

Response of Two Field-grown Maple (*Acer*) Species to Reduced Irrigation in a High Vapor Pressure, Semi-arid Climate

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Abstract. Urban forests provide many benefits for those living and working in urban areas. However, urban trees face many challenges (e.g., poor soil, drought, high vapor pressure deficits). Therefore, finding tree species adapted to urban climates is essential to maintain a healthy urban forest. In a semi-arid climate, field-grown 'Autumn Blaze' (*Acer* × *freemanii* 'Autumn Blaze') and shantung (*A. truncatum*) maple trees were subjected to three reference evapotranspiration (ET_o) based irrigation regimes (100%, 66%, and 33% ET_o) over a three-year establishment period (2003–2005). During this time, weather data, tree water relations, gas exchange, and growth data were measured. Growing-season maximum air temperature was 40.1°C, and maximum vapor pressure deficit was 6.8 kPa. Pre-dawn leaf water potential was more negative for 'Autumn Blaze' trees, and trees receiving the least amount of irrigation. However, midday stomatal conductance was similar for trees receiving 100% and 66% ET_o based irrigation regimes. In addition, stomatal conductance was greatest for 'Autumn Blaze' trees. Growth data were influenced by species and irrigation regime. However, despite differing irrigation volumes, greatest growth was not necessarily associated with trees receiving the greatest irrigation volume. Regardless of irrigation volume, these maple species maintained adequate growth and appearance when grown in an adverse, semi-arid climate. Despite reduced irrigation, each species appears to be adapted to harsh climates associated with urban environments.

Key Words. *Acer* × *freemanii* 'Autumn Blaze'; *A. truncatum*; Gas Exchange; Plant Factor; Reference Evaporation; Shantung Maple; Urban Forest; Vapor Pressure Deficit.

Trees growing in urban environments are exposed to harsh growing conditions. The heterogeneous physical environment found in urban areas expose urban trees to numerous abiotic stress factors (Zwack et al. 1999). De-icing salt (Fluckiger and Braun 1981), reduced soil moisture (Clark and Kjelgren 1990; Cregg 1995; Fahey et al. 2013), limited soil volume availability for root expansion (St. Hilaire and Graves 2001), and precipitation runoff onto impermeable surfaces (St. Hilaire and Graves 2001) reduce water accessibility to urban tree roots. Furthermore, compaction of urban soils may result in excessive soil moisture (Kawase 1981), or increase flooding potential (Zwack et al. 1999). Urban pollution may also influence growth, and limit survival of urban trees (Muir and McCune 1988). Urban soils also tend to have greater temperatures when compared to soils of non-urban areas, and greater soil temperatures may promote faster soil moisture

evaporation (Graves and Dana 1987). In addition, non-vegetative, urban surfaces (e.g., asphalt, concrete) lack evaporative cooling, and when compared to vegetative surfaces (e.g., ground covers, turf), are good conductors of energy (Montague et al. 2000). Therefore, non-vegetative surfaces store more energy, and have greater surface temperatures, when compared to vegetative surfaces (Doll et al. 1985; Montague et al. 2000). Greater surface temperatures increase longwave radiation flux and sensible heat, which increase air temperature, decrease relative humidity, and raise vapor pressure deficits (VPD) in urban areas (Kim 1992; Cregg and Dix 2001). The combination of increased longwave radiation from non-vegetative surfaces (Heilman et al. 1989; Montague et al. 2000) and greater combustion from urban vehicles create an urban heat island (Kim 1992). As a result of the urban heat island, radiation load in urban sites increases, and temperatures in

urban sites may be 8°C to 10°C greater when compared to temperatures in surrounding rural locations (Oke 1987; Harp et al. 2002). Due to increased radiation found in urban sites, atmospheric drought stress (when the rate of transpiration from tree leaves exceeds capacity of tree roots to absorb water (Cregg and Dix 2001) is common for trees growing in urban forests. Atmospheric drought stress is enhanced in urban trees due to increased temperatures, greater VPD (Cregg and Dix 2001), and limited soil moisture. Vapor pressure deficit is calculated as the difference between the amount of water vapor in the air compared to what the air could hold at saturation vapor pressure (Campbell and Norman 1998), and is one of the forces that enhance water vapor movement from tree leaves (Cregg and Dix 2001). Due to the interaction of low humidity and heat loading, in urban sites, daytime VPD often exceeds 5 kPa, while in mesic environments daytime VPD generally remains near 2 kPa (Bush et al. 2008). Because saturation vapor pressure increases exponentially with temperature, at a given relative humidity, VPD also increases as temperature increases. Therefore, greater air temperature (as found in urban heat islands) can dramatically increase evaporative demand for urban trees (Montague et al. 2000; Cregg and Dix 2001; Montague and Kjelgren 2004).

Urban forests provide numerous benefits (Jack-Scott et al. 2013). Urban trees increase property values (Anderson and Cordell 1988), improve air quality, reduce heat island effects through shading and transpiration (reduce cooling costs) (McPherson et al. 1997), and reduce stormwater runoff (Sanders 1984). In addition, urban trees may provide socioeconomic benefits (increase neighborhood unity, reduce violence and crime rates, alleviate stress, and provide spiritual fulfillment) to urban residents (Dwyer et al. 1992; Zhang et al. 2007; Troy et al. 2012). Research also indicates urban populations have positive attitudes toward urban trees, and value urban tree shade, aesthetics, improvement of air quality, and the ability of urban trees to reduce noise (Lohr et al. 2004; Jack-Scott et al. 2013).

The ability of urban trees and forests to mitigate effects of urban heat islands depends on maintaining a healthy canopy cover (Fahey et al. 2013). However, the average life span of urban trees is very short. An early report by Foster and Blaine (1978) indicated average life span of urban street trees in

Boston, Massachusetts, U.S. to be 10 years. That is, on average, trees needed to be replaced every 10 years. Sklar and Ames (1985) indicated established, urban street trees in Oakland, California, U.S., had an annual mortality rate of 6% to 8%. In a another study conducted in Oakland, California, annual mortality rate of newly planted, urban street trees averaged 19% over a two-year period (Nowak et al. 1990). A more recent study suggests urban street trees in Baltimore, Maryland, U.S., have an annual mortality rate of 6.6% (Nowak et al. 2004). Others (Berrang et al. 1985) indicate life spans of urban trees can be substantially less when compared to trees growing in rural or native sites.

Gas exchange (stomatal conductance, transpiration rate, photosynthetic rate) of woody plants is controlled by the response of the plant to its environment (Montague et al. 2000), and urban heat loads can have a strong influence on urban tree physiology, growth, and survival. Leaves of woody plants placed over non-vegetative surfaces intercept more sensible heat and surface longwave radiation when compared to plants over a vegetative surface (Montague et al. 2000; Montague and Kjelgren 2004). Consequently, trees over non-vegetative surfaces often have greater leaf temperature, increased exposure to VPD, and lower stomatal conductance (g_s) when compared to plants over vegetative surfaces (Montague et al. 1998; Montague et al. 2000; Montague and Kjelgren 2004). How transpiration is influenced by increased evaporative demand depends on the extent to which a plant regulates stomatal opening (Choudury and Monteith 1986). To regulate transpiration, stomata of many woody plants close as VPD increases (Choudury and Monteith 1986; Montague et al. 2000). Plants that maintain open stomata dissipate more energy through transpirational, evaporative cooling, but transpire more water. Plants that close stomata transpire less water, but limit photosynthetic rate (A) and increase respiration due to greater leaf temperatures (Montague et al. 1998; Bauerle et al. 2003; Montague et al. 2004).

Depending upon species and climate, woody landscape plants grown over non-vegetative surfaces in urban-like environments may have increased g_s and transpiration (Potts and Herrington 1982; Zajicek and Heilman 1991), or decreased g_s and transpiration (Kjelgren and Clark 1993; Montague et al. 1998; Montague et al. 2000; Montague et al.

2004) when compared to woody plants growing over vegetative surfaces. Kjelgren and Clark (1993) found morning-to-evening g_s of sweetgum (*Liquidambar styraciflua*) trees in an urban plaza in Seattle, Washington, U.S., was lower when compared to g_s for sweetgum trees in a nearby park. Montague et al. (1998; 2000; 2004) found containerized shrubs (*Euonymus kiautschovicus* 'Manhattan' and *Cornus sericea*), containerized trees (*Acer platanoides* 'Crimson King', *Salix matsudana* 'Navajo' and *Platanus occidentalis*), and balled and burlapped *Acer platanoides* 'Emerald Queen' and *Tilia cordata* 'Greenspire' trees grown over pine bark mulch had greater leaf temperature, were exposed to greater VPD, had lower g_s , and less water loss when compared to shrubs and trees growing over established turf.

Cregg and Dix (2001) monitored crown air temperature, leaf water potential, and gas exchange (g_s and A) of mature (15–30 year old) trees (*Fraxinus pennsylvanica* 'Marshall's Seedless', *Quercus rubra*, and *Pinus nigra*) growing in an urban and a rural college campus site. They reported greater air temperature and VPD for trees in the urban site. In addition, tree crown air temperature and pre-dawn leaf water potential (ψ_l) were lower, and gas exchange was greater for *Q. rubra* and *F. pennsylvanica* 'Marshall's Seedless' trees growing at the rural college campus location. For *P. nigra*, differences between sites was minimal.

Additionally, Zajicek and Heilman (1991) indicate containerized crapemyrtle (*Lagerstroemia indica*) cultivars ('Hope', 'Seminole', 'Victor', and 'Carolina Beauty') placed over pine bark mulch had greater water loss when compared to plants grown over turf, or bare soil. Transpiration rates for honeylocust (*Gleditsia triacanthos inermis*) and green ash (*Fraxinus pennsylvanica*) trees grown over non-vegetative surfaces in urban settings were also greater when compared to transpiration rates for trees grown over vegetative surfaces in rural sites (Potts and Herrington 1982; Whitlow and Bassuk 1988).

Because water deficits often develop in urban landscapes, more information is needed to establish irrigation requirements for urban trees. An ideal method to schedule irrigation would be to estimate water requirements, and replenish the root system with the required volume (Mathers et al. 2005). However, because irrigation requirements of many landscape tree species are not well

known, and vary with climate (Montague et al. 2004; Kjelgren et al. 2005), nursery and landscape irrigation managers are often unsure of the volume of water that landscape trees require (Beeson 2005). In fact, because of the lack of information regarding tree irrigation requirements, landscape and nursery trees are frequently irrigated in excess (which may result in waterlogged soil, poor plant growth, increased irrigation runoff, leached nutrients, increased water bills, and misuse of irrigation water) or deficit amounts (which may result in poor plant growth, poor plant aesthetics, and plant death) (Kjelgren et al. 2000; Montague et al. 2004; Mathers et al. 2005). In either case, performance of ornamental tree species will not meet production or landscape expectations.

A robust approach to estimate the water needs of plants is to define plant water loss factors by a constant, standardized measure of reference water loss that is a function of climatic factors (Levitt et al. 1995). The American Society of Civil Engineers Penman-Monteith (ASCE-PM) equation has defined reference evapotranspiration (ET_o) as the rate of evapotranspiration from a short, cool-season reference grass surface (Allen et al. 2005), and variables needed to calculate ET_o (wind speed, air temperature, humidity, incoming shortwave solar radiation) are readily available from automated weather stations. The ASCE-PM approach determines plant water loss by parameterizing empirically measured plant evapotranspiration (E_c) as a function of ET_o using a Plant Factor (PF). The dimensionless PF is computed as:

$$[1] \quad PF = (E_c) / (ET_o)$$

where both E_c and ET_o have units of depth of water evaporated (mm) / (unit time). Water loss of turf-grass is closely related to ET_o. Therefore, PF values have been developed for many turf species (Carrow 1995; Ervin and Koski 1998). However, due to the difficulty of quantifying values (Kjelgren et al. 2000), the great diversity of species (Sun et al. 2012), and the reality that PF values determined in one climate may not translate to another climate (Kjelgren et al. 2005), there are a limited number of PF values reported for landscape tree species (Levitt et al. 1995; Montague et al. 2004; Niu et al. 2006; Fox and Montague 2009; Costello 2013).

There is a great need to evaluate tree species to determine species that are adapted to the limited soil moisture and harsh climate often found in urban landscapes (Costello 2013). 'Autumn Blaze' maple is one of the many Freeman maple cultivars (*Acer × freemanii*) developed from crosses between silver maple (*A. saccharinum*) and red maple (*A. rubrum*) (Santamour 1993). Research indicates Freeman maples are more resistant to stress when compared to red maples (Bachtell 1989), and Zwack et al. (1999) suggests Freeman maples are more ornamental when compared to silver maples. Shantung maple (*A. truncatum*) is native to China (Pair 1987), and has been found to be a drought- and heat-tolerant species (Liu 1989; Pair 1994; Wang et al. 2006). Even though each of these species are considered tolerant of high temperatures and adapted to xeric conditions, research investigating response of Freeman and shantung maples to limited soil moisture while growing in a semi-arid (high VPD) climate has yet to be conducted. Therefore, in a semi-arid, high-VPD site (used to simulate an urban environment), this research investigated water relations, gas exchange, and growth of two newly transplanted, field-grown maple varieties subjected to three ETo-based irrigation regimes.

MATERIALS AND METHODS

Research was conducted in a field nursery located in Lubbock, Texas, U.S. Prior to year one of the study, nine container-grown (11.4 L) trees of *A. × freemanii* 'Autumn Blaze' and *A. truncatum* were planted 2.5 m apart in east-west rows with 3.0 m between each row. Soil consisted of an Amarillo fine sandy loam (fine-loamy, mixed, superactive thermic Aridic Paleustalfs) with a pH of 8.5, organic matter content of 0.8%, and CEC 13.5 meq 100 g⁻¹. Irrigation regimes were based upon estimated tree root area (cm²) and local ETo (mm). During the first growing season of the study (April–October), tree root area was estimated using the radius of the plant's container (23.0 cm) plus an additional 15.2 cm. Following the first growing season, radius means of each variety were estimated to equal 122 cm and 183 cm, for the second and third growing seasons, respectively (Fox et al. 2014). Weather data were collected from an onsite weather station (Campbell Scientific, Inc., Logan, Utah, U.S.). Weather data were used to calculate daily total ETo. Reference evapotranspira-

tion was calculated using ETo calculation software (Allen 2000). Based on total weekly ETo and estimated root surface area, irrigation was applied once each week at one of three PF values [100%, 60%, and 30% of ETo (high, intermediate, and low, respectively)]. Irrigation volume was calculated as follows:

$$[2] \quad V = [((ETo) - (P)) * (A)] / (1000)] * (PF)$$

where V is irrigation applied each week (L), P is weekly precipitation (cm), A is mean soil surface area above each tree's roots (cm²), and PF is fraction of ETo (1.0, 0.66, or 0.33). Once each week trees were irrigated through a drip irrigation system. To achieve the desired irrigation volume, each tree had one, two, or three emitters (3.8 L hr⁻¹) placed at the base of the tree. Trees were not fertilized or pruned during the experiment, and weed control was performed by hand (each tree was surrounded by bare soil from trunk to drip line). To aid establishment, during the growing season prior to the study all trees were irrigated at 100% ETo. Irrigation treatments began during the second growing season, and continued for two additional growing seasons.

Daily maximum air temperature, and VPD at maximum daily air temperature during each growing season were plotted against day of the year (01 May through 31 August). From May through September, monthly pre-dawn ψ_p and midday gs were measured six days after an irrigation event. Water relations and gas exchange data were measured the following dates for year one (16 June, 30 June), year two (27 May, 03 June, 17 June, 01 July, 21 July, and 05 August), and year three (09 June, 30 June, and 16 September). Pre-dawn ψ_1 was measured at 0600 (Central Daylight Savings Time) on two randomly selected, mature leaves from each tree. Leaves were excised before dawn, immediately sealed in a plastic bag, and placed in a portable cooler. Pre-dawn ψ_1 was measured within a half-hour of excision with a pressure chamber (model 3005; Soilmoisture Corp., Santa Barbara, California, U.S.). Each day pre-dawn ψ_1 was measured, midday (1200 to 1400) gs was measured with a steady-state porometer (model LI-1600; LI-COR®, Lincoln, Nebraska, U.S.). For gs data collection purposes, single trees of each treatment combination (irrigation regime × species) were grouped, and one measurement cycle (time required to measure gs on each tree in group)

included a tree from each treatment \times species combination. Measurement cycles were repeated throughout the day until g_s on all trees were measured. Stomatal conductance data were measured on five mature, full-sun leaves from each tree.

Each year (prior to budbreak and in November), trunk diameter 15 cm above soil level was measured on each tree using a digital caliper (Mitutoyo Corp., model 500-196, Japan). For each tree, trunk cross-sectional area increase was determined as the difference between spring and autumn measurements. Also in the spring of each year, 10 arbitrarily selected shoots on each tree were selected, and shoot elongation (based on growth from the bud scale scar to the terminal bud) was measured on selected shoots in late autumn. At the termination of each growing season, each tree was defoliated and total leaf area for each tree was measured using a portable leaf area meter (model LI-3000 with LI-3050A conveyor attachment; LI-COR, Lincoln, Nebraska, U.S.).

Because statistical trends in yearly data were similar (irrigation regime effects did not differ between years), water relations and gas exchange data for each variety, irrigation treatment, and year were pooled (pre-dawn ψ_1 and g_s for each species \times irrigation regime were taken as the mean of 66 and 165 measurements, respectively). In addition, trends in yearly growth data were similar. Therefore, growth data from each growing season were also pooled (shoot elongation, trunk cross sectional area increase, and total tree leaf area for each species \times irrigation regime were taken as the mean of 90, 9, and 9 measurements, respectively). Data were exposed to ANOVA appropriate for a randomized block design (three randomized irrigation regime blocks with three trees of each species planted randomly within each irrigation block). If differences were identified, means were separated by Fisher's least significance difference procedure (LSD, $P \leq 0.05$) (SAS Institute Inc., Version 9.2 for Windows® operating system). For trunk cross-sectional area increase, total tree leaf area, pre-dawn ψ_1 , and g_s , there were no species \times irrigation treatment interactions. Therefore, only main effects (irrigation regime or species) data are presented. However, an irrigation by species interaction occurred for shoot elongation. Therefore, shoot elongation irrigation \times species means are presented. In addition, g_s versus VPD data (VPD

at time of day when g_s data were measured) were analyzed by regression analysis. Based upon significance of the equation and coefficient of determination (R^2) value, linear curves were selected for each species \times irrigation treatment (SAS Institute Inc., Version 9.2 for Windows operating system).

RESULTS AND DISCUSSION

Total volume of water applied to each tree in the low-irrigation regime ranged from 483 L during the first growing season, to 2,072 L during the third growing season. Irrigation to each tree receiving intermediate irrigation ranged from 967 L during the first growing season to 4,145 L during the third growing season. During the first growing season, each high-irrigation regime tree was irrigated with 1,466 L. While during the third growing season, each high-irrigation tree received 6,443 L. Throughout the experiment period, all trees of each variety survived and appeared healthy. Annual precipitation in Lubbock, Texas, U.S., averaged 48.2 cm from 1997 to 2007 (Anonymous 2008). During the experiment period, total yearly precipitation was greater than average during the second year of the study (68 cm), but lower than average during the first and third years of the study (21 cm and 33 cm, respectively). Weather variables measured at the experiment site varied throughout each growing season, but trends were similar between growing seasons. In addition, climatic conditions during each growing season were typical for summer days in the Texas High Plains.

In the first growing season, maximum daily air temperature and maximum daily VPD were 39.5°C and 6.5 kPa, respectively (Figure 1). Minimum, maximum daily air temperature and minimum, maximum daily VPD for the first growing season were 15.9°C and 0.8 kPa, respectively. During the second growing season, maximum daily air temperature was recorded as 38.8°C, while maximum daily VPD was 6.2 kPa. Climatic data from growing season number three indicate maximum daily air temperature was 40.2°C, and maximum daily VPD was 6.8 kPa. Minimum, maximum daily air temperature, and minimum, maximum daily VPD for growing season number three were recorded as 8.2°C, and 0.14 kPa, respectively. Mean, maximum daily temperature for each growing season was 31.5°C, 30.5°C, and 31.3°C for growing sea-

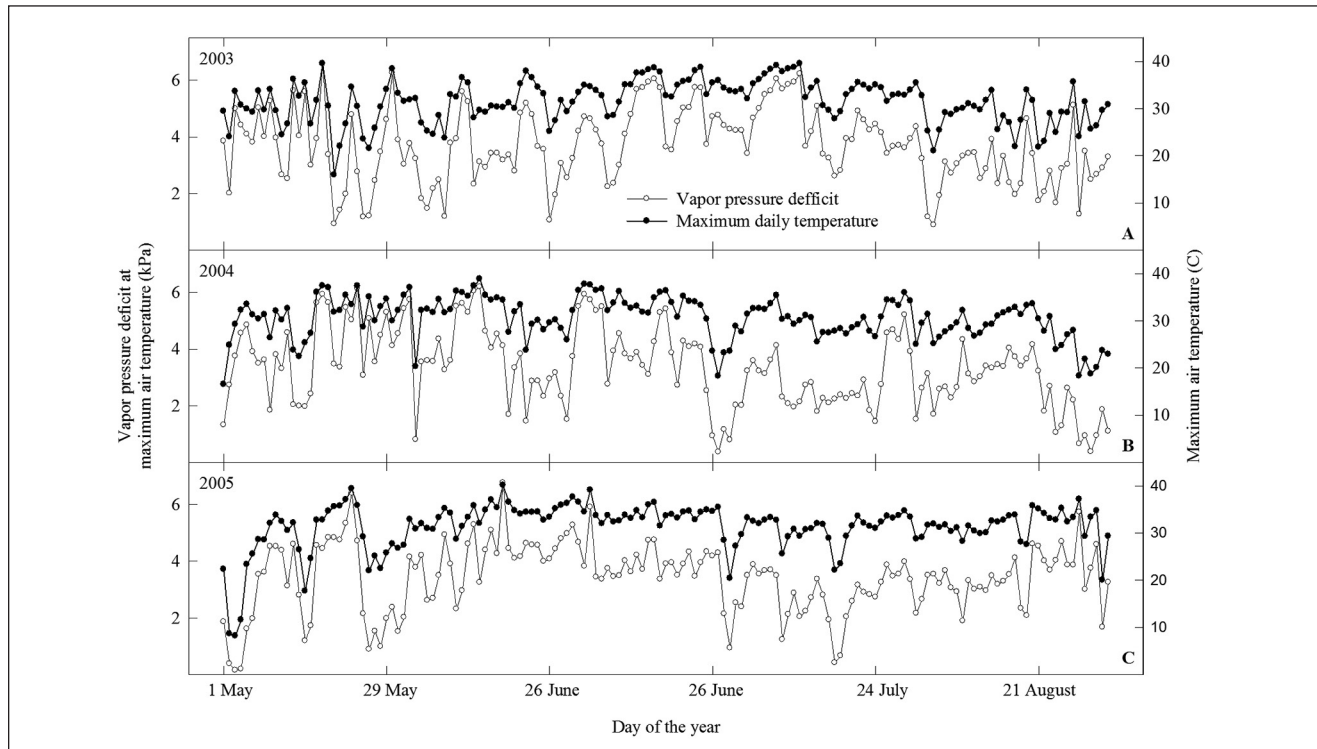


Figure 1. Growing season maximum daily air temperature and maximum daily vapor pressure deficit at maximum daily air temperature for Lubbock, Texas, U.S., during A) 2003, B) 2004, and C) 2005 growing seasons.

sons one, two, and three, respectively. Additionally, mean maximum daily VPD for each growing season was 3.7, 3.3, and 3.4 kPa for growing seasons one, two, and three, respectively. During growing seasons one, two, and three, maximum daily vapor pressure deficit was greater than 4.0 kPa for 38%, 31%, and 33% of growing season days, respectively.

In a study investigating response of green ash, Austrian pine (*Pinus nigra*), and northern red oak (*Quercus rubra*) to urban VPD, Cregg and Dix (2001) reported summer maximum air temperatures in Lincoln, Nebraska, U.S., ranging from 18°C to 42°C, and VPD ranging from 6.3 to 12.1 kPa. The results of the current study are similar to a study conducted by Bush et al. (2008). They examined gas exchange and growth of a number of tree species [*A. platanoides* (Norway maple), *G. triacanthos*, *Platanus acerifolia* (London planetree), *Populus fremontii* (Freemont cottonwood), *Quercus gambelii* (gambel oak), and *Q. rubra*] growing in urban Salt Lake City, Utah, U.S. Over the course of a single summer they reported daily maximum temperatures ranging from 10°C to 35°C, and vapor pressure deficits ranging from less than 1 to 5 kPa. Although not conducted in an urban setting, climatic con-

ditions encountered by trees in the current study simulate conditions reported for many urban areas.

Pre-dawn ψ_1 was least negative for trees receiving the greatest amount of irrigation (Figure 2A), while trees receiving the least amount of irrigation had the most negative pre-dawn ψ_1 . Between species (across all irrigation treatments), ‘Autumn Blaze’ maple trees were under less water deficit stress (more positive ψ_1) when compared to shantung maple trees (Figure 2A). More negative pre-dawn ψ_1 reflects limited soil moisture available to the roots, or an inefficient water conducting system (Nash and Graves 1993; Zwack et al. 1998). Water deficit stress (more negative ψ_1) in response to reduced irrigation has been reported for numerous woody landscape plants (Stabler and Martin 2000; Niu et al. 2008; Montague and Fox 2009), and several maple species in particular (Pair 1994; Zwack et al. 1998; Zwack et al. 1999; Barton and Walsh 2000; St. Hilaire and Graves 2001; Bush et al. 2008). Little information is available relating ψ_1 to water deficit stress of shantung maple. However, Barton and Walsh (2000) examined ψ_1 of transplanted (using a 1.2 m tree spade) and non-transplanted shantung maple trees. They reported pre-dawn and

midday ψ_1 of transplanted trees to be more negative (greater water deficit stress) when compared to non-transplanted shantung maple trees. Zwack et al. (1998) exposed containerized Freeman maples ('Autumn Fantasy', 'Celebration', and 'Marmo') to four water deficit cycles. They concluded drought-stressed seedlings had more negative ψ_1 when compared to non-drought stressed seedlings. Leaf water potential data indicate relative stress differences between species and irrigation regimes, and water deficit stress severity of stress imposed (Zwack 1998).

In the current study, data indicate stress levels between irrigation treatments were somewhat similar, and 'Autumn Blaze' maple might be somewhat more drought-tolerant when compared to shantung maple. However, irrigation treatments in this research did not produce water deficit stress levels (as measured by pre-dawn ψ_1) to the extent as those imposed in previous research. Nash and Graves (1993) exposed 'Franksred' red maple to pre-dawn ψ_1 levels of -0.9 MPa. Containerized Freeman maples exposed to four consecutive drought cycles reached pre-dawn ψ_1 levels of -1.36 MPa (Zwack et al. 1998). Most negative mean pre-dawn ψ_1 reached in this research was -0.52 MPa (low irrigated trees and shantung maple). Although statistical differences were found between ψ_1 treatments and species, the greatest differences between irrigation regimes was just 12% (between low- and high-irrigation regimes, and shantung and 'Autumn Blaze' species). Because drought-stressed plants could not eliminate internal water deficits during the night, data indicate a large change in irrigation regime can have a small, yet significant influence on plant water status.

Stomatal conductance data indicate trees receiving intermediate and high-irrigation treatments had greatest mean gs (Figure 2B). Also, 'Autumn Blaze' trees had greater mean gs when compared to shantung maple trees. In addition, for each species and irrigation regime, a linear relationship is indicated as gs decreased in response to increasing VPD (Figure 3). Reduced gas exchange in response to water deficits is common for many landscape tree species (Stabler and Martin 2000; Montague et al. 2007) and has been documented for maple (Zwack et al. 1998; Zwack et al. 1999; Cregg and Dix 2001; Baurele et al. 2003; Bush et al. 2008). Compared to irrigated controls, Baurele et al. (2003) found containerized 'Autumn Blaze' maple seedlings had decreased gas

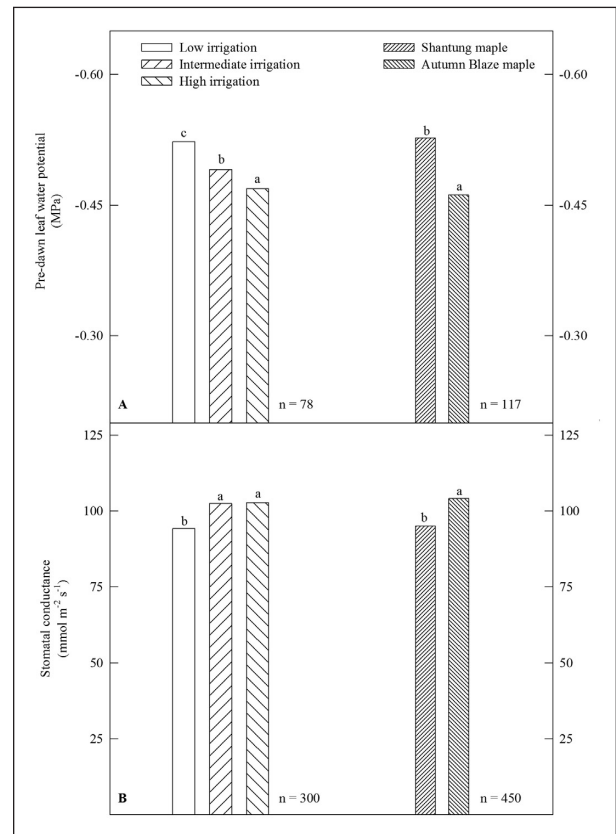


Figure 2. Effect of irrigation volume (low = 33%, intermediate = 66%, and high = 100% of reference evapotranspiration) on A) pre-dawn leaf water potential and B) stomatal conductance of field-grown shantung maple (*Acer truncatum*) and 'Autumn Blaze' maple (*A. x freemanii* 'Autumn Blaze') trees. Different letters indicate effect of irrigation volume on pre-dawn leaf water potential, or stomatal conductance (Fisher's least significance difference procedure, $P \leq 0.05$).

exchange (gs and A) just one day after the beginning of a drought cycle, and after a five-day drought cycle gs and A were reduced 80% and 70%, respectively. Zwack et al. (1999) exposed containerized 'Autumn Blaze' seedlings to three water deficit cycles. They reported reduction of gs after each deficit cycle.

However, few reports are found that demonstrate gas exchange does not change as field-grown, woody landscape species are exposed to reduced irrigation. Data from the current study suggest gs was similar for trees receiving intermediate and high-irrigation treatments. In addition, gs for trees receiving the low-irrigation regime were just 8% lower when compared to trees that received high and intermediate irrigation volumes (Figure 2B). For several growing seasons, Fox et al. (2014) irrigated field-grown Texas and Mexican redbud (*Cercis canadensis*) vari-

eties at 33%, 66%, and 100% of ETo. They indicate gs of these varieties did not differ when irrigated at 66% or 100% ETo. Active accumulation of solutes in leaves (osmotic adjustment) allows for turgor maintenance, despite low plant water potential, and has been documented in red, Freeman, and other maple species (Abrams and Kubiske 1990; Khalil and Grace 1992; Zwack et al. 1998; Zwack et al. 1999).

Although not evaluated in this study, it might be hypothesized turgor potential of drought-stressed plants (trees in the intermediate and low-irrigation regimes) was more negative when compared to plants receiving the high-irrigation treatment (Zwack et al. 1998). Because osmotic adjustment helps plants sustain gs and A rates during periods of drought, it is possible gas exchange of trees receiving the intermediate and low-irrigation treatments

osmotically adjusted. Therefore, gs of intermediate trees was similar to trees receiving the high-irrigation treatment. Although several authors have demonstrated shantung maple (Liu 1989; Wang et al. 2006) and Freeman maples (Zwack et al. 1999; Baurele et al. 2003) have drought resistance; research presented here may be the first to document results on gas exchange of field-grown shantung and 'Autumn Blaze' maple trees in response to drought conditions.

Linear equation probability values (VPD × gs) were not significant for each species × irrigation regime relationship (Figure 3). Therefore, the independent variable (VPD) did not reliably predict the dependent variable (gs). Therefore, for these maple trees, VPD did not influence gs. Decreased gs in response to increasing VPD has been documented for numerous woody plant species (Mon-

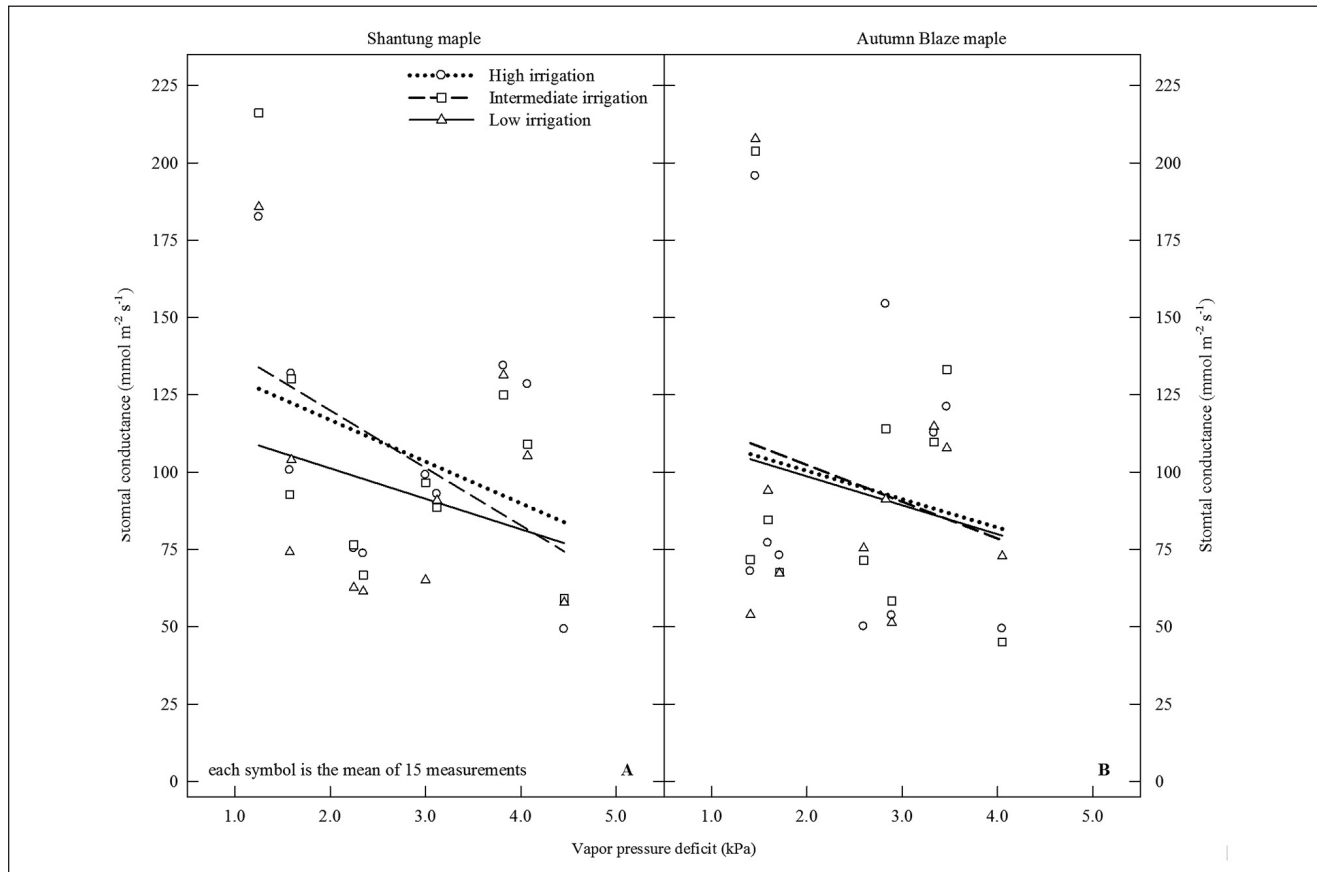


Figure 3. Influence of vapor pressure deficit on stomatal conductance (gs) for field-grown shantung maple (*Acer truncatum*) and 'Autumn Blaze' maple (*A. x freemanii* 'Autumn Blaze') trees irrigated at three irrigation volumes (low = 33%, intermediate = 66%, and high = 100% of reference evapotranspiration). Predicted regression line equations are followed by R² values and significance for the equation: A) shantung maple high irrigation: $gs = 144.1 - 13.6x$, $R^2 = 0.16$, $P = 0.25$; shantung maple intermediate irrigation: $gs = 157.4 - 18.6x$, $R^2 = 0.21$, $P = 0.17$; shantung low irrigation: $gs = 121.1 - 9.9x$, $R^2 = 0.08$, $P = 0.44$; B) 'Autumn Blaze' maple high irrigation: $gs = 118.9 - 9.2x$, $R^2 = 0.03$, $P = 0.63$; 'Autumn Blaze' maple intermediate irrigation: $gs = 126.6 - 12.1x$, $R^2 = 0.06$, $P = 0.49$; 'Autumn Blaze' low irrigation: $gs = 117.2 - 9.3x$, $R^2 = 0.04$, $P = 0.59$.

tague et al. 1998; Montague et al. 2000; Montague and Kjellgren 2004; Bush et al. 2008). Previous research indicates stomatal closure in response to increasing VPD is a mechanism to regulate plant water status and avoid damaging effects of water deficit stress, such as excessive cavitation (Bush et al. 2008). However, maple trees in this study did not exhibit such behavior. Increased g_s in response to increasing VPD (g_s therefore not controlled by VPD) has been reported for a limited number of tree species (Montague et al. 2000; Bush 2008), and because A is directly influenced by g_s (Niu et al. 2008), this response is a possible adaptation to maximize gas exchange in environments where soil water is non-limiting (Montague 2000; Bush 2008).

Differences among irrigation treatments were not found for trunk cross-sectional area increase (Figure 4A). However, across all irrigation regimes, shantung maple had 57% more trunk cross-sectional area increase when compared to 'Autumn Blaze' maple. Total tree leaf area was greatest for trees receiving the greatest amount of irrigation volume, and 'Autumn Blaze' maple trees had 48% more total leaf area when compared to shantung maple trees (Figure 4B). Shoot elongation data had an irrigation \times species interaction (Figure 4C). Therefore, shoot elongation irrigation \times species means are presented. For shantung maple, trees receiving the intermediate irrigation volume had the greatest shoot elongation. However, 'Autumn Blaze' trees receiving the intermediate and high-irrigation regime had greater shoot elongation when compared to low-irrigation trees. Reduced apical growth is a common response for plants exposed to water deficit stress (Kramer and Boyer 1995), and has been documented in maple (Abrams and Kubiske 1990; St. Hilaire and Graves 2001). Although few studies have investigated gas exchange of field-grown (or urban-grown) trees in high-VPD, urban-like climates (Cregg and Dix 2001; Bush et al. 2008), previous reports on apical growth of field-grown trees subjected to reduced irrigation in semi-arid, high-VPD climates is sparse. In a study closely associated with this research project, in a high-VPD, semi-arid climate, Fox and Montague (2009) subjected numerous tree species (*Acer*, *Cercis*, *Fraxinus*, *Prunus*, and *Quercus*) to variable, ETo-based irrigation rates (33%, 66%, and 100% ETo). They determined total tree leaf area and shoot elongation for field-grown trees were not always cor-

related with trees receiving the greatest amount of irrigation volume. Fox et al. (2014) reported comparable results for several redbud varieties. All reduced irrigation trees in research reported here were subjected to at least minor water deficit stress (Figure 2). Overall, apical growth for maple trees likely was reduced due to reallocation of assimilates. One of the mechanisms trees use to acclimate to mild soil drying is to shift allocation of carbohydrates from apical to root growth. Thus increasing root surface area by decreasing the apical growth fraction, but increasing the root fraction of total plant biomass (Khalil and Grace 1992; Kramer and Boyer 1995).

Shantung maple is native to semi-arid regions of northern China (Pair 1987), and is thought to be

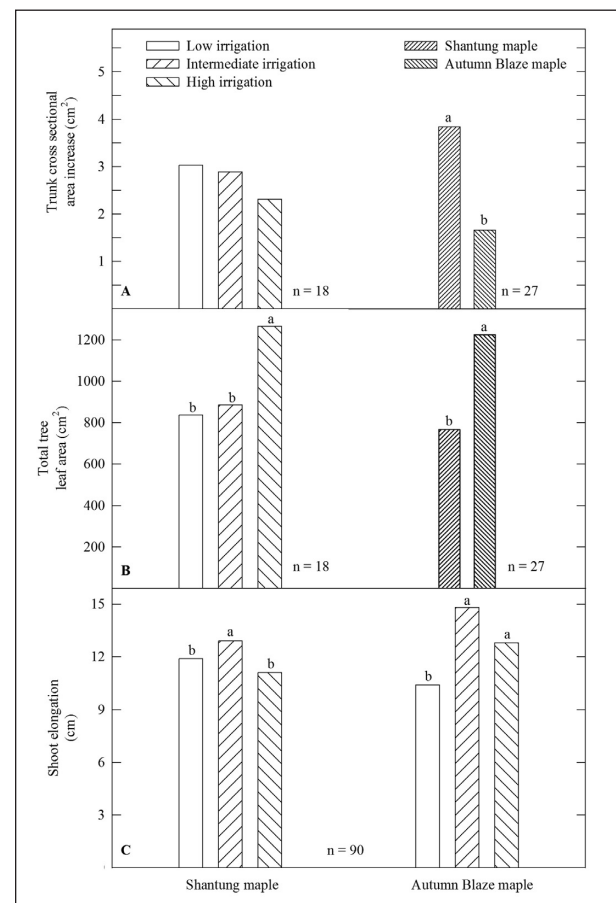


Figure 4. Effect of irrigation volume (low = 33%, intermediate = 66%, and high = 100% of reference evapotranspiration) on **A)** trunk cross-sectional area increase, **B)** total tree leaf area, and **C)** shoot elongation for field-grown shantung maple (*Acer truncatum*), and Autumn Blaze maple (*A. × freemanii* 'Autumn Blaze') trees. Different letters indicate effect of irrigation volume on trunk cross-sectional area, leaf area, and shoot elongation (Fisher's least significance difference procedure, $P \leq 0.05$).

well adapted to heat, cold, drought, and variable soil types (Liu 1989; Pair 1994; Wang et al. 2006; Fox and Montague 2009). Freeman maples are the result of controlled pollination, or natural crosses between red and silver maples (Bachtell 1989; Santamour 1993) and considerable genetic variation in relation to drought tolerance exists within parent populations (Bachtell 1989; Abrams and Kubiske 1990; Santamour 1993; Zwack et al. 1998; Bauerle et al. 2003). With increased emphasis on sustainable and stress-resistant trees in urban landscapes (Zwack et al. 1998), it is urgent for trees planted in urban landscapes to be acclimated to those environments. This research demonstrates 'Autumn Blaze' and shantung maple trees are well adapted to the high-temperature, high-VPD, low soil moisture conditions found in many urban sites. For over three growing seasons, each species maintained acceptable growth, appearance, form, and health under extreme climatic and soil moisture conditions. There is a great need for well-designed, long-term research to investigate response of tree species to urban growing conditions (Cregg and Dix 2001). Therefore, this research demonstrates long-term field research in semi-arid climates can replicate urban growing conditions, and be used to help increase the knowledge base of tree species adapted to harsh, urban environments.

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Résumé. Les forêts urbaines procurent de multiples bénéfices aux individus vivant et travaillant en milieu urbain. Cependant, les arbres urbains sont confrontés à de nombreux défis (sols pauvres, sécheresse, faible humidité atmosphérique, par exemple). Par conséquent, trouver des espèces d'arbres adaptées aux conditions climatiques urbaines est essentiel au maintien d'une forêt urbaine en santé. Dans un climat semi-aride, des érables de Freeman 'Autumn Blaze' (*Acer × freemanii* 'Autumn Blaze') et des érables de Shantung (*Acer truncatum*) croissant en plein champ ont été soumis à trois régimes distincts d'irrigation correspondant à des taux d'évapotranspiration de 100%, 66% et 33% pendant une période d'établissement de trois ans (2003-2005). Durant cette période, les données climatiques, les relations hydriques, les échanges gazeux et les données de croissance ont été mesurés. La température maximale ambiante a été de 40,1 °C et le déficit de pression de vapeur maximale était de 6,8 kPa. Le potentiel hydrique des feuilles avant l'aube était plus négatif chez les érables de Freeman 'Autumn Blaze' et chez les arbres ayant reçu le plus faible volume d'arrosage. Cependant, la conductance stomatique en mi-journée était similaire pour les arbres recevant les régimes d'arrosage produisant des évapotranspirations de 100% et 66%. En outre, la conductance stomatique était la plus élevée chez les érables 'Autumn Blaze'. Les données de croissance étaient influencées en fonction des espèces et des régimes d'arrosage. Cependant, en dépit des différents volumes d'arrosages, le taux de croissance le plus élevé n'étaient pas nécessairement as-

socié aux arbres qui recevaient le plus grand volume d'irrigation. Indépendamment du volume d'irrigation reçu, ces deux espèces d'érables ont maintenu une croissance et une apparence adéquates, lorsque cultivées dans un climat semi-aride défavorable. Malgré une irrigation réduite, chaque espèce semblait adaptée aux climats rigoureux associés aux milieux urbains.

Zusammenfassung. Urbane Waldflächen liefern viele Vorteile für diejenigen, die in urbanen Räumen leben und arbeiten. Dennoch sind Stadtbäume vielen Problemen ausgesetzt (z.B. verarmte Böden, Trockenheit, hohe Saftdruckdefizite). Daher ist es für die Erhaltung eines gesunden urbanen Baumbestands nötig, an die urbanen Klimaverhältnisse angepasste Baumarten zu finden. Über einen Zeitraum von drei Jahren (2003-2005) wurden in einem semi-ariden Klima an zwei Ahornsorten (*Acer × freemanii* 'Autumn Blaze') und (*A. truncatum*) aus der Freilandzucht basierend auf der Evapotranspiration (ET₀) drei unterschiedliche Bewässerungsmethoden (100%, 66%, and 33% ET₀) getestet. Während dieser Zeit wurden die Wetterdaten, Baum-Wasser-Relationen, Gasaustausch und Wachstumsdaten registriert. Die Maximale Lufttemperatur betrug in der Vegetationsperiode 40,1°C und das maximale Saftdruckdefizit betrug 6,8 kPa. Das Blattwasserpotential vor der Dämmerung war bei „Autumn Blaze“-Bäumen mehr negative und bei Bäumen, die die wenigste Wassermenge durch Bewässerung erhielten. Zusätzlich war die stomatale Leitfähigkeit bei „Autumn Blaze“-Bäumen am größten. Die Wachstumsdaten wurden beeinflusst durch Art und Bewässerungsart. Dennoch war ungeachtet der unterschiedlichen Bewässerungsmengen das größte Wachstum nicht assoziiert mit den Bäumen, die das meiste Wasser bekommen haben. Unabhängig von dem Bewässerungsvolumen entwickelten sich die Ahorne adäquat, wenn sie in einem semi-ariden Klima fußen. Trotz reduzierter Bewässerung schien sich jede Art an die herrschen Bedingungen in urbanen Umfeldern anzupassen.

Resumen. Los bosques urbanos proporcionan muchos beneficios para aquellos que viven y trabajan en las zonas urbanas. Sin embargo, los árboles urbanos se enfrentan a muchos desafíos (por ejemplo, la pobreza del suelo, la sequía y el déficit de presión de vapor elevado). Por lo tanto, la búsqueda de especies de árboles adaptadas a climas urbanos es esencial para mantener un bosque urbano saludable. En un clima semi-árido, árboles de maple de 'Autumn Blaze' (*Acer × freemanii* 'Autumn Blaze') y *A. truncatum* fueron sometidos a tres condiciones de evapotranspiración de referencia (ET₀) basados en regimenes de riego (100%, 66% y el 33% ET₀) durante un período de establecimiento de tres años (2003-2005). Durante este tiempo, se midieron los datos del tiempo, las relaciones árbol - agua, intercambio de gases y los datos de crecimiento. La temperatura del aire máxima en la estación de crecimiento fue de 40.1 °C, y el déficit de presión de vapor máximo fue de 6,8 kPa. El potencial hídrico foliar fue más negativo para los árboles 'Autumn Blaze' y los árboles que recibieron la menor cantidad de riego. Sin embargo, la conductancia estomática fue similar para los árboles que recibieron regimenes de riego de 100% y 66 de ET₀. Además, la conductancia estomática fue mayor para los árboles 'Autumn Blaze'. Los datos de crecimiento fueron influenciados por las especies y régimen de riego. Sin embargo, a pesar de diferentes volúmenes de riego, los crecimientos mayores no estuvieron necesariamente asociados con los árboles que recibieron el mayor volumen de riego. Independientemente del volumen de riego, estas especies de maple mantuvieron el crecimiento y la apariencia adecuada cuando crecieron en un clima semiárido adverso. A pesar de la irrigación reducida, cada especie parece estar adaptada a climas extremos asociados con los entornos urbanos.