Leaf hydraulic parameters are more plastic in species that experience a wider range of leaf water potentials

Daniel M. Johnson¹, Z. Carter Berry², Kathryn V. Baker¹, Duncan D. Smith³, Katherine A. McCulloh³, Jean-Christophe Domec⁴,⁵

¹ College of Natural Resources, University of Idaho, Moscow, ID 83844, USA
² Department of Natural Resources and the Environment, University of New Hampshire, Durham, NH 03824, USA
³ Department of Botany, University of Wisconsin-Madison, Madison, WI 53706, USA
⁴ Bordeaux Sciences Agro, UMR INRA-ISPA 1391, 33195, Gradignan, France
⁵ Nicholas School of the Environment, Duke University, Durham, NC 27708, USA

Running title: Anisohydry and leaf hydraulic adjustment

Author for correspondence:
Daniel M. Johnson
College of Natural Resources
University of Idaho
875 Perimeter Drive MS1133
Abstract

1. Many plant species experience large differences in soil moisture availability within a season, potentially leading to a wide range of leaf water potentials ($\Psi_{LEAF}$). In order to decrease the risk of leaf dehydration, among species, there is a continuum ranging from strict control (isohydry) to little control (anisohydry) of minimum $\Psi_{LEAF}$.

2. In central Texas USA, species are exposed to a range of soil moisture from wet springs to hot, dry summers. There are diverging water management strategies among the four dominant woody species in this system; two of these species are more isohydric ($Prosopis$ glandulosa, $Quercus$ fusiformis) while two others are more anisohydric ($Diospyros$ texana, $Juniperus$ ashei).

3. To maintain leaf turgor and photosynthesis during periods of limited soil moisture, anisohydric species may adjust leaf hydraulic parameters more than isohydric species. To test this hypothesis, we quantified iso/anisohydry from three years of $\Psi_{LEAF}$ predawn and midday measurements, and we measured the changes in turgor loss points ($\Psi_{TLP}$), osmotic potential at full hydration ($\Psi_{\pi 100}$), and resistance to leaf hydraulic dysfunction (leaf $P_{50}$) throughout the spring and summer of 2016.

4. $Diospyros$ and $Juniperus$ experienced more negative $\Psi_{LEAF}$ and adjusted $\Psi_{TLP}$ and $\Psi_{x100}$ in response to both drying soils during the summer also in response to rainfall events during September. In contrast, the more isohydric species ($Quercus$ and $Prosopis$) did not appear to adjust $\Psi_{TLP}$ or $\Psi_{x100}$ in response to soil moisture. The more anisohydric species also adjusted leaf $P_{50}$ during periods of reduced soil moisture.
5. Our results suggest that species that experience wider ranges of $\Psi_{\text{LEAF}}$ have a greater ability to alter leaf hydraulic properties. This provides insight on how species with different strategies for water potential regulation may modify properties to mitigate drought effects in the future.

Keywords: drought, embolism, pressure-volume curves, transpiration, turgor, isohydry, Texas, semi-arid

Introduction
To sustain carbon capture via photosynthesis and cell growth, plants must maintain adequate leaf hydraulic function (leaf hydraulic conductance, $K_{\text{LEAF}}$) and leaf cell turgor. If $K_{\text{LEAF}}$ is reduced then the whole-plant hydraulic conductance is impaired (Johnson et al. 2016) and stomata must constrict to prevent plant hydraulic failure and leaf desiccation (e.g., Brodribb & Holbrook 2003; Johnson et al. 2009). Decline in $K_{\text{LEAF}}$ under drought may at least partially be a consequence of the mesophyll cells losing turgor and shrinking, thus mechanically increasing resistance to water flow (Brodribb & Holbrook 2004; Scoffoni et al. 2014). If turgor is lost, stomata can close, plant cell metabolic processes can decline, and, if water potentials are severe enough, cell walls can collapse and cells can undergo plasmolysis and become metabolically inactive (Taiz et al. 2015). Although stomata are the primary regulators of leaf water status, the ability to adjust cell turgor and leaf hydraulic parameters could also ensure that leaves continue to photosynthesize under progressively drier conditions.

While some studies have shown that $K_{\text{LEAF}}$ changes in response to water availability (Brodribb & Holbrook 2003; Johnson et al. 2009), few studies have addressed how changes in the vulnerability of $K_{\text{LEAF}}$ to hydraulic dysfunction may co-occur with shifts in leaf
osmotic/turgor parameters during decreasing soil water availability. Martorell et al. (2015) found leaf resistance to hydraulic dysfunction increased and that leaf turgor loss point ($\Psi_{\text{TLP}}$, leaf water potential at turgor loss) and osmotic potentials became more negative in cultivars of *Vitis vinifera* throughout the summer as water potentials became more negative. Another recent study found strong relationships between $\Psi_{\text{TLP}}$, osmotic potential at full turgor, and degree of iso/anisohydry across multiple species (Meinzer *et al.* 2016) demonstrating the potential influence that these synchronous changes may have during drought periods. A few studies have individually shown changes to leaf osmotic/turgor parameters in response to soil drying. For example, Maréchaux *et al.* (2017) observed seasonal adjustment in $\Psi_{\text{TLP}}$ between wet and dry seasons in tropical lianas and Binks *et al.* (2016) observed leaf-level osmotic adjustments in response to long-term drought treatments. Meinzer *et al.* (2014) observed that an anisohydric species (a species that allows leaf water potential [$\Psi_{\text{LEAF}}$] to decline with declining soil water potential) adjusted its $\Psi_{\text{TLP}}$ and osmotic potential with seasonal drying but that a co-occurring isohydric species (a species that regulates minimum leaf water potential much more strictly through stomatal closure) did not adjust these parameters. Meinzer *et al.* (2014) hypothesized that anisohydric species, in general, have to be able to adjust $\Psi_{\text{TLP}}$ and osmotic potentials to compensate for their relatively limited stomatal control of $\Psi_{\text{LEAF}}$.

Shifts in leaf hydraulic function may be particularly important or adaptive in areas that experience extreme variation in soil moisture conditions. Vegetation in semi-arid regions, such as our study sites in central Texas, USA, is predicted to be severely impacted by major drought events relative to other community types (Ma *et al.* 2015). Plants in semi-arid and arid habitats typically experience large fluctuations in the amount of available moisture over spring and summer (e.g., Bailey 1979). Relatively anisohydric species that inhabit these areas are therefore

This article is protected by copyright. All rights reserved.
likely to experience $\Psi_{\text{LEAF}}$ values that range from near zero to highly negative in the same season, while more isohydric species will avoid highly negative $\Psi_{\text{LEAF}}$ due to stomatal closure during drier periods. One strategy for more anisohydric plants to maintain turgor under drying soils would be to have highly negative osmotic potentials and turgor loss points, but this would require investment in high concentrations of compatible solutes. Similarly, making $K_{\text{LEAF}}$ resistant to hydraulic dysfunction would require investment in xylem with thick cell walls and/or small diameter lumens (Blackman et al. 2010; Domec et al. 2016), where thicker cell walls require greater carbon investment and smaller diameter lumens are less conductive than wider ones (Sperry et al. 2006). Additionally, making $K_{\text{LEAF}}$ resistant to hydraulic dysfunction would require changes in the water pathway outside the vein xylem (Scoffoni et al. 2014, 2017) and may include changes in membrane properties and/or aquaporin activity.

This study examined how $K_{\text{LEAF}}$ and leaf osmotic and turgor loss parameters varied throughout the spring and summer in a semi-arid woodlands ecosystem of central Texas, USA. Four species were selected that comprise approximately 94% of the vegetation cover (Moore et al. 2016, Schawantes et al. 2017, Johnson et al. in press) and are known to have contrasting stomatal strategies along the anisohydric/isohydric spectrum. For example, different predawn minimum water potentials have been observed in several of the common species of this region during dry parts of the summer (Kukowski et al. 2013). We used the hydroscape framework of Meinzer et al. (2016) for determination of a species' degree of iso/anisohydry. We hypothesized that as soils dry over the course of the summer 1) species with larger hydroscape areas (i.e., more anisohydric) would exhibit large shifts in leaf turgor loss and osmotic potentials relative to species with smaller hydroscape areas (i.e., more isohydric); and 2) species with larger hydroscape areas would adjust their resistance to leaf hydraulic dysfunction.
Methods

The study site was located in the Edwards Plateau region (west-central Texas) in Colorado Bend State Park near Bend, TX (31.0451° N, 98.4762° W). This site has karst topography with shallow soils (typically less than 20 cm) with underlying fractured limestone (see Auken et al. 1980; Brown et al. 2011 for more detailed site descriptions). The area is considered semi-arid (based on the methods of Zomer et al. 2007, 2008) and has a mean annual temperature of 19.5 °C and a mean annual precipitation of 702 mm, which is unevenly distributed in many years with the majority occurring in the spring, fall, and winter months (see Johnson et al. 2014 for example). The ecosystem is characterized by open savanna-like woodlands, and the dominant woody species are Diospyros texana Scheele, Juniperus ashei J. Buchholz, Prosopis glandulosa Torr., and Quercus fusiformis Small.

This study was conducted from April through September of 2016. Ten individuals of Diospyros texana, Juniperus ashei, Prosopis glandulosa, and Quercus fusiformis were identified and tagged. These individuals were used for all physiological measurements with each set of measurements (e.g., water potential measurements) being performed on randomly selected individuals within the ten selected trees. All measurements were made on fully expanded leaves. Meteorological data were obtained from a NOAA National Climatic Data Center station in Lampasas TX (31.106° N, 98.196° W; Fig. S1).

Water potential measurements

Leaf water potential measurements were performed at predawn (5:00 - 6:00 local time) and mid-afternoon (ca. 15:00 local time) on fully sun-exposed south-facing shoots on May 13th,
May 14th, June 18th, June 19th, July 23rd, July 24th, and September 24th, 2016. Leaf water potential ($\Psi_{\text{LEAF}}$) was measured using a pressure chamber (PMS Instruments, Albany, OR, USA) on three to four individuals per species. Additionally, we had previously measured predawn and midday water potentials in the same species as part of field campaigns in 2013 and 2015, and those measurements were included in the hydroscap area calculations. About half of the water potential measurements from 2013 came from a nearby field site (Powell’s cave site near Menard, TX, 30.918° N, 99.787° W, see Jackson et al. 1999; McElrone et al. 2004). The other 2013 measurements and all 2015 measurements came from the same field site as used in 2016 (Colorado Bend site). Water potentials were averaged within month and site.

*Leaf hydraulic conductance and pressure-volume curves*

For constructing leaf hydraulic conductance ($K_{\text{LEAF}}$) and pressure-volume (P-V) curves, six branch samples (one per tree from six trees) were collected prior to dawn for each species on monthly sampling dates (May 14th, June 19th, July 24th and September 24th 2016). Branch samples of approximately 30 cm were clipped and immediately placed in plastic bags with wet paper towels and put into a cooler. Pressure-volume curves and leaf hydraulic conductance were measured on these samples either the same day or shipped overnight to the lab where measurements began the following day. $K_{\text{LEAF}}$ (mmol m$^{-2}$ s$^{-1}$ MPa$^{-1}$) was determined using a timed rehydration method described in Brodribb and Holbrook (2003), which is based on an analogy between rehydrating a leaf and discharging a capacitor:

$$K_{\text{LEAF}} = C_{\text{leaf}} \ln(\Psi_o / \Psi_f)/t$$

(Eq. 1)
where $C_{\text{leaf}}$ = capacitance (mmol m$^{-2}$ MPa$^{-1}$), $\Psi_o$ = leaf water potential prior to partial rehydration (MPa), $\Psi_f$ = leaf water potential after partial rehydration, and $t$ = duration of rehydration (s). For measurement of $K_{\text{LEAF}}$, sampled branches were rehydrated with distilled water until $\Psi_{\text{LEAF}}$ was close to -0.5 MPa (~ 1 hour) and/or placed on the lab bench to dry for different amounts of time to reach a range of leaf water potentials. Branches were then bagged, placed in the dark, and allowed to equilibrate for at least 2 hours. Leaves ($\textit{Prosopis}$ and $\textit{Quercus}$) or shoot tips (~3 cm in length; $\textit{Diospyros}$ and $\textit{Juniperus}$) were then excised for determination of $\Psi_o$. Leaves or shoot tips from the same branch were rehydrated for a period of $t$ (ranging from 10 to 60 seconds), and $\Psi_f$ was measured. Leaf water potential was measured using a pressure chamber. Leaf $P_{50}$ was determined as the water potential corresponding to 50% of maximum leaf hydraulic conductance (see Statistical analyses). $K_{\text{LEAF}}$ curves were constructed using 25-98 leaves per species for each month (see Fig. S3) and maximum $K_{\text{LEAF}}$ was determined by calculating a mean of the five largest $K_{\text{LEAF}}$ values for each month and species.

Five to six leaves of each species were used to construct pressure-volume curves. Pressure–volume curve measurements were conducted on individual leaves or shoot tips, as above. To prevent artifacts, samples were not rehydrated (see Meinzer et al. 1988, 2014). The curves were created by plotting the inverse of $\Psi_{\text{LEAF}}$ against relative water content (RWC, %), obtained from repeated determinations of fresh mass and $\Psi_{\text{LEAF}}$ during slow dehydration of the shoot tip or leaf on the laboratory bench until values of $\Psi_{\text{LEAF}}$ neared -4.0 MPa. For normalizing $C$ on a leaf area basis, leaf areas for all species except $\textit{Juniperus}$ were obtained by scanning and measuring one-sided leaf area in ImageJ (Schindelin et al. 2015). For $\textit{Juniperus}$, leaf area was calculated as the surface area of a network composed of cylindrical segments, which was obtained by multiplying silhouette area (also from ImageJ) by $\pi$. 

This article is protected by copyright. All rights reserved.
Leaf capacitance (mmol m\(^{-2}\) MPa\(^{-1}\)), osmotic potential at full turgor (\(\Psi_{t100}\), MPa), and water potential at leaf turgor loss point (\(\Psi_{TLP}\), MPa) were estimated from pressure-volume curves (Scholander et al. 1965; Tyree & Hammel 1972). The \(\Psi_{LEAF}\) corresponding to turgor loss was estimated as the point where the plot of \(1/\Psi_{LEAF}\) vs RWC becomes linear. The slope of the quasi-linear relationship prior to, and following turgor-loss provided \(C_{leaf}\) in terms of RWC (\(C_{rwc}\)) for pre-turgor loss and post-turgor loss respectively. The osmotic potential at full turgor was taken as the y-intercept of a line fitted to the post-turgor loss data for a plot of \(1/\Psi_{LEAF}\) versus 100-RWC.

The bulk tissue modulus of elasticity (\(\varepsilon\), MPa) was estimated as the slope of the relationship between turgor pressure (the difference between the osmotic potential line fitted to the post-turgor loss data as above and the water potential curve) and RWC (as in Meinzer et al. 2014).

Leaf mass per area (LMA, g m\(^{-2}\)) was calculated as:

\[ LMA = \frac{DM}{LA} \]  
(Eq. 2)

where DM is the leaf dry mass and LA is the leaf area.

Hydroscape areas capture the predawn to midday \(\Delta \Psi_{LEAF}\) integrated across the range of soil moisture favorable for photosynthesis. Hydroscape areas were determined in a similar fashion to Meinzer et al. (2016) with the exception that we defined the lower boundary as the convex hull containing observed mean water potentials rather than as the linear regression through these water potentials (see Fig. 1). Furthermore, the boundaries of the hydroscape were not extrapolated to predawn water potentials of zero nor to water potentials where predawn \(\Psi_{LEAF}\) equals midday \(\Psi_{LEAF}\) (i.e., intersection with the 1:1 line). These differences were because we were not able to observe the current study species at predawn \(\Psi_{LEAF} = 0\) or at predawn \(\Psi_{LEAF} = \text{midday } \Psi_{LEAF}\). We considered this a conservative estimate of the hydroscape area.
**Statistical analyses**

For between-species and between-sampling date comparisons of physiological parameters, ANOVAs with post hoc Holm-Sidak comparisons were performed. ANOVA and post-hoc tests were performed using Sigmaplot 12.5 (Systat Software Inc., San Jose, CA, USA). Sigmoid models of the form: \( y = y_0 + \frac{a}{1 + e^{-\frac{x-x_0}{b}}} \) were fit to the \( K_{\text{LEAF}} \) data, and maximum \( K_{\text{LEAF}} \) was determined by averaging the five highest \( K_{\text{LEAF}} \) values per time period and species. Leaf resistance to leaf hydraulic dysfunction values (\( P_{50} \)) were considered significantly different if their 95% confidence intervals (confidence intervals from sigmoidal curve fits) did not overlap.

**Results**

*Juniperus* and *Diospyros* had much greater hydroscap areas (12.2 and 11.6 MPa\(^2\), respectively) than either *Prosopis* or *Quercus* (4.9 and 3.0 MPa\(^2\), respectively; Fig. 1). *Juniperus* and *Diospyros* experienced predawn and midday \( \Psi_{\text{LEAF}} \) that were 1 to 2.5 MPa more negative than *Quercus* and *Prosopis* (Fig. 1, S2; \( p < 0.001 \)). Turgor loss points were more negative in July in *Diospyros* and *Juniperus* than in *Quercus* and *Prosopis* (Fig. 3a, all \( p \) values < 0.05). Turgor loss points in *Diospyros* and *Juniperus* increased by 1.4-1.5 MPa between July and September (\( p < 0.001 \) for both comparisons). In July, osmotic potentials at full turgor were significantly more negative in *Diospyros* than in either *Prosopis* (Fig. 3b; \( p < 0.001 \)) or *Quercus* (\( p = 0.007 \)). Osmotic potential at full turgor increased by 1.1 MPa in both *Diospyros* and *Juniperus* between July and September (\( p < 0.001 \) for both comparisons). In contrast to the patterns observed in *Diospyros* and *Juniperus*, \( \Psi_{\text{TLP}} \) and \( \Psi_{\text{\pi}100} \) decreased linearly in *Prosopis* and *Quercus* between May and September. However, this decrease in \( \Psi_{\text{\pi}100} \) was only significant for *Quercus* (May vs. September comparison \( p = 0.023 \)) but the decrease in \( \Psi_{\text{TLP}} \) was significant in both *Prosopis* and *Quercus*.
Quercus (p = 0.005 and 0.028, respectively). There were no significant changes in ε over the measurement period for Quercus and Juniperus (p = 0.945 and 0.944, respectively), but ε significantly decreased in Prosopis (p = 0.018) and increased in Diospyros (p = 0.004) between May and September (Fig. 4a). There were no differences in leaf mass per area (LMA) between species in May but by July LMA was 1.6-1.9x greater in Diospyros than the other species (p < 0.001 for all comparisons; Fig. 4b). At the end of the study (September) there were no significant differences in LMA between species.

Maximum $K_{\text{LEAF}}$ was highly variable in Quercus, ranging from 35.5 mmol m^{-2} s^{-1} MPa^{-1} in May to 11.3 mmol m^{-2} s^{-1} MPa^{-1} in September (Fig. 5, p < 0.001). The variation in maximum $K_{\text{LEAF}}$ across the measurement period was less pronounced in the other species; however, there were still differences across the measurement periods. In both Juniperus and Prosopis, $K_{\text{LEAF}}$ was greater in May than in any other months (p from <0.001 – 0.007); and in Diospyros, $K_{\text{LEAF}}$ was lowest in September compared to other months (p < 0.001). Different species also had different trends in leaf P_{50} values measured across the season. In both Juniperus and Quercus, P_{50} was more negative in July than in the other months (except in Quercus, September was not significantly different from July). Diospyros’ P_{50} declined from -1.5 MPa in May to -2.8 MPa in June, to -3.6 MPa in July and then increased to -2.5 MPa in September. In Prosopis, there were no significant changes in P_{50} across the measurement period. All species were predicted to lose near 100% of $K_{\text{LEAF}}$ in the driest part of the season except Quercus which was predicted to lose 57%.

All species had predawn leaf water potentials that were less negative than their $\Psi_{\text{TLP}}$ (Fig. 6; except Juniperus in July). However, only Quercus maintained midday $\Psi_{\text{LEAF}}$ less negative or the same as leaf $\Psi_{\text{TLP}}$. All other species experienced midday $\Psi_{\text{LEAF}}$ that was more negative than

This article is protected by copyright. All rights reserved.
Ψ_{TLP}, especially in July. *Diospyros* had the greatest seasonal range in Ψ_{TLP} (1.8 MPa), Ψ_{π100} (1.8 MPa), and leaf P_{50} (2.1 MPa; Fig. 7). *Juniperus* also had large seasonal ranges in Ψ_{TLP} (1.5 MPa) and Ψ_{π100} (1.1 MPa), but less range in leaf P_{50} (0.75 MPa). *Quercus* and *Prosopis* had less variability in leaf hydraulic properties than the other two species; seasonal range in Ψ_{TLP}, Ψ_{π100}, and leaf P_{50} varied by 0.5 – 1.0 MPa across the season in *Quercus* and *Prosopis*.

There were strong correlations between leaf hydraulic parameters when all data were combined (Fig. 8). The positive relationship between Ψ_{TLP} and Ψ_{π100} was particularly strong (r^2 = 0.85), as was the negative relationship between P_{50} and LMA (r^2 = 0.58). Somewhat less strong, but still significant were correlations between LMA and Ψ_{π100} (r^2 = 0.39), LMA and Ψ_{TLP} (r^2 = 0.50), P_{50} and Ψ_{π100} (r^2 = 0.45), and P_{50} and Ψ_{TLP} (r^2 = 0.46).

**Discussion**

This study tested whether strategies for regulating water balance (anisohydry/isohydry) were related to seasonal shifts of leaf pressure-volume parameters and leaf vulnerability to hydraulic dysfunction within a semi-arid central Texas ecosystem. To our knowledge, this is the first study demonstrating unique shifts in leaf biophysical and hydraulic parameters across a summer and across the dominant woody species of an ecosystem. The observed patterns in Ψ_{LEAF}, Ψ_{TLP}, and Ψ_{π100} supported our first hypothesis. Species that were more anisohydric (larger hydroscape areas) had the most plasticity in leaf pressure-volume parameters. We also found evidence that supported our second hypothesis because the species that experienced the widest range of Ψ_{LEAF} altered significantly their resistance to leaf hydraulic dysfunction during the driest part of the summer.
Due to extreme variability in rainfall in arid and semi-arid habitats, these species must produce tissue that can respond to wide ranges of $\psi_{\text{LEAF}}$. New leaf tissue is typically produced in spring when moisture is abundant. But in many semi-arid habitats, such as the one in the current study, hot, dry summers resulting in depletion of soil moisture often occur even during years not considered “drought years” (e.g., Kukowski et al. 2013). Plants have evolved different strategies for dealing with this range of soil moistures. For example, plants exist along a continuum of stomatal regulation of leaf water status: some plants close stomata at set $\psi_{\text{LEAF}}$ values, while others allow their $\psi_{\text{LEAF}}$ to decrease with declining soil moisture (Tardieu & Simmoneau 1998; Martinez-Vilalta et al. 2014; Meinzer et al. 2014, 2016). In central Texas, Juniperus and Prosopis have more anisohydric characteristics and thus, larger hydroscapes, while Diospyros and Quercus are more isohydric (Fig. 1). During dry periods, more isohydric plants risk carbon imbalances due to lack of photosynthesis, while anisohydric plants risk hydraulic dysfunction (McDowell et al. 2011; Sevanto et al. 2014)

Although stomatal closure to maintain leaf water potentials has large and obvious impacts on leaf physiological processes, changes in leaf biophysical properties can also allow for maintenance of physiological functioning during soil moisture depletion. In particular, more negative $\psi_{\text{TLP}}$ and $\psi_{\text{v100}}$ and greater $\epsilon$ can maintain leaf physiology by maintaining protoplast volume and turgor as $\psi_{\text{LEAF}}$ become more negative (Kaiser 1982; Marshall & Dumbroff 1999; Saito & Terashima 2004), thus extending photosynthesis with drying soils. We hypothesized that species with larger hydroscapes would be able to be more plastic and adjust leaf biophysical properties more readily than species with smaller hydroscapes. The data presented here support observations in the Pinus edulis/Juniperus monosperma woodlands of New Mexico USA. There, the more anisohydric $J. \text{monosperma}$ had more negative $\psi_{\text{TLP}}$ with decreasing water availability,
but $\Psi_{TLP}$ in the more isohydric *P. edulis* did not change (Meinzer *et al.* 2014). Additionally, in *Larrea tridentata*, a strongly anisohydric desert shrub, $\Psi_{TLP}$ was observed to change by as much as 2 MPa over short time periods (Meinzer *et al.* 1998). Another recent study found that a more anisohydric species (*Acacia aptaneura*) adjusted $\Psi_{TLP}$ during drought cycles but a more isohydric species (*Eucalyptus camaldulensis*) did not (Nolan *et al.* 2017). In the current study, the more anisohydric *Diospyros* and *Juniperus* experienced the most negative $\Psi_{LEAF}$ (and the widest range of $\Psi_{LEAF}$) and had more negative $\Psi_{TLP}$ and $\Psi_{\pi100}$ values than *Quercus* and *Prosopis*, which experienced much smaller ranges and less negative $\Psi_{LEAF}$. Additionally, LMA in *Diospyros* increased nearly three-fold from May to July and then decreased by the same amount by September. This threefold increase and decrease in LMA is typically observed between leaf-out in the spring, midsummer and fall senescence (Reich *et al.* 1991) but in the current study all leaves were fully hardened in May and were not senescent in September. Meinzer *et al.* (2014) hypothesized that anisohydric species, in general, may have a greater capacity to alter leaf biophysical properties than more isohydric species, and our data support this hypothesis. In the anisohydric species in this study, we observed decreases in $\Psi_{TLP}$ and $\Psi_{\pi100}$ during the driest parts of the summer and increases after soil moisture increased due to rainfall. Further, Meinzer *et al.* (2016) also demonstrated that $\Psi_{TLP}$ and $\Psi_{\pi100}$ were strongly correlated with a species’ degree of isohydry and suggested that these parameters could be used as proxies for a species’ location along the isohydry/anisohydry continuum. Our results support this idea, as *Juniperus* and *Diospyros* had both the most negative $\Psi_{LEAF}$ and the greatest adjustment in $\Psi_{TLP}$ with drying soils. Although, our results also highlight the importance of comparing species’ relative degree of isohydry during periods of seasonal minimum soil water status.
Surprisingly, all species in the current study except *Quercus* experienced afternoon \( \Psi_{\text{LEAF}} \) values that were more negative than their \( \Psi_{\text{TLP}} \). In fact, recent studies have suggested that \( \Psi_{\text{LEAF}} \) less negative than those associated with turgor loss should result in stomatal closure and loss of leaf hydraulic conductance, thus preventing the loss of turgor (Bartlett *et al.* 2016; Scoffoni & Sack 2017). One likely effect of turgor loss would be for mesophyll cells to shrink and become photosynthetically inactive or inhibited in the afternoon. Reductions in turgor are also likely to be at least partially responsible for the observed decline in photosynthesis with \( \Psi_{\text{LEAF}} \) that occurs independent of stomatal closure (Tezara *et al.* 1999; Lawlor & Tezara 2009). Overall, evidence that plants may often surpass \( \Psi_{\text{TLP}} \) suggests that a reevaluation of the physiological significance of this parameter is needed.

In addition to changes in leaf biophysical properties, we also hypothesized that more anisohydric species would exhibit changes in their resistance to hydraulic dysfunction. Although seasonal changes in maximum leaf hydraulic conductance have been observed (Brodribb & Holbrook, 2003; Lo Gollo *et al.* 2005), measurements of seasonal changes in resistance to leaf hydraulic dysfunction are rare in the literature. In a recent study, Martorell *et al.* (2015) observed more negative leaf P\(_{50}\) (along with more negative \( \Psi_{\text{TLP}} \) and \( \Psi_{\pi100} \)) in *Vitis* subjected to decreasing water potentials. In the current study, *Diospyros* and *Juniperus* had more negative leaf P\(_{50}\) during July than either June or September. Leaf P\(_{50}\) in *Quercus* did decline seasonally, but it appeared to be a nearly linear decline and not a response to reduced soil moisture availability in July.

Interestingly, seasonal changes in \( \Psi_{\text{TLP}} \) and \( \Psi_{\pi100} \) in *Quercus* (as well as *Prosopis*) were very similar in shape to their seasonal changes in leaf P\(_{50}\). Due to leaf xylem development occurring early in the year, these changes in leaf P\(_{50}\) were likely due to changes in the water pathways outside the leaf xylem (Buckley 2015; Scoffoni 2015). The negative relationship between leaf
P_{50} and LMA (Fig. 8) supports this idea because increased LMA after leaves have hardened must come from additional chemical inputs to mesophyll tissue since veins have already formed. However, there could also be cellular changes in the mesophyll (e.g., alteration of cell walls) that could result in this relationship but were not accounted for here.

In the current study, the more anisohydric species (larger hydroscapce areas) altered leaf \( \Psi_{TLP} \), \( \Psi_{a100} \), and resistance to leaf hydraulic dysfunction with declining leaf water potentials, whereas the more isohydric species did not. One exception was in Quercus where July leaf P_{50} was significantly more negative than in May. Decline of \( K_{\text{LEAF}} \) with declining \( \Psi_{\text{LEAF}} \) may be the consequence of leaf vein xylem embolism (Nardini et al. 2001, 2003; Johnson et al. 2012, Brodribb et al. 2016) but also bundle sheath and mesophyll cells losing turgor and shrinking, thus mechanically increasing resistance to water flow (Brodribb & Holbrook 2004; Scoffoni et al. 2017). The concept of a turgor-limited passage through the bundle sheath and mesophyll is supported by the correlations between the point of turgor loss and \( K_{\text{LEAF}} \) (Brodribb & Holbrook 2003; Woodruff et al. 2007; Domec et al. 2009, 2016). These leaf-level adjustments have significant implications for ecosystems with increasing exposure to frequent and severe droughts. At present, it is unclear how common these leaf-level adjustments are in habitats with limited soil moisture or during droughts. As more severe droughts become an ever-present reality for many ecosystems, studies need to further consider species-specific abilities to modify physiology. Plant responses to soil drying are complex and require an integrated understanding of seasonal variation in hydraulic functioning. A better understanding of the plasticity of leaf hydraulic parameters during periods of limited soil moisture availability will lead to better predictions of tree physiological processes under scenarios of increasing drought severity and frequency.
Authors’ Contributions

DMJ, ZCB, DDS, KAM and JCD designed the study. DMJ, ZCB, DDS, KAM, KVB and JCD performed the data collection and analysis. DMJ, ZCB, DDS, KAM, KVB and JCD all participated in writing the manuscript.

Data availability

All data from the study are available in the Dryad Digital Repository (https://doi.org/10.5061/dryad.vb188, Johnson et al. 2018).

Acknowledgements

This work was funded by NSF-IOS1549971 and USDA-AFRI (#2012-00857). DDS and KAM were partially supported through NSF-IOS1146751 and NSF-IOS1557906. We would like to thank the staff at Colorado Bend State Park for their assistance. We also thank Wayne Polley, Philip Fay, Chris Kolodziejczyk, Katherine Jones, Anne Gibson, and Kyle Tiner for assistance in coordination of field campaigns and Erika Berglund for assistance with field data collection. The authors have no conflicts of interest.

References


This article is protected by copyright. All rights reserved.


This article is protected by copyright. All rights reserved.


This article is protected by copyright. All rights reserved.


US Drought Monitor, National Drought Mitigation Center (NDMC), the U.S. Department of Agriculture (USDA) and the National Oceanic and Atmospheric Administration (NOAA).


This article is protected by copyright. All rights reserved.
Figure Legends

Figure 1. Mean midday (MD) versus predawn (PD) leaf water potentials (from 2013 [open symbols], 2015 [grey symbols], and 2016 [black symbols]; see methods for details) and fitted hydroscape boundaries for four dominant woody species of the Texas Edwards Plateau: *Diospyros texana, Juniperus ashei, Prosopis glandulosa* and *Quercus fusiformis*. Numbers in parentheses are calculated hydroscape areas. Error bars are standard errors.

Figure 2 Pressure-volume curve parameters in *Diospyros texana, Juniperus ashei, Prosopis glandulosa* and *Quercus fusiformis*; a) water potential at turgor loss (Turgor Loss Point, $\Psi_{\text{TLP}}$) and b) osmotic potential at full turgor ($\Psi_{\pi100}$). Error bars are standard errors.

Figure 3. a) Pressure-volume curve parameters in *Diospyros texana, Juniperus ashei, Prosopis glandulosa* and *Quercus fusiformis*; a) bulk tissue modulus of elasticity ($\varepsilon$) and b) leaf mass per unit area (LMA). Error bars are standard errors.

Figure 4. Maximum leaf hydraulic conductance (a) and the water potential at which $K_{\text{LEAF}}$ declined by 50% (b, leaf $P_{\text{50}}$) in *Diospyros texana, Juniperus ashei, Prosopis glandulosa* and *Quercus fusiformis*. Error bars in panel a are standard errors and error bars in panel b are 95% confidence intervals.

Figure 5. Mean predawn ($\Psi_{\text{PD}}$) and midday ($\Psi_{\text{MD}}$) leaf water potentials and leaf turgor loss points (TLP) in each species. Error bars are standard errors.

This article is protected by copyright. All rights reserved.
Figure 6. Variation in leaf hydraulic parameters in each species: Maximum observed TLP – Minimum observed TLP (a), Maximum observed $\pi_{100}$ – Minimum observed TLP $\pi_{100}$ (b), and Maximum observed $P_{50}$ – Minimum observed $P_{50}$. All y-axis data were plotted against the seasonal minimum water potential for each species. Error bars are standard errors.

Figure 7. Correlation analysis of all leaf mass per unit area (LMA), bulk tissue modulus of elasticity ($\varepsilon$), osmotic potential at full turgor ($\Psi_{\pi100}$), water potential sat 50\% loss of $K_{\text{LEAF}} (P_{50})$ and water potential at turgor loss ($\Psi_{\text{TLP}}$) data. Symbols for each species are the same as in previous figures. Only significant ($p < 0.05$) relationships are shown with fitted lines.
Fig. 1
Fig. 3

This article is protected by copyright. All rights reserved.
Fig. 4

This article is protected by copyright. All rights reserved.
Fig. 5
Fig. 6

This article is protected by copyright. All rights reserved.
Fig. 7