WATER AS A LIMITING FACTOR IN THE DEVELOPMENT OF URBAN TREES[1]

by James R. Clark and Roger Kjelgren

Abstract. Trees growing in urban and forest situations experience internal water stress. Water may be a significant growth limiting factor in both situations. Supply and demand considerations, such as the reservoir of water in urban soils and the atmospheric factors which regulate demand, are important. Urban foresters may play an important role in managing water deficits through timely irrigation and species selection. The differential responses of tree taxa to internal water stress makes species selection critical in managing urban trees. Yet the lack of comprehensive experimental observations of tree response to drought in cities makes this difficult.

Soil water deficits, and the plant water stress which accompany them, are significant limiting factors in the growth of urban trees. Yet, Whitlow and Bassuk (22) observed, "very few data are available to document the severity and frequency of water deficits in urban street trees." Nonetheless, observation of urban trees across a wide geographic range has demonstrated some clear patterns: newly transplanted street trees die if supplemental water is not provided, mature trees may die during relatively mild, periodic droughts, and urban trees have relatively short life-spans. The goal of this paper is to provide a framework for plant responses to water deficits in urban areas and to develop an overview of water as a limiting factor for the growth of urban trees.

Patterns of Water Use by Trees

Plant water use is dynamic, varying over the course of a day as well as a season. Water loss is driven by atmospheric demand, limited by the available soil moisture reservoir, and modified by plant anatomy and physiology. Whether atmospheric demand or soil supply is the limiting factor responsible for plant water stress is an unresolved question. For trees growing in New York City, Whitlow and Bassuk (22) suggested that atmospheric demand was more significant than supply in inducing water stress in urban trees.

This question cannot be addressed without consideration of both the time scale involved and the intensity of individual stress events. For example, are water deficits occurring over short- or long-term periods of time? What is the extent of soil moisture (and internal plant) depletion? We have little or no information about the intensity of urban water stress events and their influence on plant development. Both diurnal and seasonal patterns of water use by urban trees can be distinguished.

Diurnal water use. During the sun-lit hours of a day, transpiration (foliar and cuticular) frequently exceeds absorption of soil water by roots, and water stored in roots, stems and branches may be depleted by transpirational water loss. This creates mid-day deficits (9). During the night, when transpirational demand is minimal, absorption of soil water often restores tissues to full turgor and relieves any deficit. Mid-day water deficits are a normal occurrence, developing under atmospheric conditions promoting transpiration (even under non-limiting soil moisture conditions). They may or may not be significant to overall plant productivity and water balance.

Seasonal water use. As soil moisture is progressively depleted, a tree may be unable to relieve internal water deficits on a daily basis. Thus, each successive day may begin with a slightly greater internal deficit, which increases in severity until the soil moisture reservoir is replenished. Since plant water status exists in equilibrium with soil moisture, the intensity of this seasonal deficit can be assessed by measuring the seasonal progression of plant water stress. Seasonal water stress is commonly measured as pre-dawn leaf water potential (LWP) which reflects overall plant water balance.

Plant Response to Water Stress—General Considerations

Adaptation vs. acclimation. Plants may be adapted to resist water stress and possess the ability to acclimate to such conditions. Adaptations are heritable characters which confer the

[1] Adapted from a presentation made at the 1989 Annual Conference of the International Society of Arboriculture, St. Charles, IL.

ability to survive repeated drought conditions. The mechanisms which allow this, range from deep, wide-spreading root systems to the shedding of foliage. Adaptation to water stress occurs as an evolutionary process, over many generations, in response to continuing drought conditions in a natural habitat.

Acclimation is the active process of developing morphological and physiological modifications in response to environmental cues. Closure of stomata, osmotic adjustment, alteration of leaf orientation and reduction in leaf area are examples of acclimation to water stress. "Drought hardening" occurs in response to short-term, localized water deficits, permitting physiology, anatomy and morphology to be actively changed.

The adaptation to naturally occurring drought poses a significant limitation to species dispersal. Since individual plants or groups of plants possess the ability to tolerate water stress, the identification of material adapted to drought is a logical avenue for selection of genotypes tolerant of water stress. The known variation in drought hardiness among provenances of Douglas-fir (13), poplar (16) and red maple (20) are examples of this process. Identification of such genotypes is on-going effort in both forest management (15) and urban forestry (Whitlow, personal communication).

Plant Response to Water Stress—Specific Considerations

Plants respond to drought by: 1) drought avoidance, with the plant not subject to drought (used by annual plants only); 2) drought tolerance through desiccation avoidance, where plants avoid dehydration; 3) drought tolerance through dessication tolerance, where plants tolerate dehydration (14). Harris (6) described plants in these 3 response-categories as evaders, conservers and spenders, respectively. He noted that most temperate deciduous landscape trees fell into the spender class. However, Levitt (14) suggested that most woody plants possess some combination of both types of drought tolerance (the distinction between "most woody plants" and "deciduous landscape trees" may be significant).

Spenders act to maintain a high plant water status, even with drying soil. This is accomplished by two mechanisms: 1) osmotic adjustment and 2) extensive root systems. Osmotic adjustment is a response to a decrease in total internal water potential. By lowering osmotic potential, cell turgor is to be maintained, preventing wilting. For a given LWP, plants with osmotic adjustment may be able to keep to their stomata open longer than those without the capacity for adjustment. The capacity to osmotically adjust varies widely among common urban trees (1). An extensive root system allows the maintenance of water absorption as soil moisture content decreases by making the root system a more efficient exploiter of the root zone water supply. Any description of "extensive" is difficult, for this term reflects a balance of root and shoot within historical site conditions. For example, some soils may not be conducive to the development of a deep root system.

Conservers develop morphological, physiological and anatomical characters that restrict water loss. These might include closure of stomata, a thicker cuticle, leaf presentation to reduce radiation loading, increased capacity for water transport, and increased root:shoot ratio.

Water Deficits in Cities vs. Forests

Urban trees are commonly thought to experience water deficits more severe than those encountered in forests. Given the limited observations of water stress in urban trees, this statement should not be held as universally true.

Many urban trees develop diurnal and seasonal water deficits (Table 1). Mid-day LWP values have not exceeded -2.5 MPa, while minimum pre-dawn LWP values are between -0.8 and -1.2 MPa (no water deficit would be measured at 0.0 MPa). Whitlow and Bassuk (22) did not detect a seasonal decrease in predawn LWP, i.e., internal

Table 1. Extent of predawn and mid-day water deficits in urban trees.

Author	*Site*	*Species*	*Leaf water potential pre-dawn (MPa)*	*mid-day (MPa)*
Whitlow and Bassuk	NYC	Fraxinus, Tilia	-0.9	-2.5
Kjelgren	Seattle	Liquidambar	-1.0	-1.1
Peterson and Eckstein	Hamburg	Tilia	-1.8	—
Potts and	Syracuse	Gleditsia	-1.2	-2.5

water deficits were relieved each night. A seasonal pattern of internal deficits did develop in *Liquidambar* in Seattle (11), where predawn potentials declined from -0.25 MPa in June to -1.0 MPa in late August.

Such water potential measurements, and the internal plant water relations they represent, are no more severe than those found in natural forests (9). Walters *et al.* (21) summarized typical LWP for woody riparian and wetland communities in the southwest United States. Predawn LWP values below -2.0 MPa frequently occurred. High values were associated with moist habitats such as streambanks and higher elevations; lower values were associated with drier, warmer habitats. For 6 woody species in Austria, mid-day LWP ranged from -1.42 to -3.86 MPa (8). Over the course of the growing season, predawn LWP became increasingly severe, reaching -3.16 MPa in the shallow rooted *Cornus* sp. and -2.36 MPa in the more deeply rooted *Quercus* sp. Predawn LWP reached 1.9 MPa for *Quercus alba* growing in Missouri (7).

An exception to the pattern of similar internal water deficits in urban and forest trees was noted by Peterson and Eckstein (17), who found that forest-grown *Tilia* developed only moderate seasonal water deficits. Pre-dawn LWP declined from -0.3 MPa to -0.8 MPa for such trees. This is in contrast to their observations of street trees of the same taxa, where LWP declined from -0.3 to 1.8 MPa over the May-September measurement period (Table 1).

An Overview of Water Management for Urban Trees

Water can limit development of urban trees over both short and long time periods. While the midday stomatal closure experienced by many deciduous trees may reduce water loss, such closure also reduces overall photosynthetic productivity. Over longer periods of water stress, the development of extensive root systems and high root:shoot ratios reduce the proportion of plant productivity expressed in the canopy. In severe, continuing episodes of reduced water availability, plants may die.

The intensity of water stress in urban trees, and its effect on plant development, depends on several factors including the character of urban plantings, the species typically used, and management practices.

Unique nature of urban plantings. Landscape plantings in urban areas differ in at least two ways from natural plantings: 1) unusual combinations of environmental factors, not seen in forests, are frequently encountered and 2) trees often are physically isolated from one another. Urban areas are a mosaic of small, fragmented spaces, each with a unique microclimate. The variation in radiation loading, evaporative demand, soil, surface covering, physical space etc, in this mosaic is extreme (3). Complex combinations of environmental factors may present an individual species with microclimates never encountered in nature.

In addition, many urban trees exist in isolation from the continuous canopy frequently found in forests. This isolation creates a different set of microclimatic conditions surrounding the tree, and increases the atmospheric demand for water loss. For example, the relative humidity is much lower in the area around isolated trees, which increases evaporative loss. The stomatal behavior of isolated trees may be more closely coupled to atmospheric demand than in closed-canopy forest trees (10), resulting in greater water use.

The species distribution in urban areas differs from that in forests. In urban areas, deciduous trees predominate (especially when regeneration has been artificial). This may be significant for water use, since evergreen plants are usually more drought tolerant than deciduous plants (4). As part of a program to identify taxa with potential for use in urban roof-top gardens, Duhme (4) developed classes of intensity of water use. In general, deciduous trees used the greatest amount of water, followed by broad- and needle-leafed evergreen plants.

Management Considerations

Species selection. For forest trees, "Choosing the proper species is the most powerful genetic method we have of managing drought-stress" (15). Unfortunately, no comprehensive summary of experimental observations on the degree/extent of drought tolerance of common urban tree species and cultivars is available. Thus, we cannot select drought tolerant species for urban areas.

Two extensive summaries of "drought tolerance" developed from field observations are those of Gerhold *et al.* (5) and Berrang and Karnosky (2). However, there is still a significant lack of guiding information on what constitutes demonstrated drought resistance.

It is unclear if there is an advantage to using taxa which are conservers over those that are spenders. Whitlow and Bassuk (22) noted that a water spender *(Fraxinus pennsylvanica)* and water conserver *(Tilia cordata)* were both successful street trees in New York City. Whether water spenders, with their extensive root systems, create more problems than conservers with pavement heaving has not been addressed.

A further complication to the use of broadly-based lists of "drought tolerance" is the paucity of information dealing with the ability of a taxa to possess both spendor and conserver characters (as Levitt suggested may occur). Since most deciduous landscape trees are water spenders, the ability to develop additional characters or mechanisms that would reduce water loss would permit growth to continue in the face of drought. This appears to be the case with sweetgum *(Liquidambar styraciflua)*. This species exhibited both types of mechanisms as a function of the historical site conditions (11). These mechanisms included osmotic adjustment, mid-day stomatal closure, vertical leaf presentation, reduced leaf area and lower transpiration rates.

Until more comprehensive experimental results are available, it seems inappropriate to make broad recommendations about selecting taxa resistant to water stress. Peterson and Eckstein (17) and Whitlow *et al.* (23) offered some specific recommendations for drought tolerant taxa appropriate for cities based on a series of field observations.

Site character—availability of soil moisture. Water deficits depend upon the relationship of water uptake to loss. Site character enters into both the supply and demand sides of this relationship. Water uptake is related to the size of the soil moisture reservoir and the presence of roots to absorb that moisture. For containerized and tree pit situations, estimates of the reservoir can be made in a straightforward manner, using the approach of Rakow (19). Creating such estimates is far more complex for traditional in-the-ground landscapes. It is clear that some assessment of the size of the soil moisture reservoir for any urban planting is an integral part to understanding the potential of water deficits to develop.

The availability of soil moisture during intermittent drought depends upon seasonal recharge, either natural or artificial. Mid-summer precipitation is limited in many areas (Table 2) and may not be sufficient to satisfy the water demand of landscape plantings. The nature of the soil surface in many parts of cities prohibits surface recharge even if precipitation occurs. Some water may move under pavement as water vapor. While subsurface recharge may be a significant source of water for urban trees, little is known about its pattern or potential.

Table 2. Pattern of seasonal precipitation for selected cities in the United States.

	Annual precip'n (in.)	*Monthly precipitation (in.)*					*May-Sept total*	*Per cent of annual*
		May	*June*	*July*	*Aug.*	*Sept.*		
Seattle	34	2.0	1.5	1.0	0.6	1.1	6.2	18
San Francisco	22	1.0	0.4	0.1	0.1	0.2	1.8	8
Minneapolis	25	2.2	3.8	3.9	2.6	2.6	15.1	60
Washington D.C.	42	3.5	3.6	3.5	4.0	4.0	18.6	44
Birmingham	53	5.0	3.8	5.0	5.0	3.4	22.2	42
Boston	43	3.3	3.3	3.3	3.5	3.6	17.0	40
Denver	14	2.0	1.8	1.5	1.5	1.3	8.1	58
Phoenix	8	0.2	0.1	0.6	0.9	0.8	2.6	33

Differences in the observations of Whitlow and Bassuk (22) and Kjelgren (11) may be, in part, due to differences in seasonal precipitation. New York City receives substantial amounts of rainfall during the growing season. In contrast, Seattle receives only 18% of its annual rainfall from May-September. Considering that a 35 ft. tree may lose 35 gal. of water a day in mid-summer (12), the value of applying small amounts (ex. 20 - 100 gal. biweekly) of supplemental water on an irregular basis seems minimal. Yet, sweetgum responded to such small amounts during a season of severe drought in Seattle (11). Ottman (personal communication) also observed benefits from applications of 20 gal. of water, especially in downtown tree pits. Even small amounts of water clearly affect survival and net productivity. From these observations, the value of supplemental irrigation seems undeniable.

Site character—loss of soil moisture. Urban spaces possess vastly different physical environments, with signifcant variation in evaporative demand (11, 22). Site analysis will define the relative intensity of demand on soil water by evaluating such factors as radiation load, wind, intensity/spacing of planting, etc. Without supplemental water, newly transplanted urban trees have poor survival rates. In Seattle, survival rates of transplanted trees approach 100% when trees are irrigated for 2 years (M. Black, personal communication; Clark, unpublished). Without supplemental water, survival rates may be 20%. Poor survival rates are not unique to urban areas, and occur for trees in any location—landscape, nursery, forest, etc.

Mature (i.e., established) trees are thought to be better able to tolerate water stress than seedlings or newly transplanted material. This may be due to the development of a root:shoot ratio in response to historical (i.e., long-term) site and management conditions. Trees growing on poor quality forest sites are known to have higher root:shoot ratios than those growing on good sites. This long-term acclimation to poor site quality should also occur in urban plantings.

A large tree which has not received supplemental irrigation for many years should be able to withstand the effects of an unusually dry year better than a tree whose regular pattern of irrigation is disrupted. In the latter case, the ability of the tree to take up water is balanced with historically high soil moisture availability. When that availability is reduced, the tree must restore a functional balance between growth pattern and site conditions. As with any change to mature trees, this may take several years. If severe water stress conditions develop as a result of a reduction in site soil moisture, trees may die or lose vigor. A drought situation can be disastrous for a tree which has received irrigation and fertilizers for many years prior to the water stress.

An additional consideration is the spatial distribution of trees in a planting. The stomatal behavior of isolated trees is more closely coupled to the surrounding environment than that of closed canopy trees. Thus, the creation of a canopy boundary layer through close spacing and dense planting may serve to reduce edge and wind effects. While the development of an individual trees may be reduced by increased competition, there may be a benefit to the entire planting.

At least two additional maintenance practices may affect water use by urban trees. The first involves inclusion of groundcovers, turf, seasonal plantings, etc. in a tree planting. Such materials will reduce the size of the soil moisture reservoir through their own water use. Since water is a major factor in competition, the effect of such adjunct plantings on tree vigor could be significant (see 6).

Second, supplemental fertilizers decrease root-shoot ratios and increase total leaf area, thereby reducing the overall drought resistance. Conversely, adequate fertility does maintain plant vigor, a significant component to stress responses. Further, osmotic adjustment depends upon adequate nutrition. Kjelgren (11) found that small amounts of supplemental fertilizer significantly increased the stomatal conductance and relative water content of water-stressed sweetgum growing in nutritionally poor soils.

Summary

Both urban and forest trees may encounter diurnal and longer-term periods of reduced water supply. In cities, the degree of reduction may vary widely, but does not occur in a random manner. Site factors such as exposure, pavement, and soil all interact with management activities and planting character in determining the relative intensity of water supply and demand. The response of urban trees to internal water deficits falls into several categories and is species-dependent. There is a need for comprehensive measurement of species responses to water deficits so that drought tolerance in urban areas may be more accurately assessed.

Acknowledgments. Thanks to Tom Hinckley, Al Wagar,and Tom Whitlow for their thoughtful and constructive reviews.

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