2015-12-01

Water Use of Four Commonly Planted Landscape Tree Species in a Semi-Arid Suburban Environment

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A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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December 2015

ABSTRACT

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Native plant communities and agricultural land are commonly converted to urban areas as cities across the Western United States continue to grow and expand. This expansion is typically accompanied by afforestation where a common goal among communities is to maximize shade tree composition. Planted forests in these regions are commonly composed of introduced tree species native to mesic environments and their ability to persist is dependent on consistent irrigation inputs. Many potential ecosystem services may be derived from planting trees in urban and suburban areas; however, there are also costs associated with extensive afforestation, and shade tree cover may have significant implications on municipal water budgets. In this study I evaluate variation in daily and seasonal water use of regionally common suburban landscape tree species in the Heber Valley (Wasatch County, Utah). I had two primary objectives: (1) to identify and understand the differences in transpiration between landscape tree species in a suburban setting and (2) to assess the sensitivity of sap flux and transpiration to variation in vapor pressure deficit, wind speed, and incoming shortwave radiation. I used Granier's thermal dissipation method to measure the temperature difference (ΔT) between two sap flux probes. The empirical equation developed by Granier was used to convert ΔT into sap flux density (J_o) measurements, which were then scaled to whole-tree transpiration. There were consistent and substantial differences in sap flux between tree species. I found that *Picea pungens* under irrigated growing conditions, on average, had J_o rates that were 32% greater and whole tree water use (E_T) rates that were 550% greater than all other species studied. The findings of J_o may be partially explained by xylem architecture and physiological control over stomatal aperture. However, the rate of water flux in the outermost portion of sapwood does not necessarily determine the magnitude of whole tree transpiration. Rather, E_T in this study was largely explained by the combined effects of irrigation, tree size, and sapwood to heartwood ratio.

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INTRODUCTION

Municipalities in semi-arid regions across the western United States are commonly converted from native grass and shrubland ecosystems or agriculture to urban forest communities where shade tree composition is maximized (Bush et al., 2008; Pataki et al., 2011). Urban forests within these regions are commonly composed of introduced angiosperm tree species, native to mesic environments, and their ability to persist is fundamentally dependent on water inputs from regularly scheduled irrigation (Bush et al, 2008; McCarthy et al., 2011; Pataki et al., 2011). There are many potential benefits of urban forests, which may explain the drive to increase tree canopy cover in urban landscaping; however, as cities expand in arid regions and water use becomes a greater concern there is a need to identify the water use costs associated with urban tree cover.

Urban forest ecosystem services

It is well documented that green space in urban areas, and particularly urban forests, provide many ecosystem services that greatly benefit humans and other biota living within these unique environments (McPherson et al., 2005; Milward and Sabir, 2011; Dobbs et al., 2011; Dobbs et al., 2014; Hale et al., 2015). At a fundamental level, urban forests provide supporting services through nutrient cycling and primary production. Regulating services are also provided, including carbon sequestration, climate regulation, stormwater management, and air purification (Yang et al., 2005; Nowak et al., 2006). Urban landscape trees directly offset carbon emissions by sequestering carbon dioxide and indirectly offset carbon emissions by shading and insulating homes and buildings, thereby mitigating the need for seasonal heating and cooling (McPherson et al., 2006). Air temperatures are regulated as trees shade structures and impervious surfaces,

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and through transpiration and evaporative cooling (Millward and Sabir, 2011). Additionally, shade tree canopies intercept shortwave solar radiation, preventing built surfaces from acting as heat sinks and mitigating the urban "heat island" effect (Bolund and Hunhammar, 1999; Shashua-Bar et al., 2009; Chen et al. 2011). Stormwater runoff volumes and pollutant loading in waterways are reduced as tree canopies intercept rainfall and trees transpire available soil moisture (Bolund and Hunhammar, 1999). City trees have the ability to mitigate poor air quality which may reduce human health risks. In addition to releasing O_2, stomatal conductance allows for the uptake of harmful atmospheric pollutants (e.g. NO_2, SO_2, O_3, and CO) which are absorbed through leaf surfaces (Yang et al., 2005; Nowak et al., 2006; Millward and Sabir, 2011). Particulate matter, such as $PM_{2.5}$ and PM_{10}, are directly intercepted and filtered by canopy structures (Bolund and Hunhammar, 1999; Millward and Sabir, 2011). Urban forests also provide social and cultural services by adding aesthetic value to communities while providing recreation and education opportunities (Bolund and Hunhammar, 1999; Tyrväinen, 2000; Tyrväinen, 2001) - illustrating the cultural importance of trees within urban communities.

Urban Forest Costs and Trade-offs

In an effort to derive the many benefits associated with shade tree cover, planting programs are widely advocated in urban areas and many communities possess full-fledged urban forestry management programs (McCarthy and Pataki, 2010; Pataki et al., 2011; Young, 2011; Hale et al., 2015; Utah, 2015). The goal of such programs is to maximize the ecosystem services provided by urban forests, but there are also economic and ecological disservices and costs associated with increased urban tree cover (Dobbs et al., 2011; Hale et al., 2015). For example, there are considerable safety risks and financial costs associated with managing hazardous limbs

and dead trees. Trees may also become a public nuisance where fallen leaves, fruits, and other debris (e.g. broken limbs) require constant upkeep (Hale et al., 2015). Additionally, there may be environmental impacts associated with pollution (e.g. runoff from pesticide, herbicide, or fertilizer application) and significant costs may be incurred when cities are faced with combatting widespread pests and disease (Dobbs et al., 2011; Hale et al., 2015). Trees have the capacity to utilize exceptionally large quantities of water, thus, a potentially significant trade-off of increased urban forest cover is tree water use -particularly in arid and semiarid environments (Pataki et al., 2011; Gage and Cooper, 2015). For example, an urban tree water use study conducted in the Los Angeles metropolitan area (USA) identified individual street trees that transpired up to 190 liters of water on an average day throughout the growing season (Pataki et al., 2011). Extrapolated across the duration of that study (220 days), a single tree has the potential to transpire 42,000 liters of water during an average growing season. Understanding variation in water use between different tree species and watering protocols may be particularly important in communities within semi-arid regions where water resources are limiting. In water limited communities, tree species water use efficiency should be identified and carefully considered before tree planting program initiatives are implemented. Selection of the most ecologically appropriate tree species' will allow for the maximization of the ecosystem services provided by urban forests while minimizing the disservices and costs rising from water use.

Biophysical demands on transpiration

Transpiration accounts for the greatest water flux from terrestrial ecosystems (Chen et al., 2011) and is largely controlled by a suite of biophysical factors such as tree size, solar radiation (R), wind speed (W), and vapor pressure deficit (D) (Bush et al., 2008; Chen et al., 2011; Pataki

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et al., 2011; Livtak et al., 2012) and regularly scheduled irrigation (Bush et al., 2008; McCarthy et al., 2011; Pataki et al 2011; Peters et al., 2011). Studies of tree water use are commonly conducted in natural forested systems (Granier, 1987; Hogg and Hurdle, 1996; Ewers et al., 2001; Pataki and Oren, 2003; Gebauer et al., 2008; Hultine et al., 2010), under experimental greenhouse conditions (McCulloh et al., 2007), on field grown crops (Alarcon et al., 2003), or scaled from instantaneous leaf level gas exchange measurements (Kjelgren and Montague, 1998; Oren et al., 1999). Studies of tree water use in urban environments commonly model rates of evapotranspiration, derived from meteorological variables, but our understanding of tree level transpiration under urban conditions is still developing as few research studies have measured direct water use of mature urban trees (Bush et al., 2008; McCarthy and Pataki, 2010; Pataki et al., 2011, Litvak et al., 2012). Understanding transpiration responses to biophysical factors across a broad range of species and environmental conditions is integral to enhancing our understanding of plant water relations and anticipating future urban water demand.

Study objectives

In this study I evaluate variation in water use of regionally common suburban landscape tree species in the Heber Valley (Wasatch County, Utah, USA – Figure 1). Within the Heber Valley, rapid development is underway and the population is projected to grow 90% (from 18,000 to 35,000 residents) by 2030 (Heber City, 2014). Plant community structure in the Heber Valley is changing as the region transitions from a rural agriculture community to subdivided suburban developments with heavy shade tree composition. It is expected that the change in plant community structure will place greater demands on municipal water resources. However, this outcome may be dependent upon planting density, the extent of irrigation, and tree species

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selection. To better understand the role of planted landscape trees on municipal water budgets I quantify sap flux density (J_o) and tree transpiration (E_T) rates in two commonly planted angiosperm species (*Pyrus calleryana* and *Malus ioensis*) for which there is limited sap flux information (Liu et al., 2012; Rahman et al., 2014; Rahman et al., 2015). Additionally, this study focuses on two gymnosperm species (*Picea pungens* and *Pinus contorta*) that are part of an important functional group of landscape trees that has not been well studied. These gymnosperm species have been researched in natural settings (Adelman et al., 2008; Cermak at al., 2014; Hubbard et al., 2013), but to my knowledge there is no previous sap flux data reported for these species under urban or suburban growing conditions. Sap-flux measurements were derived from the temperature difference (ΔT) between thermal dissipation sap flux probes. Measurements collected throughout the 2014 growing season and average daily rates of water use were quantified. The four species studied here were selected because of their dominant presence that was observed throughout the study region. Within the study area they represent both native and introduced species and they are planted in both irrigated and non-irrigated environments. Thus, the selection of study trees and their arrangement within the study area allows for insightful contrasts to be made between individuals as a function of species-specific characteristics and growing conditions (Tables 2 and 3).

Previous sap flux studies conducted in urban environments have found that transpiration in response to environmental drivers (D, R, and W) may be constrained or maximized depending on the tree species climate of origin (Pataki et al., 2011), xylem architecture (Bush et al., 2008), or physiological controls over stomatal aperture (Oren et al., 1999; Bourne et al., 2015). In addition to these findings, there are likely intrinsic biological factors, such as tree size and sapwood depth, which regulate maximum transpiration that can be achieved by a given species.

I predict that the combined effects of irrigation, tree size, and sapwood/heartwood ratio, will be important determinants of maximum transpiration in this study. The primary objectives of this study are to: (1) to identify and understand the differences in transpiration between landscape tree species in a suburban setting and (2) to assess the sensitivity of sap flux and transpiration to variation in vapor pressure deficit, wind speed, and incident solar radiation.

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MATERIALS AND METHODS

Study sites

The study was located in Heber Valley (40°30'N, 111°24'W; 1708 – 1759 m) 50 miles southeast of Salt Lake City, in northern Utah. The climate is semi-arid with an annual average temperature of 12.2°C and mean annual precipitation of 368 cm (Heber City, 2014). The Heber Valley is currently transitioning from an agricultural landscape with dispersed development to a subdivided landscape composed of tract and mini ranch style homes. I selected three study sites using a stratified approach to ensure representation of common tree planting patterns that contained dominant tree species. Additionally, study sites were selected which contained mature trees of sufficient size, offered a secure location to store monitoring equipment for the study duration, and where landowners were willing to allow for invasive sap flux measurements and tree core extraction. Sap flux measurements were collected at three suburban site locations: County, Homestead, and United States Forest Service (USFS) properties. The County site consists primarily of mature *M. ioensis* (*n*=6) and large diameter *P.pungens* (*n*=4). This site was heavily managed (e.g. tree maintenance and pruning) and regularly irrigated. The Homestead was a managed site, with pruning and tree maintenance occurring regularly, but the trees receive no direct irrigation. All sample trees at this location occur directly adjacent to a heavily irrigated golf course green. This site contains fifteen mature trees with both gymnosperm and angiosperm representation. The primary species of interest at this site were *P. pungens* (*n*=8) and *P. calleryana* (*n*=3). Trees at the USFS site were watered for a short duration by drip irrigation on a weekly basis and this site has been classified as "deficit irrigated" as a result. The species of interest at this site were *P. pungens* (*n*=5) and *P. contorta* (*n*=5).

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Sap flux

Sap flux measurements were collected from 35 individuals of 8 different species. I made statistical comparisons for Colorado blue spruce (*Picea pungens; n=17*), lodgepole pine (*Pinus contorta; n=5*), prairie crabapple (*Malus ioensis; n=6*), and flowering pear (*Pyrus calleryana; n=3*). While there was not sufficient replication to include *Acer saccharinum, Ulmus pumila, Prunus virginiana*, and *Gleditsia triacanthos* in the analysis, the characteristics of each of these species and their daily average water use patterns are contained in tables 2, 3 and 8. At each site, 2 cm long thermal dissipation probes (Granier, 1987) were used to collect sap flux density (J_o) measurements on all sample trees. The probes were inserted radially into the main stem at breast height (1.4 m), with a vertical separation of 10-15 cm. All sensors were installed on the north side of the stem to minimize the effect of radiation and maintain thermal consistency. The temperature difference (ΔT) between the two probes was recorded every 30 seconds and averaged every 30 minutes with a CR1000 datalogger (Campbell Scientific, Logan, Utah). The ΔT sensor output was converted to sap flux density in the outer 2 cm of sapwood (J_o (g·m^{-2}·s^{-1})) required the empirically derived equation (Granier, 1987):

$$J_o = 119 \ (\Delta T_M/\Delta_T - 1)^{1.231} \tag{1}$$

where ΔT is the temperature difference between the two probes, and ΔT_M is the temperature difference during zero flow (i.e., the maximum value over a given period). Baseliner (Oren et al., 1999) was used to determine baseline measurements (zero flow), from which ΔT was derived and J_o could be calculated. At the conclusion of the study an increment borer was used to extract core samples from each sample tree. These cores were used to calculate the total sapwood area

(active conducting tissue) of each individual. The data collection period was May 10, 2014 to November 6, 2014 (180 day period), which encompassed the 2014 growing season.

Environmental data collection

Temperature, relative humidity, and vapor pressure deficit (D) were measured continuously at all sites for the duration of the study (CS-215; Campbell Scientific, Logan, Utah). I also measured incoming shortwave radiation (R) (SP220; Apogee Instruments, Logan, Utah) and wind speed (W) (DS-2; Decagon Devices, Pullman, Washington) continuously for the study duration (May 10 - November 6, 2014). These measurements allowed for analysis to be conducted in testing the significance of meteorological drivers over tree water flux. As with sap flux measurements, environmental data was recorded every 30 seconds and averaged every 30 minutes with a CR1000 datalogger (Campbell Scientific, Logan, Utah).

Scaling to whole-tree water use

The probes used in this study accurately measure sap flux density (J_o) for the outer 2 cm of sapwood tissue only and the cross-sectional area of sapwood (A_s) was calculated to extrapolate this value to whole tree transpiration: Where A_s is the area of the annulus of sapwood (sapwood area minus hardwood area). To accurately measure A_s, tree cores were extracted from the midpoint of the sap flux sensors on each site tree at the conclusion of the study. It should be noted that radial trends vary by species and as a function of environmental factor such as D, soil moisture, light availability and tree diameter (Lu et al., 2004; Pataki, 2011). Previous research has concluded that generalizations about radial trends in sap flow across species and environments are not possible, as it is common for urban trees to contain active sapwood far beyond the sensor length (Pataki et al., 2011). To accurately scale to whole-tree water use the

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influence of size, sapwood depth, and radial trends across the xylem must be accounted for. In a previous study (Pataki et al., 2011) evaluated radial trends for 34 tree species across a broad range of previously reported studies. The authors found a consistent pattern J_i/J_o (the ratio of sap flux at the actual depth i to the outermost 2 cm increment), noting that there was no statistical difference in the relationship between diffuse and ring porous angiosperm species, but that there was a significantly different relationship between gymnosperms. The authors fitted Gaussian functions to angiosperms and gymnosperms to derive the following equations, which I used to account for radial trends in my sample trees.

$$\text{angiosperm} \quad J_i/J_o = 1.033\, X \exp\left[-0.5\left(\frac{x - 0.09963}{0.4263}\right)^2\right]$$

(2)

$$\text{gymnosperm} \quad J_i/J_o = 1.257\, X \exp\left[-0.5\left(\frac{x + 0.3724}{0.6620}\right)^2\right]$$

(3)

Once radial trends were determined the following equation (Pataki at al., 2011) was utilized to calculate whole tree transpiration:

$$E_T = \sum_{i=1}^{n} \frac{J_i A_i}{1000}$$

(4)

where E_T is total daily transpiration (kg/d), n is the number of 2 cm increments of sapwood depth, J_i is sap flux density (g cm^{-2} d^{-1}) at depth i, and A_i is sapwood area (cm^2) at depth i.

Statistical analysis

To identify differences in sap flux density by species I aggregated all sample trees by species and site and conducted a generalized linear model analysis (R, version 3.2.2) testing J_o as a function of species (Table 4). A multiple comparisons of means (Tukey contrasts) test was applied to the model to quantify the differences between pairwise comparisons (R, version 3.2.2, package multcomp). Data for this analysis was based on daily averaged J_o values (Table 4).

Based on previous sap flux studies (Martin et al., 1998; Bush et al., 2008; Pieruschka et al., 2010), I hypothesized that J_o would be principally explained by three meteorological variables: vapor pressure deficit (D), incoming short-wave radiation (R), and wind speed (W). To test this hypothesis I developed 8 linear mixed effects models (R, version 3.2.2, package lmer) structured to analyze daily maximum J_o as a function of corresponding daily maximum D, R, and W. "Site" and "Species" were input as fixed effects within each of the 8 models to account for *P. pungens* which occurred at all three sites (Table 6). I then estimated species-specific differences in the magnitude to which each environmental variable (R, D, and W) influenced J_o. Daily maximum J_o was averaged for each species by site of occurrence and analyzed as a function of corresponding daily maximum D, R, and W. A generalized linear model (R, version 3.2.2) was constructed for each of the 6 possible species and site combinations (Table 7).

RESULTS

Species comparisons

My first objective was to identify and understand broadly the differences in transpiration between species. There were significant differences between each species in all but two comparisons (Table 4). The highest rates of J_o were observed in *P. calleryana* (258 ± 22 g·cm^{-2}·d^{-1}), an introduced angiosperm at the unirrigated Homestead site, and *P. pungens* (260 ± 23 g·cm^{-2}·d^{-1}), a native gymnosperm at the irrigated County site (Figure 2 and Table 7). There was no significant difference between the two ($P = 0.97$ Tables 4). High J_o rates were also observed in *M. ioensis* (226 ± 35 g·cm^{-2}·d^{-1}), an introduced angiosperm at the irrigated County site. Relatively low J_o was observed in *Picea pungens* at the deficit-irrigated USFS (176 ± 23 g·cm^{-2}·d^{-1}) and Homestead sites (175 ± 24 g·cm^{-2}·d^{-1}) and no significant difference was observed between the two ($P = <0.30$; Tables 4 and 7). The lowest J_o rates were observed in *P. contorta* (147 ± 22 g·cm^{-2}·d^{-1}), a native gymnosperm at the deficit-irrigated USFS site. Average daily J_o values (Table 7) were used to calculate percent differences in J_o between species. The largest species differences were observed when comparing *P. pungens* (County) and *P. calleryana* to *P. contorta* and *P. pungens* at the unirrigated and deficit-irrigated sites. Both *P. calleryana* and *P. pungens* (County) expressed J_o rates that were, on average, 76% greater than *P. contorta*, 48% greater than *P. pungens* (Homestead), and 47% greater than *P. pungens* (USFS). On average, J_o in *M. ioensis* was 53% greater that *P. contorta*, 29% greater than *P. pungens* (Homestead), and 28% greater than *P. pungens* (USFS). When comparing the three highest fluxing species to each other, J_o in *P. pungens* (County) was 2% greater than *P. calleryana* and 15% greater than *M. ioensis*.

Water flux across the entire sapwood area of an individual tree (E_T) did not directly correspond to sap-flux in the outermost 2cm of sapwood (J_o). Both *P. pungens* (County) and *P. calleryana* had high flux rates that were not significantly different from each other; however, tree transpiration (E_T) was very different between the two species (Figure 3). The greatest E_T rates were observed in *P. pungens* at County (274 ± 18 kg·tree^{-1}·day^{-1}), which exceeded that of *P. calleryana* (40 ± 15 kg·tree^{-1}·day^{-1}) by more than 500% on an average day throughout the growing season. Additionally, high flux rates were observed in *M. ioensis* while E_T was relatively low (32 ± 6 kg·tree^{-1}·day^{-1}). The lowest E_T was observed in *P. pungens* at the unirrigated Homestead and deficit-irrigated USFS sites (175.2 ± 21.5 and 175.9 ± 22.9 kg·tree^{-1}·day^{-1}, respectively), but the lowest flux rates were not observed in these trees. The lowest J_o was observed in *P. contorta*, however, E_T for these trees (45 ± 10 kg·tree^{-1}·day^{-1}) was 115% greater that *P. Pungens* (Homestead and USFS), 40% greater than *M. ioensis*, 12% greater that *P. calleryana* and the only species which transpired more water was *P. pungens* at County.

Environmental analysis

My second objective was to identify important environmental drivers of transpiration and understand how species' patterns of water flux respond to changes in environmental conditions. When I evaluated the influence of vapor pressure deficit (D), incoming radiation (R), and wind speed (W) on J_o in all species I found that the full model (Table 5, Model 1), containing all environmental variables and both random factors, carried the full model weight (AIC_c *weight* = 1) and confirmed that D, R, and W are key explanatory variables driving maximum J_o at my three study sites. The pattern of J_o in response to R was linear (Figure 5), with decreasing J_o at very high radiation levels (>1000 w·m^{-2}). J_o tended to increase in response to D at low levels (<2 kPa)

and then reach a steady state beyond that point (Figure 6). At very high D (>4 kPa) a slight decrease in J_o was observed. J_o was responsive to W (Figure 7), however, steady states were observed at low velocities (<2 m·s^{-1}). To address species-specific responses to environmental factors I developed generalized linear models testing maximum J_o as a function of D, R, and W for each species. The results indicate that species-specific response to changes in each of these environmental drivers is highly variable and that, by order of magnitude, D is the most important driver of J_o in all species but *P. contorta* (Table 6). In *P. pungens* (County) the predicted change of J_o in response to D is exceptionally large (146 ± 11 g·cm^{-2}·d^{-1}) and D was the only significant explanatory variable. Similar, but less pronounced patterns were observed in *M. ioensis*, *P. pungens* (Homestead), and *P. calleryana*. In these species the predicted changes in Jo in response to D are 85 ± 12 g·cm^{-2}·d^{-1}, 26 ± 7 g·cm^{-2}·d^{-1}, and 27 ± 11 g·cm^{-2}·d^{-1}, respectively. In *P. pungens* at the deficit-irrigated USFS site, J_o was negatively correlated to D (-11 ± 13 g·cm^{-2}·d^{-1}) and both R and W were not significant ($P =$ <0.01, Table 6). W was the second dominant driver of J_o in all species, and the primary, yet insignificant, driver in *P. pungens* at USFS (15 ± 13 g·cm^{-2}·d^{-1}, $P=$ 0.26). The predicted change of J_o in response to W was similar between *M. ioensis* (28 ± 9 g·cm^{-2}·d^{-1}), *P. contorta* (27 ± 7 g·cm^{-2}·d^{-1}), and *P. pungens* (Homestead) (26 ± 7 g·cm^{-2}·d^{-1}). R was a significant explanatory variable in *P. calleryana*, *P. contorta*, and *P. pungens* (Homestead), but the predicted change in J_o in response to R for each of these 3 species (0.4 ± 0.07 g·cm^{-2}·d^{-1}) was very low, indicating that R, in comparison to D and W, was not the dominant driver of J_o in this study.

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DISCUSSION

Species Specific Water Use

My first objective was to identify and understand broadly differences in water use between species. I found substantial and consistent differences in water use, suggesting that urban forest community composition is a key control over municipal water budgets. The differences between species may be partially explained by xylem architecture or species-specific physiological controls over stomatal aperture. However, I observed that patterns of J_o were not in alignment with that of E_T, where large trees with deep sapwood tended to have higher tree-level transpiration, regardless of J_o (Figure 3). Thus, the findings of this research suggest that, in addition to physiological and anatomical factors, the combined effects of irrigation, tree size, and sapwood to heartwood ratio are important determinants of tree-level transpiration (E_T).

Pataki et al. (2011) measured transpiration in *Pinus canariensis*, a gymnosperm species that had similar size, sapwood, and irrigation characteristics to *P. pungens* and *P. contorta* studied here. Pataki et al. (2011) observed *P. canariensis* trees growing under irrigated conditions that had consistently large diameters and deep sapwood, contributing to high rates of E_T. I observed a similar pattern in *P. pungens* (County), which had the greatest rates of E_T of all trees studied. In contrast, the authors found that 3 of the largest angiosperm trees they measured had very shallow sapwood, contributing to relatively low rates of E_T. This finding is supported by the contrasting results of low J_o and high rates of E_T in *P. contorta*, exceeding that of both angiosperm species, which is likely the result of relatively large diameter (23.6 ± 1.8 cm) and deep sapwood (11.0 ± 0.8 cm) in these trees. Pataki et al. (2011) also observed significantly suppressed rates of E_T in *P. canariensis* growing under unirrigated conditions. These findings,

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coupled with my own, illustrate the key interactions between tree size, sapwood depth, and water availability in determining tree-level transpiration.

Environmental Controls Over Water Use

My second objective was to assess the sensitivity of sap flux to wind speed (W), solar radiation (R), and vapor pressure deficit (D) and understand how trees respond to changes in environmental conditions. Large predicted effects were observed for J_o in response to W in all species but *P. calleryana* (Figure 4 and Table 6). Similar to this study, Kume et al. (2015), Chu et al. (2009), and Kitaya et al. (2004) observed large J_o effects in response to W and found that the magnitude and pattern of response was species-specific. Kume et al. (2015) observed that J_o in broadleaf species tended to reach steady states at high wind velocities (>8 m·s^{-1}) while conifers tended to reach a steady state at much lower speeds (<2 m·s^{-1}). The authors concluded that the variation was derived from differences in stomatal conductance rather than leaf type. A recent study of growth rates and cooling effectiveness of urban street trees identified apparent differences in stomatal conductance between two of the species studied here. Stomatal conductance in *P. calleryana* was commonly 100% higher than that of *Malus* under similar urban growing conditions, translating greater rates of transpiration and cooling capacity (Rahman et al., 2014). The high rates of water use by *P. calleryana* and relatively low rates of water use by *Malus*, observed by Rahman et al. (2014), is emphasized by my observations of relatively high J_o and E_T in *P. calleryana* at the unirrigated Homestead site and significantly reduced J_o and E_T in larger sized *M. ioensis* at the irrigated County site (Figure 2 and Table 7). Based on the findings or Rahman et al. (2014), it is possible that *M. ioensis* in this study expressed consistently lower stomatal conductance than *P. calleryana,* resulting in lower J_o and E_T.

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However, *M. ioensis* has the shallowest sapwood of all species I studied, where *P. calleryana* had sapwood/heartwood ratios that were 14% greater (Table 3). Thus, in addition to physiological factors, the low rates of E_T observed in *M. ioensis* are clearly related to low sapwood depth relative to diameter (Table 3).

Unsurprisingly, with this study conducted in a semiarid suburban system, the largest predicted changes in J_o were observed in response to *D*. The predicted change Jo for every one unit increase in D was extremely high in both species at the irrigated County site - *M. ioensis* and *P. pungens* (Figure 4 and Table 6). It is likely that trees at this site did not readily close their stomata under maximum *D* conditions because soil moisture was not limiting. This observation emphasizes that, in addition to tree size and sapwood depth, irrigation is also an important determinant of J_o in this study. The overall pattern observed (Figure 6) is consistent with the findings of Hogg and Hurdle (1997), Pieruschka et al. (2010), and Oren et al. (1999), where large responses were observed at low *D* (<1kPa), steady states occurred at high D (>1 kPa), and decreases in J_o occur at very high *D* (>4 kPa). Many authors have identified species-specific water conducting potential in response to *D* and related their findings to xylem architecture (Bush et al., 2008; Bush et al., 2010; Peters et al., 2010; Gao et al., 2015). Diffuse porous angiosperms tend to use more water than gymnosperms which conduct water through tracheid cells, and ring porous species (Bush et al., 2008; Gao et al.; 2015). This is consistent with my finding at the unirrigated homestead site where *P. calleryana* had flux rates that were 48% greater than *P. pungens*. However, *P. pungens* (County) had the greatest rates of J_o of all species studied which contradicts the assumption about absolute differences based on xylem architecture. Bush (2008) determined that, when water is not limiting, J_o in diffuse porous species will increase *with D,* even at large water vapor deficits. This finding is supported by my study, where

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the greatest modeled change of J_o in response to D was observed in both irrigated species at the County site (*P. pungens* and *M. ioensis*).

The findings of my research support that of Bush et al. (2008) and Pataki et al. (2011) and add additional insight into the controlling factors over urban tree water use. The main takeaway of this research is that the exceptionally high rate of E_T in *P. pungens* (County) is primarily the result of high water availability (Figure 4). The extraordinary water use in these conifers is also due to the size of the trees. *P. pungens* (County) was 85 to 200% larger than all other species studied (mean dbh, 44 ± 1.6 cm) and had high sapwood volume, with depths that were 92% greater than the next largest trees. Thus, under well-watered growing conditions, the mature size potential and xylem architecture of *P. pungens*, and possibly other species of the *Pinaceae* family, allows for high E_T potential with water use values exceeding that of *M. ioensis*, *P. calleryana*, and possibly other commonly planted angiosperms.

Implications for municipal water use

It is obvious that landscape trees have the potential to use a significant amount of irrigation water, particularly during peak growing conditions in mid-summer. What is remarkable from my study was that the range of individual tree water use was highly variable (19-284 liters $H_2O \cdot tree^{-1} \cdot day^{-1}$) and the magnitude is dependent on species, irrigation, and intrinsic architectural factors, such as tree size and sapwood depth. There are estimated to be approximately 12,000 landscape trees planted throughout Heber City (Utah, 2015). The predicted range of daily water use by suburban forest canopy in Heber City, based on E_T values measured in this study, is between 227,000 and 3.4 million liters of water per day during peak growing conditions. Extrapolated across the 2014 growing season, planted trees in Heber City likely

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utilized somewhere between 38 million and 600 million liters (30-490 acre feet) of water between the months of May and November.

Many semi-arid communities across the western US are experiencing rapid population growth and increased environmental pressures deriving from climate change, such as warmer temperatures and drought. As a result, municipal and regional water managers are increasingly aware of the need for conservation and sustainable use of water resources (Utah, 2013; Utah 2014; Gage and Copper, 2015). Urban trees provide valuable ecosystem services to communities such as aesthetic value, clean air, cooler temperatures, and stormwater management. However, there are tradeoffs associated with urban tree cover and water use is a significant factor. In water limited regions species, tree size, sapwood depth, and irrigation practices have potentially large implications for municipal water budgets. To maximize the benefits and minimize the tradeoffs of urban canopy cover these factors should be carefully considered during the landscape planning stages. With appropriate research and planning, urban landscapes in semi-arid regions could be composed of trees reflecting water use values toward the middle and lower range of what was measured in Heber City, yielding significant annual water savings that could be allocated elsewhere.

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TABLES

Table 1. Abbreviations used in the text.

Abbreviation	Description
A_s	sapwood area (cm^2)
A_i	sapwood area at depth i (cm^2)
D	vapor pressure deficit (kPa)
R	incoming short-wave global radiation (w/m^{-2})
W	wind speed (m/s^{-1})
E_T	tree transpiration (kg/d)
J_i	sap-flux density at depth i (g·cm^{-2}·d^{-1})
J_o	sap-flux density in the outer 2 cm of sapwood (g·cm^{-2}·d^{-1})
J_s	sap-flux density across the active sapwood (g·cm^{-2}·d^{-1})

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Table 2. Study site and species characteristics for all plots within the Heber Valley, UT.

Study site and tree species	*n*	Classification	Wood type	Local adaptation
County (irrigated)				
Picea Pungens	4	Gymnosperm	Tracheid	Native
Malus ioensis	6	Angiosperm	Diffuse porous	Introduced
Acer saccharinum*	1	Angiosperm	Diffuse porous	Introduced
Homestead (non-irrigated)				
Picea pungens	8	Gymnosperm	Tracheid	Native
Pyrus calleryana	3	Angiosperm	Diffuse porous	Introduced
Ulmus pumila*	1	Angiosperm	Semi-ring porous	Introduced
Prunus virginiana*	1	Angiosperm	Semi-ring porous	Native
USFS (deficit-irrigated)				
Picea pungens	5	Gymnosperm	Tracheid	Native
Pinus contorta	5	Gymnosperm	Tracheid	Native
Gleditsia triacanthos*	1	Angiosperm	Ring porous	Introduced

Note: Table contains list of all trees sampled at the study locations, however, statistical analysis was only conducted on the species for which there was adequte replication (*Picea pungens*, *Malus ioensis*, *Pyrus calleryana*, *Pinus contorta*).

Table 3. Tree size characteristics for all plots within the Heber Valley, UT.

Study site and tree species	*n*	Mean dbh (cm) ± SE	Sapwood depth (cm) ± SE	Sapwood area /dbh (%)
County (irrigated)				
Picea Pungens	4	44.0 ± 1.6	21.1 ± 0.8	48.0
Malus ioensis	6	20.2 ± 0.7	6.5 ± 0.4	32.2
Acer saccharinum*	1	53.4	19.4	36.0
Homestead (non-irrigated)				
Picea pungens	8	15.1 ± 0.5	7.1 ± 0.5	47.0
Pyrus calleryana	3	17 ± 2.9	7.8 ± 1.2	45.8
Ulmus pumila*	1	30.8	14.4	46.8
Prunus virginiana*	1	18.1	5.5	30.4
USFS (non-irrigated)				
Picea pungens	5	14.6 ± 1.7	7.0 ± 0.9	47.9
Pinus contorta	5	23.6 ± 1.8	11.0 ± 0.8	46.6
Gleditsia triacanthos*	1	29.4	11.2	38.1

Note: Mean dbh was measured at ~1.4 m on each sample tree. Sapwood depth was visually assessed from trees core samples. Trees without replication (*) were not used in statistical analysis.

Table 4. Statistical output for J_o analyzed as a function of species.

Linear Hypothesis	Estimate	SE	P-value
M. ioensis - *P. contorta* = 0	100.55	4.62	**< 0.01**
M. ioensis - *P. pungens* (H) = 0	57.94	3.90	**< 0.01**
M. ioensis - *P. pungens* (U) = 0	47.96	5.12	**< 0.01**
P. calleryana – *M. ioensis* = 0	33.09	5.22	**<0.01**
P. calleryana - *P. contorta* = 0	133.64	5.47	**<0.01**
P. calleryana - *P. pungens* (C) = 0	4.47	5.75	0.97
P. calleryana - *P. pungens* (H) = 0	90.59	4.87	**< 0.01**
P. calleryana - *P. pungens* (U) = 0	80.59	5.97	**< 0.01**
P. Pungens (C) - *M. ioensis* = 0	28.62	4.94	**< 0.01**
P. pungens (C) - *P. contorta* = 0	129.17	5.21	**< 0.01**
P. Pungens (C) - *P. pungens* (H)	86.12	4.58	**<0.01**
P. Pungens (C) - *P.pungens* (U)	76.12	5.72	**<0.01**
P. pungens (H) - *P. contorta* = 0	43.05	4.23	**< 0.01**
P. pungens (U) - *P. contorta* = 0	53.05	5.45	**< 0.01**
P. pungens (U) - *P. pungens* (H) = 0	9.99	4.85	0.3

Note: Trees were aggregated by species and site, yielding 6 possible site and species combinations. Based on averaged J_o daily values. Only species with adequate replication were used in the analysis. *Picea pungens* (*n*=17), *Malus ioensis* (*n*=6) *Pinus contorta* (*n*=5), *Pyrus calleryana* (*n*=3). J_o values for each species we're averaged by site. C: county, H: homestead, U: USFS Ordered alphabetically by species.

Table 5. Daily maximum J_o as a function of environmental factors. Ordered by lowest AIC_c.

Model no.	Model	AIC_c	Delta AIC_c	AIC_c weight
1	R + D + W + (1|Site) + (1|Species)	62635.2	0	1
2	R + D + (1|Site) + (1|Species)	62665.4	30.2	0
3	R + W + (1|Site) + (1|Species)	62675.3	40.1	0
5	D + W + (1|Site) + (1|Species)	62703.1	67.9	0
4	R + (1|Site) + (1|Species)	62735.8	100.6	0
6	D + (1|Site) + (1|Species)	62790.7	155.5	0
7	W + (1|Site) + (1|Species)	63029.1	393.9	0
8	(1|Site) + (1|Species)	63114.7	479.5	0

Note: Daily maximum J_o was tested as a function of corresponding maximum R (radiation), D (vapor pressure deficit), and W (wind speed) values. In all models "Site" and "Species" were input as random factors. Model 1 is the full model which carries 100 percent of the AICc weight. Models 2-7 are reduced and model 8 serves as my null hypothesis.

Table 6. Statistical output for species specific J_o as a function of environmental factors.

Model	Species	Coefficients	Estimate	SE	P-value
$R + D + W$	*M. ioensis*	R	0.06	0.06	0.33
		D	**85.22**	**12.06**	**<0.01**
		W	**28.39**	**9.49**	**<0.01**
$R + D + W$	*P. Calleryana*	**R**	**0.36**	**0.07**	**<0.01**
		D	**27.49**	**10.81**	**0.01**
		W	1.39	9.01	0.88
$R + D + W$	*P. contorta*	**R**	**0.41**	**0.07**	**<0.01**
		D	6.06	8.91	0.50
		W	**27.25**	**7.44**	**<0.01**
$R + D + W$	*P. pungens* (C)	R	-0.02	0.06	0.71
		D	**146.03**	**11.06**	**<0.01**
		W	11.29	8.68	0.19
$R + D + W$	*P. pungens* (H)	**R**	**0.37**	**0.05**	**<0.01**
		D	**26.98**	**8.99**	**<0.01**
		W	**26.21**	**6.94**	**<0.01**
$R + D + W$	*P. pungens* (U)	R	-0.04	0.13	0.73
		D	-10.97	13.01	0.40
		W	15.35	13.51	0.26

Note: Expected change in J_o as a function of environmental variables incoming shortwave radiation (R), vapor pressure deficit (D), and wind speed (W). Every one unit increase in each of the meteorological variables corresponds to an "x" unit increase in J_o. All models were grouped by species and site, yielding 6 possible species and site combinations. Based on daily maximum for J_o and corresponding maximum values for R, D, and W. C: county, H: homestead, U: USFS. Ordered alphabetically by species.

Table 7. Sap-flux in the outer 2cm of sapwood (J_o), sap-flux across the total depth of active sapwood (J_s), and total tree water use (E_T).

Site and tree species	n	J_o (g·cm^{-2}·d^{-1}) ± SE	J_s (g·cm^{-2}·d^{-1}) ± SE	E_T (kg·tree^{-1}·d^{-1}) ± SE
County (irrigated)				
Picea Pungens	4	260.2 ± 23.2	188.4 ± 17.3	273.9 ± 18.4
Malus ioensis	6	225.5 ± 34.9	180.8 ± 27.6	32.1 ± 5.5
Acer saccharinum*	1	186.9	130.3	244.9
Homestead (non-irrigated)				
Picea pungens	8	175.2 ± 24.2	138.5 ± 21.2	21.5 ± 4.9
Pyrus calleryana	3	257.8 ± 21.7	197.6 ± 20.4	40.35 ± 14.5
Ulmus pumila*	1	220.7	159.5	113.1
Prunus virginiana*	1	383.5	339.5	34.14
USFS (non-irrigated)				
Picea pungens	5	175.9 ± 22.9	139.6 ± 20.1	20.8 ± 7.4
Pinus contorta	5	147.1 ± 22.1	107.7 ± 16.6	45.1 ± 10.2
Gleditsia triacanthos*	1	63.9	47.1	25.32

Note: Average daily J_o, J_s, and E_T for each species at each site location.
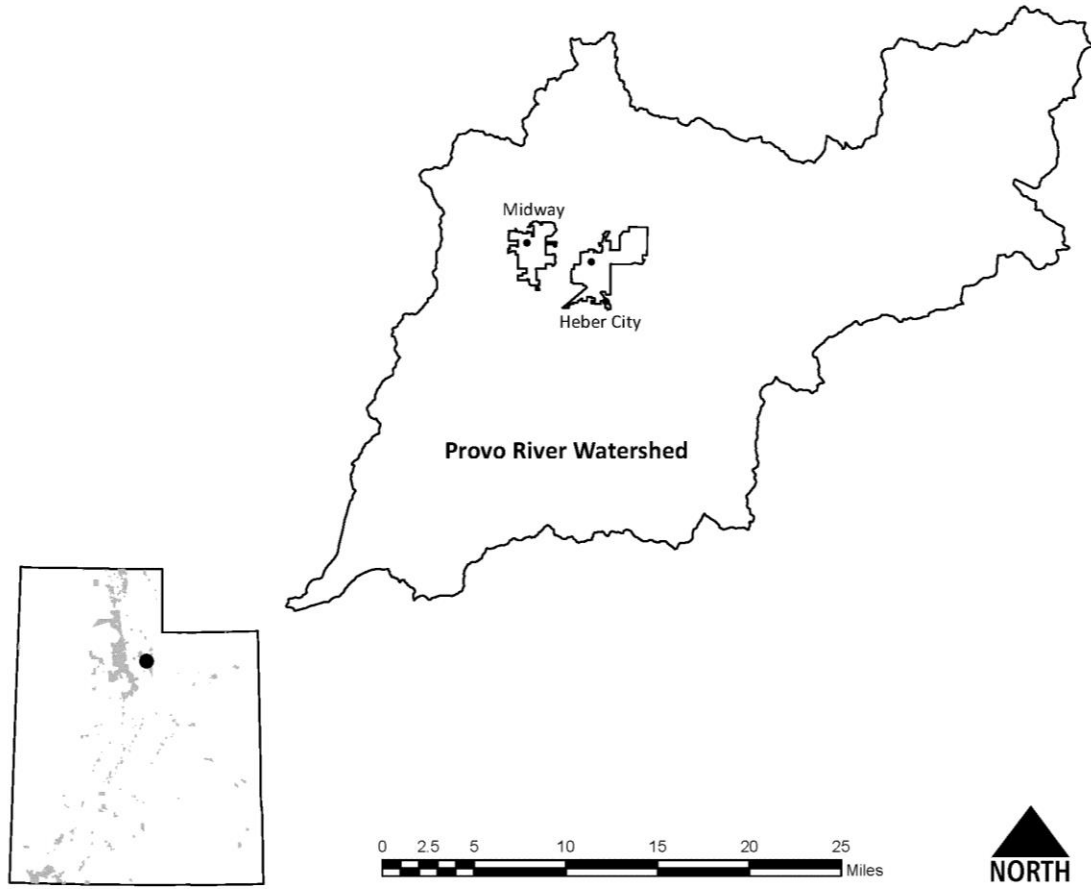
Figure 1. Map of study area. Study sites were located in Heber City, UT (n=2) and Midway, UT (n=1). Both locations occur within the middle reaches of the Provo River watershed.
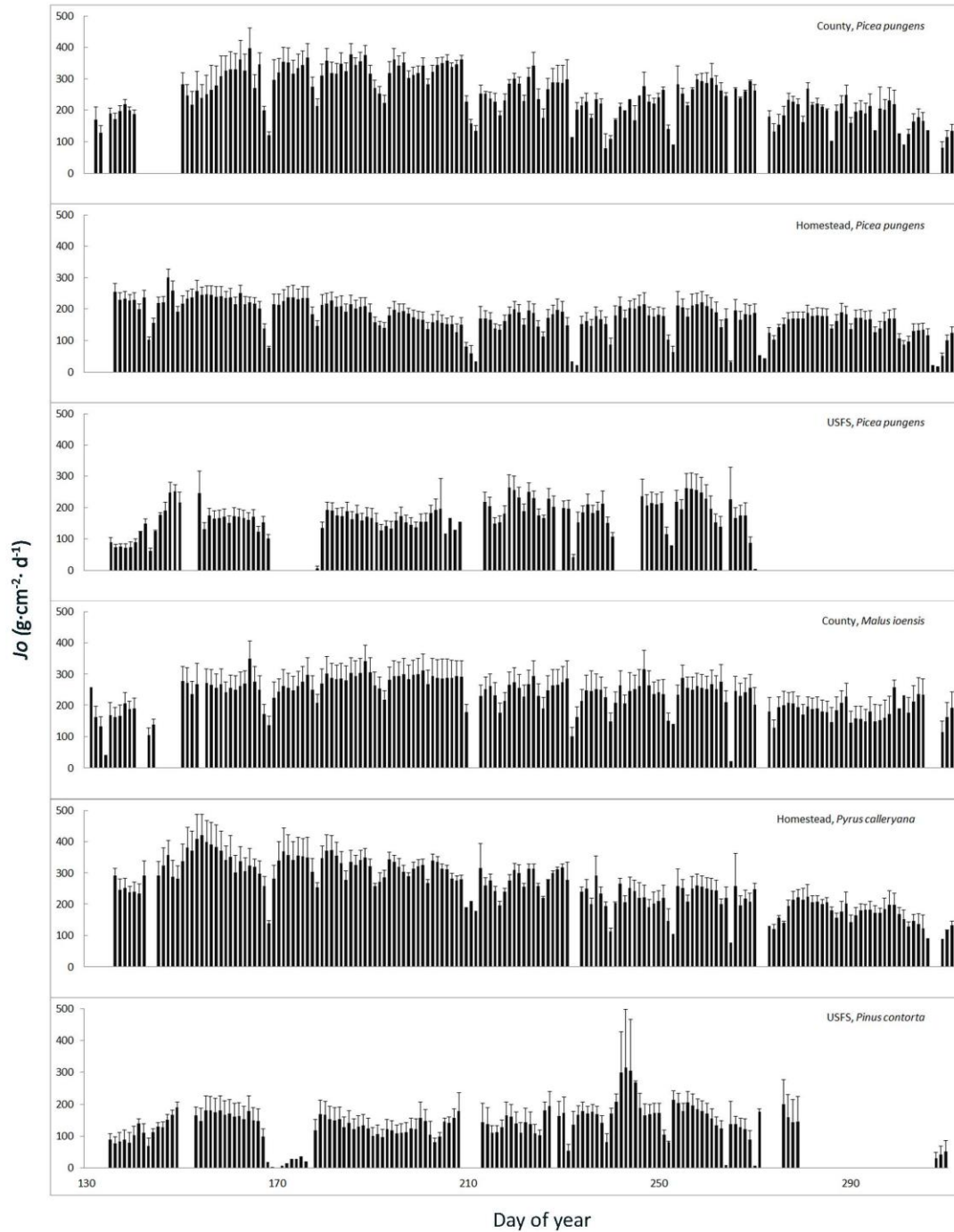
Figure 2. Patterns of sap-flux (J_o) across the 2014 growing season. Tree species aggregated by site and J_o was averaged across all individuals to yield daily flux rates. Standard Error (SE) was calculated for each species and only species with adequate replication are represented in this figure.
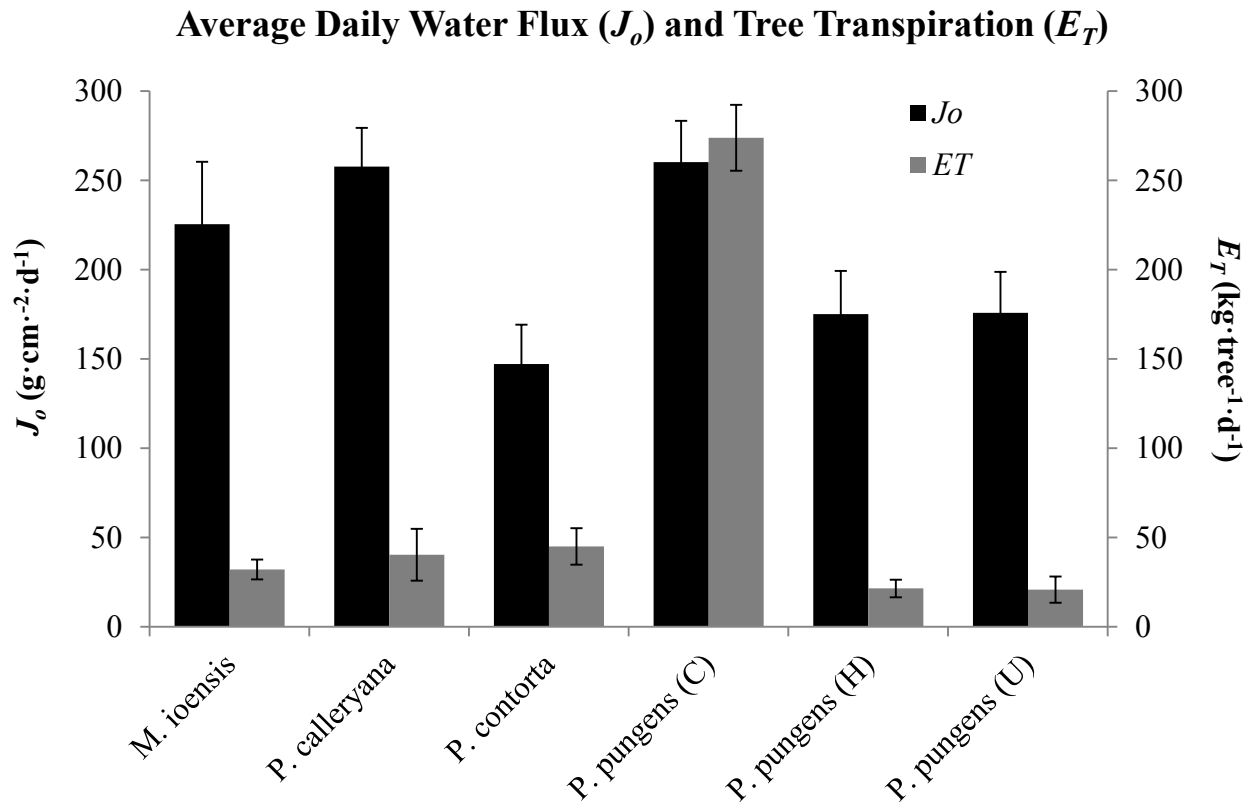
Figure 3. Average daily rates of sap-flux (J_o) and tree transpiration (E_T) by species and site. C: county, H: homestead, U: USFS. Ordered alphabetically by genus and species.
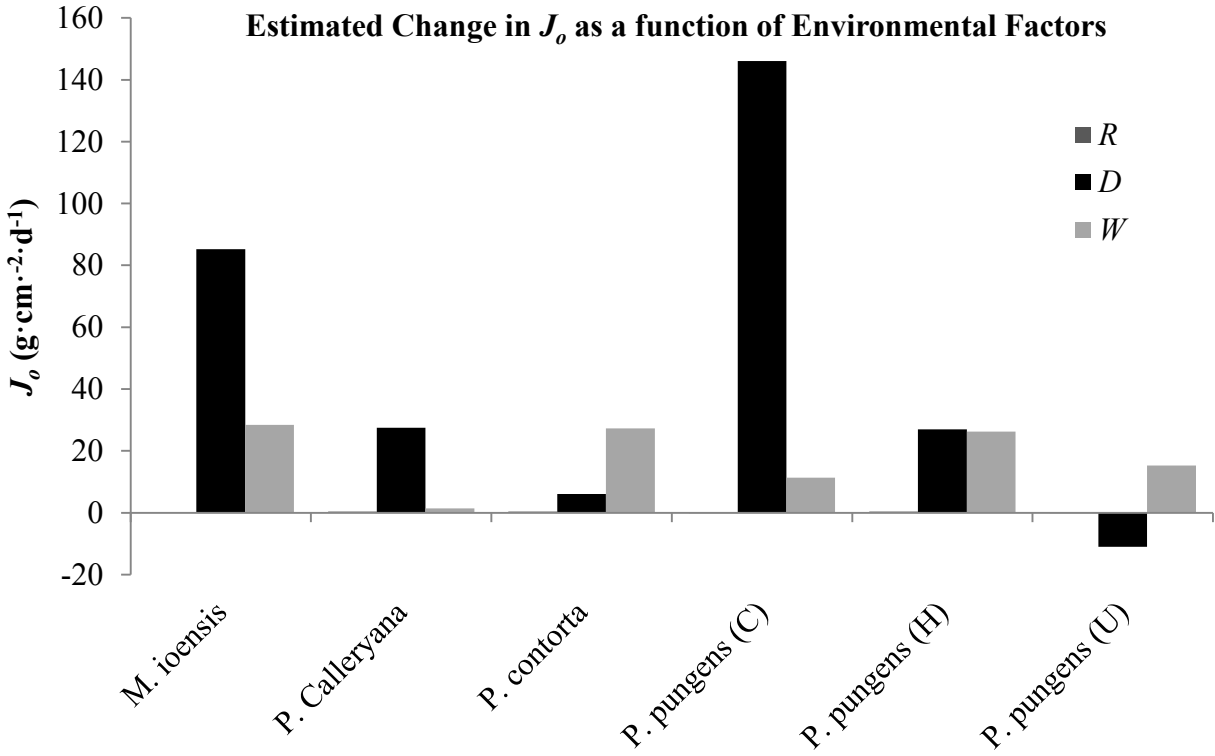
Figure 4. Estimated change in J_o as a function of environmental factors. Incoming shortwave radiation (*R*), vapor pressure deficit (*D*), and wind speed (*W*). Every one unit increase in each of the meteorological variables corresponds to an "x" unit increase in J_o. C: county, H: homestead, U: USFS. Ordered alphabetically by genus and species.
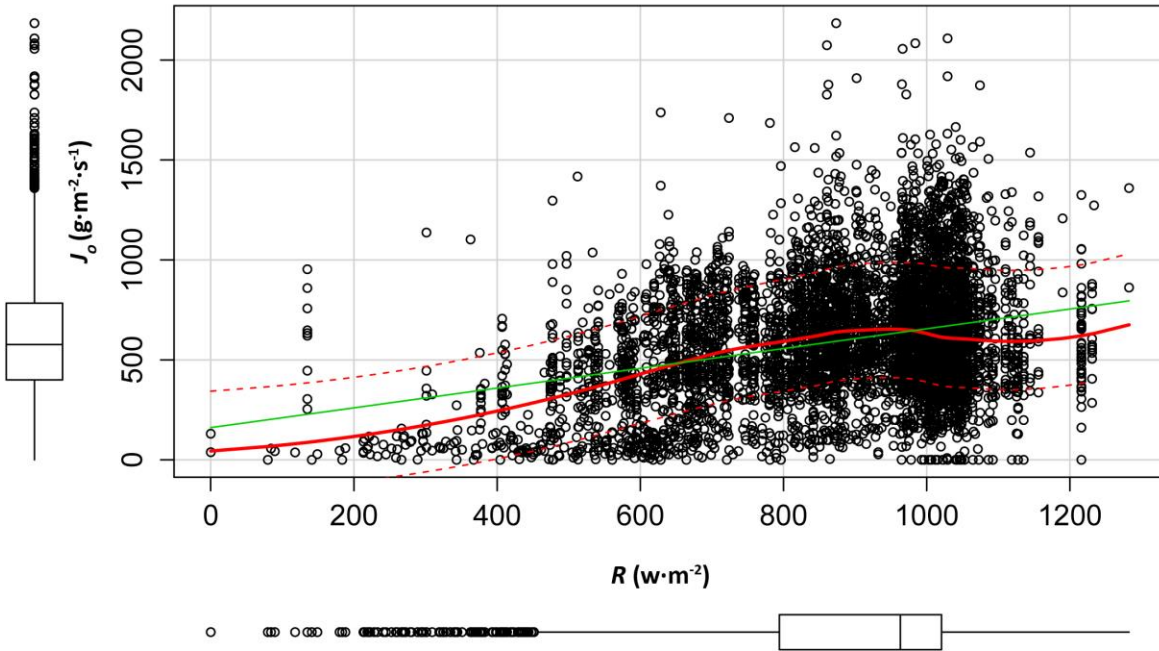
Figure 5. Sap-flux density (J_o) as a function of incoming shortwave radiation(R). Based on average daily for all trees at all sites. Green: line of best fit. Red: fitted parabolic line. Dotted red: average range of data.
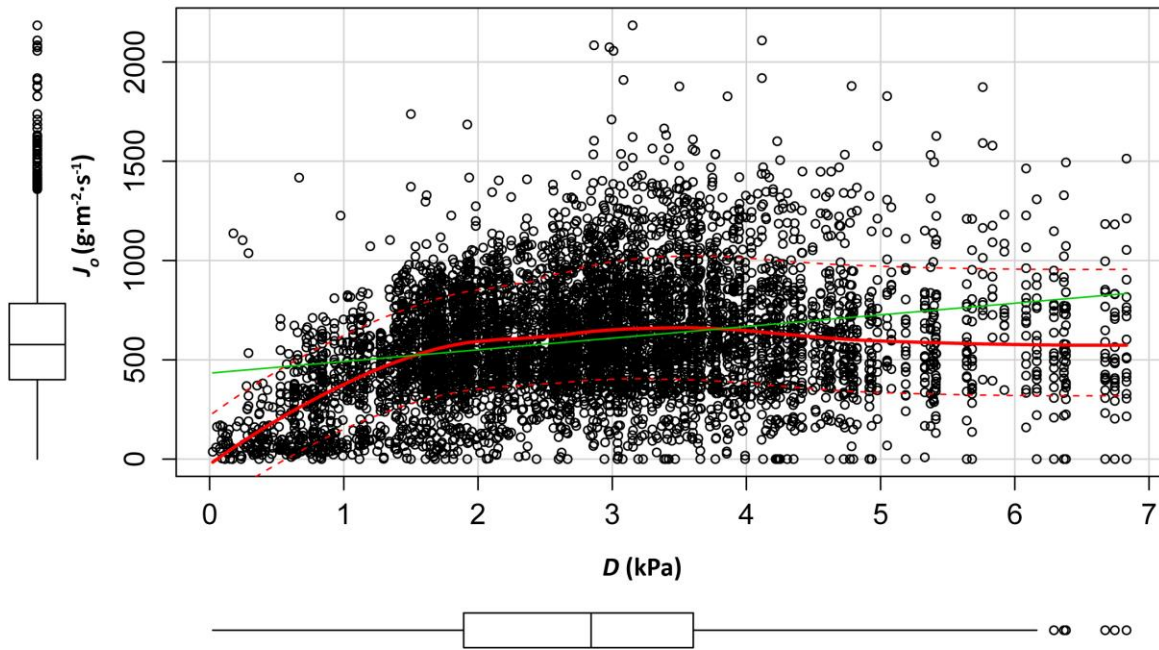
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Figure 6. Sap-flux density (J_o) as a function of vapor pressure deficit (D). Based on average daily for all trees at all sites. Green: line of best fit. Red: fitted parabolic line. Dotted red: average range of data.
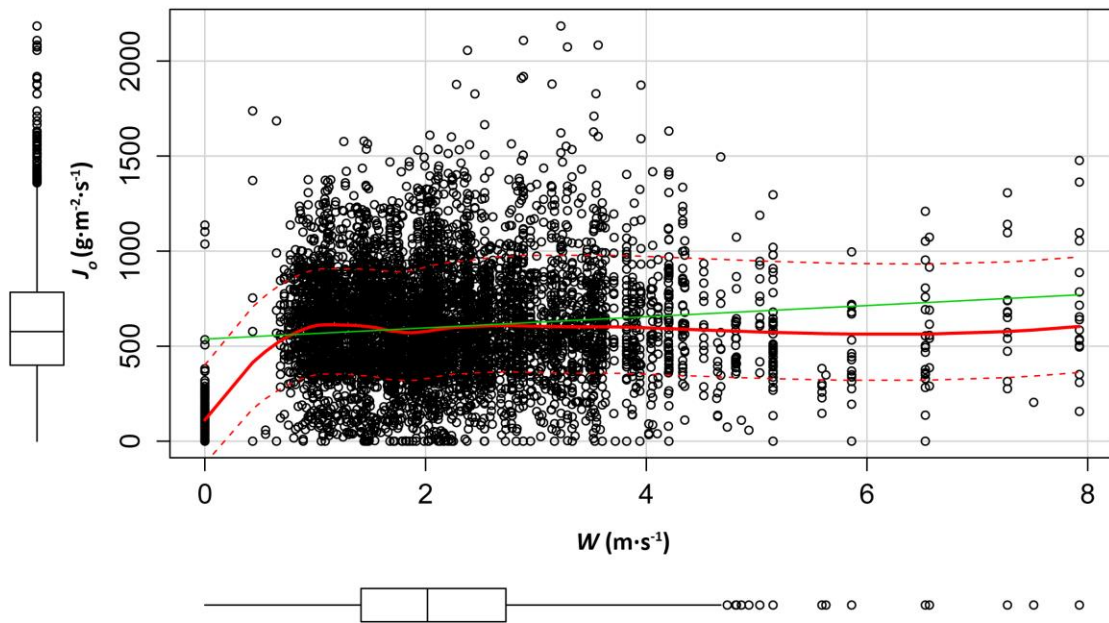
Figure 7. Sap-flux density (J_o) as a function of wind speed (W). Based on average daily for all trees at all sites. Green: line of best fit. Red: fitted parabolic line. Dotted red: average range of data.

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