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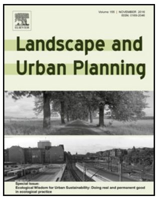

A method for estimating transpiration of irrigated urban trees in California

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HIGHLIGHTS

- Urban forest transpiration is a significant uncertainty in municipal water budgets.
- Landscape coefficients do not capture the dynamics of urban tree transpiration.
- An alternative method consistent with plant physiological mechanisms is needed.
- We propose a model based on urban tree transpiration measured in situ.

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ABSTRACT

Transpiration of urban forests in southern California is highly uncertain and challenging to quantify because of variability of tree characteristics and stomatal responses among species and locations. However, as California undergoes the most severe drought on record, it is imperative to develop approaches to estimating transpiration of irrigated urban trees (E_{Trees}). We examined the landscape coefficient method recommended by the California Irrigation Management Information System (CIMIS) and widely used to estimate irrigation needs of urban landscapes. The CIMIS method uses reference evapotranspiration (ET_0) calculated from the Penman-Monteith equation and a set of species-specific factors to adjust ET_0 for particular landscapes. We found a mismatch between CIMIS predictions and actual patterns of urban tree transpiration that we attributed to underrepresentation of tree physiological mechanisms in ET_0. As an alternative, we propose an empirical model of E_{Trees} based on *in situ* measurements on 108 urban trees (14 species) in the Los Angeles region: $E_{Trees} = E_{ref}\,(0.23 lnD + 0.002 I_0 + 0.55)$. Here D is the vapor pressure deficit of the air, I_0 is incoming solar radiation and E_{ref} is species-specific parameter representing E_{Trees} at D = 1 kPa that may be estimated using mean sapwood area of a tree stand. This model may be used to estimate E_{Trees} for practical applications and to improve representation of irrigated urban forests in hydrologic models.

Abbreviations: A_S(cm^2), Sapwood area; CIMIS, California Irrigation Management Information System (http://www.cimis.water.ca.gov); D (kPa), Vapor pressure deficit of the air measured by CIMIS weather stations; D_T (kPa), Vapor pressure deficit of the air measured within tree canopies; E_T (kgd^{-1}), Transpiration of an individual tree; E_{ref} (mmd^{-1}), Transpiration of a single species tree stand with the density of 100 trees ha^{-1} at daily average$D$ of 1 kPa (see Eq. (8)); E_{Trees} (mmd−1), Transpiration of single species tree stands with the planting density of 100 trees ha−1; ET (mm d^{-1}), Evapotranspiration (general term); ET_0 (mmd−1), Reference evapotranspiration from CIMIS; I_0(Wm^{-2}), Intensity of incoming solar radiation measured by CIMIS weather stations; k_c, Crop coefficient (see Eq. (2)); k_L, Landscape coefficient (see Eqs. (3) and (6)); k_S, Species-specific factor (see Eq. (3)); m_D(mm d^{-1}/ln(kPa)), Transpiration sensitivity of a single species tree stand with the density of 100 trees ha^{-1} to D (see Eq. (8)); m_I (mm d^{-1}/(W m^{-2})), Transpiration sensitivity of a single species tree stand with the density of 100 trees ha^{-1} to I_0 ; m_T (mm d^{-1}/ln(kPa)), Transpiration sensitivity of an individual tree to D_T (see Eq. (4)); ΔE_{ref} (mm d^{-1}), Intercept of the linear relationship between the residuals of Eq. (8) and I_0 (see Eq. (9)).

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1. Introduction

Transpiration of urban forests in southern California is a substantial yet highly uncertain component of municipal water use (Gleick et al., 2003; Mini, Hogue, & Pincetl, 2014; Ngo and Pataki, 2008; Pataki, McCarthy, Litvak, & Pincetl, 2011). Its uncertainty prevents ecohydrologic models from accurately estimating urban and regional water budgets (Howard & Israfilov, 2002; Shields & Tague, 2012; Vahmani & Hogue, 2014a, 2014b) and municipal institutions from informed planning of water allocation and landscape irrigation (Gleick et al., 2003; Mini et al., 2014; Pataki, Boone et al., 2011;). Currently, southern California is undergoing the most severe drought on record and faces further water shortages (Aghakouchak et al., 2014; Diffenbaugh, Swain, & Touma, 2015; MacDonald, 2010; Thompson, 2016; Williams et al., 2015) that highlight the need for an improved ability to model urban water fluxes (Bates, Kundzewitcz, Wu, & Palutikof, 2008; Hanak and Lund, 2008; Melillo et al., 2014). In Los Angeles, the most populated city in California, more than 50% of residential water is used for landscape irrigation (Mini et al., 2014). Yet, the urban forest is still a valued component of the urban landscape and requires continuous irrigation in Los Angeles (Clarke, Jenerette, & Davila, 2013; McCarthy, Pataki, & Jenerette, 2011; Pincetl, 2010). Under such circumstances, it is imperative to make informed decisions about water use of the urban forest. However, urban forest water use remains one of the most significant uncertainties in the urban water budget. Available data on urban forest transpiration is very limited (Costello, 2013; Pataki, McCarthy et al., 2011; Renninger, Phillips, & Hodel, 2009). The urban forest in Los Angeles contains about 6 million trees and is comprised of hundreds of species that are mostly non-native to southern California (Clarke et al., 2013; Gillespie et al., 2011; Nowak, Hoehn, Crane, Weller, & Davila, 2010; Pataki, McCarthy, Gillespie, & Generette, 2013). Even though these trees receive irrigation, atmospheric conditions in Los Angeles are often drier than in mesic regions, with lower relative humidity and higher vapor pressure deficit. This may result in transpiration patterns that are very different than in natural forests (Bush et al., 2008; Litvak, McCarthy, & Pataki, 2011; McCarthy and Pataki, 2010). Moreover, species native to the region may also show different patterns of transpiration in urban settings when they receive irrigation and are subject to other unique conditions in the urban environment (Bijoor, McCarthy, Zhang, & Pataki, 2011; Goedhart and Pataki, 2012; McCarthy & Pataki, 2010; Pataki, McCarthy et al., 2011). For example, native California sycamore (*Platanus racemosa* Nutt.) used substantially more water under urban irrigated conditions in Los Angeles than in a nearby natural riparian environment; furthermore, its transpiration was higher than a number of non-native irrigated urban trees in the same area (McCarthy and Pataki, 2010; Pataki, McCarthy et al., 2011). According to our previous study of 14 tree species in Los Angeles area, tree transpiration (E_T) ranged from as low as 0.8 ± 1.2 kg tree^{-1} day^{-1} (laurel sumac, *Malosma laurina* (Nutt.) Nutt. Ex Abrams) to as high as 176.9 ± 75.2 kg tree^{-1} day^{-1} (London plane, *Platanus hybrida* Brot.) and was highly variable among species and locations (Pataki, McCarthy et al., 2011). Therefore, transpiration of the urban forest in Los Angeles and its sensitivity to species composition is extremely difficult to predict.

Ecohydrologic models often use a landscape coefficient approach to account for urban forest transpiration as part of regional evapotranspiration (*ET*) in southern California (Spano, Snyder, Sirca, & Duce, 2009; Vahmani & Hogue, 2014a, 2014b). This approach is based on the Penman-Monteith model of surface energy balance that approximates *ET* of a reference vegetated surface (ET_0) (Monteith, 1965; Penman, 1948; Pereira and Perrier, 1999; Zhang, Hart, Gertz, Rueda, & Bergamini, 2009). The California Irrigation Management Information System (CIMIS) is a valuable resource provided by the California Department of Water Resources for using the landscape coefficient method to estimate *ET* of actual landscapes (http://www.cimis.water.ca.gov). CIMIS utilizes a set of 145 meteorological stations across California that are placed on irrigated turfgrass that serves as a reference surface for ET_0. CIMIS reports hourly and daily values of ET_0 calculated with a version of the Penman-Monteith equation:

$$ET_0 = \frac{\Delta/\lambda}{\Delta + \gamma(1 + Cu_2)}(R_n - G) + \frac{\gamma\left(\frac{37}{T_a + 273.16}\right)u_2}{\Delta + \gamma(1 + Cu_2)}D, \qquad (1)$$

where T_a is air temperature, Δ is the slope of the saturation vapor pressure versus T_a at current T_a, λ is the latent heat of vaporization, γ is the psychrometric constant, C is the surface and aerodynamic resistance coefficient, u_2 is a predefined linear function of wind speed at 2 m height, R_n is net radiation, G is the soil heat flux, and D is the vapor pressure deficit of the air (http://www.cimis.water.ca.gov/Content/PDF/PM%20Equation.pdf).

To calculate *ET* from a particular landscape, ET_0 is multiplied with a landscape coefficient k_L (Allen, Pereira, Raes, & Smith, 1998; Pereira and Perrier, 1999; Spano et al., 2009):

$$ET = k_L ET_0. \qquad (2)$$

In addition to modeling large-scale *ET*, the landscape coefficient method is routinely used by landscape managers for practical assessment of urban irrigation requirements (California Department of Water Resources, 2009; City of Los Angeles Department of City Planning, 2011). For this purpose, k_L is expressed as a product of three factors:

$$k_L = k_s k_d k_{mc}, \qquad (3)$$

where k_s is intended to correct for species-specific differences in transpiration, k_d for planting density, and k_{mc} for micro-climatic conditions (Costello, Matheny, Clark, & Jones, 2000).

To estimate *ET* of many tree species planted in California, look-up table values of k_s are provided (Costello et al., 2000). However, the performance of the landscape coefficient method and the values of k_s have never been tested against *in situ* tree transpiration in the Los Angeles area (Costello et al., 2000).

The first of the two goals of this study is to evaluate the landscape coefficient method using an *in situ* dataset of urban tree transpiration in the greater Los Angeles area (Fig. 1; Pataki, McCarthy et al., 2011). The landscape coefficient method was developed for agricultural ecosystems and has been supported by extensive research that refined landscape coefficients for crop fields (Allen et al., 1998). However, extensive surfaces of crop fields covered by a single species of uniform height are quite different from canopies of urban trees (Spronken-smith, Oke, & Lowry, 2000; Jansson, Jansson, & Gustafsson, 2006; Hagishima, Narita, & Tanimoto, 2007; Rim 2009). Even though k_L is applied to adjust for differences between ET_0 and landscape *ET*, it is not based on physiology of urban trees or mechanisms underlying differences in transpiration among species (Sinclair, Wherley, Dukes, & Cathey, 2014; Zeppel, 2013). Therefore, our second goal is to propose an alternative approach to estimating tree transpiration based on general patterns in urban tree transpiration in response to environmental factors.

Previous studies have shown that E_T is correlated with the logarithm of atmospheric vapor pressure deficit measured within tree canopies (D_T):

$$E_T = E_{Tref} + m_T \ln(D_T), \qquad (4)$$

with the coefficients E_{Tref} and m_T being proportional to each other and to the vulnerability of tree branches to cavitation (Litvak, McCarthy, & Pataki, 2012). This relationship has a fundamental physiological basis: trees with more sensitive stomatal regulation consistently demonstrate higher stomatal conductance and tran-