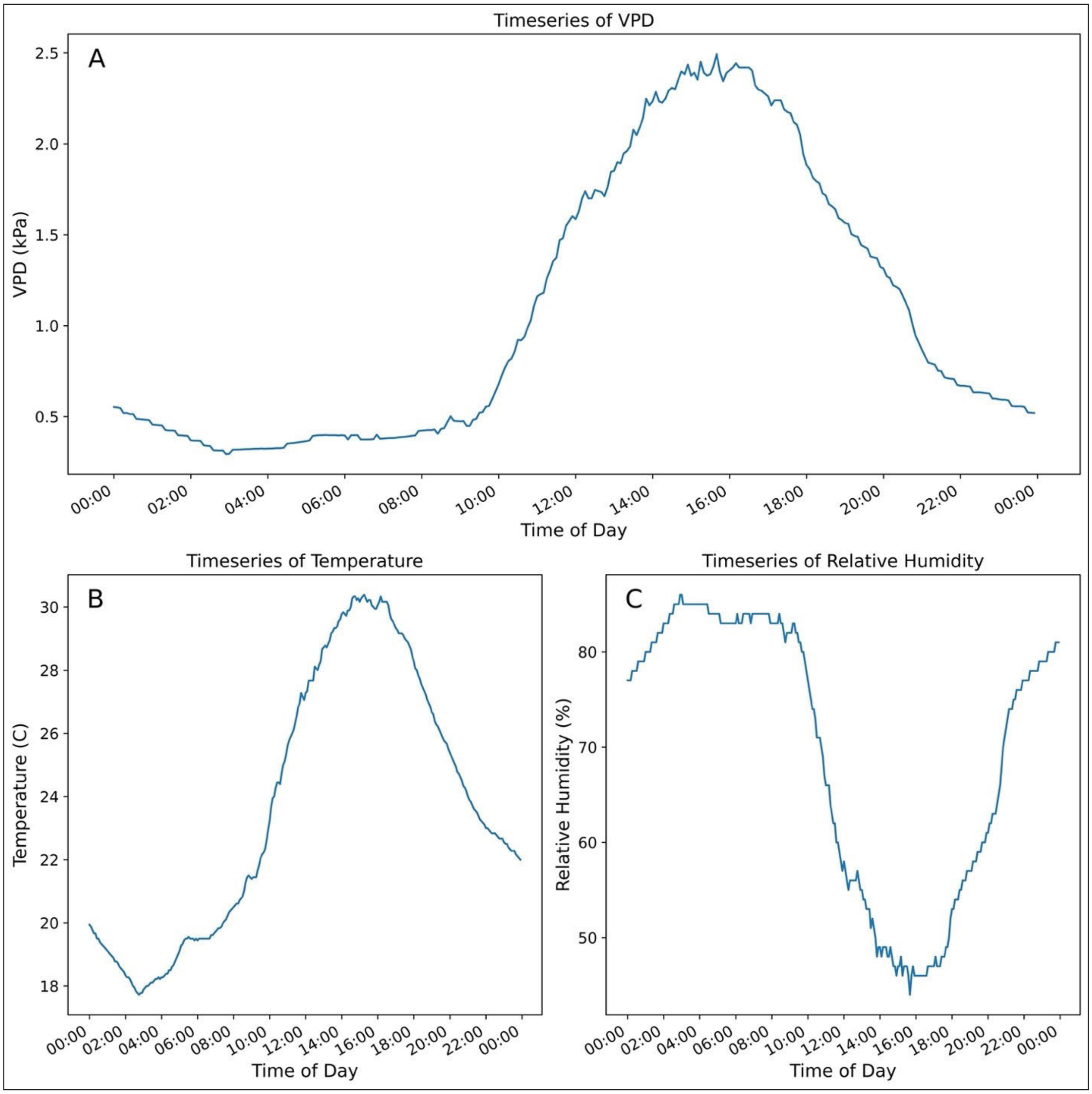

Figure 8. (A) shows the vapor pressure deficit (VPD) timeseries on the first day of sampling at Waller Creek, beginning just after midnight on October 22, 2022, and ending just before midnight on October 23, 2022. (B) shows the temperature timeseries, and (C) shows the relative humidity timeseries, both for the same time span. VPD is given in kilopascals (kPa), and temperature is given in Celsius.

Creek, predawn LWP was more negative on the first sampling day than the second (Figure 1), indicating that the intervening precipitation increased soil water content and overall tree hydration. However, at Waller Creek, predawn LWP were similar on both days of sampling (Figure 2). The consistency and low magnitude of these values reveal that tree hydration was steady and high on both days, regardless of precipitation. This difference demonstrates that the trees at South Onion Creek were more stressed than those at Waller Creek before transpiration began and suggests that soil water supply limitations are governing the dynamics of trees at Onion Creek, but those at Waller Creek are more governed by atmospheric water demand (i.e., VPD).

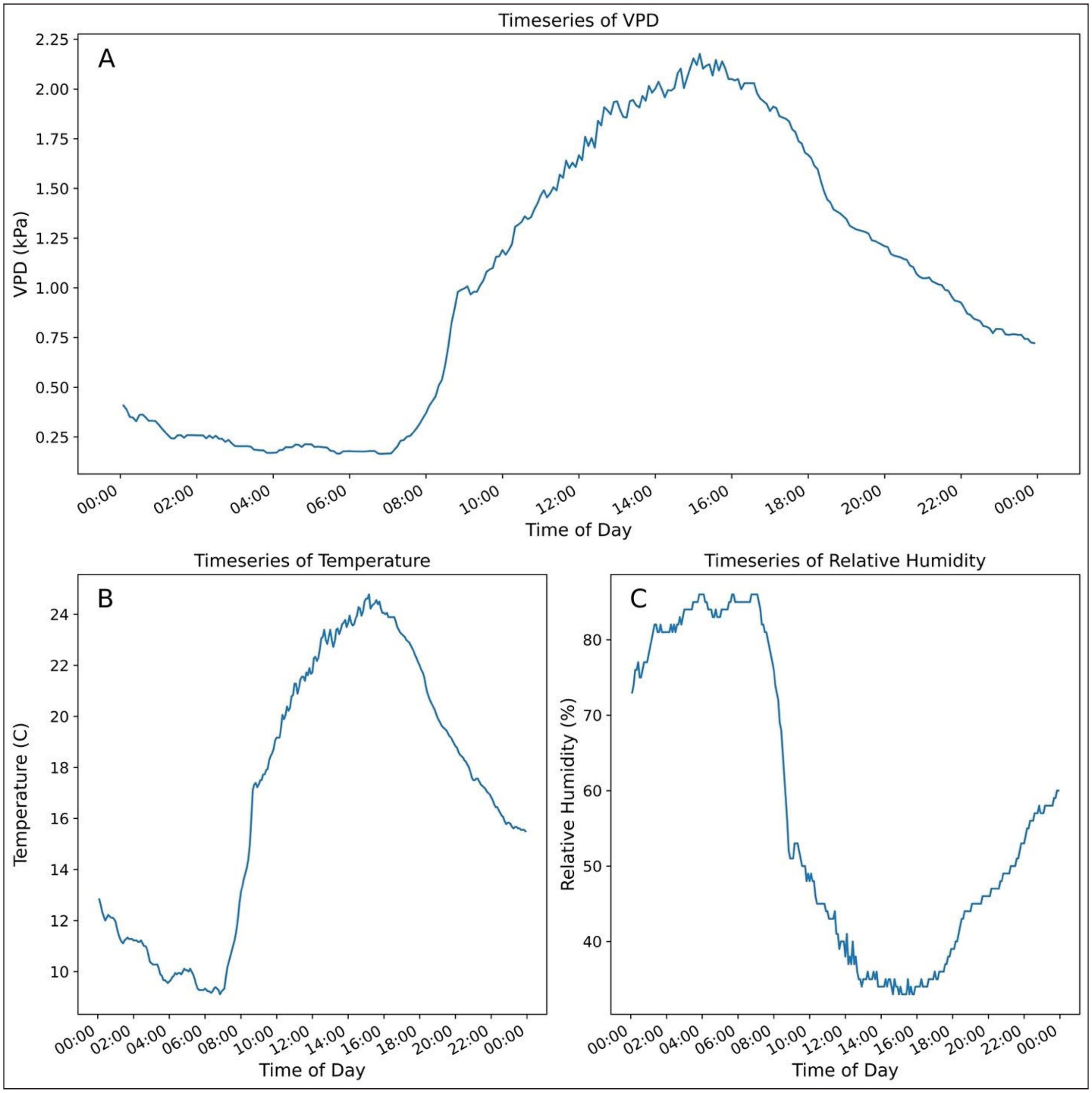

Figure 9. (A) shows the vapor pressure deficit (VPD) timeseries on the first day of sampling at Waller Creek, beginning just after midnight on October 26, 2022, and ending just before midnight on October 27, 2022. (B) shows the temperature timeseries, and (C) shows the relative humidity timeseries, both for the same time span. VPD is given in kilopascals (kPa), and temperature is given in Celsius.

CONCLUSIONS

This study revealed differences in the hydration state of riparian soils and pecan trees in urban (Waller Creek) and rural (South Onion Creek) settings, as well as a pronounced difference in tree response to water supply (soil water availability) and atmospheric demand (VPD) between sites. We attribute these differences in hydration primarily to the presence of shallow moisture horizons in the subsurface around Waller Creek as a result of the consistent baseflow in the stream due to runoff and urban leakage. Our findings support the hypothesis that trees in the urban setting are less stressed than trees in the rural setting due to having more constant access to water in the form of urban leakage. Therefore, it is possible to maintain healthy riparian ecosystems in the context of urban development. The viability of preserving these ecosystems in a warming climate is further emphasized by the fact that these results were obtained at a time when both urban and rural riparian settings were experiencing severe drought.

Although there were no substantial differences in meteorological conditions between the two settings brought on by the urban heat island effect, strong correlations between meteorological variables and LWP were only observed when soil water availability was non-limiting. Despite similar meteorological conditions between the two sites, hydrologic and soil moisture conditions were very different, given that no flow was ever established at the rural site. This suggests that for pecan trees, LWP is ultimately governed by root-zone water availability, and that indeed there could be situations where there is greater water availability in a rural setting than in an urban setting. Therefore, these results are not applicable to rural or urban stream sites in general. Answering this question more effectively would require greater breadth in the selection of study sites, so that urban and rural endmember sites, as well as sites with intermediate characteristics, are represented. Quantification of soil moisture and other hydrologic conditions would also help to find differences between urban and rural stream sites that may contribute to differences in tree hydration. However, LWP measurement continues to be a useful tool in the evaluation of tree hydration over smaller temporal and spatial scales due to the immediacy of the measurement, especially when coupled with other datasets, and can be used to answer a variety of questions of interest to hydrologists, ecologists, and others concerned with water resource and ecosystem management.

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APPENDIX

Table 1. South Onion Creek Sampling Day 1: October 8, 2022. All leaf water potential (LWP) values are given in negative megapascals (–MPa).

Time	P1 LWP (–MPa)	Time	P2 LWP (–MPa)	Time	P3 LWP (–MPa)
6:09	1.032	6:28	0.821	7:08	1.098
6:14	0.153	6:33	1.54	7:11	0.734
6:18	1.117	6:38	0.862	7:16	1.178
6:22	0.956	6:41	0.358	8:43	1.89
8:08	1.751	8:24	2.012	8:49	1.788
8:14	1.812	8:30	2.145	8:54	2.019
8:19	1.946	8:35	2.217	11:25	1.165
10:44	2.513	11:09	2.501	11:28	1.439
10:50	2.546	11:13	2.293	11:32	1.056
11:00	1.576	11:17	1.923	14:02	1.305
13:24	2.573	13:43	2.189	14:06	0.789
13:29	1.741	13:48	1.052	14:10	0.698
13:38	1.783	13:52	1.201		
		13:57	0.843		

Table 2. South Onion Creek Sampling Day 2: November 6, 2022. All leaf water potential (LWP) values are given in negative megapascals (–MPa).

Time	P1 LWP (–MPa)	Time	P2 LWP (–MPa)	Time	P3 LWP (–MPa)
6:15	0.747	6:25	0.669	6:35	0.593
6:18	0.718	6:28	0.723	6:39	0.709
6:21	0.736	6:31	0.631	6:42	0.654
7:26	0.823	7:37	0.69	7:51	0.787
7:30	0.747	7:40	0.328	7:55	0.632
7:33	0.661	7:43	0.662	7:59	0.812
11:05	1.573	7:47	0.583	11:31	1.824
11:10	1.37	11:18	0.993	11:37	1.796
11:14	1.519	11:22	1.47	11:43	1.904
13:20	1.957	11:26	0.887	13:56	2.075
13:25	1.813	13:35	2.245	14:01	2.098
13:29	1.912	13:40	1.513	14:07	1.976
		13:44	1.195		
		13:50	1.95		

Table 3. Waller Creek Sampling Day 1: October 22, 2022. All leaf water potential (LWP) values are given in negative megapascals (–MPa).

Time	P4 LWP (–MPa)	Time	P5 LWP (–MPa)	Time	P6 LWP (–MPa)
6:03	0.243	6:19	0.238	6:31	0.117
6:07	0.197	6:22	0.224	6:34	0.154
6:10	0.34	6:27	0.237	6:37	0.14
6:12	0.325	8:18	0.2	8:30	0.165
7:56	0.287	8:22	0.237	8:34	0.12
8:06	0.26	8:26	0.291	8:37	0.187
8:08	0.161	11:22	0.894	11:04	0.549
8:10	0.15	11:25	0.917	11:07	0.37
10:52	0.404	13:22	1.586	11:09	0.478
10:56	0.66	13:25	1.659	13:33	1.512
10:58	0.485	13:29	2.19	13:35	0.88
13:08	1.394			13:39	1.676
13:12	1.967			13:43	1.331
13:16	2.412				
13:19	0.411				

Table 4. Waller Creek Sampling Day 2: October 26, 2022. All leaf water potential (LWP) values are given in negative megapascals (–MPa).

Time	P4 LWP (–MPa)	Time	P5 LWP (–MPa)	Time	P6 LWP (–MPa)
6:10	0.184	6:19	0.16	6:25	0.135
6:14	0.165	6:21	0.214	6:27	0.125
6:17	0.14	6:23	0.234	6:30	0.192
7:59	0.135	8:06	0.191	8:12	0.153
8:02	0.123	8:08	0.168	8:14	0.13
8:04	0.146	8:10	0.305	8:16	0.129
11:03	1.573	11:15	0.879	11:26	0.643
11:06	0.63	11:23	0.976	11:30	0.745
11:09	0.574	13:34	1.483	11:32	0.601
11:11	0.33	13:37	2.223	13:42	0.847
13:18	2.24			13:45	0.832
13:21	1.279			13:48	0.887
13:24	1.486				
13:28	0.522				