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SIMPLIFIED LANDSCAPE IRRIGATION DEMAND ESTIMATION: SLIDE RULES

R. Kjelgren, R. C. Beeson, D. R. Pittenger, D. T. Montague

ABSTRACT. *Irrigated urban landscapes must increasingly maintain economic and ecosystem value with less water in response to drought amplified and shifted by climate change. Efficient landscape water management requires estimating water amount demanded by plants that can be replaced by irrigation to meet minimum performance expectations. The extant approach to estimating landscape water demand is conceptually muddled and often regionally inappropriate. Simplified Landscape Irrigation Demand Estimation (SLIDE) Rules distills scientifically credible assumptions about urban landscape biological and physical complexity into guidelines for estimating water demand that are conceptually accessible and operationally useful. SLIDE Rules are: 1) oasis urban reference evapotranspiration (ETo) effectively represents water use of urban turf seasonally and for day-to-day irrigation scheduling, but is less accurate for estimating water use of non-turf surfaces, especially in dry climates; 2) a discrete number of Plant Factors (PF) adjust ETo to estimate water demand of general landscape plant type categories—turf, non-turf, and desert—that are adjusted for temperature and drought responses; 3) a hydrozone controlled by one irrigation valve is the smallest landscape unit manageable for water, thus overall zone irrigation is governed by the highest water demand plant within that hydrozone; 4) for hydrozones <80% plant cover, water demand can be estimated as volume of water based of individual plants using planar leaf area expressed as projected canopy area. SLIDE is a framework for designing and regulating water-efficient urban landscapes based on selection of appropriate PF's in combination with lower density planting and hardscape. SLIDE is aimed at stakeholders in urban landscapes who primarily design and regulate, but also manage, urban landscapes to use less water.*

Keywords. *Evapotranspiration, Irrigation scheduling, Landscape irrigation, Plant density, Plant factor, Water budget, Water need index, Water use.*

Urban landscapes have value. They are designed and managed plant systems that are biologically, ecologically, and architecturally diverse. Urban landscapes are composed of herbaceous (perennial turfgrass, some groundcovers, perennial and annual flowers) and perennial woody (trees, shrubs, vines, other ground covers) species. Unlike other managed plant systems such as agriculture and forestry, urban landscapes do not produce a marketable yield (Kjelgren et al., 2000). Instead, society derives value from landscapes designed to combine diverse species that thrive in various settings to meet expectations for aesthetics, utility (screening, cooling, and erosion control), recreational function, and ecosystem services (Bolun and Hunhammar, 1999). Landscapes have secondary economic rather than primary market value: urban turfgrass value has been estimated at $100 billion dollars (Haydu et al., 2006), while the appraised value of U.S. standing urban forest has been estimated to be $2.4 trillion for 3.8 billion trees (Nowak et al., 2002).

Urban landscapes are more complex than agriculture and forestry. Urban landscapes are biophysical mosaics of impervious surfaces (buildings, paving) and plant mixtures scaling from large monocultures (turfgrass) to small, biologically diverse planting beds (Ridd, 1995). Biological diversity within this mosaic can be especially large (Dirr, 2009), as woody and herbaceous species richness can be quite high even in small urban landscapes (Smith et al., 2006). Also, since a discrete landscape arises from diverse and interrelated arrangements among developers, owners, and managers (Hope et al., 2003), urban landscapes have a behaviorally complex dimension.

IRRIGATED LANDSCAPES

Urban landscapes often need irrigation to meet water demand to maintain value, particularly when composed of non-adapted species in arid to semi-arid climates. Landscape water demand is the amount estimated to be depleted from a root zone by aboveground evaporation and transpiration (ET). If not replaced by rain or irrigation, resulting water stress degrades plant performance below societal expectations. Even in humid, high summer rainfall regions, urban landscapes may need irrigation when grown in low water-holding or shallow soils or in confined rooting

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volumes with limited water (Beeson, 2012). In humid, high summer rainfall regions, such as the Eastern United States, urban landscapes can require irrigation during periodic droughts that may last from weeks to months (Vickers, 2001).

Urban landscape water consumption is water demand (estimated ET) replaced by irrigation, and is increasingly regulated by society. Many cities with growing populations in climates with a warm, dry growing season do not have enough water to meet increasing societal (indoor and landscape) water demand, especially with a changing climate altering drought frequency and intensity (Strzepek et al., 2010). Landscape irrigation may account for 30% to 60% of total annual municipal water use in arid regions (Kjelgren et al., 2000), with similar percentages reported for central Florida (Haley et al., 2007). Consequently, urban water agencies increasingly scrutinize irrigated landscapes for water conservation opportunities to bring water consumption into alignment with limited, variable supplies (St. Hilaire et al., 2008; Vickers, 2001) or as a source of new supplies (CDWR, 2014).

Water agencies can recommend, and landscape water stakeholders apply, a precision irrigation schedule to reduce landscape water consumption. Precision irrigation schedules when and how much to irrigate a landscape. When depends on how fast ET depletes root zone water to the threshold of water stress that degrades plant performance, as measured by acceptable appearance, function, and overall health. Estimating ET of a plant or a landscape is roughly quantifiable based on weather conditions and elemental plant traits, while threshold water stress is species-specific and qualitative. How much to irrigate depends on refilling plant root zones with the amount of water depleted by ET. Irrigation amount is somewhere between a qualitative and quantitative estimate that can also be species specific. Low water use landscapes, carefully designed with fewer and more drought resistant species, complements precision irrigation in the water conservation toolbox. Drought resistant species specifically access greater soil water with deeper and more extensive roots, and often have desiccation resistant leaves able to maintain acceptable appearance at high water stress thresholds.

Reducing water consumption with these tools depends on coordination among landscape stakeholders: architects/designers, water suppliers/agencies, and landscape managers. The designer must create appropriate water efficient landscape plans for a given climate and soil. Water suppliers must set reasonable and effective regulations for development and building codes, incentive programs for water reductions, water allocations or budgets, and approved water efficient designs. Landscape managers, including professional landscape contractors, arborists, and home owners must install and maintain the water efficient designs and proficiently manage landscapes and irrigation to meet expectations with the least amount of water. Common to these stakeholders is the need for estimation of landscape water demand in a way that balances scientific accuracy with usability.

Landscape water demand estimates need to be scientifically credible, conceptually accessible, and—most importantly—easy to use. These goals are difficult to achieve given the biophysical complexity of urban landscapes. Most urban landscapes are small, diverse, and non-uniform mixtures of built surfaces (hardscape) and woody-herbaceous plants (Sexton et al., 2013), and as such are a mosaic of microclimates (Christen et al., 2012). Estimating landscape water demand for this mosaic is a conundrum not resolved by current approaches. Here we provide scientific background for a national standard from the American Society for Agricultural and Biological Engineers (ASABE) Standard 623 "Determining Landscape Plant Water Demands" (*ASABE Standards*, 2015; see table 1), that imbeds in a larger framework: SLIDE—Simplified Landscape Irrigation Demand Estimation. Our aim is to provide an alternative to current approaches that provides a sound basis for water conservation regulations, and puts design, installation, and management of water efficient urban landscapes within reach of stakeholders.

Current Approach

Estimating irrigated landscape water demand is currently based on the model used in irrigated agriculture. Crop water demand is typically estimated as a fraction of a large well-irrigated but hypothetical 120 mm high clipped cool-season turf, defined as reference or potential evapotranspiration (ETo). Estimated water demand is subtracted daily from measured or estimated root-zone water of a crop up to a depletion threshold that avoids water stress and yield reduction; at this root-zone water threshold the crop is irrigated. ETo is calculated from measured weather variables: solar radiation, humidity, wind, temperature and fixed constants for plant control of transpiration (Allen et al., 2005). These fixed plant constants are empirical snapshots of species-specific plant architecture (aerodynamic interaction with wind) and highly dynamic biological (stomatal pore opening and closing) control of transpiration. Most plants, particularly non-turf landscape plants, differ widely from the aerodynamic and stomatal constants assumed in ETo. These aerodynamic and stomatal constants are compartmentalized into crop-specific, empirically-determined adjustment factors for ETo, defined as crop coefficients (Kc) (Howell et al., 1998). Actual crop water use is then estimated as the product of ETo × Kc.

Urban ETo can be calculated from local weather variables over large, well-irrigated turf areas found at golf courses or parks that meet the baseline assumptions of ETo. Urban ETo is, in essence, that of an oasis, imbedded in a larger mosaic of variably-sized, non-uniform, biophysically diverse landscapes. As such, urban ETo at best roughly approximates actual water demand of typical urban landscapes, and much less accurately than in large-scale irrigated agriculture.

Decades ago California recognized the need to regulate urban landscape water consumption by adopting the agricultural ETo × Kc approach (CDWR, 2009). This adoption meant developing ETo adjustment factors, Kc/crop coefficients borrowed from agriculture, to link urban oasis ETo of a hypothetical turf surface to actual landscape water demand (Costello, et al., 2000; Pittenger and Shaw, 2013). What emerged met short-term needs in regulating landscape water budgets, but was not operational for irrigation scheduling. The ETo adjustments for turf were based on available research on turfgrass water demand widely used by industry and are essentially the same as presented here. However, for non-turf plants, Water Use Classification of Landscape Species (WUCOLS) was developed. WUCOLS describes subjective and provisional adjustment (species K factors) for selected California landscape species that intermingles plant transpiration with drought resistance traits (rooting depth and leaf desiccation tolerance) into a species-specific adjustment value, then further entangles two additional adjustments (Snyder et al., 2014). The additional plant density and microclimate adjustment factors overestimate the effect of multiple leaf layers and urban heating, requiring users to assign arbitrary values. This mix of ad-hoc ETo adjustment factors is complex to explain, vexing to use, and is California-centric. More importantly, because WUCOLS' assumptions are subjective and situational, they offer no scientific means to improve or adapt beyond their ad-hoc origin.

Interest, however, has grown within the green building/sustainability movement for a national standard to reliably estimate landscape water demand to guide local codes that can be adopted or cited outside California. Absent a national standard, organizations including U.S. EPA and diverse industry groups—including building organizations—have developed their own landscape water efficiency standards that are typically derived from some variant of WUCOLS. Our aim is to describe the scientific basis for the ASABE S623 standard as a credible alternative to WUCOLS for landscape water efficiency codes and the sustainable building movement, and be usable by practitioners for precision irrigation. A key goal is that underlying assumptions be testable and improvable by research.

SLIDE Rules

Simplified Landscape Irrigation Demand Estimation (SLIDE) imbeds the ASABE S623 standard in a larger framework of heuristic guidelines termed SLIDE Rules. SLIDE Rules aligns with ASABE S623 to estimate landscape plant water demand as products of ETo and scientifically-based yet discrete adjustment factors for broad plant types, not individual species. SLIDE also recognizes constraints on ETo in estimating water demand in high and low plant density landscapes at a level of the smallest manageable landscape unit, an irrigation zone with a valve that allows for when and how long to irrigate—a hydrozone. Other biological elements that affect landscape water demand and drought resistance traits, rooting depth, and leaf desiccation resistance, are critical in day-to-day landscape water management, but are species/site-specific and idiosyncratic, so beyond our scope here. SLIDE is simpler than WUCOLS at two levels. First, SLIDE is conceptually simpler because it only addresses water lost to atmospheric demand, rather than the WUCOLS plant coefficient for individual species that implicitly includes desiccation tolerance and rooting depth, two factors that are so site- and species-specific that they cannot be standardized. SLIDE also eliminates the WUCOLS microclimate and plant density factors that are scientifically fraught and site specific. Two, SLIDE eliminates complexity and confusion by defining one adjustment factor for broad plant types, rather than the selectable ranges for plant, microclimate, and plant density coefficients.

SLIDE Rule #1

Reference evapotranspiration (ETo) measured over large uniform areas of turfgrass (oasis turfgrass) is quantitatively prescriptive and representative of other turf area landscapes, but may not be directly appropriate for non-turf, non-uniform, spatially and biologically diverse landscapes.

Reference evapotranspiration for urban landscapes is typically based on the Penman-Monteith equation. Evaporation and transpiration is driven by water vapor content difference between the boundary layers of a wet surface at a given temperature, and ambient air. However, surface temperature is very difficult to measure. Penman (1948) used air temperature and net solar radiation to substitute for surface temperature by combining common aerodynamic resistances for heat and water vapor. Later, Monteith (1965) added a canopy resistance factor, a function of stomatal pore opening, that when known will accurately model transpiration from an actively transpiring plant surface. Because aerodynamic and canopy resistances are dynamic and quite variable among species, Allen et al. (2005) standardized both resistance factors as constants representing a hypothetical, large, uniform, well-watered cool-season turfgrass surface. This standardized ETo made possible comparison of evapotranspiration between times and among places. Technological advances in automated weather and telemetry have made calculating and disseminating ETo convenient and common.

However, accurate and representative ETo depend on the quality of input weather data. In order to collect quality weather data, weather stations should be sited in a large, uniform area of upwind, well-watered turfgrass fetch (i.e., golf courses, parks). Large, uniform fetch allows temperature and humidity equilibrium between the overlying air and the underlying irrigated surface. This is a fundamental assumption of ETo (Allen et al., 2005), but many urban weather stations do not meet these standards. Large turfgrass areas are in essence oases, different from surrounding urban mosaics of smaller landscapes of hardscape (pavement, buildings) and green infrastructure (smaller turf areas, mixed non-turf species). Oasis urban ETo over large turf areas acceptably approximates water demand of other large turf areas that are also aerodynamically uniform canopy surfaces. However, oasis ETo only coarsely approximates water demand of the variable mosaic of non-turf landscapes with mixed plant types and hardscape, as environmental conditions and plant variables typically differ.

Oasis urban ETo × Kc applied to the urban landscape mosaic does not meet core assumptions of using ETo to estimate plant water demand. Upwind fetch of smaller landscapes is likely to be hot hardscape or landscape plants of variable height. Aerodynamic and leaf-level stomatal resistances of mixed plant-hardscape can be very different from the constants assumed in ETo. Also, microclimate variability may include reduced solar radiation from shading, increased air temperature from adjacent pavement and buildings, and highly variable wind speeds – all differing widely from those of oasis ETo. SLIDE Rule #1 defines urban water demand estimation, and applies to subsequent SLIDE Rules, as ranging from quantitative prescriptions for uniform turfgrass surfaces, to ecologically descriptive and biophysically diverse mosaics of urban landscapes, and so often less quantitative.

SLIDE RULE #2

Plant Factors (PFs) can accurately adjust average peak season ETo to estimate landscape water demand, and they are classified by water use and temperature response traits associated with general plant types, and not by species.

SLIDE Rule #2 is the ASABE S623 standard in terms of defining adjustment factors that tether ETo to on-the-ground water demand reality (table 1). Here, we use 'water demand,' in general terms interchangeable with 'water requirements' and 'water needs,' but apply 'plant water use' only to empirical studies. We also define ETo adjustment factors as 'Plant Factors' (PF) rather than crop coefficients (Kc), to acknowledge variability inherent in empirical adjustments rather than the implied precision in the word 'coefficient.' SLIDE Rule #2 defines ETo adjustment factors that are single numbers for broad plant types of turf, non-turf, and desert plants, not individual species or subdivisions of non-turf species. Turf and non-turf species are each sub-divided according to differences in general responses to temperature and drought based on research and application of established plant physiological principles. These PF's represent minimum water demand of mature, well-established plants to provide acceptable plant performance rather than water needed for maximum yield, and so implicit is a degree of mild or incipient water stress. We do not claim that the Plant Factors in table 1 are definitive; rather they are based on our informed assessment of extant but limited science. As such, we believe they can be improved with further scientific research.

Plant Factors in table 1 were derived from available scientific studies that measured actual landscape plant water use relative to ETo. The studies referenced here in support of the PF's do not represent definitive reviews of the water use literature for different landscape plant types such as those of Romero and Dukes (2009, 2015) for landscape turf. Instead, supporting literature presented here delimits landscape plant water use relative to ETo (water demand) within which water demand can vary as much within a species as it does among species. Hence we parse that variability based on our informed judgment to establish the scientific basis for Plant Factors.

Table 1. Annual average fraction of ET_o to estimate water demand of different plant types to achieve minimum acceptable appearance of established landscape plants during the growing period.

Plant Type	Recommended Plant Factor
Turf-Cool Season	0.8
Turf-Warm Season	0.6
Woody plants–Humid climate[a]	0.7
Woody plants–Dry climate[a]	0.5
Desert plants	0.3

[a] Includes perennial wildflowers, ground covers annual flowers, and bulbs.

We have two caveats to this discussion. Root depth and leaf desiccation tolerance traits are related but distinct from water demand in being species specific and thus site specific and not amenable to standardization. Species-specific drought resistance traits are vital to managing when and how much to irrigate and so must be addressed by local design, regulation, and experienced practitioners. Also, water demand estimated as ETo × PF is that estimated to be used by the plant and so ultimately is replaced by irrigation. Crucially, water demand is not the same as irrigation water requirement. Irrigation water requirement includes additional water to compensate for irrigation system non-uniformity and inefficiency, and in given situations, to leach salt from plant root zones and/or refill aquifers.

These plant type and PF descriptions are based on an accepted body of scientific knowledge for turf, but is much more limited for non-turf species, especially trees. Water use of fruit trees has been well studied to optimize yield and market value per unit water input (Steduto et al., 2012; Villabos et al., 2013), a very different measure of performance than landscape trees. Forest tree water use has also been widely studied (Wullschleger et al., 1998) but not related to ETo because such relationships have little meaning in non-irrigated natural systems and where appropriately sited weather stations are few. Water demand of landscape trees is unique and outside this agriculture-forestry axis. Finally, while obtaining the most landscape for the least amount of water is often an overarching goal of landscape water management, we argue that PF's be discretely conservative and to err on the wetter side in estimating water demand since a landscape's appearance generates its economic value.

Turfgrass

Turfgrass Plant Factors presented in table 1 are used to estimate water demand of established stands, and they are widely used in the turfgrass industry (see Kneebone et al., 1992), and comprehensively reviewed by Romero and Dukes (2009, 2015). Here we summarize key points of turf water use and variations relative to ETo such that the simplifications behind turf PFs can be understood. Variation in water loss among landscape turfgrass species is de facto separated biologically and practically by genetic differences in photosynthesis in response to temperature (Beard, 1989). Warm-season (C4) grasses, such as bermudagrass (*Cynodon dactylon)*, are physiologically more water efficient than C3 grasses. C4 grasses fix more carbon per unit water transpired and are more tolerant of high temperatures than cool-season C3 grasses (Beard and Kim, 1989). Thus, C4 grasses are common in landscapes in warm temperate to tropical climates. A PF=0.6 was established from research (Meyer et al., 1985) and is widely accepted and used in the industry, especially on an annual basis (Wherley et al., 2015). Cool-season grass species such as fescues (*Festuca*), bluegrass (*Poa*), and bentgrass (*Agrostis*) use more water per unit carbon fixed and are more tolerant of cold winter temperatures, thus a research-based and industry-accepted PF=0.8 works well in climates where these grasses are adapted (Meyer et al., 1985; Howell et al., 1998; Fu and Huang, 2004).

Warm- and cool-season turf PFs work acceptably well operationally and simplify substantial day-to-day, seasonal, and year-to-year variation within each group (Romero and Dukes, 2015). This variation may be due to site-specific issues such as mowing height, microclimate such as shading and advective energy (heating) from adjacent hot surfaces like pavement, and management practices that are not well captured by ETo calculated from a weather station located some distance away (Devitt et al., 1992; Duong, 2014). Water use relative to ETo also varies within a season for both turf types. Warm season PF's can range from approximately 0.3 late fall/winter to 0.8 mid-summer (Wherely et al., 2015). Similarly, cool season PF's can range from 0.7 to 1.0, generally lower in spring/fall, and higher mid-summer (Howell et al., 1998). Finally, management and climate factors can cause substantial year-to-year and seasonal variation in PF's in the range of 10% (Fu et al., 2004; DaCosta and Huang, 2006; Duong, 2014). Even within a genus water use can vary among species and between years and seasonally (DaCosta and Huang, 2006). In general this variation appears randomly distributed around the generally accepted, average PFs for turf (Howell et al., 1998) that allow them to function well enough operationally.

Studies to develop warm- and cool-season turf PF's include some degree of transient deficit irrigation (Gibeault et al., 1985; DaCosta and Huang, 2006; Richardson et al., 2008) that still allows visually acceptable appearance and plant health, but also achieves some degree of water savings. On the wetter end of the spectrum, studies of turf with unlimited water typically show no improvement in visual appearance above these PF levels (Howell et al., 1998).

Woody Plants

The two Plants Factors for woody plants in table 1 represent simplification of substantial variation in water use among non-turf species. These two PF's apply to established plants and imply mild or incipient water stress that does not affect plant performance and encompass substantial variation in reported water use among and within species not captured in ETo, and again not species differences in leaf and root drought resistance traits. Also, a higher PF in humid when compared to arid climates may appear counter intuitive, but arises from architectural features that increases ventilation that links to physiological (stomatal) control of water use, rather than genetic differences in physiology as is the case for turfgrass.

Ventilation

Most woody plants are taller and more aerodynamically ventilated than low-growing turfgrass. Therefore, woody plants have more direct control over transpiration through stomatal aperture opening and closing (Goldberg and Bernhofer, 2008). Greater height and rougher, more uneven, plant surface results in greater wind penetration through woody plant crowns and a boundary layer of undisturbed air reduced to the level of the leaf, rather than the top of the canopy for lower, dense plant stands like a crop or turfgrass (Jarvis and McNaughton, 1986). Trees in urban landscapes are typically isolated or freestanding rather than in dense forest stands, so more crown leaf area is exposed to solar radiation as well as wind, and it is less buffered by adjacent trees (Ringgard et al., 2012). Consequently ambient temperature and humidity levels are imposed directly on leaves and stomata in woody plants compared to low, uniform plant surfaces like turf (Daudet et al., 1999).

Stomatal Sensitivity to Low Humidity

Greater ventilation means greater stomatal control over transpiration, the basis for separating the two woody PFs. In dry air and high ETo rates, woody plants risk cavitation (embolism) from tension in their xylem water columns pulled by excessive transpiration against gravity (Ambrose et al., 2010). Cavitation creates embolisms, air bubbles that break xylem water columns and prevent upward water movement pulled by transpiration. Embolisms cause water stress in plant tissue downstream from the cavitation. Many woody plant species regulate stomatal aperture to restrict transpiration to avoid cavitation of xylem water columns at high ETo, so control risk at high ETo by closing stomata to limit transpiration, moderating internal xylem water potential.

Dry air is quantified by vapor pressure deficit (VPD), the difference between actual and potential water vapor in air. The effect of stomatal sensitivity on water use of woody plants to VPD was reported decades ago (Chouhury and Monteith, 1986), this response is now framed as isohydric. Isohydric behavior is common in woody species (Wullschleger et al., 1998; Villabos et al., 2013), particularly plants in arid climates that experience dry air for long durations (McDowell et al., 2008). Anisohydry is the reciprocal of isohydry, found in species where high transpiration rates are an opportunistic, competitive advantage to deplete soil water faster than surrounding plants (Tardieu and Simmoneau, 1998). Anisohydric behavior is less common, but is found in plants from desert (Levitt et al., 1995) to riparian (Sala et al., 1996) habitats. Anisohydric species have alternative strategies once easily accessible soil water is depleted. These include a permanent water table in riparian habitats or deep rooting in arid habitats (Kjelgren et al., 2009), as well as reverting to isohydry under severe water stress (Domec and Johnson, 2012). Because most anisohydric species are hydraulically flexible, their higher water use is not a trait that can be consistently and reliably distinguished in woody PF's. Consequently, the dry 0.5 and humid 0.7 PFs in table 1 are simply based on geography. Woody plants grown in humid climates with generally low VPD have a 0.7 PF because their stomata remain more fully open, but have a 0.5 PF when grown in dry climates where stomata closure in response to increased VPD is greater and more prolonged.

To illustrate effects of humidity on ET, an example of stomatal sensitivity to VPD for the isohydric species (*Liquidambar styraciflua*) cultivar 'Moraine' sweet gum is presented. Trees from the same nursery were subjected to midsummer VPD's concurrently in arid and humid climates (fig. 1) as adapted from Kjelgren et al. (2005). Sweetgum stomata steadily closed from morning to afternoon in arid Utah as VPD increased to 4 kPa (fig. 1a). In contrast, in humid central Florida where maximum VPD was about 2.5 kPa, sweetgum stomata did not appreciably close. Trees in both climates were free standing and well ventilated. In Utah, air moving over leaves was drier (lower ambient vapor pressure) than in Florida, and at a given leaf temperature, sweetgum stomata in Utah closed more at higher VPD. Partial stomatal closure in response to higher leaf-air VPD translated into lower transpiration rates at ETo rates above 4 mm/day (fig. 1b). The same cultivar was also concurrently measured in Texas where stomatal closure was even greater than Utah, likely due to a negative effect from wind and higher VPD's than Utah (Kjelgren et al., 2005).

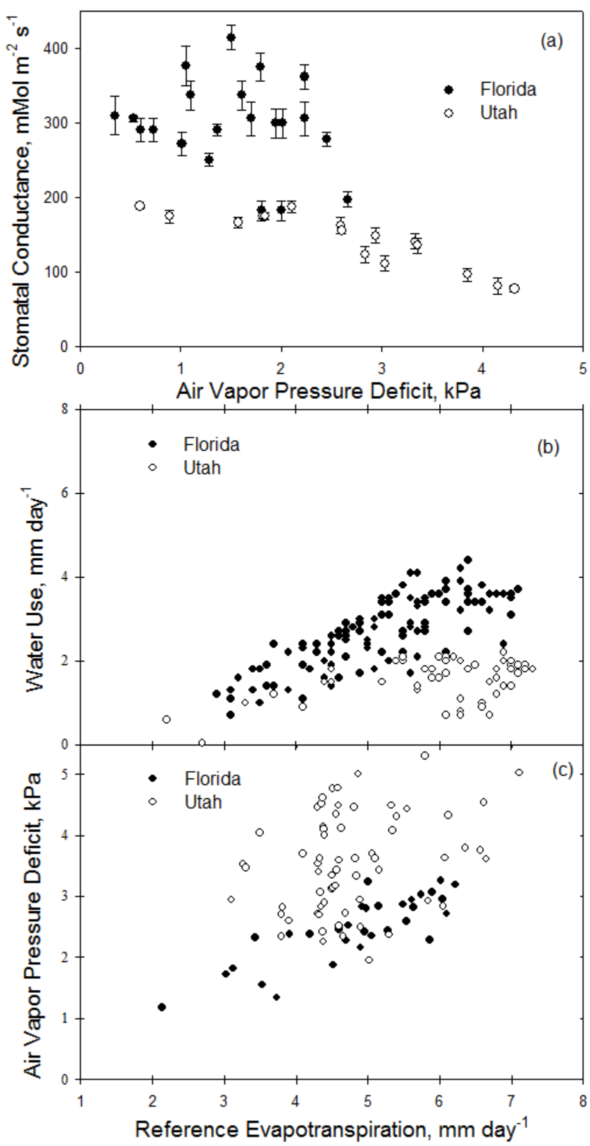

Figure 1. Sensitivity of tree transpiration to dry air (Kjelgren et al., 2005. (a) Response of sweetgum (*Liquidambar styraciflua*) stomatal conductance to air vapor pressure deficit in a humid climate (Central Florida) and arid climate (Utah). (b) Relationship between daily ETo (reference evapotranspiration) and daily high vapor pressure deficit for the months of June and July in Utah (2006), and July Florida (2005).

ETo ranges were similar in both Utah and Florida but for different climate reasons. Evaporation in arid climates is VPD limited, but since the relationship between high VPD and high ETo in arid climates is highly variable (fig. 1C), the relationship between tree transpiration and high ETo was equally highly variable (fig. 1A*)*. By contrast, Florida is more humid during its prime May-September growing season so VPD is lower, thus evaporation and ETo are controlled more by radiation and wind speed. But since VPD levels are lower in Florida, tree stomatal closure is less and the relationship between transpiration and ETo is more linear (fig. 1b).

Woody plants differ from turf in wind response. Wind increases aerodynamic conductance in low, dense plant stands like turf, thus more wind usually means greater ET. But wind typically does not increase woody plant transpiration, such as a single, free-standing tree crown (Laplace et al., 2013), in forest stands (Kim et al., 2014), in orchards (Villabos et al., 2013), or in arid urban climates (Kjelgren et al., 2005). Urban microclimates also affect VPD response in any climate. Woody landscape plants are often grown surrounded by hot surfaces, such as mulch and pavement. These surfaces radiate heat and energy that raises leaf-air VPD. Increased leaf-air VPD increases stomatal closure, reducing water use further (Kjelgren and Montague, 1998; Montague and Kjelgren, 2004).

Woody Plant Factors

Here we provide evidence to support woody plant PFs. Figure 2 illustrates how stomatal sensitivity to VPD interacts with tree transpiration (sealed from surface evaporation) and ETo. Plant factors for two isohydric species (green ash-*Fraxinus pennsylvanica*, plane tree-*Platanus x acerifolia*) (extracted from Montague et al., 2004) were highly variable but overlapping around PF=0.5. In contrast, equally variable but anisohydric corkscrew willow's (*Salix matsudana*) PF ranged from 0.7 to 1.1 (fig. 2a). The three species in figure 2b (Norway maple-*Acer platanoides*, linden-*Tilia cordata*, mulberry-*Morus alba*) were isohydric, with linden and mulberry overlapping at PF=0.5 (extracted from Montague and Kjelgren, 2004, Rashall, 2016). Norway maple did not overlap at 0.5, perhaps because it is shade tolerant, with a very dense crown, and thus produces more shaded leaves that contributed little to overall tree transpiration compared to the other species with less dense crowns, especially corkscrew willow. A salient point for arid and humid climate PFs, figure 2c shows highly variable PF's for sweetgum (*Liquidambar styraciflua* 'Moraine') in two dry, low humidity climates (northern Utah, Texas panhandle) that were lower than much more humid central Florida where PF's centered on 0.7 (Kjelgren et al., 2005), but overlapping close to PF=0.5.

A key point from these studies is that day-to-day variability in PF's within a species was generally as great as variability among species. Within species variation may in part be due to ETo not adequately representing actual water use of woody plants in dry climates as well as it does in humid climates (Villalobos, 2013). Also, variation in water use among species may in turn be partially due to measurement technique. Most empirical studies of woody PF's follow the model of dividing daily total volumetric water use of individual trees by total leaf area at the time of measurement, i.e. data in figure 2. Resulting daily depth of water use is then divided by ETo to reach a daily PF for an individual tree. However, species differences in tree crown density and leaf area may confound this calculation because shaded leaves transpire at a lower rate, but are given the same weight as sunlit leaves that transpire at a higher rate. Thus factoring out shaded leaves can give a better representation of tree water use based on sunlit leaf area (Periera et al., 2006). For example, in figure 2b maple total leaf area was over twice that of linden over three years.

Another approach that factors out shaded leaf area is to divide volumetric water use by ETo (in related units) to estimate a 2-dimensional effectively transpiring leaf area (ETLA). So, dividing linden and maple total leaf area by an estimate of leaf area index (LAI; estimated as per Periera et al., 2006) approximates sunlit leaf area (essentially vertically projected crown area, or PCA). This PCA can then be related to linden and maple ETLA, volumetric water use ÷ ETo (fig. 3). The relationship between ETLA and PCA produced similar slopes between the two species (fig. 3a). Forcing the fitted ETLA versus PCA line through zero, the resulting slope approximates a PF of around 0.6 for these data. Although higher than the PF=0.5 recommended here, assuming LAI=three likely overestimated actual LAI of maple and linden.

Similarly, in a humid climate Beeson (2013a) related volumetric water use of large trees with weighing lysimeters (Beeson, 2011) to directly measured PCA for

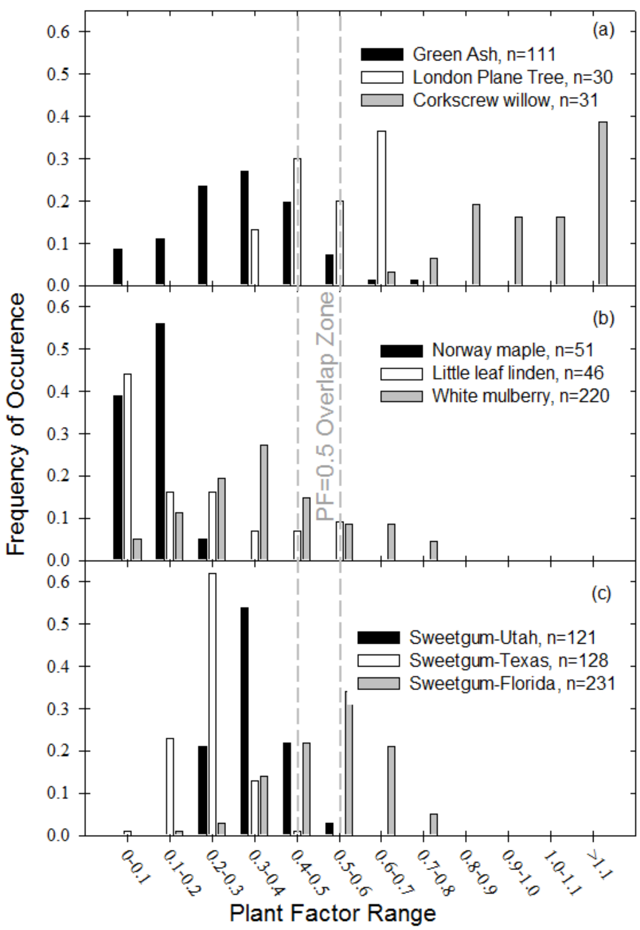

Figure 2. Frequency distribution of commonly-used tree Plant Factors (daily transpiration divided by same day reference evapotranspiration), and number of individual tree data points for the following species: (a) green ash (*Fraxinus pennsylvanica*), London plane tree (*Platanus* x *acerifolia*), and corkscrew willon (*Salix matsudana*) (from Montague et al., 2004); (b) Norway maple (*Acer platanoides*), little leaf linden (*Tilia cordata*) (from Montague and Kjelgren, 2000), and white mulberry (*Morus alba*) (from Rashall et al., 2015); (c) sweetgum (*Liquidambar styraciflua* 'Moraine') (from Kjelgren et al., 2005).

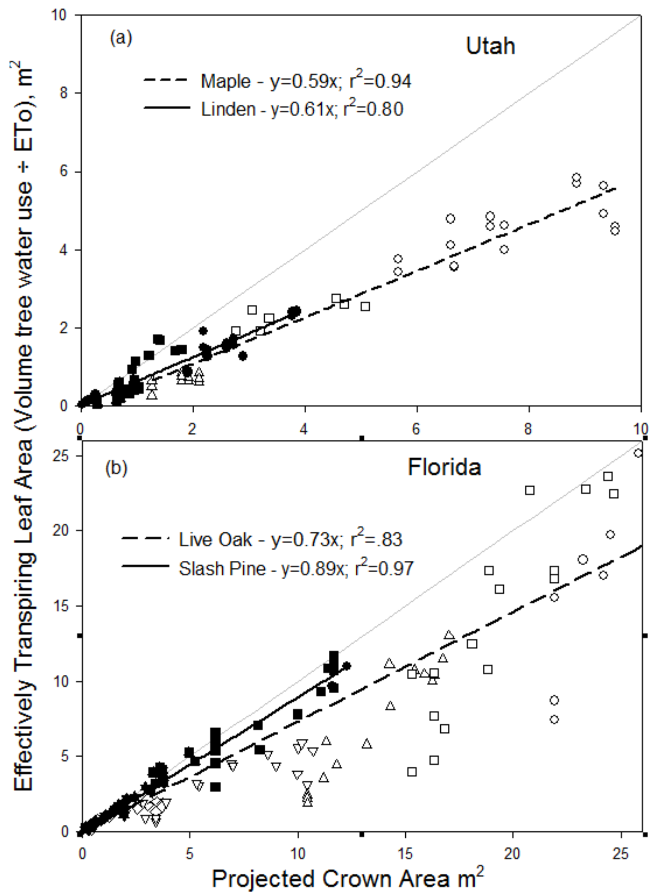

Figure 3. Relationship between effectively transpiring leaf area (ETLA - volumetric water use ÷ ETo) and projected crown area (PCA). Different data symbols represent individual tree daily use over successive years, and slope of line fitted through zero approximates species PF. (a) Norway maple and little leaf linden, 1995-1997, in Utah with increasing crown size over three years [note: PCA not measured during the study, so estimated using the LAI correction of Pereira et al. (2006)]. (b) In Florida, single tree water use of slash pine (*Pinus elliottii*), 2006-2011, and live oak (*Quercus virginiana*), 2001-2006, with increasing crown size over six years.

individual trees of live oak (*Quercus virginiana*) and slash pine (*Pinus elliottii*) over six years with increasing crown size. Using PCA measured periodically as it changed over each season (relating to volumetric water averaged over seven days around each PCA measurement), avoided the daunting effort and variability of measuring actual total leaf area changing over a season. Water use per unit area (slope) and line fit (r^2) was lower in oak than pine, but showed that water use corrected to ETLA can be estimated from PCA, and the resulting PF's (oak=0.73) is acceptably close to the humid PF of 0.7, although the pine PF based on ETLA is higher at 0.89. Again the pine and oak data are for individual trees so not yet definitive pictures of each species' water use behavior.

Table 2 presents the limited number studies of landscape woody PFs relative to ETo. We point out the diversity of methods used to study landscape plant water use, each with its own limitations. Most of the presented studies are from arid or semi-arid climates, and they support the 0.5 PF for arid climates. Field-based rate studies estimating minimum water requirements for several shrub, tree, and woody groundcover species common in Southern California landscapes revolved around the PF=0.5 for warm arid regions (Pittenger et al., 2002; Shaw and Pittenger, 2004; Pittenger et al., 2009). Similarly PF's generally around 0.5 have been reported for *Quercus shumardii* in Texas (Fox and Montague, 2009; Pannkuk et al., 2010) and for *Q. virginiana* (live oak) in Arizona (Levitt et al., 1995). However, live oak appears anisohydric in its native range of Florida to Texas (Heilman et al., 2009), but appears isohydric under severe soil water deficits (Kukowski et al., 2013), so may be opportunistically anisohydric, as noted for other anisohydric taxa (Domec et al., 2012). In contrast, the anisohydric native desert species mesquite (*Prosopsis alba*) averaged a PF>1 (Levitt et al., 1995). Pataki et al. (2011) found very wide variation in transpiration of Los Angeles urban trees. Given potentially flexible hydric behavior, our assessment is that PF=0.5 is appropriate for desert trees because appearance expectations are higher than other desert plants and a PF=0.5 maintains health to meet those expectations.

Woody plant water use related to ETo is less studied in humid climates, but in central Florida available studies suggests PF=0.7 is appropriate for most species in a high summer rainfall climate (Beeson, 2012). Woody plants in humid climates experience periodic high VPD and some degree of isohydric behavior (Schmidt-Walter et al., 2014) that can reduce seasonal water use somewhat (Fischer et al., 2013). This could become an issue if temperatures are consistently higher in regions of transition to arid climates, where summer peak daily ET is in the 2.5 to 3 kPa range, or possibly with climate change. Also, our assessment is that the two PF's can apply to newly planted trees with limited rooting volume, but that they be irrigated more frequently (Gunnel et al., 2008).

The distinction between the two woody plant factors is geographic (fig. 4). The 0.5 PF applies in the central Great Plains westward through the Intermountain West to the central and southern Pacific coast where July maximum daily VPD is greater than 3 kPa (30 hPa in figure 3 legend). In regions where midsummer VPD is mostly 2.5 kPa (25 hPa) or less, the PF=0.7 is most appropriate. These regions of PF=0.7 occur in most of the Eastern United States and the U.S. Pacific Northwest. The transitional zone of 2.5 to 3 kPa changes with latitude and is diagonal, running from the cooler eastern Montana to hotter eastern Texas. This somewhat aligns with the 100th meridian (longitude), and is associated with shifts in rainfall to below 500 mm (20 in.) annual precipitation. Cooler spring and later summer temperatures means VPD levels are likely to be lower, but since irrigation is less common and water stress during low rainfall periods is of greater concern, we recommend a PF=0.7 in these transitional areas. A key point regarding woody PF's is that species in high VPD zones may use water at less than 50% of ETo, but irrigating at 50% ETo will not injure trees unless poorly drained soil is an overriding limitation. Small amounts of extra water is a small cost to ensure reasonable tree health.

OTHER LANDSCAPE PLANTS

Ground covers (woody and herbaceous), herbaceous flowering perennials and annuals, and flowering bulbs are also vital elements in urban landscapes. Water use studies of these plant types are few so the PFs presented here are mostly our judgements based on available data.

- **Annual flowers.** Water use of annuals is minimal, but Henson et al. (2006) reported PF approximately 0.5 for 15 species in a semi-arid climate, so for simplicity we recommend annuals be grouped by climate with woody plants.
- **Herbaceous perennial flowers and ground covers.** Low growing (generally <1 m height) herbaceous perennials and ground covers can be found in every possible plant community. The PF for woody and desert plants would apply to perennials based on native habitat (Reid et al., 2012; Sun et al., 2012). Ground covers (<0.5 m) can be herbaceous or woody, with transpiration similar to woody plants (Sun et al., 2012). We recommend the same woody plant PFs of 0.5 for perennials and ground covers in arid climates (Pittenger et al., 2001; Shaw and Pittenger, 2004), and like for woody plants, 0.7 in humid climates.
- **Flowering bulbs.** Bulbs are unique in that most common species—tulips, daffodils—are naturally arid zone ephemerals that complete their life cycles before high summer ETo, so they perform acceptably on stored winter precipitation in most climates. However, they do need some water in spring and their landscape use and ecophysiology are similar to annual flowers, so the recommendation they also be grouped with woody plants by climate.

Table 2. Literature summary of water use studies of plants used in irrigated landscapes, including lead author, date, species studies (if <10), method used to study water use, climate where study conducted, and comments about water use and Plant Factors.

Authors	Plant Type	Species	Method	Climate	Comments
Bates and Montague, 2015	Tree	*Acer x fremanii, A. truncatum*	Rate[a]	Semi-arid	PF's of 1.0, 0.66, and 0.33. Greatest growth often found at lower PF's.
Beeson, 2013a	Tree	*Acer Rubrum, Ilex aquifolium x cornuta, Magnolia grandiflora, Pinus elliottii, Quercus virginiana, Ulmus parvifolia*	Lysimeter[b]	Humid	Over 5-6 year production period, ETo varied 5-15% day-to-day across all species
Beeson, 2012	Shrub	*Rhaphiolepis indica*	Lysimeter	Humid	PF approximately 0.7, varied 5-15% day-to-day
Beeson, 2010	Shrub	*Viburnum odoratissimu*	Lysimeter	Humid	PF approximately 0.7, varied 5-15% day-to-day
Beeson, 2005	Shrub	*Ligustrum japonicum*	Lysimeter	Humid	PF approximately 0.7, varied 5-15% day-to-day
Chen and Beeson, 2013	Perennial	*Asplenium nidus, Chamaedorea elegans*	Lysimeter	Humid	Under shade, PF 0.2-0.4 for Asplenium, 0.9-1.4 for Chamaedorea
Fox et al., 2014	Tree	*Cercis canadensis*	Rate	Semi-arid	PF's of 1.0, 0.66, and 0.33. Greatest growth often found at lower PF's
Fox and Montague, 2009	Tree	*Acer buergeranum, A. campestre, A. × freemanii, A. truncatum, Cercis canadensis mexicana, C. canadensis texensis, Crataegus phaenopyrum, Fraxinus velutina, Prunus mexicana, Q. robur)*	Rate	Semi-arid	PF's of 1.0, 0.66, and 0.33. Greatest growth often found at lower PF's
Henson et al., 2006	Annual	17 herbaceous common annual species	Rate	Semi-arid	Most species performed acceptably at PF=0.5, while petunia hybrid and Glandularia at PF=0.25
Kjelgren et al., 2008	Tree	*Pterocarpus indicus, Lagerstroemia loudonii, Swietenia macrophylla, Cassia fistula*	Lysimeter	Tropical	Evergreen Swietenia, Pterocarpus PF=0.2-0.4 deciduous Lagerstroemia, Cassia PF=0.3-0.7, 0.3-1.0, respectively
Kjelgren et al., 2005	Tree	*Liquidambar styraciflua*	Lysimeter	Arid (semi) humid	In arid, semi-arid climates PF ranged from 0.2 to 0.6, in humid climate PF 0.6 to 0.8
Levitt et al., 1995	Tree	*Prosopis alba, Quercus virginiana*	Lysimeter	Arid	Prosopsis PF 0.7-1.4, Quercus 0.3-0.7
Mata-Gonzalez et al., 2014	Tree	*Artemesia tridentat, Ericameria nauseosa, Atriplex confertifolia*	Rate	Arid	Great Basin desert species transpired at 0.8-15% of total seasonal evaporation that approximated ETo
Montague et al., 2004	Tree	*Fraxinus pennsylvanica, Platanus x acerifolia, Tilia cordata, Salix matsudana, Acer platanoides*	Lysimeter	Arid	PF's: Acer 0.1-0.3, Fraxinus-Platanus 0.3-0.7, Tilia 0.3-1.2, Salix 0.8-1.5
Morari and Giardini, 2001	Land-scape	2000 species in northern Italy botanical garden	Water Balance[c]	Humid	PF 0.55 early spring to 0.8 midsummer; variation between years 0.5-15 by month
Niu et al., 2006	Shrub	*Abelia grandiaflora, Buddleia davidii, Euonymous Japonica, Ilex vomitoria, Nerium oleander*	Lysimeter	Arid	PF's calculated based on surface area of lysimeter, not leaf area, and ranged from 0.5-4
Pannkuk et al., 2010	Tree	*Quercus shumardii*	Water balance	Semi-arid	PF 0.36-0.68 for isolated tree, but adding oak to grass landscape did not change combined PF
Pataki et al., 2011	Tree	*Platanas racemosa, P. hybrida, Ulmus parviflora, Pinus canariensis, Sequoia sempervirens, Ficus microcarpa, Jacaranda chelonia, Gleditsia triacanthos, Koelruteria paniculata, Lagerstroemia indica, Ficus microcarpa*	Sap flow[d]	Arid	Whole tree transpiration variation from 30-80% within a species. Stand level PF's from 0.3-0.6
Pittenger et al., 2009	Palm	*Archontophoenix alexandrae, Chamaerops humilis, Syagrus romanzoffiana, Trachycarpus fornunei, Washingtonia filifera*	Rate	Arid	Maintained minimally acceptable appearance at PF=0-0.5
Pittenger et al., 2001	Ground cover	*Baccharis pilularis,Drosanthemum hispidum, Gazania rigens, Hedera helix, Potentilla tabernaemontanii, Vinca major*	Rate	Arid	Minmum PF's: Potentilla and Gazania 0.5 or greater, Vinca 0.4, Baccharis, Drosanthemum, Hedera 0.3
Shaw and Pittenger, 2004	Shrub	30 species, mostly from Mediterranean climates	Rate	Arid	Most species performed acceptably at PF=0.36 or PF=0.18; performance of 11 species was not affected by water amount
Smeal et al., 2010	Shrub/ Perennial	78 listed species nearly all from interior U.S. high deserts, 75% woody	Rate	Arid	62% of species PF's in range 0-0.35, including all woody plants, 25% of species, all herbaceous perennials, PF in range 0.4-0.75
Staats and Klett, 1995	Ground cover	*Cerastium tomentosum, Sedum acre*	Rate	Semi-arid	PF's approximately 30% for both species
Sun et al., 2012	Land-scape	Mixed perennial and woody species from high desert, mesic, and intermediate climates	Lysimeter	Arid	Desert shrub PF from 0.4-0.6, non-desert from 0.4-0.9; all perennials PF 0.3-0.6

[a] Rate: field grown where water applied as percent of reference evapotranspiration.
[b] Weighing lysimeter where water measured as change in daily rate.
[c] Water balance where plant water use calculated as difference between measured water inputs and outputs (including drainage lysimeters).
[d] Sap flow where plant water use measured as velocity of sapwood water (from thermal input) times sapwood area.

- **Tropical regions.** SLIDE is likely to be used in other regions with seasonal dry periods such as the monsoonal tropics (Kjelgren et al., 2011, 2008). However, water use studies of of tropical and semi-tropical plants in tropical urban areas are few. Kjelgren et al. (2008) reported PF = 0.3-0.5 for evergreen species

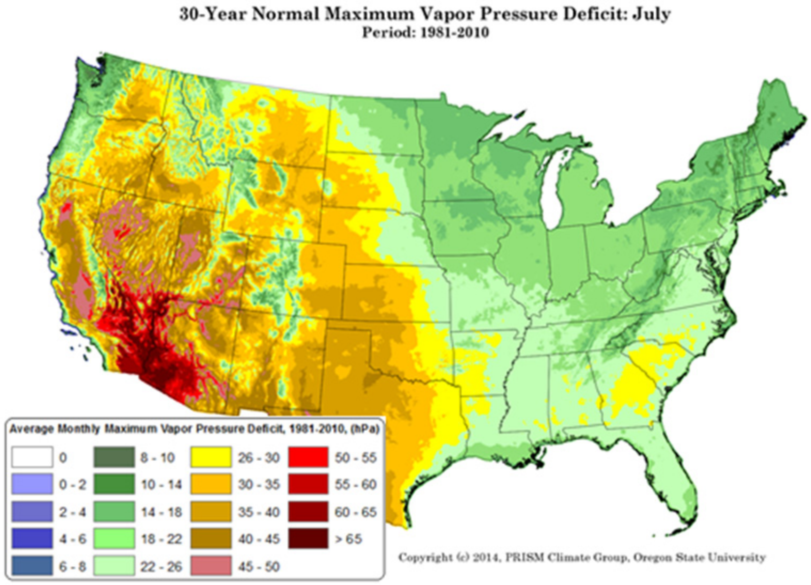

Figure 4. Map showing 30-year average July average daily high vapor pressure deficit in hectaPascals (kPa × 10). Map courtesy of PRISM Climate Group, Oregon State University. (http:/www.prism.oregonstate.edu/).

(*Swietenia, Pteroarpus*) during the dry season in SE Asia. But for deciduous species *Cassia and Lagerstroemia* from monsoonal dry forests, PF's were in the 0.7-0.8 range. Given high humidity even during monsoonal dry periods, we suggest a PF=0.7 for tropical tree species for monsoonal and wet evergreen regions, and similar to the United States, PF=0.5 for tropical arid to semi-arid regions, but further studies would aid in a more definitive recommendation.

The ETo × PF approach has been applied to non-turf plants in most landscape settings (St. Hilaire et al., 2008). The 0.5 PF in dry climates appears sufficient for established, mature, ostensibly isohydric trees, shrubs, and groundcover species (Pittenger et al., 2001, 2002, 2009) to perform acceptably in climates with high growing season VPD. A PF=0.7 is more appropriate for woody plants and groundcovers growing in humid, high summer rainfall climates (Ringgaard et al. 2012, Kim et al., 2014), or plants native to wet habitats growing in any climate (Sala et al., 1996).

Desert/Dry Environment Plants

Desert plants are adapted to survive high temperatures (high ETo) and low rainfall, and often shallow, coarse low water holding capacity soil, so their water use is typically different from a uniform crop or a turfgrass surface. Desert species have modified physiology or leaf morphology to reduce transpiration, decoupling their water demand even further from ETo. An example is crassulacean acid metabolism species, such as cacti and other desert succulents that transpire and assimilate carbon at night, an extreme desert adaptation that means water use of these plants water has no connection to ETo on a day-to-day basis. We do note that reduced transpiration rates of desert species is one adaptation to deserts along with leaf physiology and morphology that resist desiccation, often in concert with root systems that exploit deep soil, extract more soil water, or scavenge light rain in surface soil, during dry periods (Mata-Gonzalez, 2014). While leaf and root traits that affect water use (Levitt et al., 1995) are outside the scope of this article, these traits define desert species and so need to be woven into water conservation planning on a situational basis at the practitioner level.

These combinations of physiological, morphological, and phenological traits enable desert plants to survive on limited precipitation in their native climate. These traits define the perennial wildflowers, shrubs, and succulents/cacti that dominate desert habitats. Water use studies of these desert species are few, but point to PFs around 0.3, albeit varying substantially from nearly zero to 0.8 (Pittenger et al., 2009, 2002, 2001; Shaw and Pittenger, 2004; Smeal et al., 2010; Mata-Gonzalez, 2014; see table 2 for details). While desert species water use typically has little relationship to ETo on a day-to-day basis, over a growing season they do use water, even succulents. Based on available information, we judge that a PF=0.3 will likely make acceptable estimates of water use of desert, and seasonally dry species, on a long-term, seasonal basis. We recommend that the dry PF=0.3 be applied only to desert shrubs and perennial wildflowers. For desert trees, as stated, we recommend the greater 0.5 PF because of their flexible water use and greater expectations of performance. Again leaf and root drought tolerant traits in desert tree species would need to be addressed on a situational basis.

SLIDE RULE #3

A landscape zone controlled by one irrigation valve is the smallest manageable area for water in a landscape, and is a hydrozone; when plant types are mixed in a zone the water demand is governed by the plant type with the highest PF.

SLIDE Rule #3 gives guidance for design of irrigation zones, and to the regulatory agencies that regulate design to conserve water. An irrigation zone with one valve is the smallest landscape area manageable for water (Sun et al., 2012). This concept is typically labeled hydrozoning, and is already widespread in landscape design and practitioner communities. Value of hydrozoning is now more important with new technology that automatically links local day-to-day ETo to an irrigation controller. The controller determines when and how much a zone is irrigated (Davis and Dukes, 2010). An efficient hydrozone is defined as one where all species in a zone have the same water demand, based foremost on PF but secondarily on rooting, and leaf traits for practitioners scheduling when to irrigate (Sun et al., 2012), and so can be managed for maximum irrigation efficiency and water savings (Grabow et al., 2013).

In irrigation zones where species have mixed PFs, water use for a zone is determined by the species with highest water demand. An iconic example is a tree in a dry climate with a PF=0.5 and relatively deep roots imbedded in cool-season turfgrass, PF=0.8, with much shallower roots. In this situation, turf will deplete their shallower root zone much more rapidly and require irrigation more frequently, such that turf controls when and how much the combined turf-tree landscape is irrigated. Reciprocally, in a humid climate with trees (PF=0.7) imbedded in warm-season turfgrass with a PF=0.6, water use of the hydrozone would be that of trees, 0.7 PF.

Managing hydrozones with mixed microclimates, such as shading, is the same as zones with mixed PF species: sunlit areas with highest water demand controls the irrigation schedules for the entire zone. Shaded microclimates are common in landscapes, particularly from buildings (Kjelgren, 1995), but also shrubs and flowers under tree shade. Shading doubly depresses transpiration, from both less insolation and energy, and stomatal closure at low light levels (Kjelgren, 1995). Hydrozones entirely shaded can be managed on a case-by-case basis for lower water demand, but zones with mixed sun and shade from buildings will be driven to managing for the higher, sunlit water demand.

Similarly, landscapes in full sun but surrounded by extensive pavement or mulch creates a hot urban microclimate (Kjelgren and Clark, 1992a). Such landscapes with sparse plant cover, or street trees installed in pavement cut-outs, subjects plants to high energy load and potentially stressful leaf temperatures (Montague and Kjelgren, 2000). Because of stomatal sensitivity to vapor deficits, greater heat loading on plant leaves in a high energy landscape means large leaf-to-air vapor deficits that further increase stomatal closure, thereby in most (isohydric) species transpiration is reduced and water demand moderated (Kjelgren and Montague, 1998; Montague and Kjelgren, 2004). In addition, quantifying water demand in high energy urban microclimates is very site specific, like shading, so we don't recommend a separate PF for extensive hardscape, high energy situations. Instead, site specific situations, very small turf areas (like parking strips) and plantings of riparian, anisohydric woody species, need to be managed by the practitioner on a case-by-case basis.

SLIDE RULE #4

Water demand of mixed plant types with dense plant cover is that of a 'big leaf' governed by high PF species; demand of sparse plant cover is that of individual plants governed by leaf area as measured by projected canopy area.

SLIDE Rule #4 provides guidance for landscape design regulators to reduce landscape water use by reducing plant cover. This SLIDE Rule describes the observation that landscape water demand increases with more plants up to a threshold such that demand of landscapes designed for a lower density should be estimated differently than high density plantings.

DENSE CANOPY COVER >80%

Adjusting crop water use estimates, amended for partial canopy cover is accepted practice in agriculture, where 80% is a widely observed threshold for canopy closure above which water use doesn't increase appreciably with more cover up to 100% (Bos et al., 2008; Steduto et al., 2012). A landscape analog is nursery production. Beeson (2010, 2012) has shown for several container-grown shrub species that transpiration reached its maximum at 75% to 85% canopy cover. Closer to typical urban landscapes, Sun et al. (2012) showed that water use was governed by canopy density up to 85% coverage, independent of plant types (herbaceous perennials, shrubs) or putative drought/water use classifications. At 80% density threshold, adjacent plants interact to shade and buffer each other from wind such that transpiration is mainly at the top of the canopy/"big leaf" (Beeson, 2005), but roots also intermingle to increase competition for water (Sun et al., 2012).

Layered plant canopies (LAI>1) has been suggested to be additive and increase landscape water use above ETo (Costello et al., 2000). However, energy balance theory and research refutes the idea that multiple leaf layers increases overall transpiration. Urban landscapes often resemble savannas, with variable tree cover imbedded in complete ground cover vegetation. Overstory shading reduces incoming radiation (Ringgaard et al., 2014) and lowers stomatal opening (Kjelgren and Clark, 1992b) of the underlying ground cover, reducing transpiration to keep overall stand (Schmidt-Walter et al., 2014), or landscape (Pannkuk et al., 2010), water use relatively constant. Similarly, Litvak et al. (2014) showed in an arid climate that combined tree and underlying turf water use was lower than adjacent full sun turf alone. From a regulatory perspective, water use of large tree crowns may need to be accounted for at the overall landscape level rather than within a hydrozone if canopies extend across multiple irrigation zones. In a landscape with >80% plant cover, SLIDE Rule #3 would apply, where plant type with the highest PF and water use dictates water demand of the hydrozone.

SPARSE CANOPY COVER <80%

Incomplete plant cover is a key tool, along with using lower PF species, to reduce overall landscape water demand in dry climates. Wide spacing between plants is a defining feature of arid to semi-arid regions and can be emulated in irrigated landscapes. The 80% density threshold defines the point where mulch and porous hardscape (impervious surfaces often being excluded from landscaped areas in many municipal water conservation ordinances) is large enough, and leaves few enough, to reduce overall water demand (St. Hilaire et al., 2008). Isolated, freestanding plants in a <80% cover landscape (such as street trees imbedded in pavement cut-outs) have less overall landscape transpiration and more rooting volume and less competition for water, particularly for anisohydric species.

Water savings from lower overall plant density within a hydrozone can also be realized by grouping trees, shrubs, and flowers into dense islands or oases with >80% cover surrounded by permeable hardscape imbedded with no or very few plants. Water savings from lower plant density also applies to an entire landscape. Turf hydrozones (or zones covered by ≥80% turf) can be interspersed with hydrozones of non-turf species with plant cover <80% to create landscapes with overall plant cover less than 100% that would demand less water than landscapes with 100% cover. Lower plant density would be less needed in humid, high summer rainfall climates and could increase other problems such as weeds.

Water demand of low plant density hydrozones is the sum of the water volumes transpired by the single plants, or oasis grouping, which is the product of the effective transpiring leaf area × water demand (ETo × PF). Estimated water demand as a volume for isolated plant or oasis can be efficiently matched by a water volume applied with a drip or low-volume sprinkler system that applies water directly to the plant root zone and avoids evaporative loss and reduces weeds in, for example, non-planted mulched areas. In a dry, but especially a humid climate, the effective transpiring leaf area equals the sunlit leaf area due to shaded leaves receiving less solar radiation to evaporate water (Ringgaard et al., 2012). Projected crown area (PCA) as a reasonable approximation of sunlit leaf area as shown in figure 3 and elsewhere (Beeson, 2013b; Chen and Beeson 2013) is a simpler way to measure water use among different tree species (Pereira et al., 2006). In humid regions, water demand of isolated woody plants can be accurately estimated from ETo × PF × PCA (Beeson, 2013b). In arid climates, isolated tree water use can be similarly estimated from ETo × PF × PCA (fig. 3), but PF's in arid climates may not be as closely related to ETo due to the greater sensitivity to VPD.

USING SLIDE RULES

Primary target audiences for SLIDE Rules are the landscape design community, water agencies, and entities associated with preparing and enforcing urban water conservation programs and ordinances. Landscape architects and designers have a dual role. They design water efficient landscapes—and sometimes the irrigation systems—to meet client aesthetic and functional expectations. The design community increasingly must design landscapes for estimated water demand to stay below a target budget or allocation set by regulators. Also, landscape architects/designers often provide guidance to 3rd party irrigation designers, contractors, and end users on appropriate irrigation system installation and management. A key outcome of SLIDE Rules is enabling the design community to meet any water allocation or water budget goal by using appropriate plant factors and plant densities. SLIDE Rules gives the design community a simple way to estimate water demand in fully planted hydrozones (≥80% cover) by using ETo × PF × planted area and in sparsely planted hydrozones (<80% cover) by estimating two-dimensional plant icons proportional to PCA using ETo × PF × individual plant PCA.

SLIDE Rules can serve water and regulatory agencies as a science-based and defensible means to estimate landscape water demand. These estimates are more easily translated than previous methods into guidelines to evaluate landscape designs for compliance with water allocations and inform water conservation ordinances. SLIDE Rules can inform the expanding number of industry groups promoting green, sustainable building standards and codes that encompass sustainable, water efficient landscapes. Often these standards and codes have simplistic statements on limiting turf and planting the remaining area, assumed to be non-irrigated, with native plants, an unreasonable demand in many arid areas. SLIDE Rules 2 and 4 provide tools for these industry groups to develop more climate-realistic standards.

Another regulatory application of SLIDE Rules is to track landscape compliance with water allocations, and impacts of water conservation programs. This approach compares estimated landscape water demand to actual water applied to landscapes extracted from water meter readings (used for billing), or through remote sensing of irrigated landscaped area (Farag et al., 2011). Glenn et al. (2015) have refined this approach by quantifying the Landscape Irrigation Ratio (LIR): actual water use extracted from billing data for a given time period divided by estimated water demand for that same time period that describes capacity to conserve. SLIDE Rules can reasonably estimate the landscape water demand denominator in LIR calculations, weighted by percent turf and non-turf cover, with an empirical correction for trees imbedded in turf. LIR can then be used to identify end users with high capacity to conserve and target with water conservation programs. Performance of end users in response to specific conservation programs can then be tracked as changes in capacity to conserve as measured by LIR. For example, combined water demand for a 93 m^2 (1000 ft^2) landscape 60% turf/40% non-turf in Salt Lake City (seasonal ETo = 1016 mm/40 in.) would be approximately 17,000 gal (64 m^3) that can be compared to actual water use from water meter data. Calculating water demand for a landscape with mixed (turf, non-turf) plant types would not be credible with WUCOLS because of the large number of arbitrary assumptions regarding crop coefficients that would be required.

SLIDE Rules will be of variable value to the landscape practitioner community. In any climate, those with intimate experience and knowledge of their landscape can manage for the absolute minimum water use regardless of SLIDE

Rules. SLIDE Rules adds little to existing turf water management practices apart from standardizing existing Plant Factors. ETo-based irrigation controllers have de facto standardized the PF's presented here for humid (Grabow et al., 2013), and arid (Devitt et al., 2008) locations. Currently there is no minimal science-based guidance for setting irrigation schedules for non-turf zones, a gap that SLIDE Rules fills through PF's for non-turf and desert plant zones.

SLIDE Rules bring particular value to practitioners in estimating isolated tree water demand, especially during drought. Normally well-watered trees and other high-value perennial plants, either isolated or imbedded in turf, can be targeted with supplemental water volume estimated from Rule 4 to refill root zones during drought. SLIDE does not address minimum frequencies between irrigations needed for high value trees to survive a drought that are governed by species drought resistance (leaf and root traits). Applying too frequently wastes water. However, applying water too infrequently or too small an amount may still waste water if it is not enough to alleviate water stress to allow stomatal opening and photosynthesis to recover (May et al., 2013).

CONCLUSION

SLIDE Rules' heuristic guidelines are based on combinations of established scientific concepts and industry practice. ETo as the basis for SLIDE captures weather factors that relate to plant water demand, most closely for turfgrass, moderately well for woody species in humid climates, much less so for woody species in dry climates, but poorly related to desert plant water demand (Rule 1). Turf PF's (Rule 2) are based on a solid body of scientific literature and that are widely used in industry. Woody plant PF's are based on established agricultural and ecological understanding of the role stomatal sensitivity to humidity plays in water use. Desert PF's are based on basic ecophysiological principles characteristic of how plants survive in hot, dry climates. The science supporting SLIDE Rules and its woody PF's underscores the lack of scientific basis for WUCOLS. As a consequence, SLIDE Rules also provides more credible, understandable, and easily accessible PF numbers.

Hydrozones are an established concept in landscape design to which Plant Factors bring a more rigorous definition to hydrozoning (Rule 3) in how to combine plants with similar water demand. The understanding that incomplete plant cover means less water use (Rule 4) is plainly observable in desert ecosystems but also widely used in scheduling irrigations for row crops. Incomplete plant cover to reduce water use is widely incorporated but poorly understood and defined in many landscape conservation standards. Taken together, a possible benefit of SLIDE Rules would be to nudge industry entities and their standards away from inflexible and often arbitrary (scientifically and in application) regulations that demand turf replacement with non-irrigated native plants (or irrigating solely with rainwater) in arid climates, a misguided notion honored only in design compliance but not applied in practice. SLIDE Rules addresses water demand that can be defined and regulated, but species selection for water conserving landscapes really cannot. Individual species drought resistance root and leaf traits interact with site conditions in limitless idiosyncratic ways that are very difficult to enforce. Also, species selection regulations often misguidedly focus on native plants. Native to a region does not automatically mean drought tolerance, as a riparian cottonwood (*Populus* species) native to the western United States would perform no better, if not worse, in a non-irrigated landscape in a desert than a maple from a high summer rainfall hardwood forest.

A key perspective SLIDE Rules brings to water efficient landscaping is estimating volume of water demanded as the product of ETo, PF, and some measure of transpiring leaf area such as projected crown area, or the entire planted area when combined plant canopies cover at least 80% of the ground surface. Estimated volume of water demand gives end-users a tool to save high value trees during severe drought. SLIDE Rules innovates in bringing this information together in a cohesive framework that is accessible and usable by stakeholders in water efficient landscaping. Assumptions underpinning SLIDE Rules are based on extant but limited science and we do not claim the PF's in table 1 to be definitive, but hope this document inspires further scientific research that can test and revise these assumptions as new information is developed. Possible areas for research:

- Further water use studies of herbaceous perennials, trees, shrubs and desert plants in dry and humid climates, particularly further developing the PCA versus ETLA approach for developing Plant Factors for woody plants.
- Better understanding of intra-seasonal variation in water use in turf (Wherely et al., 2015), and non-turf landscapes (Morari and Giardini, 2001), where early and late season water use is lower than peak summer.
- Minimum tree water demand to survive with moderate to severe water stress.
- How to best refill an isolated tree root zone, and how long should the tree be allowed to deplete limited soil water, during drought.
- Refining understanding of how plant density affects water use.
- Remote sensing of actual urban landscape water use to ultimately replace ETo.

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