Allometric relationships between primary size measures and sapwood area for six common tree species in snow-dependent ecosystems in the Southwest United States

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Abstract High-elevation, snow-dependent, semiarid ecosystems across southwestern United States are expected to be vulnerable to climate change, including drought and fire, with implications for various aspects of the water cycle. To that end, much less is known about the dynamics of transpiration, an important component of the water cycle across this region. At the individual-tree scale, transpiration is estimated by scaling mean sap flux density by the hydroactive sapwood area (SA). SA also remains a key factor in effectively scaling individual tree water-use to stand level. SA across large spatial scales is normally established by relating SA of a few trees to primary size measures, e.g., diameter at breast height (DBH), tree height (H), or canopy

diameter (CD). Considering the importance of SA in scaling transpiration, the primary objective of this study was therefore to establish six species-specific (aspen, maple, white fir, ponderosa pine, Douglas fir, Englemann spruce) allometric relationships between SA and three primary size measures (DBH, CD, or H) across two high-elevation, snow-dependent, semiarid ecosystems in New Mexico and Arizona. Based on multiple statistical criteria (coefficient of determination, index of agreement, Nash–Sutcliffe efficiency) and ease of measurement in the forest, we identified DBH as the primary independent variable for estimating SA across all sites. Based on group regression analysis, we found allometric relationships to be significantly ($p < 0.05$) different for the same species (ponderosa pine, Douglas-fir) across different sites. Overall, our allometric relationships provide a valuable database for estimating transpiration at different spatial scales from sap flow data in some of our most vulnerable ecosystems.

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Abbreviations

MAPE	Absolute percentage error
AIC	Akaike information criterion,
R^2	Coefficient of determination
CZO	Critical Zone Observatory
CD (m)	Canopy diameter
DBH (cm)	Diameter at breast height
IOA	Index of agreement
JRB	Jemez River Basin
ZOB	Zero-Order Basin
JRB SE ZOB	Jemez River Basin South-East Zero Order Basin

JRB SW ZOB	Jemez River Basin South-West Zero Order Basin
LiDAR	Light detection and range
MAT (°C)	Mean annual temperature
MAP (mm)	Mean annual precipitation
NSE	Nash–Sutcliffe efficiency
NAM	North American summer monsoon
SA (cm ²)	Sapwood area
SE	Standard error
SEE	Standard error of estimate
<i>H</i> (m)	Tree height
VCNP	Valles Caldera National Preserve

Introduction

High-elevation, snow-dependent, semiarid forest ecosystems across the southwestern United States are vulnerable to climate change (Williams et al. 2010; Allen et al. 2015), with significant implications for the associated coupled human–natural systems (Seager et al. 2007). These include changes in the hydrologic inputs to these ecosystems including alteration in the timing of the peak streamflow runoff and changes in precipitation frequency and magnitude (Barnett et al. 2005). However, by comparison, in part because of the difficulty in obtaining evapotranspiration estimates at the landscape scale across mountainous terrains (Reba et al. 2009), much less is known about the impact of climate change on this important water flux.

Transpiration is the dominant component of evapotranspiration compared to soil evaporation across high elevation ecosystem (Wilson et al. 2001). The water-use of individual trees, referred to as sap flux or sap flux density is commonly measured using sap flow techniques (Granier 1987; Clearwater et al. 1999). Sap flux density is multiplied by the sapwood area (SA) of the cross section of a trunk to obtain tree-level transpiration and multiplied by the sap wood area index (sapwood area/ground area) or by leaf area index (leaf area/ground area) to quantify transpiration per square meter of ground area (Vertessy et al. 1997; Bovard et al. 2005; Herbst et al. 2007; Kumagai et al. 2007; Loranty et al. 2008; Mackay et al. 2010). Scaling of sap flux density to the canopy and landscape level to quantify transpiration is crucial for addressing critical questions not only with regard to impact of climate change but also with regard to “*forest water use and potential water conservation on ecosystem-scale processes*” (Warren et al. 2011).

Therefore, a reliable estimation of SA has remained a key component when quantifying transpiration at various spatial scales (tree, stand) (Wullschleger et al. 2001). SA is quantified by establishing allometric relationships between sapwood depth of a representative subset of trees and more easily measured stand parameters such as diameter at breast

height (DBH) (or other substituting factors) using a representative sample of trees (Vertessy et al. 1995; Cienciala et al. 2000; Roberts et al. 2001; Wullschleger et al. 2001). Allometric relationships can enable the use of measurements from those trees to represent the greater ecosystem.

SA within a tree has been known to vary as a function of species (Kaufmann and Troendle 1981) and site conditions (Xie et al. 2012), even though some researchers have found these relationships to be independent of the aforementioned factors (e.g., Pastor et al. 1984; Bartelink 1996, 1997). Analysis of individual tree water-use across the high elevation ecosystem of the Southwest United States have found pronounced interspecies variability in sap velocity, necessitating the need to establish species-specific allometric relationships for the dominant vegetation across these sites (Small and McConnell 2008; Mitra and Papuga 2012).

To the best of our understanding, data on species-specific allometric relationship of the dominant vegetation across these sites remain scarce (McDowell et al. 2002). DBH remains the main scaling parameter for quantifying SA. We were motivated to analyze whether other independent structural properties such as canopy diameter (CD) or tree height (*H*) can be used to predict SA. These variables have been less frequently used, and we are not aware of any studies that have revealed an allometric relationship between SA and CD (or *H*) for vegetation across Arizona and New Mexico.

These relationships may prove valuable for future research that requires scaling sap flux density to multiple spatial (tree/stand) resolution. The primary objective of this study was therefore to present allometric relationships linking SA to primary size measures (DBH, CD, *H*) of common conifer and deciduous species across the high-elevation system in the Southwest United States.

Materials and methods

Study area

Our study sites are located in the semiarid high elevation mixed-forest ecosystems of southern Arizona and northern New Mexico (Fig. S1). In northern New Mexico, the site is located in the Valles Caldera National Preserve (VCNP), west of Los Alamos, New Mexico. In southern Arizona, the site is located in the Santa Catalina Mountains (SCM) of the Coronado National Forest, northeast of Tucson, Arizona. Our study sites are part of the University of Arizona (UA) Santa Catalina Mountain–Jemez River Basin Critical Zone Observatory (UA SCM-JRB CZO; www.czo.arizona.edu) (Fig. S1).

Mean elevation at VCNP is 2768 m a.s.l. (range 2167–3434 m) and mean slope of the relief is 12.8° (maximum 75.4°) (U.S. Geological Survey 2003; Veatch et al.

Table 1 Mean ($\pm$ SE) of diameter at breast height (DBH), canopy diameter (CD) and tree height (H) of the dominant conifer and deciduous species that were surveyed in New Mexico (NM) and Arizona (AZ), United States

Location	Site	Common name	Species	N	DBH, cm ($\pm$ SE)	CD, cm ($\pm$ SE)	H , cm ($\pm$ SE)
NM	US-Vcm	Engelmann spruce	<i>Picea engelmannii</i>	73	20.7 (1.03)	2.6 (0.1)	11.2 (0.5)
	US-Vcp	Ponderosa pine	<i>Pinus ponderosa</i>	57	34.9 (2.07)	3.7 (0.13)	15.6 (0.33)
	JRB SW ZOB	Douglas-fir	<i>Pseudotsuga menziesii</i>	12	28.79 (1.97)	3.51 (0.30)	NA
		Engelmann spruce	<i>Picea engelmannii</i>	8	35.12 (2.48)	4.76 (0.26)	15.90 (1.15)
	JRB SE ZOB	Douglas-fir	<i>Pseudotsuga menziesii</i>	8	15.06 (3.19)	2.87 (0.39)	NA
		Engelmann spruce	<i>Picea engelmannii</i>	11	32.26 (2.54)	5 (0.28)	15.65 (1.01)
		Quaking aspen	<i>Populus tremuloides</i>	10	47.89 (3.7)	5.98 (0.61)	18.96 (0.99)
AZ	Schist ZOB	Douglas-fir	<i>Pseudotsuga menziesii</i>	10	55.98 (9.978)	NA	NA
		White fir	<i>Abies concolor</i>	13	55.78 (5.6)	5.71 (0.54)	21.66 (4.17)
		Maple	<i>Acer grandidentatum</i>	12	21.94 (1.37)	NA	NA
	Granite ZOB	Douglas-fir	<i>Pseudotsuga menziesii</i>	14	47.47 (6.36)	5.44 (0.59)	22.22 (2.55)
		White fir	<i>Abies concolor</i>	14	31.65 (3.70)	4.64 (0.22)	15.91 (1.42)
	Oracle Ridge ZOB	Ponderosa pine	<i>Pinus ponderosa</i>	20	56.85 (2.40)	NA	NA

NA, insufficient data

2009). The climate is semiarid continental with a mean annual temperature (MAT) between 6 and 10 °C (Table S1). Mean annual precipitation (MAP) is bimodal and is influenced by both the North American summer monsoon (NAM) as well as winter storms that originate from the Pacific Ocean. Approximately 65% of MAP falls in the form of snow between October and April and the remaining 35% as rain between July and September (Molotch et al. 2009).

MAP in the upper elevations of the SCM is $\sim 820 \text{ mm a}^{-1}$ (Brown-Mitic et al. 2007; Table S1). Nearly 25% of that precipitation originates from the NAM, while the remainder falls in the form of snow and rain between December and March (Brown-Mitic et al. 2007). Except during the monsoon season, the SCM remains dry throughout the rest of the year with the average relative humidity typically below 30% (Gochis et al. 2006).

Two sites at VCNP are located within Jemez River watershed and are dominated by Engelmann spruce (*Picea engelmannii*) and ponderosa pine (*Pinus ponderosa*) (Brooks and Vivoni 2008; McDowell et al. 2008). These two sites will henceforth be referred to by their Ameriflux Site Codes as US-Vcm (coordinates: 35.88, -106.54) and US-Vcp (coordinates: 35.86, -106.59) respectively.

The third VCNP site, less than 3.21 km from the MC Tower site and at a similar elevation, is part of the Jemez River Basin High-Elevation Zero Order Basin (JRB ZOB). Vegetation within the JRB ZOB is dominated by mixed conifer and spruce–fir forest, quaking aspen (*Populus tremuloides*) as well as grassland.

Our two high-elevation study sites at SCM are located in Marshall Gulch, a 1.54 km² catchment within the Upper Sabino Canyon watershed (coordinates: 32.43, -110.77) (Lyon and Troch 2010). These two sites, granite zero order

basin (granite ZOB, 5.6 ha) and schist zero-order basin (schist ZOB, 4.9 ha) have similar weather, shape and slope (Table S1). Dominant vegetation within both the catchment include Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), ponderosa pine (*P. ponderosa*) and big-toothed maple (*Acer grandidentatum*) (Jardine 2011).

Our third field site in the SCM is the Oracle Ridge ZOB (coordinates: 32.58, -110.76). The elevation varies between 2000 and 2300 m a.s.l., with the dominant vegetation at this site being ponderosa pine. Descriptive statistics of the dominant vegetation across all the sites that were surveyed to estimate are summarized in Table 1.

Field measurements

A single 30 m $\times$ 30 m plot was established at the JRB SE and JRB SW ZOBs, and a 60 m $\times$ 60 m plot size was established at the schist and granite ZOBs. The difference in plot size was to account for the higher stand density at JRB SE and JRB SW ZOBs and the sparse vegetation at the schist and granite ZOBs. At the US-Vcm and US-Vcp sites, we constructed variable-radius plots (Babst et al. 2014). All trees with DBH greater than 6 cm were surveyed in each plot.

Within each plot, we measured DBH (1.37 m above ground), H and CD of each tree. CD was the average crown spread of the shortest and longest measurement from one edge of the crown to the other. H was measured with an electronic laser range finder (NIKON Forestry Pro Laser Rangefinder/Hypsometer). Within each plot, increment cores were collected at breast height with a 5-mm-diameter borer to estimate sap wood area. Two perpendicular cores were collected to account for eccentricities in growth around the circumference. The portion between the heartwood and bark

was identified to be the sapwood depth. For all the samples, the boundary between heartwood and sapwood was based on the darker color of the heartwood. This visual inspection was consistent with the method established by other researchers (Hatton et al. 1995; Vertessy et al. 1995; McDowell et al. 2008). SA was calculated as the difference between total xylem area and the heartwood area, and wherever two cores were collected, mean of the two radii represents the total SA of the tree.

Allometry

The species-specific allometric relation between SA and the three size measures DBH, CD, or H was modeled using a power law (Causton 1985; Sanaei et al. 2019):

$$A_s = \beta x^\alpha \quad (1)$$

where α is the scaling exponent, β is a normalization constant, x is the primary size measure (DBH, CD, H), and A_s is SA. The natural log (ln) transformation can be expressed in a linear form as follows:

$$\ln A_s = \alpha \ln x + \ln \beta, \quad (2)$$

Equations 1 and 2, mathematically equivalent, are different statistically, thereby necessitating the need to apply a back-correction factor to correct bias in logarithmic regression estimates (Ali et al. 2015; Paul et al. 2016). The back-correction factor (CF) was calculated as follows (Sprugel 1983):

$$CF = \exp\left(\frac{SEE^2}{2}\right). \quad (3)$$

The final equation will have the following form:

$$\ln A_s = CF(\alpha \ln x + \ln \beta \pm \epsilon). \quad (4)$$

We used a group regression procedure to determine whether model deviance changed significantly when we generalized the regression coefficients (α and β) for the same vegetation across different sites.

Statistical summary includes errors (SE) and standard error of estimates (SEE). The primary model selection criteria was coefficient of determination (R^2). However, to get a better sense of the deviation between measured and predicted values, we also measured mean absolute percentage error (MAPE), Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970) and index of agreement (IOA) (Willmott 1981). The Akaike information criterion (AIC) was calculated to get an understanding of the trade-off between model fit and model complexity. Heteroskedasticity for the best model fit (Eqs. 1 or 4) was analyzed visually by plotting the residuals (model-measured SA) against the best explanatory variable (SA, DBH, H). All statistical analysis were conducted in R (version 3.3.2, R Core Team 2016).

Result

In New Mexico (NM), DBH, CD and H of ponderosa pine at US-Vcp were all greater than for spruce at the US-Vcm (Table 1). Of all the vegetation surveyed at JRB, aspen had the highest DBH, CD and H (Table 1). In Arizona (AZ), there was no significant difference between the DBH of Douglas-fir obtained at the schist and granite ZOBs ($p < 0.05$). Maple at schist ZOB and ponderosa pine at Oracle Ridge had the smallest and largest DBH of all the species that were surveyed in Arizona.

In the case of spruce collected in NM, DBH was positively correlated ($p < 0.05$) with SA with both the power (Exp, Eq. 1, Fig. 1a, Table 2) and log (Eq. 4, Table S2) functions accounting for more than 90% of the variation. NSE and IOA values for both the model fits (power, log) were close to unity (Table 2, Table S2). The overall model accuracy error, as measured by MAPE was lower when the log format was used (Table 2, Table S2). Unlike DBH, R^2 and NSE and IOA values were much lower when H (or CD) was

Fig. 1 Relationship between sapwood area (SA) and diameter at breast height (DBH) for Engelmann spruce (*Picea engelmannii*) (a) and quaking aspen (*Populus tremuloides*) (b). Detailed summary statistics of the model fits are in Table 2

Table 2 Parameters and fit statistics for the relationship between sapwood area (SA, cm²) and diameter at breast height (DBH, cm) for different species in New Mexico (NM) and Arizona (AZ), United States

Species	Site	Parameter	α (SE)	β (SE)	SEE	MAPE	R^2	NSE	IOA	AIC
<i>Picea engelmannii</i>	NM	DBH	1.86 (0.08)	1.02 (0.29)	103.22	18.05	0.95	0.95	0.97	1154.6
<i>Populus tremuloides</i>	NM	DBH	2.78 (0.35)	0.02 (0.02)	78.68	18.38	0.97	0.94	0.98	107.85
<i>Pseudotsuga menziesii</i>	NM	DBH	1.73 (0.23)	1.64 (1.34)	124.82	23.08	0.91	0.83	0.95	253.73
	AZ	DBH	1.57 (0.27)	1.81 (2.11)	303.09	74.27	0.89	0.79	0.94	303.48
<i>Pinus ponderosa</i>	NM	DBH	2.08 (0.11)	0.36 (0.13)	39.27	12.71	0.95	0.91	0.97	563.82
	AZ	DBH	1.89 (0.32)	0.61 (0.81)	364.33	36.82	0.83	0.68	0.89	325.85
<i>Acer gradidentatum</i>	AZ	DBH	2.3 (0.41)	0.37 (0.49)	98.86	19.34	0.93	0.86	0.96	111.97
<i>Abies concolor</i>	AZ	DBH	1.62 (0.17)	1.43 (1.06)	250.89	26.39	0.93	0.87	0.96	392.78

α and β , model parameters; SE, standard error; SEE, SE of estimate; R^2 , adjusted coefficient of determination; MAPE, mean absolute percentage error; NSE is Nash–Sutcliffe efficiency; IOA, index of agreement; AIC, Akaike information criterion

Fig. 2 Relationship between sapwood area (SA) and diameter at breast height (DBH) for Douglas fir (*Pseudotsuga menziesii*) (a, b) and ponderosa pine (*Pinus ponderosa*) (c, d). Detailed summary statistics of the model fits are in Table 2

regressed against SA (Table S2). Spruce samples collected from US-Vcm, JRB SW ZOB and JRB SE ZOB sites were pooled together for this analysis.

All estimators (R^2 , NSE and IOA) also established DBH as a strong independent variable to estimate SA for aspen at the New Mexico sites (Fig. 1b, Table 2). For Douglas-fir in New Mexico, the strength of correlation between SA and DBH was strong when the power (Fig. 2a, Table 2) function

was used in comparison to the log function (Table S2). Correlation between SA and CD was equally strong, irrespective of the fact whether the power or natural log function was used (Table S2). Douglas-fir in New Mexico consisted of samples collected from both JRB SW ZOB and JRB SE ZOB sites. Similarly, the power function (Eq. 1) provided a strong fit between SA and DBH for Douglas fir samples collected from Arizona (Fig. 2b, Table S3).

Fig. 3 Relationship between sapwood area (SA) and diameter at breast height (DBH) for big-toothed maple (*Acer grandidentatum*) (a) and white fir (*Abies concolor*) (b). Detailed summary statistics of the model fits are in Table 2

DBH accounted for more than 90% of the variation in SA using both the power (Eq. 1) and log (Eq. 4) functions for ponderosa pine in New Mexico (Fig. 2c, Table 2, Table S2). The strength of the correlation was slightly weaker in Arizona for the same species for both model fits (Fig. 2d, Table 2, Table S3). CD and H were, however, weakly correlated with SA of ponderosa pine at US-Vcp (Table S2). We did not collect data for CD and H for ponderosa pine at Oracle Ridge.

DBH was the best estimator of SA for maple at Arizona, with both power (Table 2) and log functions (Table S3) providing similar coefficient of determination (Fig. 3a). We did not have sufficient data to analyze the relation of CD and H of maple with SA. In case of white fir at Arizona, both DBH (Eqs. 1, 4) and CD (Eq. 2) were strongly correlated with SA (Fig. 3b, Table 2, Table S3). We did not find any strong association between H and SA for white fir (Table S3). White fir consisted of data collected from both schist and granite ZOBs.

Group regression analysis did not highlight significant impact ($p > 0.05$) of site conditions in modulating the allometric relationship between SA and DBH (or CD and H) for Douglas-fir (and white fir) at the Schist and Granite ZOBs (when analyzed separately). This result was also true at MC ZOB, where conditions at US-Vcm, JRB SW ZOB and JRB SE ZOB sites were not a significant factor ($p > 0.05$) in influencing the allometric relationship for Douglas-fir and spruce

(based on group regression analysis). Hence, the data for the same vegetation across these sites were pooled together to analyze the relationship between SA, DBH, CD and H . However, based on group regression analysis, α and β for both Douglas-fir (Fig. 2a, b) and ponderosa pine (Fig. 2c, d) across New Mexico and Arizona were significantly different ($p < 0.05$).

Discussion

For quantifying the relationship between the active fluid-transporting surface area of common southwestern conifer and deciduous tree species against easily measured stand variables such as DBH, H or CD in high-elevation, snow-dependent, semiarid ecosystems of the Southwest United States, we analyzed conifer and deciduous species separately because of their major differences in biomass, growth strategy, water transport pattern and abiotic stress responses (Dunisch and Morais 2002; Bovard et al. 2005; Mitra and Papuga 2012). They also have very different wood anatomy and, therefore, different specific conductivity. For example, the tracheids within coniferous species can conduct water, whereas only vessels within nonconductive fiber cells conduct water in angiosperm species.

We analyzed the model fits using multiple objective mathematical indicators (R^2 , MAE, IOA, NSE) because data transformation can distort our understanding of the “closeness” between measured and modelled data (Krause et al. 2005). Ideally, an ideal model fit will have high R^2 values, NSE and IOA values close to 1. The MAPE values, however, differed between the two model fits (Table 2; Tables S2, S3). However, we did not use these values as a criterion, primarily because they can in general be biased toward poorly predicting models (Toffalis 2015). A complete summary of the advantage and disadvantages of using MAPE as a selection criterion for model fit has been extensively documented (Hyndman and Koehler 2006; Kim and Kim 2016). Similarly, as the number of candidate models was only two (power and log, Eqs. 1, 4) with only two parameters, we did not use AIC as a criterion to select the optimum model fit.

DBH remains a well-established variable for tree allometry analysis (Landsberg and Gower 1997; TerMikaelian and Korzukhin 1997). Our attempt to quantify the relationship between SA and CD (or H) was primarily driven by the motivation to identify other independent variables that can be used to model SA. To that end, CD (e.g., white fir in Arizona and Douglas fir in New Mexico) was strongly correlated with SA.

However, apart from statistical performance, application in the field was a significant factor in our choice of the best model fit (Niklas 1994). Hence, we have selected DBH (Eq. 1) as the primary independent variable because

DBH can be measured with more precision than CD or H in the forest (Bond-Lamberty et al. 2002). The high degree of correlation between SA and DBH for all the species surveyed was consistent with general allometric theory (Cermak et al. 1992; Vertessy et al. 1995; Wullschleger and King 2000; Gebauer et al. 2008; Matyssek et al. 2009; Kume et al. 2010). We presented the results as both power (Eq. 1) and log functions (Eq. 4) to facilitate comparison of our results with other published data for similar vegetation and from different ecosystems. Except for Douglas fir in NM, there were no major differences (based on R^2) between the two model formats in predicting SA from DBH (Table 2, Tables S2, S3). Residual plots for SA versus DBH (Eq. 1) did not detect any non-random pattern for any of the species that we surveyed in New Mexico and Arizona (Fig. S2).

We do not believe our approach in estimating the wet-dry transition in tree cores overestimated SA. Bush et al. (2010) showed that the use of dyes on tree cores highlighted significant differences in the heartwood and sapwood transition only for ring-porous species. In our study, we sampled conifer species and diffuse-porous angiosperms and found no significant differences between our approaches of sapwood area estimation versus the use of dyes. We note that a critical factor not addressed by our study is the impact of stand age in modulating the allometric relationships. Multiple factors change with stand age, including soil and management conditions, presenting even more of a challenge. Still, our data set provides a much-needed step forward for calculating water balance in vulnerable semi-arid ecosystems.

We were motivated to compare the SA-DBH allometry of ponderosa pine and Douglas fir across the JRB and SCM site to analyze the representativeness of the SA-DBH relationship for the same species across the southwestern mountain ecosystem of the United States. Based on group regression analysis, the parameter coefficients differed significantly for each species (Eqs. 1, 4) across the two sites. This result was not surprising and may have been influenced by multiple factors apart from elevation, including age of the tree and structure of the stand (Hernandez-Santana et al. 2015).

Conclusions

Our comprehensive assessment of the allometric relationship of the dominant vegetation across high-elevation, snow-dependent, semiarid ecosystems in the southwestern United States (Arizona and New Mexico) is a valuable addition to the existing body of literature (McDowell et al. 2002). Establishment of species-specific allometric models will simplify estimation of evaporation, transpiration and carbon flux using tree height and canopy diameter measurements measured remotely by terrestrial and aerial light detection and

range (LiDAR) (Zhao and Popescu 2007; Falkowski et al. 2008; Swetnam and Falk 2014). With the exception of high point density terrestrial laser scanning, diameter at breast height cannot be measured directly using relatively lower-density aerial LiDAR scanning collections. Having robust species-level models that predict individual tree SA and total fluid flux based on tree size are a critical part of accurately estimating landscape-scale evaporation and transpiration and predicting potential hydraulic failure and tree death (Farrior et al. 2013; Gentine et al. 2016).

A natural extension of this research will be incorporating this species-specific SA-DBH allometric data to estimate stand-level transpiration (Granier 1987; Meinzer et al. 2001; James et al. 2002; Ford et al. 2004; Oishi et al. 2008). The analysis of species contribution to total stand transpiration is an emergent topic (Gebre et al. 1998; Ewers et al. 2002; Kostner et al. 2002; Pataki et al. 2005; Hernandez-Santana et al. 2015; Venkatraman and Ashwath 2016). A recent study across Alaska and western Canadian boreal forests found significant differences among deciduous and conifer tree species in their capacity to take up snowmelt water (Young-Robertson et al. 2016). Such analysis remains strongly relevant across the Southwest United States considering the expected shift in vegetation composition across this region due to changes in the climate change and, consequently, the terrestrial water cycle (Swetnam and Betancourt 1998; Diefenbaugh et al. 2008; Schwinning et al. 2008; Brusca et al. 2013).

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Author contributions BM conceived the study, collected tree core samples, analyzed the data and wrote the manuscript. SP conceived the study and assisted in data analysis and writing the manuscript. TS provided feedback and assisted in writing the manuscript. MRA assisted in collection of tree core samples and provided feedback during the development of the manuscript. NA assisted in collection of tree core samples and provided feedback to improve the manuscript.

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