Adding trees to irrigated turfgrass lawns may be a water-saving measure in semi-arid environments

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ABSTRACT

Evapotranspiration (ET) of irrigated urban plants is a large yet uncertain component of urban water budgets in semi-arid regions. A detailed understanding of plot-scale ET and its sensitivity to plant species composition is necessary to improve estimates of urban water vapour fluxes and water balance. We used portable enclosed chambers and empirical equations to quantify ET from (1) unshaded urban lawns covered exclusively by turfgrass and (2) urban lawns comprised of open-grown trees and turfgrass groundcover in the Los Angeles Metropolitan area. Turfgrass at all locations had a non-limiting supply of soil water because of regular sprinkler irrigation. ET of irrigated turfgrass reached a maximum of 10.4 ± 1.3 mm d^{-1} and was always higher than plot-scale tree transpiration, which did not exceed 1 mm d^{-1}. In summer, total plot ET of the lawns with trees was lower than lawns without trees by 0.9–3.9 mm d^{-1}. Turfgrass ET was highly sensitive to solar radiation, and the ratio of ET of lawns with trees to ET of lawns without trees decreased with tree canopy cover. Hence, reductions in turfgrass ET caused by shading effects of open-grown trees were more important in influencing total landscape ET than the addition of tree transpiration. This suggests that low-density planting of trees that partially shade irrigated urban lawns may be a water-saving measure in semi-arid irrigated environments. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS   urban evapotranspiration; irrigated lawns; festuca arundinacea; cynodon dactylon; stenotaphrum secundatum; platanus racemosa; pinus canariensis; washingronia robusta

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INTRODUCTION

Turfgrass and trees are common components of urban vegetation, with turfgrass covering 39–54% and tree canopies covering 19–27% of the total urban area in the USA (Dwyer *et al*., 2000; Milesi *et al*., 2005). In the semi-arid southwestern USA, irrigation of urban landscapes consumes a large fraction of municipal water and competes for water with agriculture (Colby *et al*., 2006; Evans and Sadler, 2008; Sabo *et al*., 2010). In the highly populated Los Angeles metropolitan area, one-third of household water is used outdoors (Gleick *et al*., 2003), where much of it is inevitably lost to evapotranspiration (ET) (Decker *et al*., 1962; Kurc and Small, 2004; Ngo and Pataki, 2008). However, a detailed understanding of irrigated landscape ET and particularly its sensitivity to plant species and composition is lacking (Gleick *et al*., 2003; Ngo and Pataki, 2008; Pataki *et al*., 2011a; Peters *et al*., 2011; Shields and Tague, 2012). ET of vegetated cities is challenging to quantify because of its high sensitivity to

plant composition and irrigation regimes that are highly heterogeneous (Grimmond and Oke, 1999; Kotani and Sugita, 2005; Offerle *et al*., 2006; Balogun *et al*., 2009; Peters *et al*., 2011). Previous efforts to measure urban ET (Grimmond *et al*., 1996; Grimmond and Oke, 1999) and plant transpiration (Renninger *et al*., 2009; McCarthy and Pataki, 2010; Litvak *et al*., 2011; Pataki *et al*., 2011b; Goedhart and Pataki, 2012) in the Los Angeles area have shown a high degree of temporal and spatial variability.

Large-scale urban ET is usually quantified using micrometeorological techniques such as eddy covariance (Offerle *et al*., 2006; Balogun *et al*., 2009; Peters *et al*., 2011; Nordbo *et al*., 2012), as well as airborne and satellite remote sensing measurements combined with models (Arthur-Hartranft *et al*., 2003; Furaus *et al*., 2005; Boegh *et al*., 2009; Anderson *et al*., 2012). For measuring small plot ET, the most direct method is water mass balance that involves weighing lysimeters (Jensen *et al*., 1990; Rana and Katerji, 2000; Łabędzki, 2011). However, installation of lysimeters in urban environments is usually impractical (Marek *et al*., 1988; Grimmond *et al*., 1992). Vapor density measurements inside portable transparent chambers were successfully used for measuring ET in agricultural

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ecosystems (Dugas *et al.*, 1991; Steduto *et al.*, 2002; McLeod *et al.*, 2004; Centinari *et al.*, 2009) and are a feasible option for small-scale plots (Brown *et al.*, 2010; Raz-Yaseef *et al.*, 2010; Macfarlane and Ogden, 2012). In addition, empirical models based on surface energy balance (Penman, 1948; Monteith, 1965; Eichinger *et al.*, 1996; Allen *et al.*, 1998; Pereira and Perrier, 1999) may be employed to estimate plot-scale ET of homogeneous and moist vegetated surfaces such as turfgrass (Brown *et al.*, 2010; Centinari *et al.*, 2012; Todorovic *et al.*, 2013). The California Irrigation Management Information System (CIMIS) operated by the California Department of Water Resources provides open access to ET calculated with a version of Penman–Monteith equation using data from a network of weather stations mounted above standardized plots of irrigated grass (http://wwwcimis.water.ca.gov/; Temesgen *et al.*, 2005). CIMIS reports irrigated turfgrass ET rates in Los Angeles Metropolitan Area of up to ~7 mm d^{-1}.

At the watershed scale, grassland ET is usually lower than forest ET, especially where tree roots access the water table (Zhang *et al.*, 2001; Larcher, 2003, Peel *et al.*, 2010). In natural ecosystems, trees tend to be more deeply rooted than grasses and thus less susceptible to episodic or seasonal water stress (Jackson *et al.*, 1996; Scott *et al.*, 2008; Lu *et al.*, 2011). However, the comparative water relations of urban trees versus lawn grasses are unknown. The access of urban trees to irrigation water depends on their highly variable rooting distributions imposed by the presence of built infrastructure and frequent watering regimes (Gilman *et al.*, 1987; Day and Bassuk 1994; Grabosky and Gilman 2004). Besides irrigation, urban trees may routinely access other water sources, such as run-off and groundwater (Bijoor *et al.*, 2011). In addition, transpiration of urban trees is difficult to estimate because of the unique growing conditions, novel species composition (often more diverse than natural forests, Pouyat *et al.*, 2007; Pataki *et al.*, 2011b), and large, up to ten-fold, differences in water use among urban, horticultural species (Pataki *et al.*, 2011b). Hence, there is a relatively low predictability of the water relations of irrigated urban trees in semi-arid climates (Dwyer *et al.*, 2000; McCarthy and Pataki, 2010; Litvak *et al.*, 2011). According to sap flux measurements of irrigated trees in the Los Angeles Basin, plot-scale transpiration of urban trees in this region ranges from less than 0·1 to ~2·5 mm d^{-1} and appears to be controlled by species composition, irrigation practices (which generally result in well-watered soils), atmospheric conditions, and planting density, which is much lower than natural forests (Bush *et al.*, 2008; McCarthy and Pataki, 2010; Litvak *et al.*, 2011; Pataki *et al*, 2011b).

Several studies from different parts of the world suggest that turfgrass may sometimes dominate landscape ET and exceed the transpiration rates of urban trees. Large-scale, ground-area-specific ET of suburban areas mostly covered by non-irrigated turfgrass was higher in the summer than nearby areas dominated by deciduous broadleaf and conifer trees that received little or no irrigation in the Minnesota-Saint Paul metropolitan area (Peters *et al.*, 2011). Peters *et al.* (2011) estimated landscape ET from eddy covariance and quantified tree transpiration from sap flux measurements. Similarly, a surface energy balance study in a temperate, humid city in Japan showed that ground area specific summertime grassland ET was significantly higher than ET of adjacent pine forest that had similar precipitation inputs and groundwater table depth (Kotani and Sugita, 2005). Moreover, in a small-scale comparative study of irrigated yard designs in the arid Negev Highlands region of southeastern Israel, ET from a yard covered by turfgrass was larger than ET from a yard of similar size that had small shade trees in addition to turfgrass groundcover (Shashua-Bar *et al.*, 2009; Shashua-Bar *et al.*, 2011). The irrigation was adjusted to compensate for evaporational losses, and thus, neither turfgrass nor trees were water limited. Shashua-Bar *et al.* (2009) used mini-lysimeters to measure turfgrass ET and sap flux sensors to measure tree transpiration. They attributed lower ET of the second yard to the following: relatively sparse tree canopies did not suppress the growth of irrigated turfgrass but significantly lowered its ET by reducing incoming solar radiation and wind. Water use of the small trees was lower than the reduction of turfgrass ET, and thus, adding trees led to decreased total ET. This contradicts previous suggestions that tree transpiration is always significantly larger than turfgrass ET and, therefore, that planting trees that partially shade turfgrass would not lead to water savings (Feldhake *et al.*, 1983).

The goal of this paper is to assess the contribution of turfgrass and the role of tree shading in ET of irrigated landscapes in the Los Angeles region. We used portable chamber measurements and empirical modelling to estimate irrigated turfgrass ET and analyse its variability and environmental controls. We measured and modeled ET of open, unshaded turfgrass as well as turfgrass shaded by open-grown trees and estimated transpiration of shade trees from previous sap flux measurements of irrigated trees in Los Angeles (Renninger *et al.*, 2009; Pataki *et al.*, 2011b). Hence, we estimated total plot-scale ET of irrigated urban landscapes containing either turfgrass only or turfgrass and trees to evaluate the effect of tree shading on landscape ET. We asked the following questions: Is turfgrass ET lower or higher than urban forest transpiration in this region? Does adding open-grown trees to turfgrass landscapes increase or decrease total landscape ET? We hypothesized that ET of irrigated turfgrass is close to its physical limit during a hot and dry summer in Los Angeles region (http://wwwcimis.water.ca.gov/; Allen *et al.*, 1998) and may exceed transpiration of open-grown urban trees, which is constrained by species composition, planting density, and environmental conditions (Pataki *et al.*, 2011b). Thus,

when irrigated turfgrass and urban trees grow together on the same lawn, we expected the shading effects of trees to be more important than the addition of tree transpiration to total plot ET, even though the leaf area of the resulting two-layer canopy is higher. If this is the case, then adding low-density tree plantings to unshaded lawns in irrigated cities may actually be a water-saving measure.

METHODS

Study sites

We conducted this study in the Los Angeles metropolitan area, California, which is located in a coastal plain by mountain ranges in the north, east, and south (the Los Angeles Basin). The climate is Mediterranean, with mean annual temperatures of 17·0–18·3 °C and annual precipitation of 32·6–37·7 cm, which is mainly winter rain (Western Regional Climate Center, http://www.wrcc.dri.edu).

We chose eight managed lawns in three locations: the campus of the University of California, Irvine (location #1), California State University Fullerton Arboretum (location #2), and the Los Angeles County Arboretum and Botanic Garden in Arcadia (location #3). At each location, we chose one site comprised of non-shaded turfgrass (Grass-1, Grass-2, and Grass-3) and one site containing turfgrass and trees partially shading the grass (Grass&Trees-1, Grass&Trees-2, and Grass&Trees-3). Tree species present on these sites are commonly planted in the region, and their transpiration rates have been measured in previous studies: transpiration of California sycamore (*Platanus racemosa* Nutt.) and Canary Island pine (*Pinus canariensis* C.Sm.) in Los Angeles region was reported in McCarthy and Pataki (2010) and Pataki *et al.* (2011b); transpiration of the Mexican fan palms (*Washingronia robusta* H.Wendl.) at the site Grass&Trees-3 was measured in 2007 by Renninger *et al.* (2009). We also made measurements at two additional sites: Grass&Trees*-1 in the University of California, Irvine, with turfgrass shaded by trees and a building, and Grass&Trees*-2 in Fullerton Arboretum, with turfgrass very slightly shaded by nearby trees. We could not quantify tree transpiration at Grass&Trees* sites and used them for characterizing turfgrass ET only, as transpiration of tree species at those sites has not been measured, and there were an insufficient number of trees for measurement replication. We assessed tree canopy cover using satellite images (Google Map Data, Europa Technologies, INEGI) and an image processing program (ImageJ, National Institutes of Health, USA). Refer to Table I for study site descriptions.

The lawns at Irvine and Fullerton (locations #1 and #2) were irrigated with automatic sprinklers on a daily basis. Irrigation of the lawns in Arcadia (location #3) was controlled manually by site personnel; on average, those lawns were watered 1–2 times per week in summer (more during hot days) and not watered in winter. Because the studied lawns remained in public use during the study, we could not install collectors to measure the amount of applied water; instead, we measured soil water content (SWC).

Turfgrass species composition of the studied lawns was typical of landscaping practices in the region. In Irvine, the lawns were planted with tall fescue (*Festuca arundinacea* Schreb.) and Bermuda grass (*Cynodon dactylon* (L.) Pers.), with some weeds that were mostly clover (*Trifolium* spp.). The lawns in Fullerton were dominated by Bermuda grass, and in Arcadia, there was a combination of Bermuda grass and St Augustine grass (*Stenotaphrum secundatum* (Walt.) Kuntze). All the lawns were mowed once a week.

Environmental measurements

We made diurnal measurements of environmental parameters at each study site during 3 days in summer (June 2010) and 3 days in winter (January/February 2011) and additional summertime measurements at locations #1 and #2 during three days in August 2010 (Table I). The meteorological conditions during measurement periods were typical for coastal southern California summer and winter and included a dry episode in August at location #2.

We arranged the measurements along a transect representative of a light-shade pattern at each study site, making 12 replications of incoming shortwave radiation (I_O) and six replications of atmospheric temperature (T_a) and relative humidity. We measured I_O with Apogee pyranometers (Apogee Inc, Logan, Utah) connected to hand-held digital voltmeters, and T_a and relative humidity with HOBO Pro V2 dataloggers (Onset Computer Corporation, Bourne, MA) at 1 m above the grass. The dataloggers recorded T_a and relative humidity every 2 s. We made rotations between study sites that allowed us to repeat these series of measurements three to six times per day in summer and five to nine times per day in winter (along with chamber measurements described in the succeeding text). Then, we extracted T_a and humidity data from the datalogger records to determine atmospheric vapor pressure deficit (D) concurrent with chamber measurements. We estimated daily I_O and mean daylight D by fitting Gaussian functions to diurnal profiles of these variables:

$$y = a \exp\left[-\frac{1}{2}\left(\frac{t-t_0}{b}\right)^2\right] \qquad (1)$$

followed by analytical integration:

$$\int_{-\infty}^{+\infty} y \cdot dt = ab\sqrt{2\pi}. \qquad (2)$$

We also measured SWC at 0–5 cm depth using portable sensors (ML2x Theta Probe with HH2 moisture metre,

Table I. Site characteristics including area, species composition, height, tree canopy cover, and estimated leaf area index.

Study site	Area (m²)	Grass composition	Grass height (cm)	Grass LAI estimates (m²m⁻²; ±SE)	Tree composition	Tree canopy cover (%)	Measurement dates
Location #1 – campus of the University of California, Irvine							
Grass-1	271	Bermuda grass (95%) Tall fescue (3%) Weeds (2%)	5.5	June: 3·6±0·4 August: 3·0±0·3 February: 1·8±0·3	No trees		13, 14, and 19 June 2010 17, 19, and 20 August 2010 28 January and 2 and 6 February 2011
Grass&Trees-1	1011	Bermuda grass (90%) Tall fescue (4%) Weeds (6%)	6	June: 3·7±0·6 August: 3·1±0·4 February: 2·0±0·6	Canary Island pine (n=4) California sycamore (n=2)	68·8	
Grass&Trees*-1 (this site was also shaded by nearby building)	326	Tall fescue (65%) Bermuda grass (34%) Weeds (1%)	6.5	June: 4·1±0·7 August: 5·5±0·9 February: 1·6±0·2	Red bud trees (*Cercis Canadensis* L.) (n=11)	24·8	
Location #2 – California State University Fullerton Arboretum							
Grass-2	512	Bermuda grass (100%)	5.5	June: 8·0±0·9 August: 3·9±0·3 February: 3·9±0·5	No trees		21, 22, and 23 June 2010 23, 24 and 25 August 2010 1, 3, and 9 February 2011
Grass&Trees-2	279	Bermuda grass (100%)	11	June: 5·5±1·5 August: 3·1±1·2 February: 2·6±0·5	Canary Island pine (n=2)	83·7	
Grass&Trees*-2	531	Bermuda grass (100%)	3.5	June: 4·0±0·5 August: 3·2±0·5 February: 1·8±0·3	Fishtale palm (*Caryota urens* L.) (n=2)	6·4	
Location #3 – Los Angeles Arboretum and Botanic Garden							
Grass-3	858	St Augustine grass (89%) Bermuda grass (11%)	4	June: 5·8±0·8 February: 3·3±0·5	No trees		15, 16, and 17 June 2010 26, 27, and 31 January 2011
Grass&Trees-3	663	Bermuda grass (88%) St Augustine grass (12%)	4	June: 5·0±0·8 February: 3·7±0·8	Mexican fan palm (n=6)	9·4	

LAI, leaf area index; SE, standard error.

Delta-T Devices LTD, Cambridge, UK, and HydroSense Soil Water Measurement System, Campbell Scientific Inc., Logan, Utah, USA). These measurements of soil moisture were restricted to shallow depth to avoid damaging irrigation plumbing systems. We measured SWC at the same six locations as I_O, T_a, and relative humidity at each site four to six times a day in June and one to three times a day in August and January/February. We reduced the frequency of soil moisture measurements because average SWC remained stable over the course of the day. Because even small differences in soil structure and composition may affect reflectometry-based SWC measurements, we divided measured SWC by its maximum value obtained at each location and used the resulting relative SWC ($0 < \Theta < 1$) to compare study sites and analyse the influence of Θ on turfgrass ET.

In addition, we measured energy fluxes associated with irrigated grass. To quantify net radiation (R_N), we chose a spot with a 10-m footprint of unshaded irrigated turfgrass at each location and mounted a net radiometer (CNR1, Kipp & Zonen, Delft, Netherlands) on a portable tripod stand (T-1000, Columbia Weather Systems, Hillsboro, Oregon, USA) at 1 m height. We measured R_N and its components during 1 day at each location, derived linear relationships between I_O and R_N for each location, and used this relationship to estimate R_N from diurnal measurements of I_O. To assess the ground heat flux (G), we installed five soil heat-flux plates (HFPO1, Huxeflux Thermal Sensors B.V., Delft, Netherlands) at 5 cm depth for 1 day in June at each study site. The data from net radiometer and soil heat-flux plates were logged every 30 s and averaged every 15 min by dataloggers (CR1000 and CR3000, Campbell Scientific Inc., Logan, Utah).

Leaf area indices of turfgrass

At the end of the measurement period in June, August, and January/February we collected the aboveground grass biomass from six small (25 cm^2) sub-plots on the same transects as ET_{ch} measurements (described in the succeeding text) at each site to estimate leaf area index (m^2 m^{-2}). The small size of the samples was dictated by the necessity of avoiding any visual damage to the studied public areas at the request of the site managers. We sorted the grass to remove thatch and senesced leaves and measured an area of a subset of green leaves by using an imaging software (ImageJ, National Institutes of Health, USA). We dried and weighed this subset of leaves as well as the remaining biomass to determine specific leaf area (SLA, cm^2 g^{-1}) and obtain leaf area indices (Table I) by multiplication of biomass per unit ground area by SLA (Bréda, 2003).

Evapotranspiration from turfgrass

To quantify ET from turfgrass, we used portable cuboid chambers (0·18 m height and 0·28 m width) made of clear PVC (McLeod et al., 2004). Air temperature and humidity inside the chambers was recorded by HOBO Pro V2 wireless dataloggers (Onset Computer Corporation, Bourne, MA, USA) every 2 seconds. These small-sized dataloggers were attached to chamber walls close to the top where they were above the grass yet provided minimum shade. To make a measurement, a chamber was tightly pressed on the surface for 1 min. Between measurements, the chambers were ventilated for at least 1 min with ambient air.

We calculated the mass density of water vapour inside the chamber (ρ_v, kg m^{-3}) by using the ideal gas law:

$$\rho_v = \frac{e}{R_v(273.15 + T)}, \qquad (3)$$

where e is the vapor pressure inside the chamber in Pa, $R_v = 461 \cdot 5\,\mathrm{J\,K^{-1}\,kg^{-1}}$ is the gas constant for water vapor, and T is the temperature inside the chamber in °C. The increase of ρ_v caused by ET ($d\rho_v/dt$) was obtained as a slope of ρ_v versus time for stable periods of 10 seconds. ET (m^{3}H$_2$O m^{-2} s^{-1}) was calculated from chamber measurements as

$$\mathrm{ET_{ch}} = k\,\frac{h}{\rho_w}\,\frac{d\rho_v}{dt}, \qquad (4)$$

where h is the height of the chamber (0·18 m), $\rho_w = 10^3$ kg m^{-3} is the mass density of water, and k is the calibration factor discussed in the following text.

We made six chamber measurements at evenly spaced locations, along transects with typical light-shade distributions at each study site (coinciding with the measurements of I_O and D, described in the preceding text). We visited study sites one by one at each location, repeating these series of measurements three to six times per day in summer and five to nine times per day in winter. Preliminary tests showed that Gaussian curves fit very well with diurnal ET_{ch} plotted against time. Therefore, to obtain daily ET_{ch} with a reasonable degree of confidence, we collected most of the data around midday, to cover the portion of Gaussian curve where its slope is changing sign (Stannard, 1988). We fitted Gaussian functions to diurnal ET_{ch} profiles (p < 0·0001; R^2 from 0·82 to 0·99) and calculated daily ET_{ch} by analytical integration, similarly to I_O and D (Equation (1) and (2)).

Because of the possible artefacts of using the chamber method, such as shielding near-surface winds and absorption of water vapor by chamber walls (Davidson et al., 2002; Steduto et al., 2002; McLeod et al., 2004), as well as slow sensor response times, calibration was necessary for calculating actual ET from these measurements. For calibration, we inserted 0·22 m × 0·22 m sod samples of tall fescue (four samples on 29 June 2011 and eight samples on 16 February 2012 and 23 February 2012) and Bermuda grass (four samples on 9 March 2012) in metal mesh frames, watered generously, allowed them to drain, and

sealed them with plastic wrap from the sides and underneath to avoid leakage. We kept the samples outside our building at the campus of the University of California, Irvine. The same day, we made chamber measurements of each sample outside followed by a quick trip to the laboratory to weigh the samples on a precise balance (0·01 g resolution, 3100 g capacity; OHAUS AdventurerPro AV 3102, OHAUS Corporation, Parsippany, NJ, USA) within a minute after each chamber measurement. We repeated outside chamber measurements followed by weighing in the laboratory hourly, for several hours a day. During these procedures, the samples were exposed to ambient conditions most of the time; they were covered by a chamber for a total of 2 min each hour and spent the other 2 min per hour inside for weighing. These measurements were made from 10 AM to 5 PM on 29 June 2011, from 11 AM to 5 PM on 16 February 2012, from 3 PM to 4 PM on 23 February 2012, and from 1 PM to 3 PM on 9 March 2012, to capture as wide range of ET as possible. We calculated mean hourly ET by averaging the consequent pairs of hourly measurements and plotted uncalibrated mean hourly chamber ET against mean hourly gravimetric ET (Figure 1). The resulting calibration factor $k = 4·26 \pm 0·05$ was then applied to the ET_{ch} calculation [Equation (4)].

Model estimation of turfgrass ET

In addition to chamber measurements, we estimated turfgrass ET using a modified Penman equation similar to the one used by CIMIS (Allen *et al.*, 1998; http://wwwcimis.water.ca.gov):

$$ET_O = \frac{\Delta}{\Delta + \gamma} \frac{R_N - G}{694.5\left(1 - 9.46 \times 10^{-4}T_a\right)} + \frac{\gamma}{\Delta + \gamma} D(0.030 + 0.0576u), \quad (5)$$
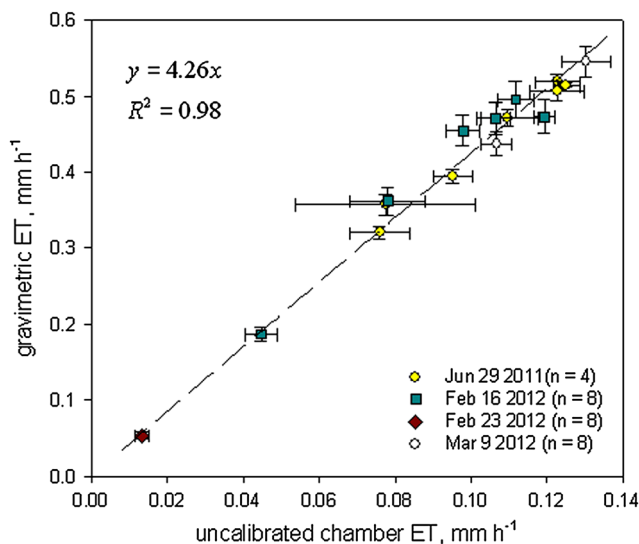

Figure 1. Hourly gravimetric water loss of turfgrass samples plotted against measured evapotranspiration (ET) from chambers (calibration curve). Error bars show 1 standard error and n in parentheses represents the number of samples.

where ET_O is modelled ET, Δ is the slope of saturation vapour pressure as the function of temperature at the ambient temperature, γ is the psychrometric constant, R_N, G, T_a, and D were measured as described in the previous text, and u is the wind speed at 2 m high, for which we used the data available from CIMIS weather stations. ET_O is ET of standardized irrigated grass surface that is considered a 'reference crop' (http://wwwcimis.water.ca.gov/cimis/infoEtoOverview.jsp; Allen *et al.*, 1998; see more on ET_O in the Discussion). We calculated daily ET_O similarly to daily ET_{ch} [Equations (1) and (2)].

Plot-scale ET

Plot-scale ET was calculated by summing up average daily turfgrass ET (ET_{ch} or ET_O) for each measurement period and transpiration from tree canopies (E_C, mm d^{-1}). We estimated E_C at the Grass&Trees sites and summed turfgrass ET and E_C to assess total plot ET (because the major water input was irrigation at the ground level, we assumed that evaporation from trees was negligible compared with E_C).

The site Grass&Trees-1 contained two California sycamores and four Canary Island pines; the site Grass&Trees-2 contained two Canary Island pines (Table I). To estimate their transpiration, we used the data from previously published sap flux measurements of irrigated trees in the Los Angeles region (McCarthy and Pataki, 2010; Pataki *et al.*, 2011b). Similar to those studies, the trees at our sites were mature, had mean diameter at breast height of $57·9 \pm 7·0$ cm (±standard error), grew under the same climatic conditions, and received regular irrigation. We used the data for California sycamore and Canary Island pine trees with the highest transpiration rates reported for these species (Pataki *et al.*, 2011b) to model their transpiration (E_T, kg d^{-1} per tree) as linear functions of environmental variables ($p < 0·0001$; $R^2 = 0·83$ for California sycamore and $R^2 = 0·69$ for Canary Island pine):

$$E_{T_1} = 13·4 + 8·9\ln D + 1·0 PAR + 24·0\Theta \quad (6a)$$
$$\text{for Canary Island pine, and}$$

$$E_{T_2} = 38·9 + 34·2\ln D + 1·2 PAR \quad (6b)$$
$$\text{for California sycamore,}$$

where PAR (mol m^{-2} d^{-1}) is photosynthetically active radiation reaching the canopies. Trees for which these empirical equations were fit were not water limited (McCarthy and Pataki, 2010; Pataki *et al.*, 2011b). In fact, E_T of California sycamores was higher than similar trees in a natural riparian forest in the same region (Pataki *et al.*, 2011b).

We used Equations (6a) and (6b) to estimate E_T at our study sites assuming that trees had access to unlimited soil moisture ($\Theta = 1$). To better represent the environmental conditions to which tree canopies were exposed, we used D

and I_O from nearby unshaded lawns Grass-1 and Grass-2. We estimated PAR (mol m^{-2} d^{-1}) as $2 \times I_O$ (MJ m^{-2} d^{-1}). Then, we used the total ground areas of each lawn (A, m^2) to calculate the contribution of tree transpiration into plot-scale ET as

$$E_C = \frac{1}{A} \sum n_i E_{T_i}, \qquad (6c)$$

where n_i is the number of trees as shown in Table I. We estimated single tree transpiration (E_T) and transpiration per ground area (E_C) but could not estimate transpiration per leaf area because of the lack of leaf area data for California sycamores and Canary Island pines (McCarthy and Pataki, 2010; Pataki et al., 2011b, Litvak et al., 2012). In winter, California sycamores at Grass&Trees-1 were leafless and did not contribute to E_C.

The site Grass&Trees-3 contained six Mexican fan palms whose transpiration was measured by Renninger et al. (2009) in the summer of 2007. The palms were up to 34 m in height with a small number of leaves comprising the compact canopy. Renninger et al. (2009) reported total transpiration of these palms on a leaf area basis. To assess the upper limit of transpiration rates per tree, we multiplied maximum sap flux per leaf area ($1 \cdot 7 \pm 0 \cdot 2$ kg d^{-1} m^{-2}) by maximum leaf area ($1 \cdot 74 \pm 0 \cdot 21$ m^2). To obtain canopy transpiration, we multiplied tree transpiration by the number of palm trees on the site and divided by the plot area (Table I).

Statistical analyses

We fitted Gaussian curves [Equations (1) and (2)] to estimate daily sums of I_O, daily averages of D, and daily ET using SIGMAPLOT (Version 10, Systat Software Inc., Chicago, IL, USA). In addition, we used SIGMAPLOT to test linear models for ET [Equations (7a) and (7b) in the Results section] and calculate corresponding parameters. To evaluate site-to-site and summer-to-winter differences of ET and environmental parameters, we performed t-tests, analyses of variance (ANOVA), and Tukey's honest significance tests using R software (version 2.10.1, the R Foundation for Statistical Computing, http://www.r-project.org). We used analysis of covariance to test homogeneity of regression coefficients for different study locations using R software (Table II).

RESULTS

Environmental parameters

At all Grass sites and Grass&Trees*-2 site (that was very slightly shaded), incoming radiation was similar to nearby CIMIS weather stations (Figure 2). At all locations, summertime I_O of Grass sites was significantly higher compared with corresponding Grass&Trees sites (repeated measures ANOVA; $p \ll 0 \cdot 0001$ for location #1, $p = 0 \cdot 0019$ for location #2, and $p = 0 \cdot 0046$ for location #3). Summertime I_O of Grass sites was also significantly higher than wintertime I_O (repeated measures ANOVA; $p \leq 0 \cdot 0001$ for locations #1 and #3, and $p = 0 \cdot 004$ for location #2). I_O of Grass&Trees sites at all locations did not significantly change from summer to winter ($p = 1 \cdot 0$ for locations #1 and #2, and $p = 0 \cdot 1$ for location #3).

Unlike I_O, average light-day D did not differ significantly among the sites at each location (Figure 2, $p = 1 \cdot 0$ for all). Overall, daytime mean D varied between $0 \cdot 29 \pm 0 \cdot 02$ kPa (location #3, January 27th) and $2 \cdot 50 \pm 0 \cdot 14$ kPa (location #2, August 23rd). The highest value of D was measured at location #2 on 23–25 August ($p \leq 0 \cdot 026$). High D on these days was also reported at the CIMIS stations near all study locations (http://www.cimis.water.ca.gov).

Normalized relative SWC at the 0–5 cm depth ($0 < \Theta < 1$) was spatially and temporally variable, with an apparent increase from summer to winter at all sites ($p < 0 \cdot 0001$). We observed minimum $\Theta \approx 0 \cdot 17$ on June 19th at Grass&Trees*-1 and on June 16th at Grass-3. Θ reached its maxima in January/February at all sites except Grass-2 where maximum Θ was detected in August (Figure 2).

Turfgrass ET

We assumed that nighttime ET$_{ch} = 0$ as our measurements at sunrise and sunset did not show detectable ET, and dew was present on the grass in early mornings. ET$_{ch}$ reached

Table II. Regression coefficients for a linear model of measured chamber evapotranspiration (ET$_{ch}$) as a function of incoming shortwave radiation (I_O), atmospheric vapor pressure deficit (D), and relative soil water content (Θ): ET$_{ch} = aI_O + bD + c\Theta$, with $\pm$ standard errors.

Location	a	b	c	R^2
#1	$(7 \cdot 0 \pm 0 \cdot 3) \times 10^{-4}$[a]	$0 \cdot 08 \pm 0 \cdot 01$[a]	$-0 \cdot 10 \pm 0 \cdot 02$[a]	0·87
#2	$(6 \cdot 0 \pm 0 \cdot 4) \times 10^{-4}$[a]	$0 \cdot 19 \pm 0 \cdot 01$[b]	$-0 \cdot 28 \pm 0 \cdot 03$[b]	0·87
#3	$(6 \cdot 0 \pm 0 \cdot 6) \times 10^{-4}$[a]	$0 \cdot 13 \pm 0 \cdot 02$[c]	$-0 \cdot 22 \pm 0 \cdot 03$[b]	0·86
Overall	$(6 \cdot 0 \pm 0 \cdot 3) \times 10^{-4}$	$0 \cdot 17 \pm 0 \cdot 01$	$-0 \cdot 22 \pm 0 \cdot 02$	0·86

Coefficients in the table correspond to ET$_{ch}$ in mm h^{-1}, I_O in W m^{-2}, and unitless Θ. All coefficients are significant with $p < 0 \cdot 0001$. Different letter superscripts in each column indicate significant differences among coefficients at $\alpha = 0 \cdot 95$.
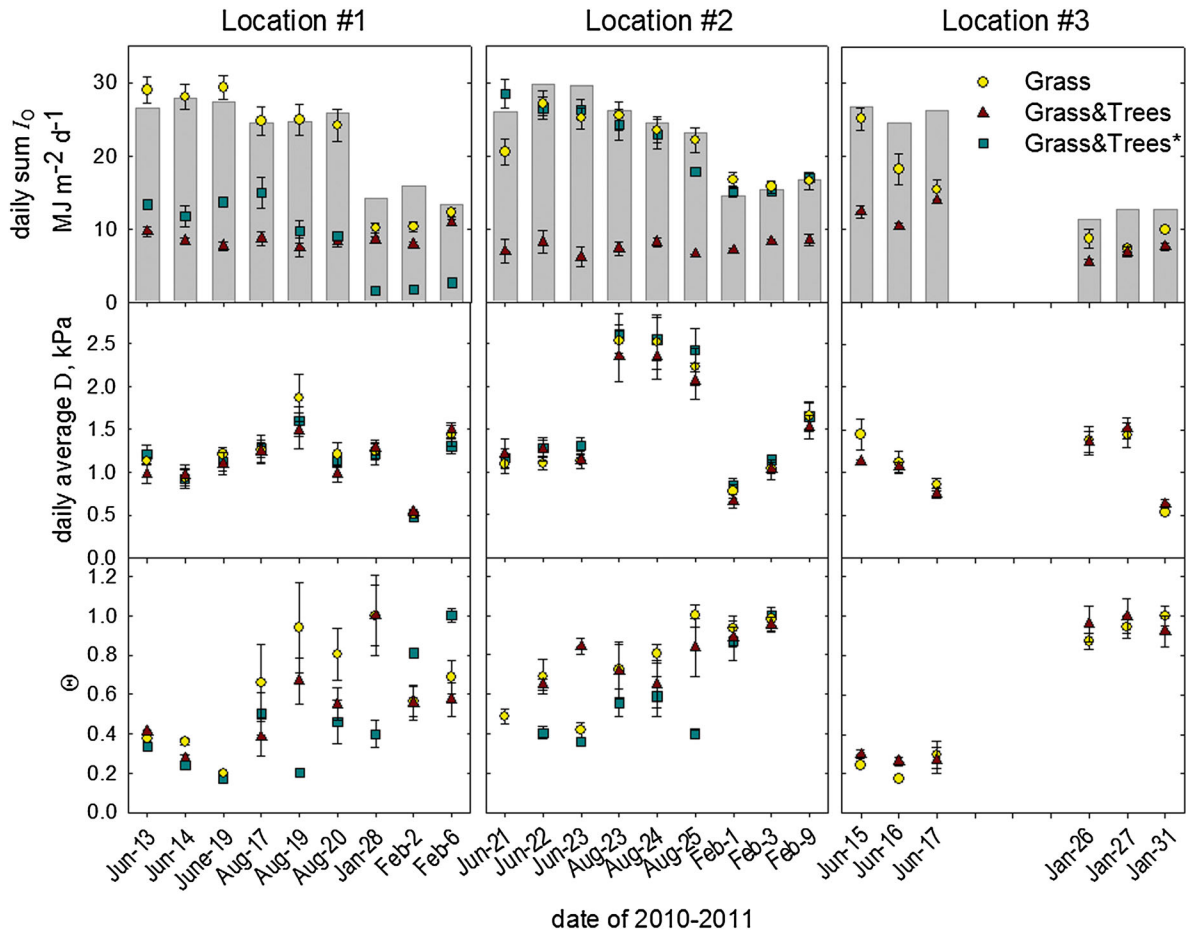
Figure 2. Incoming shortwave radiation (I_O), atmospheric vapour pressure deficit (D), and relative soil water content (Θ) at each of the three types of study sites. Grey bars show I_O from the closest California Department of Water Resources weather stations (station #75 Irvine for location #1, station #78 Pomona for location #2, and station #133 Glendale for location #3, http://wwwcimis.water.ca.gov). Note that the x-axis is not linear. Error bars show the modelling error of Gaussian integration for I_O and D, and 1 standard error for Θ.

its daytime maximum between 1 PM and 2 PM in summer and between 12 PM and 1 PM in winter. Maximum summertime ET_{ch} was 1.40 ± 0.06 mm h^{-1}, measured at Grass-2 (in August), and maximum wintertime ET_{ch} was 0.56 ± 0.04 mm h^{-1}, measured at Grass-1 (Figure 3).

ET_{ch} (mm h^{-1}) was linearly correlated with I_O ($R^2 = 0.67$, $p < 0.0001$), D ($R^2 = 0.56$, $p < 0.0001$), and Θ ($R^2 = 0.19$, $p < 0.0001$, Figure 4). We fitted the simple linear model

$$ET_{ch} = aI_O + bD + c\Theta, \qquad (7a)$$

that adequately captured ET_{ch} variations across all study sites and seasons ($R^2 = 0.86$, Table II). Weak negative correlations between ET_{ch} and Θ may be caused by enhanced evaporation from upper soil in response to I_O and D that contributes to the total ET from turfgrass surface.

Daily ET_{ch} (Figure 5a) varied from 0.14 ± 0.04 mm d^{-1} (Grass&Trees*-1, February) to as high as 10.4 ± 1.3 mm d^{-1} (Grass-2, August). Daily ET_{ch} in June and August was significantly higher than January/February (ANOVA, $p \leq 0.0004$) at all grass sites and also at Grass&Trees*-2 site that had minimal tree cover. There was no significant

difference between daily ET_{ch} averaged for summer and winter measurement periods at Grass&Trees-1 ($p \geq 0.49$). In June and August but not in winter, daily ET_{ch} at Grass&Trees-1 was significantly lower than Grass-1 ($p = 0.0001$ for June; $p = 0.001$ for August). ET_{ch} at Grass&Trees*-1 was significantly lower than Grass-1 in August only ($p = 0.03$). At location #2, daily ET_{ch} of all three sites was highest in August ($p \leq 0.009$). In addition, in June and August but not in winter, daily ET_{ch} at Grass&Trees-2 was significantly lower than Grass-2 ($p = 0.0006$ for June; $p = 0.001$ for August) and Grass&Trees*-2 ($p = 0.0007$ for June; $p = 0.005$ for August).

Daily ET_O was similar to measured values except for some periods in summer, when ET_O was lower than ET_{ch}, especially at location #2 in August 2010 (Figure 5b).

Plot-scale ET

Tree transpiration modeled with Equations 6 (a, b, c) is shown in Tables III and IV. Plot-scale ET was estimated as ET of turfgrass at Grass sites and the sum of tree transpiration (E_C, Table IV) and turfgrass ET at Grass&Trees sites (Figure 6). We did not estimate plot-
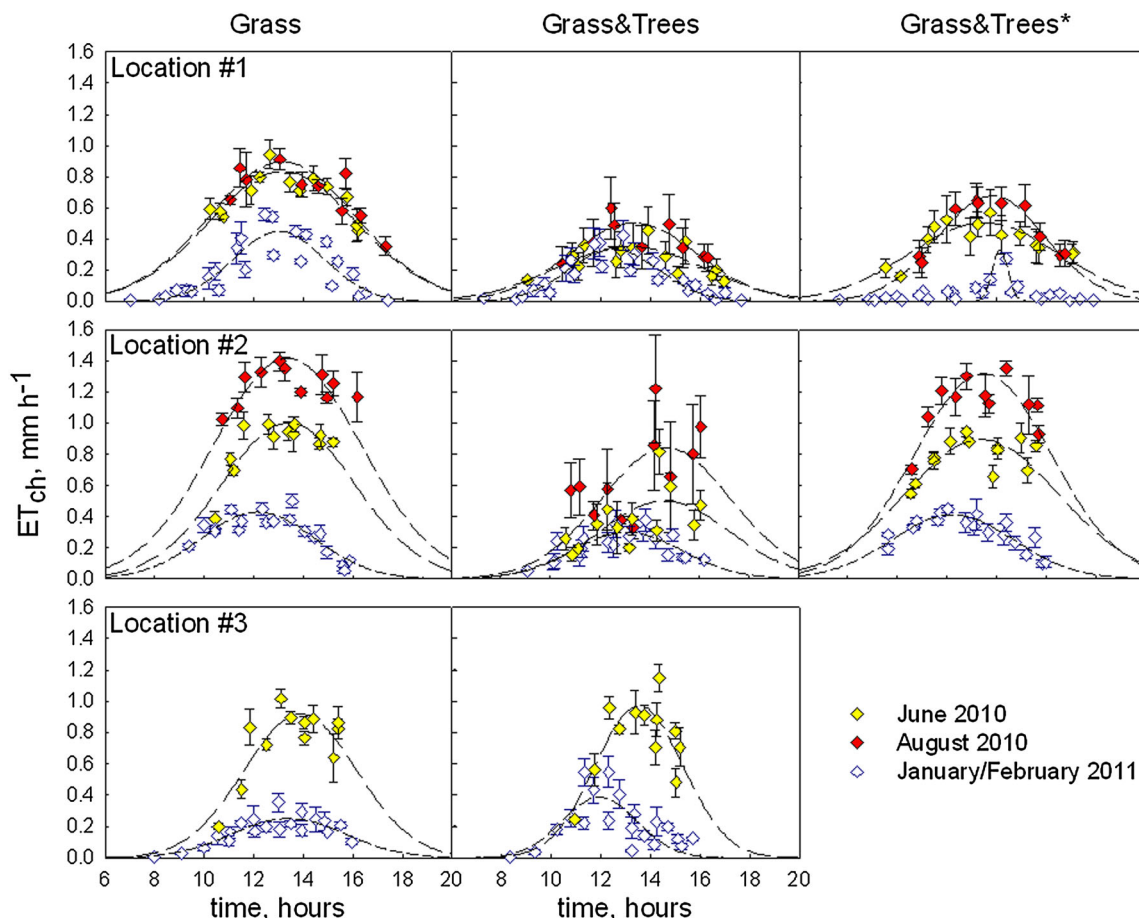
Figure 3. Ensemble averaged diurnal evapotranspiration of irrigated turfgrass measured by the portable chamber (ET_{ch}). Error bars show 1 standard error.
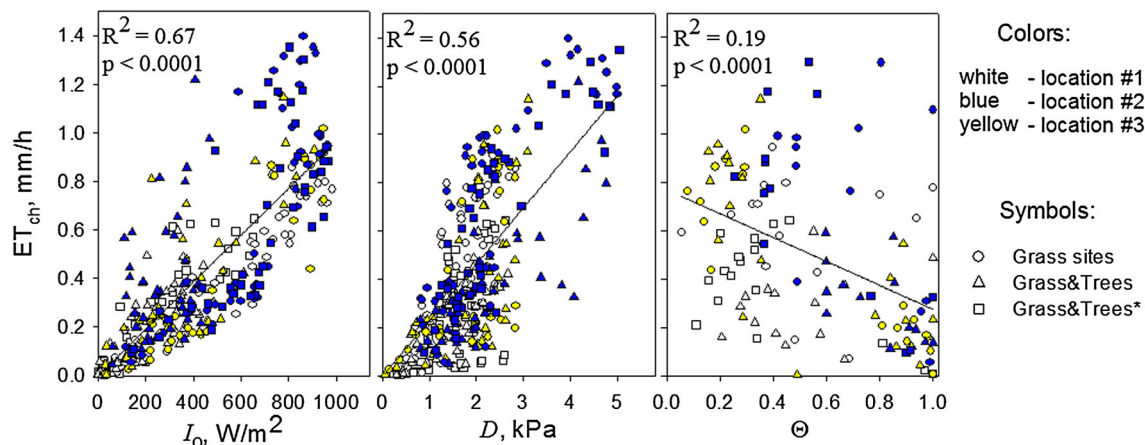

Figure 4. Chamber evapotranspiration (ET_{ch}) as a function of I_O, D, and Θ with linear regression lines and statistics. All data from all study sites are shown.

scale ET for Grass&Trees* sites because of the absence of tree transpiration data. In June and August, average plot ET (Figure 6) from the Grass sites was significantly higher than plot ET from the Grass&Trees sites (repeated measures ANOVA, $p \leq 0.0001$ for both chamber-based and model-based cases). In winter, however, there was no significant difference ($p = 1.00$ for chamber-based and

$p = 0.83$ for model-based estimates). Overall, plot ET calculated with ET_{ch} was higher than plot ET calculated with ET_O ($p = 0.001$, paired t-test). Averaged plot ET_{ch} during summer measurements varied from 3.2 ± 0.04 mm d^{-1} (Grass&Trees-1, June) to 9.6 ± 0.90 mm d^{-1}(Grass-2, August), and averaged plot ET_O during summer measurements varied from 2.6 ± 0.06 mm d^{-1} (Grass&Trees-2,
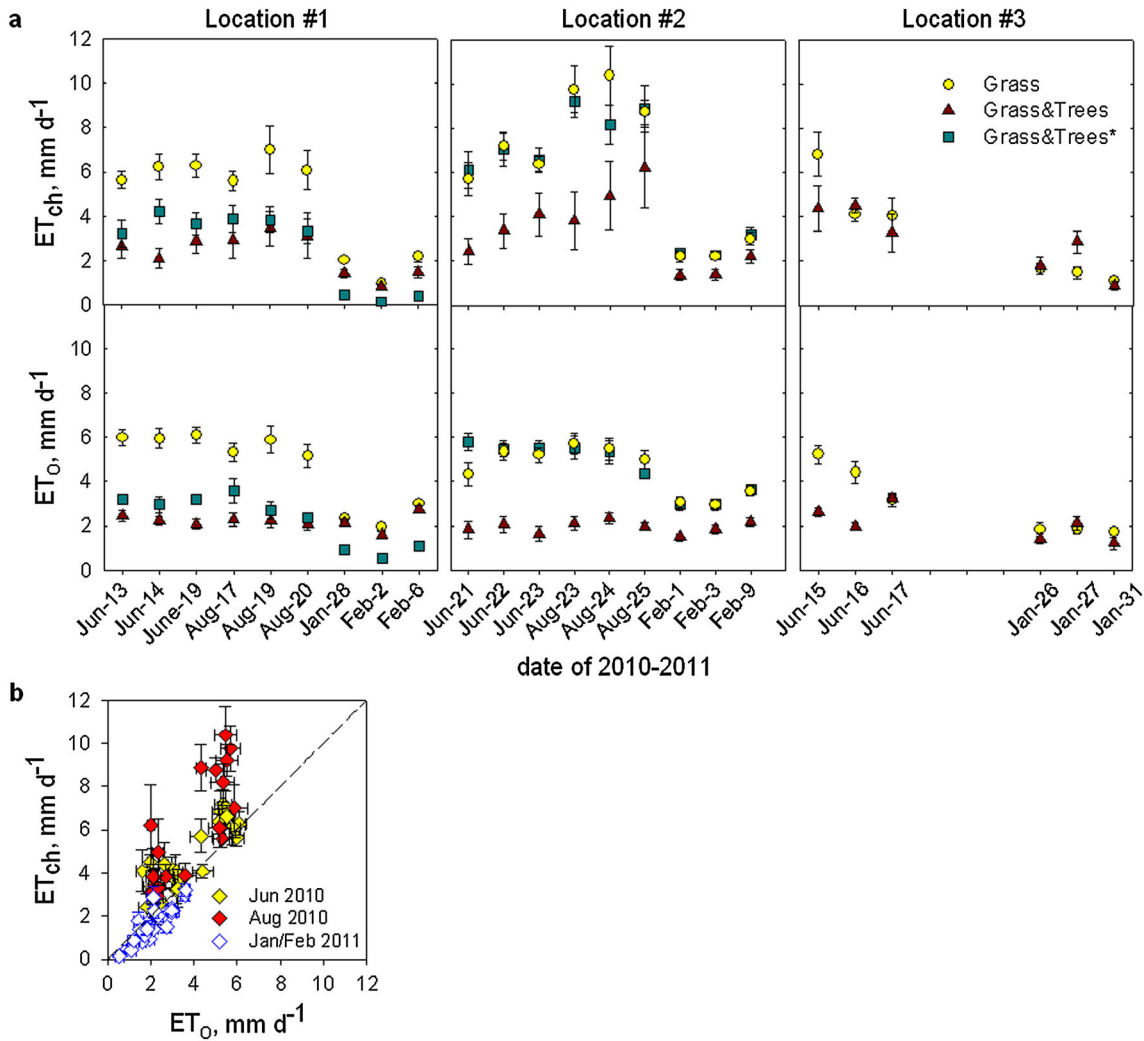
Figure 5. (a) Daily sums of turfgrass evapotranspiration measured by portable chambers (ET_{ch}, upper panel) and modeled using a modified Penman–Monteith equation (ET_O, lower panel). Note that the *x*-axis is not linear. Upper panel error bars show propagated standard error, and lower panel error bars show propagated model error. (b) ET_{ch} plotted against ET_O, with the 1:1 line shown.

Table III. Tree transpiration (E_T, kg d^{-1} per tree ± propagated model error) for each study period, modeled with Equations (6a) and (6b) in the text for California sycamore and Canary Island pine assuming saturating soil moisture conditions and derived from Renninger *et al.* (2009) for Mexican palm.

Study site		Tree transpiration, kg d^{-1}		
		June	August	January/February
Grass&Trees-1	California sycamore	130 ± 10	131 ± 10	0·00*
	Canary Island pine	103 ± 8	100 ± 8	61 ± 6
Grass&Trees-2	Canary Island pine	102 ± 8	103 ± 8	75 ± 6
Grass&Trees-3	Mexican palm	≤2·9 ± 0·5	≤2·9 ± 0·5	≤2·9 ± 0·5

*Transpiration of winter-deciduous California sycamores was considered to be zero during wintertime.

June) to $6·0 ± 0·13$ mm d^{-1} (Grass-1, June). Averaged plot ET_{ch} during winter measurements varied from $1·4 ± 0·22$ mm d^{-1} (grass-3) to $2·5 ± 0·15$ mm d^{-1} (Grass-2), and averaged plot ET_O during winter measurement varied from $1·6 ± 0·00$ mm d^{-1} (Grass&Trees-3) to $3·2 ± 0·11$ mm d^{-1} (Grass-2). Plot ET in winter was lower than plot ET in summer for both chamber-based and model-based calculations (p < 0·0001 for both).

Table IV. Total tree transpiration per ground area of each lawn at Grass&Trees sites (E_C, mm d^{-1} ± propagated model error) for each study period, calculated with Equation (6c) in the text.

Study site	Tree transpiration, mm d^{-1}		
	June	August	Januray/February
Grass&Trees-1	0·66 ± 0·04	0·65 ± 0·04	0·24 ± 0·02*
Grass&Trees-2	0·73 ± 0·06	0·74 ± 0·06	0·54 ± 0·05
Grass&Trees-3	0·03 ± 0·00	0·03 ± 0·00	0·03 ± 0·00

*Transpiration of winter-deciduous California sycamores was considered to be zero during wintertime.

Tree canopy cover

We evaluated the influence of tree shading on daily ET of turfgrass by considering tree canopy cover (Table I) as a factor reducing incoming sunlight:

$$ET_{ch} = a(1 - \alpha)I_{O\,max} + bD_O + c\Theta. \qquad (7b)$$

where I_{Omax} (W m^{-2} d^{-1}) is I_O measured at Grass sites, α is tree canopy cover ($0 < \alpha < 1$), and D_O is daily averaged D at Grass sites. This model explained 79% of the variability in ET_{ch} across all study sites (Grass&Trees*-1 not considered) and all seasons with significant parameters $a = 0·17 ± 0·02$, $b = 2·0 ± 0·2$, and $c = -1·3 ± 0·4$ (p < 0·0001).

To quantify the overall effect of tree canopies on turfgrass ET, we considered ET of shaded sites (Grass&Trees and Grass&Trees*) relative to ET of sun-exposed sites (Grass) at the same location:

$$\text{relative } ET_{ch}(\text{Grass\&Trees} - i) = \frac{ET_{ch}(\text{Grass\&Trees} - i)}{ET_{ch}(\text{Grass} - i)},$$

and

$$\text{relative } ET_{ch}(\text{Grass\&Trees*} - 2) = \frac{ET_{ch}(\text{Grass\&Trees*} - 2)}{ET_{ch}(\text{Grass} - 2)},$$

where $i = 1·2,3$ is the location number. Site Grass&Trees*-1 was not included in this analysis because it was shaded by a building in addition to trees. Relative ET_{ch} averaged across all seasons was consistently higher at the sites with low tree canopy cover and lower at the sites with high tree canopy cover (Figure 7). There was a significant linear relationship between tree canopy cover and relative ET_{ch} and a marginally significant relationship between tree canopy cover and relative ET_O (Figure 7).

DISCUSSION

We hypothesized that turfgrass ET would be higher than tree transpiration and that the effect of tree shading may lead to lower plot-scale ET. The results support these hypotheses. In particular, summertime ET of unshaded turfgrass varied from ~2 to ~6 mm d^{-1} (according to the modified Penman equation) and to 10 mm d^{-1} (according to chamber measurements), while tree transpiration remained less than 1 mm d^{-1} (Table IV and Figure 5). During summer, the reduction of turfgrass ET at the shaded sites was larger than tree transpiration at those sites, which led to lower total summertime plot-scale ET at the sites that contained trees compared with the unshaded sites (Figure 6).
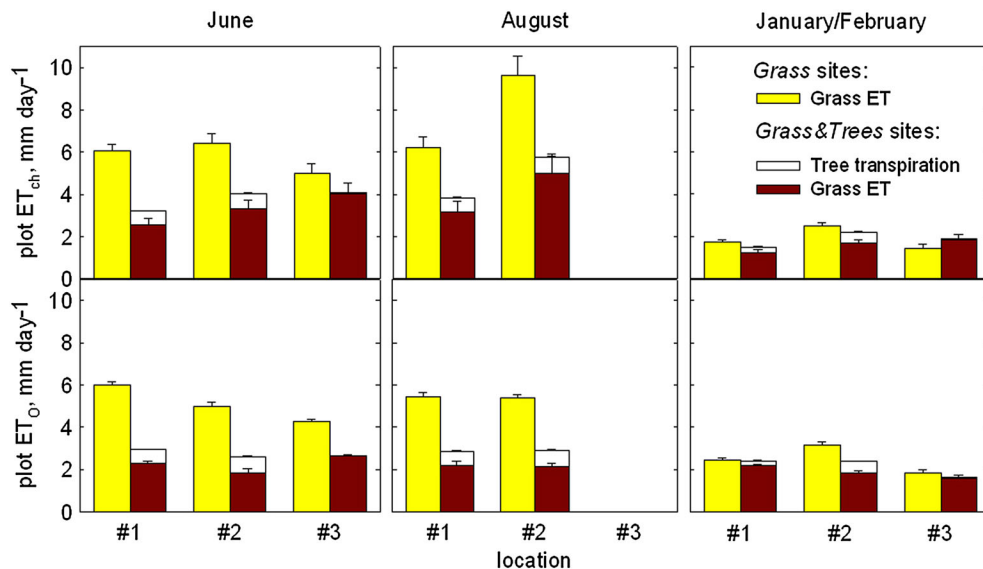

Figure 6. Total plot evapotranspiration (ET) and its components with turfgrass ET calculated using chamber data (ET$_{ch}$, upper panel) and a modified Penman–Monteith equation (ET$_O$, lower panel) and averaged for each study period. Tree transpiration was modeled on the basis of highest transpiration rates measured in Pataki *et al.*, 2011b and Renninger *et al.*, 2009 as an upper bound. No data were collected at location #3 in August. Upper panel error bars show propagated standard error, and lower panel error bars show propagated model error.
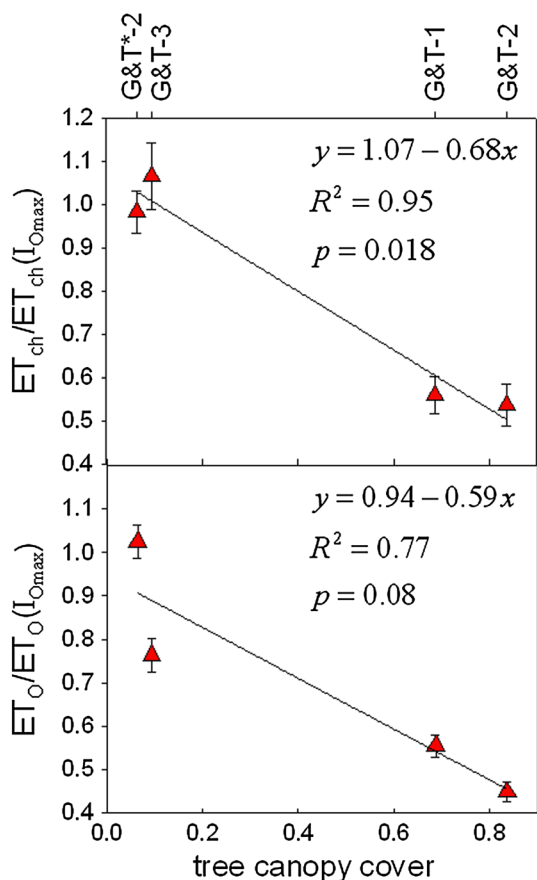
Figure 7. Average relative evapotranspiration (ET) of turfgrass at shaded sites with respect to ET of Grass sites [ET(I_{Omax})] at each location, as a function of tree canopy cover. Upper panel – average relative ET calculated using chamber data (ET$_{ch}$), lower panel – average relative ET calculated with modified Penman equation (ET$_O$). Notation: G&T = Grass&Trees. Site Grass&Trees*-1 is not included (see text for details). Error bars show propagated standard error.

Chamber measurements

We evaluated ET of irrigated turfgrass by using small enclosed chambers. Chamber measurements are convenient for use on urban recreational lawns because the measurement time is short (less than 1 min), the method is suitable for small areas, and it is non-invasive. However, environmental conditions inside chambers may differ from ambient and introduce biases to measured fluxes (Davidson *et al.*, 2002). Even when fluxes are calculated during the first 15–20 s of chamber deployment as was the case here, chambers still suppress incoming radiation, alter air pressure, block near-surface winds, increase air and surface temperature, and change water vapour concentration gradients (Davidson *et al.*, 2002; Steduto *et al.*, 2002). Often, fans are attached inside enclosed chambers to mimic ambient air mixing. However, artificial air circulation may enhance ET inside chambers by excessively mixing humid air adjacent to the grass with drier air above. To test the influence of fans on ET, we made 10 simultaneous

chamber measurements with and without small fans. Small fans (one per chamber) were attached to the upper part of chamber wall and created wind speeds of $1 \, \mathrm{m \, s^{-1}}$ and $2 \, \mathrm{m \, s^{-1}}$ right above the grass surface. The resulting ET (uncalibrated) was $0 \cdot 12 \pm 0 \cdot 01 \, \mathrm{mm \, h^{-1}}$, $0 \cdot 16 \pm 0 \cdot 00 \, \mathrm{mm \, h^{-1}}$ and $0 \cdot 20 \pm 0 \cdot 05 \, \mathrm{mm \, h^{-1}}$, corresponding to wind speeds of 0, $1 \mathrm{m \, s^{-1}}$, and $2 \, \mathrm{m \, s^{-1}}$. ET values obtained with the fans were significantly higher than ET without fans (p < 0·003 for both wind speeds, *t*-tests). Larger chambers tend to significantly overestimate ET because of its high sensitivity to fan speed (Grau, 1995; Dugas *et al.*, 1997; Heijmans *et al.*, 2004; McLeod *et al.*, 2004; Stannard & Weltz, 2006). Therefore, while air mixing inside chambers may reduce the discrepancy between chamber and gravimetric measurements, it would also complicate the interpretation of resulting ET under field conditions. Still, the relatively large calibration coefficient that we obtained ($k = 4 \cdot 26$) indicates the importance of calibration of small, static chambers (Figure 1). The coefficient can be used with confidence only for values within the range of the calibration experiment (Figure 1) and may be invalid when near-surface conditions are very different from the conditions during calibration. Despite these limitations, we suggest that exposing calibration samples to ambient (as opposed to controlled) conditions greatly reduced chamber biases to provide reasonable ET estimates.

Modified Penman method

We used a modified Penman equation to obtain independent estimates of irrigated turfgrass ET based on weather parameters. While the modified Penman equation was developed for atmospheric relative humidity values of 45% and higher (Allen *et al.*, 1998), our measurements indicated that relative humidity was as low as 29·4% in August at location #2. During that measurement period, *D* varied from 2·6 kPa (24 August 2010, 10:30 AM) to 5·4 kPa (23 August 2010, 2:30 PM) and provided the highest daily averaged *D* values in our study (Figure 2). These conditions were caused by Santa Ana winds – strong offshore winds that often cause dry conditions in coastal southern California (Bowden *et al.*, 1974; Hughes and Hall, 2009; Keeley *et al.*, 2009). Even though strong winds did not directly affect ET at our study sites (wind speed did not exceed $2 \, \mathrm{m \, s^{-1}}$ at the nearby CIMIS weather station #78, http://wwwcimis.water.ca.gov/), micrometeorological conditions, plant physiological behaviour, and processes inside chambers might be significantly altered during high *D* events; hence, both chamber and model estimates of ET should be treated with caution (Figure 5).

ET$_O$ calculated with the modified Penman equation is provided by CIMIS to assist landscape managers with estimating ET of irrigated landscapes (http://wwwcimis.water.

ca.gov). Various correction factors are suggested to increase the predictive power for real landscape ET (Costello *et al.*, 2000; Kumar *et al.*, 2012): $ET_{landscape} \approx ET_O \times k_d \times k_{mc} \times k_s$. ET_O, by definition, approximates ET of large areas of green, cool season grass that is actively growing, completely covers the ground, is not water limited, and has fixed parameters such as height (10–18 cm), surface resistance to water vapor diffusion (70 s m^{-1}) and albedo = 0·23 (Allen *et al.*, 1998). The coefficients k_d, k_{mc}, and k_s represent landscape density, microclimate properties, and species specific water use, respectively, and are arbitrarily assigned on the basis of landscape characteristics (Costello *et al.*, 2000). For our study sites, we assigned $k_d = 1$ because turfgrass completely covered the ground. The sites were relatively small and surrounded by heat-absorbing surfaces (buildings, pavement, and parking lots), and therefore, turfgrass ET could have been affected by advected heat, especially on hot and dry summer days. For such conditions, high values of k_{mc} (from 1·1 to 1·4) are recommended (Costello *et al.*, 2000). In this study, ET_O was in reasonable agreement with ET_{ch}, but it was lower than ET_{ch} in the summer (Figure 5). Accounting for surface advection would likely improve the agreement with ET_{ch}. The third, 'crop' coefficient, k_s, was developed to estimate ET corresponding to the levels of irrigation necessary for maintaining growth and aesthetic qualities of turfgrass; k_s of 0·80 to 0·95 is suggested for cool season grasses, and lower values of k_s, from 0·60 to 0·85, are suggested for warm season grasses (Allen *et al.*, 1998; Costello *et al.*, 2000). Our study sites were mostly covered by warm season grasses (Bermuda grass and St Augustine grass), with the exception of tall fescue (a cool season grass) that was present at location #1. Warm season grasses have more sensitive stomatal regulation and thus may use less water than cool season grasses, especially when soil water is limited (Carrow *et al.*, 1990). At our study sites, Θ was not limiting ET (Figure 4), likely indicating that the levels of irrigation were adequate or higher than necessary. Under such conditions, differences between cool season and warm season grasses may not be detectable (Carrow *et al.*, 1990). Therefore, the use of crop coefficients for turfgrass under conditions of unlimiting soil water and high D may provide misleading ET estimates.

Contributions of turfgrass and trees to plot-scale ET

The maximum ET_{ch} (10·4 ± 1·3 mm d^{-1}) was obtained in August at Grass-2 site (Figure 5). This value is uncertain because it was affected by Santa Ana wind conditions (discussed previously) and exceeded the ET range included in the chamber calibration (Figure 1). However, the maximum ET_{ch} in this study is similar to maximum irrigated turfgrass ET reported in other semi-arid and Mediterranean regions. For instance, Feldhake *et al.* (1983) reported ET of irrigated, sun-exposed turfgrass in Colorado of up to 10·8 mm d^{-1} in a study with mini-lysimeters.

Bastug and Buyuktas (2003) reported maximum ET of 9·8 mm d^{-1} at an irrigated golf course during hot, dry summer conditions in Mediterranean Antalya, Turkey, using water budget calculations based on measured soil moisture profiles. The high ET_{ch} maximum values that we measured were lower than reported maxima for the studied turfgrass species (12·0 mm d^{-1} for Bermudagrass, 12·2 mm d^{-1} for St Augustine grass, and 12·6 mm d^{-1} for tall fescue (Kneebone and Pepper, 1984; Carrow *et al.*, 1990). This suggests very high water use by irrigated turfgrass in semi-arid climates given non-limiting soil water supply. In particular, high summertime ET_{ch} in this study suggests that turfgrass was not limited by soil moisture and did not experience water stress.

In contrast, the contribution of trees to plot-scale ET was considerably lower than turfgrass (Figure 6). However, California sycamore is among irrigated urban trees in Los Angeles area with the highest transpiration rates, comparable with mesic forests (Pataki *et al.*, 2011b), and E_T estimated in this study (Table III) are similar to the highest values from previous studies (McCarthy and Pataki, 2010; Pataki *et al.*, 2011b; Litvak *et al.*, 2012). We attribute low E_C (Table IV) of the trees with relatively high E_T (Table III) to low planting density of trees on urban lawns. To evaluate whether our estimates of tree transpiration are consistent with previous studies, we roughly estimated leaf level stomatal conductance (g_S, m s^{-1}) of California sycamore trees as

$$g_S = \frac{E_T}{A_L \cdot d \cdot \Delta M}, \qquad (8)$$

where A_L is the projected leaf area, d is the day light duration (~12 h) in seconds, and ΔM (g m^{-3}) is the concentration gradient of water vapor at a leaf surface estimated as

$$\Delta M \approx \frac{D}{R_v \cdot T} \approx 14 \cdot 5 \frac{g}{m^3} \qquad (9)$$

with $D = 2$ kPa and $T = 298$ K. To assess A_L, we multiplied averaged sapwood areas at breast height (A_S) of California sycamores that were used to calculate E_T ($A_S \approx 800$ cm^2, Litvak *et al.*, 2012) with published $A_L:A_S$ ratios. To our knowledge, there are no published $A_L:A_S$ values for this tree species; thus, we used a range of reported $A_L:A_S$ for multiple tree species to assess the range of possible g_S. Overall, $A_L:A_S$ varied from 0·04 to 1·88 m^2 cm^{-2} in previous studies with no significant difference between angiosperm and gymnosperm species (Waring and Gholz, 1977; Kaufmann and Troendle, 1981; Waring *et al.*, 1982; Oren *et al.*, 1999; Oren and Pataki, 2001; McDowell *et al.*, 2002; Meadows and Hodges, 2002; Medhurst and Beadle, 2002; Mokany *et al.*, 2003; Stancioiu and O'Hara, 2005). The resulting A_L estimates for a California sycamore range from 30 to 1000 m^2. Substituting these values into Equation (8) (and multiplying the results to 41 000 mmol m^{-3} for unit conversion, Korner *et al.*, 1979; Jones, 1992),

the resulting g_S ranges from 6 to $200 \, \text{mmol} \, \text{m}^{-2} \, \text{s}^{-1}$, with higher g_S corresponding to lower A_L. The maximum value of $g_S = 200 \, \text{mmol} \, \text{m}^{-2} \, \text{s}^{-1}$ is similar to the maximum g_S of broadleaf and coniferous forests (Federer *et al.*, 1996). According to porometer measurements made in a summer afternoon (CS-1 Leaf Porometer, Decagon Devices Inc., Pullman, WA) in the Los Angeles County Arboretum and Botanic Garden, sunlit leaves of California sycamore showed $g_S = 134 \pm 6 \, \text{mmol} \, \text{m}^{-2} \, \text{s}^{-1}$ and shaded leaves had $g_S = 63 \pm 5 \, \text{mmol} \, \text{m}^{-2} \, \text{s}^{-1}$, which is within the estimated range of g_S. Hence, our estimated rates of tree transpiration fall within expected values.

While the direct contribution of estimated tree transpiration to plot-scale ET was much lower than turfgrass, the reduction of Grass ET at Grass&Tree sites in the summer exceeded plot-scale tree transpiration (Figure 6). This resulted in lower plot-scale ET of Grass&Trees sites compared with Grass sites. As expected, incoming radiation was the major driver of turfgrass ET (Allen *et al.*, 1998): turfgrass ET was strongly correlated with I_O (Figure 4) and showed noticeable declines in winter compared with summer (Figure 5a). Also, the ratio of turfgrass ET at Grass&Trees sites to turfgrass ET of Grass sites was proportional to tree canopy cover (Figure 7). Therefore, we attribute lower summertime ET of Grass&Trees sites to the effect of tree shading. In addition to shading, trees may have lowered turfgrass ET by shielding wind and, in case of limiting water supply, competing for soil water with turfgrass. However, we do not expect these effects to be as important as shading because studied lawns were surrounded by other trees and buildings that shielded wind and because the turfgrass was not limited by soil water (Figure 4).

CONCLUSIONS AND IMPLICATIONS

We studied ET of irrigated turfgrass lawns with and without trees. Our results suggest that the lawns with open-grown trees had lower summertime ET compared with the lawns without trees. Tree transpiration at the plot-scale was lower than turfgrass and lower than summertime reductions of turfgrass ET at the sites with trees (Figure 6). The relative effect of trees on turfgrass ET was proportional to tree canopy cover (Figure 7). These results suggest that adding trees (including species with high transpiration rates) to unshaded, irrigated lawns may lead to lower plot-scale ET in summer. According to recommendations of the California Department of Water Resources, trees do not require additional irrigation when planted on adequately watered turfgrass (Costello *et al.*, 2000). Our conclusion goes further, suggesting that adding trees may lower the irrigation requirements of urban lawns. Public opinion tends towards lush green vegetation (Yabiku *et al.*, 2007; Larson *et al.*, 2009), and planting trees on turfgrass may be

an acceptable water-saving solution for landscape planners who do not desire a conversion to xeriscaping (Hurd, 2006).

Adding trees to irrigated lawns may provide other ecosystem services besides water savings. Even though both shading and ET were shown to lower urban temperatures (Myrup *et al.*, 1993; Spronken-Smith & Oke, 1998; Jenerette *et al.*, 2007; Jenerette *et al.*, 2011), shading provides more thermal comfort for people (Shashua-Bar *et al.*, 2011). Shashua-Bar *et al* (2009) recorded the lowest surface temperatures under trees planted on turfgrass during the hottest part of summer days when compared with unshaded turfgrass, turfgrass shaded by a fabric mesh, and trees on an inset in concrete pavement. Therefore, the combination of turfgrass and trees was the most beneficial for surface cooling. In addition, some trees may provide other practical and aesthetic benefits, such as fruits and flowers.

It is worth noting that our measurements were made in a semi-arid region with abundant irrigation and virtually unlimited soil water. Changes in irrigation regimes may change ET patterns and even affect plant survival and function. For example, severe water stress caused by mandatory irrigation restrictions during dry years may be lethal for trees growing on turfgrass, while turfgrass may recover as soon as irrigation resumes (Costello *et al.*, 2000). Also, this study focused on mature trees and well established lawns, while recently established plantings should not be expected to function similarly. Finally, ET estimates are inevitably affected by calibration and scaling errors, in addition to site-specific variability caused by differences in tree density and irrigation regimes, among other factors. While this study suggests that planting trees on irrigated turfgrass may lead to water savings, further research of urban plant ET on a range of spatial and temporal scales is necessary. Overall, the development of water-wise landscaping strategies for semi-arid urban environments in the face of water scarcity is complex. This study of the water use patterns of irrigated landscapes suggests a potential approach for developing such strategies.

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