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A comparative study of the water budgets of lawns under three management scenarios

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Abstract The fate of irrigation in urban ecosystems is highly uncertain, due to uncertainties in urban ecohydrology. We compared irrigation rates, soil moisture, evapotranspiration (ET), stomatal conductance, and water budgets of landscape ecosystems managed with different turfgrass species and irrigation technologies. The "Typical" landscape had a cool-season fescue and was irrigated by an automatic timer. The "Alternative1" landscape had a warm-season paspalum and a "smart" soil moisture sensor-based irrigation system. The "Alternative2" landscape had a cool-season native sedge and a "smart" weather station-based drip irrigation system. ET was measured with a portable closed chamber and modeled using a Penman-Monteith approach, and the two methods agreed well. The water applied to the Alternative1 was 54 % less than the water applied to the Typical landscape, and the water applied to the Alternative2 was 24 % less. Soil moisture was similar in the Typical and Alternative2, while Alternative1 was drier in spring. The stomatal conductance of sedge was lower than the other two species, but its ET was not lower due to higher leaf area. Irrigation efficiencies (ET/applied irrigation) were 57 - 58 %, 86 – 97 %, and 78 - 80 % for the Typical, Alternative1, and Alternative2 landscapes, respectively. Runoff was less than 2 % in each landscape, and excess irrigation primarily drained below the root zone. Differences in irrigation efficiency between landscapes were due mainly to irrigation application, which varied more than species water use. Smart irrigation systems provided substantial water savings relative to a timer-based system, and prevented significant drainage losses. The utilization of smart sensors was more important than the choice of turfgrass species for irrigation efficiency.

Keywords Urban water budget · Evapotranspiration · Turfgrass · Soil moisture · Urban irrigation

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Introduction

Water resources are limited in semi-arid areas so it is important to understand the fate of applied irrigation and determine which management practices result in irrigation inefficiency in urban ecosystems. Lawn is the U.S.'s largest irrigated crop, with a surface area three times greater than irrigated corn, the largest agricultural crop (Milesi et al. 2005). Lawn area will continue to grow, as urban land cover is projected to increase by ~79 % in the United States by 2025 (Alig et al. 2004). Milesi et al. (2005) estimated that lawn could use 60 million acre-feet of water per year in the U.S., or more water than the seven greatest water-using crops combined (Diep 2011). Urban landscape irrigation could account for a major portion of urban water use in arid/semi arid regions (Gleick et al. 2003; Mayer 2000), thus urban irrigation and lawn ecohydrology need further research (Pataki et al. 2011). The fate of applied irrigation is critical to understand as irrigation applied in excess of evapotranspiration leads to runoff and/or subsurface drainage that impairs water quality (Carey et al. 2012). Runoff or drainage due to excess urban irrigation has caused insecticides to be ubiquitous contaminants in surface streams (Jiang et al. 2012), aquatic ecosystems (Gan et al. 2012), and groundwater (Slavens and Petrovic 2012).

Turfgrass usually requires supplemental irrigation, especially in arid and semi-arid areas, where precipitation is much lower than crop water demand. Accurate estimates of evapotranspiration (ET) are needed to determine the irrigation requirements for turfgrass and other crops (Allen et al. 1998; Katerji and Rana 2006; Perez et al. 2006), and can contribute to water and financial savings (Lecina et al. 2003). Some common ET measurement methods include lysimeters, eddy covariance, Bowen ratio, soil water balance, and sap flow (Allen et al. 2011). ET is sometimes measured by open or closed chamber methods, which involve monitoring the changes in humidity inside a usually portable chamber over the crop canopy (Dugas et al. 1997; McLeod et al. 2004; Balogh et al. 2007; Burkart et al. 2007; Centinari et al. 2009; Mueller et al. 2009; Teitel et al. 2011; Langensiepen et al. 2012). Usually, ET is estimated by theoretical models that rely on weather measurements, such as the Penman-Monteith equation (Monteith 1965). Since methods to measure or model ET are time and cost intensive, it is often difficult for landscape managers to accurately predict plant demand, and irrigation can be in excess (Barnes 1977; White et al. 2007). As in other regions, California has developed estimates of crop evapotranspiration (ET) to provide guidelines for irrigation. The California Irrigation Management Information System (CIMIS) is a freely available online database that uses weather data in a modified version of the Penman equation (Pruitt and Doorenbos 1977; Snyder and Pruitt 1985; Penman 1948) to calculate hourly reference ET, the loss of water from a standardized, well-watered crop surface which is usually cool-season grass (ET_0). The CIMIS and the Penman-Monteith ET equations result in ET_0 calculations that are similar (www.cimis.water.ca.gov). ET_0 is converted to landscape ET for a crop by multiplying ET_0 with a crop-specific coefficient. Although reference ET_0 already represents grass ET, Meyer et al. (1985) determined that turfgrass can be maintained for optimum performance with annual average crop coefficients of 0.8 and 0.6 for cool-season and warm-season grass, respectively, and 0.64 and 0.36 for minimum performance.

Automatic timer-based irrigation controllers are commonly utilized by homeowners, but may be inefficient because they deliver irrigation irrespective of climatic or soil conditions. Controllers are now available that can adjust water application in response to changing environmental conditions, and are commonly termed "ET," "weather-based," or "smart" controllers. They are programmed to calculate ET_0 adjusted for landscape type based on weather and/or soil parameters. Controlled experiments have shown water savings of 40-70 % when using these devices, but some large real-world studies have shown savings less than

10 % (Dukes 2012). Smart controllers may promote water and cost savings using a variety of methods, often in comparison to historical water use (USBR 2008; McCready and Dukes 2011; Dukes 2012; Cardenas-Lailhacar and Dukes 2012). Some studies have examined water savings of smart controllers relative to potential evapotranspiration (ET_0) estimates and crop coefficients for agricultural crops (Zapata et al. 2009; Kisekka et al. 2010; Migliaccio et al. 2010). However, there are few comparative studies of smart controllers in residential landscapes (Pittenger et al. 2004), and none that include direct measurements of plant function or water use, or of the fate of applied irrigation water. In addition, much of the scientific research on smart controllers has been conducted in humid rather than arid regions (Dukes 2012). In arid/semi-arid regions, irrigation requirements and thus volume of water savings may be potentially higher. It is necessary to evaluate the water application of smart controllers relative to actual plant water demand in arid/semi-arid climates.

In addition to irrigation technology, the choice of turfgrass species or cultivar may also affect water use. Tall fescue is a C_3 (cool-season) perennial bunchgrass popular because of its lush, dark-green appearance as well as its assumed drought tolerance (Swarthout et al. 2009). It is commonly planted in warm climates, though evapotranspiration of cool-season grasses such as fescue is reported to be 12-47 % higher than that of warm-season grasses (Feldhake et al. 1983; Huang and Fry 2000).The C4 (warm-season) grass seashore paspalum has been proposed as a lower water use species for warm climates. It is a dense, salt-tolerant grass (Lee et al. 2004), thought to be deep-rooted and drought resistant (Huang et al. 1997). Warm-season grasses such as paspulum may transpire between 2 and 5 mm per day (Huang and Fry 2000). Finally, native sedges (*Carex* spp.) are commonly believed to have a low transpiration rate, and thus have been proposed as an alternative lawn species (Daniels 1997). However, *Carex* spp. are C_3 species of riparian meadows (Winward 1986) and their transpiration rates can be quite high (up to 8.8 mm per day) (Busch 2001). In addition, their survival is related to soil moisture and groundwater depth (Steed and DeWald 2003). Thus, whether native sedges have low rates of water use in urban landscapes needs to be assessed.

The objective of this research was to examine three simulated residences consisting of 1) a cool-season fescue grass with conventional timer irrigation, 2) a warm-season grass with a “smart” soil moisture based irrigation system and 3) a native sedge grass with a “smart” drip irrigation system to identify which residential scenario was best at reducing water use in a semi-arid climate (Fig. 1). In addition to monitoring total water application, we directly measured the components of the water budget, including runoff, and soil moisture storage, and total ET. We also measured stomatal conductance of turfgrasses. This approach provides additional information about irrigation efficiency and the fate of irrigation water applied in excess, which can be stored in the soil, lost as surface runoff, or drained below the rooting zone. Here, we define the irrigation efficiency (IE) as the ratio of ET to total applied water (irrigation + precipitation). The simulated residences were designed and managed at the South Coast Research and Extension Center in Irvine, CA to simulate typical versus recommended practices for southern California. They consisted of model houses complete with driveways, curbs and gutters, and both front and backyards meant to simulate irrigation and rainfall runoff and interception patterns. Our study was focused on the lawn portions of the simulated residences, which were outfitted with instrumentation for monitoring and recording measurements for mass balance of water in ways that are generally too intrusive and intensive to conduct in real residences. For example, this experiment was designed to isolate runoff from a single simulated residence for measurement. It would not have been possible to isolate runoff from residences in actual neighborhoods, as this runoff is commingled from many residences. Thus, this was a test of complete, parcel-scale landscape designs, the "designed experiment" approach to studying the performance of landscape architecture (Felson and Pickett 2005), and therefore it was not replicated in the manner of experimental turfgrass plots.

We compared both measurements and model estimates of ET in order to accurately determine landscape ET. We used a portable closed chamber-based approach to measure ET, and compared this to estimates from the Penman-Monteith model, with inputs of stomatal conductance, leaf area, and vapor pressure made on-site. We then constructed the complete water budgets of landscapes using both methods for comparison. We asked: (1) How did the irrigation method affect the total amount of water applied in each landscape? (2) How did each turfgrass species perform in terms of growth rate, stomatal conductance, and ET? (3) What was the water balance and irrigation efficiency or IE (ET/applied water) of each landscape? We expected that the Typical landscape would have the highest irrigation rate, soil moisture, stomatal conductance and the lowest IE. In contrast, we expected the Alternative2 landscape to have the lowest irrigation rate, soil moisture, stomatal conductance, and highest IE. For the Alternative1 landscape, we expected the lowest ET and the highest growth rate. In general, we sought to test the performance of these three landscape designs and their management practices to improve our understanding of urban ecohydrology and the best management practices for increasing irrigation efficiency of lawn ecosystems.

Methods

Study sites

The three simulated residences in this study were established for research and demonstration purposes at the South Coast Research and Extension Center, part of the University of California experimental station network, at 33°41′20.16″N, 117°43′24.26″W at 123 m a.s.l. in the semi-arid, Mediterranean climate of Irvine, CA (Fig. 1). The soil type for all landscapes was loamy sand, and was 79 % sand, 10 % silt, and 12 % clay (UC Davis Analytical Laboratory, August 2005). Grasses on the landscapes were started as sod (West Coast Turf, Palm Desert, CA). Grass areas were split into a front and back yard with a shed structure in between. The grass area in the back yard of the Alternative1 landscape was not studied as it was still being established. Each landscape had some non-turf groundcovers primarily at the peripheries, including shrubs and trees; only the turfgrass areas were the focus of this study. In the Typical, these species were conventionally believed to be high-water use, in the Alternative1 they were low-water use, and in the Alternative2 they were California native. Each landscape included a driveway and concrete sidewalk in the front yard. In the Typical

Fig. 1 Photographs of the three simulated residences that were the subjects of this study. The landscape types for these residences were **a** the "Typical" landscape with a cool-season fescue and automatic timed irrigation, **b** the "Alternative1" landscape with a warm-season paspalum and "smart" soil moisture sensor-based irrigation, and **c** the "Alternative2" landscape with a cool-season native sedge and "smart" weather station-based drip irrigation

landscape, the driveway was made of continuous concrete, while the other two driveways were more permeable. The Alternative1 driveway was of a mixture of concrete, flagstone, and slot drains, and the Alternative2 driveway was of interlocking concrete pavers. Landscapes were fertilized based on rates recommended by the University of California Agriculture and Natural Resources online tool for each grass species (http://www.ipm.ucdavis.edu/TOOLS/TURF/).

Typical landscape

Tall fescue (*Schedonorus phoenix* (Scop.) Holub) was planted in the Typical landscape in September 2006 with an area of 131.6 m^2. It was mowed once a week and as needed in winter, to a height of 7.6 cm. It was fertilized with 4.9 g N/m^2 on April 15 and September 16 in 2008 and on February 23 and June 8 in 2009 with Scotts® Turf Builder® (32 % nitrogen, 0 % phosphorus, and 4 % potassium). It was fitted with a Rain Bird 4 Station ESP Modular Series Controller and Rain Bird Matched Precipitation Rate (MPR) spray nozzles for automatic timed irrigation (Rain Bird, Azusa, CA). Until December 31, 2008, the lawn was watered 10 min per day, daily. It was watered 12 min per day on 2 days per week from January 1 to March 23, 2009, 8 min per day on 4 days per week from March 24 to May 7, and 12 min per day every other day after May 8. These rates were based on estimation of historical reference ET on a seasonal basis (http://www.bewaterwise.com/calculator.html).

Alternative 1 landscape

The Alternative1 landscape was planted with seashore paspalum (*Paspalum vaginatum*) in September 2006 with an area of 42.5 m^2. The type and schedule of fertilization was the same as fescue, except it received less (2.5 g N/m^2) at each fertilization event. It was mowed at the same frequency, except to a height of 2.5 cm. Irrigation was triggered by measurements of low soil moisture measured by a Watermark Electronic Module (Irrometer, Riverside, CA) connected to a Rain Bird ESP Modular Series Controller. The soil moisture threshold for triggering irrigation was 25 kPa at 25 cm depth.

Alternative 2 landscape

The native sedge (*Carex* spp.) in the Alternative2 landscape was planted in January 2007 with an area of 54.03 m^2. It was not fertilized, and was clipped once in November 2008 to a height of 2.5 cm. Drip irrigation was triggered by onsite measurements of weather conditions with a Hunter ET System connected to a Hunter ICC irrigation controller (Hunter, San Marcos, CA). The system was programmed to irrigate at 80 % of reference ET, as calculated by its measurements of weather.

Measurements

We measured ET, leaf-level stomatal conductance, and soil moisture on 20 sampling days throughout July 2008 – July 2009. Within each turfgrass landscape, we chose five fixed sampling locations randomly and measured each parameter at each location 3–6 times per sampling day to capture diurnal variation. ET was measured with a portable chamber method, described in detail by Litvak et al. (2013). Briefly, a relative humidity and air temperature datalogger (HOBO® Pro V2, Bourne, MA) was placed in a clear Perspex chamber that was 17.8 cm in height and 28.0 cm in width and length for the short turfgrasses in the Typical and Alternative1 landscapes, and 24 cm in height and 31.5 cm in width for the taller sedge in the

Alternative2 landscape. The slope of the relationship between water vapor content and time over a 30 s interval was determined, and multiplied by a calibration factor to calculate ET. Litvak et al. (2013) used a weighing lysimeter to determine the calibration factor, 4.26 ± 0.05, which corrects for artifacts due to reduced wind speed, vapor absorption by Perspex, and lags in sensor response time. We tested whether the two different chambers would measure water vapor content slopes differently. Damp paper towels (n=8) were placed outdoors in sunlight and were measured by both chambers within a minute of each other. As there was no difference in slopes between the two chambers (p>0.1), we assumed the same calibration factor could be applied to the slightly larger chamber to estimate ET. Calibrated ET rates were plotted against the time of day and fitted with Gaussian curves (SigmaPlot, Version 10.0, Systat Software, Inc.) for each day. Daily ET was determined as the area under these curves.

Stomatal conductance (g_l) was measured with a porometer (SC-1, Decagon Devices, Pullman, WA). Soil volumetric water content (VWC) at 0–5 cm depth was measured with a portable soil moisture probe (TH_2O/ML2x/HH2, Dynamax, Houston, TX), which we calibrated for our soil type. We measured the actual soil moisture by the difference between wet and dry weight. This was related to the meter voltage output by a third-order polynomial with accuracy within 2.4 % VWC.

The vapor pressure deficit (VPD) was determined using measurements of vapor pressure at 2 m height (HOBO® Pro V2, Bourne, MA). We also measured within-canopy grass VPD on August 26, 2009 for the Typical and Alternative1 landscapes to compare measurements above and within the canopy. Incoming solar radiation (I_o) data were available from the CIMIS station located 0.3 km from the experimental sites (www.cimis.water.ca.gov, Irvine station #75).

Following each mowing event, clippings collected by the bag attachment of the lawn mower from the entire area of each turfgrass landscape were collected, dried and weighed for growth rate measurements. Small areas (102.6 cm^2, n=5) of native sedge were randomly selected and clipped to the soil surface, dried, and weighed every other week for aboveground biomass measurements, as this landscape was not mowed regularly. We removed thatch/dead grass from these samples to estimate the amount of live vegetation.

Specific leaf area (SLA) was determined every other week by measuring leaf area on a subset (n=5) of harvested fresh leaves (ImageJ software, U.S. National Institute of Health, http://rsb.info.nih.gov/ij/) and dividing leaf area by dry weight. Leaf area index (LAI) was determined by multiplying biomass production (g/cm^2) by SLA. The LAI of the stubble (remaining grass following mowing) was determined by removing small areas (19.6 cm^2) following mowing in May 2009 following careful removal of thatch from live vegetation.

Soil moisture sensors (CS616, Campbell Scientific, Inc., Logan, UT, USA) 30 cm in length were installed diagonally in the plant root zone to measure soil VWC up to 15 cm, 20 cm, 25 cm depth at three randomly-selected fixed locations in Typical, Alternative1, and Alternative2 landscapes, respectively. These depths corresponded with observed rooting depths, although for each species roots were concentrated in the top 5 cm of soil. These probes were installed at 3 randomly-selected fixed locations on each landscape (these locations differed from the locations of the ET measurements since the installation of the CS616 sensor would have made chamber ET measurements difficult). The CS616 uses time domain reflectometry (TDR) to measure soil VWC by measuring the delay time between transmission and reception of an electromagnetic pulse, and this delay time is converted to VWC using a calibration equation. We calibrated these CS616 sensors for our soil type. Actual soil moisture was measured by the difference between wet and dry weight, which was linearly related to the delay time with accuracy within 2.7 % VWC. We also placed a soil water potential sensor (Watermark, Irrometer, Riverside, CA) below the rooting zone at 40 cm in the Typical landscape to monitor possible drainage events. This landscape was expected to have a low IE and thus visible drainage of irrigation water applied in excess. The CS616 and water potential sensors were logged on data loggers (CR10X, Campbell Scientific, Inc., Logan, UT, USA) every 30 s and averaged every 30 min.

In addition to ET, we measured the following components of the water budget: irrigation water inputs, soil water storage, and runoff, and we estimated drainage by difference. The water budgets were shown in units of depth measurement (mm or L/m^2) to allow for easy comparison between landscapes, which had different areas. Soil moisture storage was measured as the change in VWC over time. Runoff flow rate (L/d) was measured by collecting all surface runoff in 0.3 × 0.3 m concrete vaults downslope of each landscape. Electronic water sensing sump pumps (Water Ace, Ashland, Ohio) transported runoff through an oscillating piston type water meter pulse flow meter (C700, Elster AMCO Water, Langley, Canada) which was logged daily (CR1000, Campbell Scientific, Inc., Logan, UT, USA). Although the area that the runoff collectors covered included some non-turf areas of the landscapes, we assumed that all runoff came from turfgrass, which was the largest component of each landscape. Therefore, the recorded values may be slight over-estimates of turf runoff. Precipitation data were obtained from a CIMIS station located 0.3 km from the experimental sites (www.cimis.water.ca.gov, Irvine station #75). Irrigation water inputs were collected and measured on a weekly basis between March 14, 2008 and July 22, 2008 by distributing 18 cups evenly every ~7 m^2 on the Typical lawn. On the other two lawns, 3 cups were evenly spaced (more cups were not permitted as these landscapes served a demonstration purpose). The drip irrigation in the Alternative2 landscape created a short height spray of water that was possible to collect in the cups. All cups were filled with 2 cm of mineral oil to prevent evaporation. We estimated the amount of water lost by evaporation in the sprinkler water spray in three sprinklers of the Typical landscape on June 4, 2009 using the electrical conductivity method. This was done by measuring changes in salinity between water at the sprinkler head and landing point (McLean et al. 2000).

Modeled ET

We used the Penman-Monteith equation to calculate ET (mg/m^2/s), based on (Allen et al. 1998).

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{VPD}{r_a}}{\Delta + \gamma\left(1 + \dfrac{g_a}{g_s}\right)} \tag{1}$$

where R_n is the net radiation measured at the nearby CIMIS station 0.3 km from the sites (www.cimis.water.ca.gov, Irvine station #75), G is the soil heat flux, calculated as 10 % of R_n (Allen et al. 1998), vapor pressure deficit (VPD) was determined using vapor pressure measurements at 2 m height, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ is the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, and g_a and g_s are the aerodynamic and bulk surface conductances.

The aerodynamic conductance (g_a) was calculated using the following equations from (Allen et al. 1998):

$$g_a = \frac{k^2 u_z}{\ln\dfrac{z_m - d}{z_{om}} \ln\dfrac{z_h - d}{z_{oh}}} \tag{2}$$

where k is von Karman's constant, u_z is wind speed measured at the nearby CIMIS station, z_m is the height of wind measurements (2 m), z_h is height of humidity measurements (2 m), and d is the zero plane displacement height:

$$d = \frac{2}{3} * h \tag{3}$$

where h is crop height. We used 0.076 m and 0.025 m for fescue and paspalum, respectively, based on their mowing heights, while we used 0.12 m for sedge, based on average height in spring.

We estimated z_{om}, the roughness length governing momentum transfer, as:

$$z_{om} = 0.123 * h \tag{4}$$

We estimated z_{oh}, the roughness length governing transfer of heat and vapor, as:

$$z_{oh} = 0.1 * z_{om} \tag{5}$$

Bulk surface conductance (g_s) was calculated according to (Allen et al. 1998):

$$g_s = g_l * LAI_{active} \tag{6}$$

where g_l is stomatal conductance, which was directly measured. LAI_{active}, or the LAI of actively transpiring leaves, was determined based on Allen et al. (1998):

$$LAI_{active} = 0.5 * 24 * h \tag{7}$$

ET was modeled diurnally and fitted with Gaussian curves (SigmaPlot, Version 10.0, Systat Software, Inc.) for each day. Daily ET was determined as the area under these curves.

Data analyses

Measured ET values were filtered to remove points where $I_o<10$ Wm^{-2} and $VPD<0.1$ kPa. Filtered ET was modeled as a function of VPD and S linearly, similar to Granier and Breda (1996):

$$ET = y_0 + a * \ln(VPD) + b * I_o \tag{8}$$

The residuals of this model were used in standard linear regression analysis against measured VWC (0–5 cm) at the site of the ET measurement as well as against root zone VWC (0 to 15 cm, 20 cm, and 25 cm depth for the Typical, Alternative1, and Alternative2 landscapes, respectively) at 3 fixed locations on the site to evaluate the influence of soil moisture on ET.

Drainage was estimated as a residual of the water budget, the other components of which were directly measured or estimated:

$$D = P + I - ET - R - \Delta SM \tag{9}$$

where D, P, I, R, ΔSM are subsurface drainage, precipitation, irrigation, runoff, and change in soil moisture storage, respectively. A two-hour running average of the soil water potential was calculated for smoothing. The complete water budget was calculated for the period from March 14, 2009 to July 22, 2009 for all three turfgrass landscapes, and for a period of one year starting July 9, 2008 for the Typical landscape. The annual budget was calculated only for the Typical landscape because annual irrigation was known only for this landscape.

All statistical analyses were performed with SAS 9.1.3 software (SAS Institute Inc., Cary, NC). The influence of landscape and time on plant and soil properties was evaluated with repeated measures analyses of variance (ANOVA) using the General Linear Model. For stomatal conductance, we removed points where $I_o < 10\ Wm^{-2}$ and $VPD < 0.1$ kPa, and we compared seasonal rather than daily values, since it was not possible to take measurements simultaneously on all landscapes. Post-hoc tests were conducted using the Tukey Standardized Range Test. Two-tailed paired t-tests were used to compare measured stomatal conductance. For all analyses, $p < 0.05$ was considered significant, and $p < 0.1$ was considered marginally significant.

Results

Climatic conditions during the study period are shown in Fig. 2. Maximum daytime temperature was 32.0°C in April, while the minimum was 8.3°C in December (Fig. 2a). Episodes of high daytime temperature corresponded with Santa Ana winds, a reversal in the direction of the sea breeze due to high pressure in inland deserts. Average measured VPD above the grass canopies varied between 0.8 and 3.2 kPa (Fig. 2b). Average daytime I_o declined from highs of ~475 Wm^{-2} in spring and summer to ~300 Wm^{-2} in winter (Fig. 2c). The precipitation was 214 mm during the study period, and occurred only in winter and spring months (Fig. 2d). There was an approximately 8 month period without precipitation, when irrigation was the only source of water to the plots. Within-canopy VPD was <0.6 kPa on August 25, 2008.

The average VWC in the rooting zone was initially similar in all three landscapes (~18 ± 1 %), and increased slightly during summer in the Typical and Alternative2 landscapes by 1 % and 3 %, respectively (Fig. 3), but declined in the Alternative1 landscape by 4 % ($p < 0.0001$). There was no difference in soil moisture among landscapes until May 22, 2009, when the Alternative1 landscape became marginally drier than the Alternative2 landscape (Fig. 3; $p = 0.0607$). The observed upper limit in VWC for the surface soils (0–5 cm) was ~44 % (not shown), which corresponds to the porosity of our loamy sand soil type (Rawls et al. 1982). The surface soils (0–5 cm) were usually saturated or near saturation (within 10 ± 6 %), although soil deeper than 5 cm was unsaturated (Fig. 3). There were sharp increases in soil moisture during irrigation events, as shown for VWC recorded in the root zone of the Typical landscape (Fig. 4). The water potential sensor placed below the root zone at 40 cm also showed increases corresponding with irrigation events.

The growth rate of paspalum and fescue were similar, except in spring and summer when paspalum growth rate increased (Fig. 5a). Aboveground biomass for native sedge between August and November 2008 did not change significantly (Fig. 5b; $p > 0.1$) and was 340.7 ± 242.9 g/m^2 (SD). Following the clipping of native sedge in November 2008, biomass declined to 102.6 ± 63.9 g/m^2 and did not change significantly over time ($p > 0.1$). There was no trend in SLA over time for any of the species (not shown; $p > 0.1$) and SLA differed among all species ($p < 0.05$). SLA was highest in paspalum at 313 ± 46 cm^2/g and intermediate for fescue at 232 ± 33 cm^2/g. SLA was lowest in the native sedge at 150 ± 32 cm^2/g for flat leaves and 58 ± 36 cm^2/g for triangular leaves, which were present following spring. The one-sided LAI of stubble measured in May was 6.8 ± 2.4 for fescue and 5.9 ± 1.8 for paspalum. The LAI of the mowed biomass added a trivial amount of leaf area to the stubble LAI (0.2 ± 0.1 for fescue and 0.6 ± 0.3 for paspalum). The one-sided LAI for the native sedge wa s 8.7 ± 3.9.

Stomatal conductance did not change seasonally for any species (Table 1, Fig. 6; $p > 0.1$), and there was no difference in stomatal conductance of fescue versus paspalum ($p > 0.1$). However, native sedge had lower stomatal conductance than fescue ($p = 0.0153$) and paspalum ($p = 0.0027$).

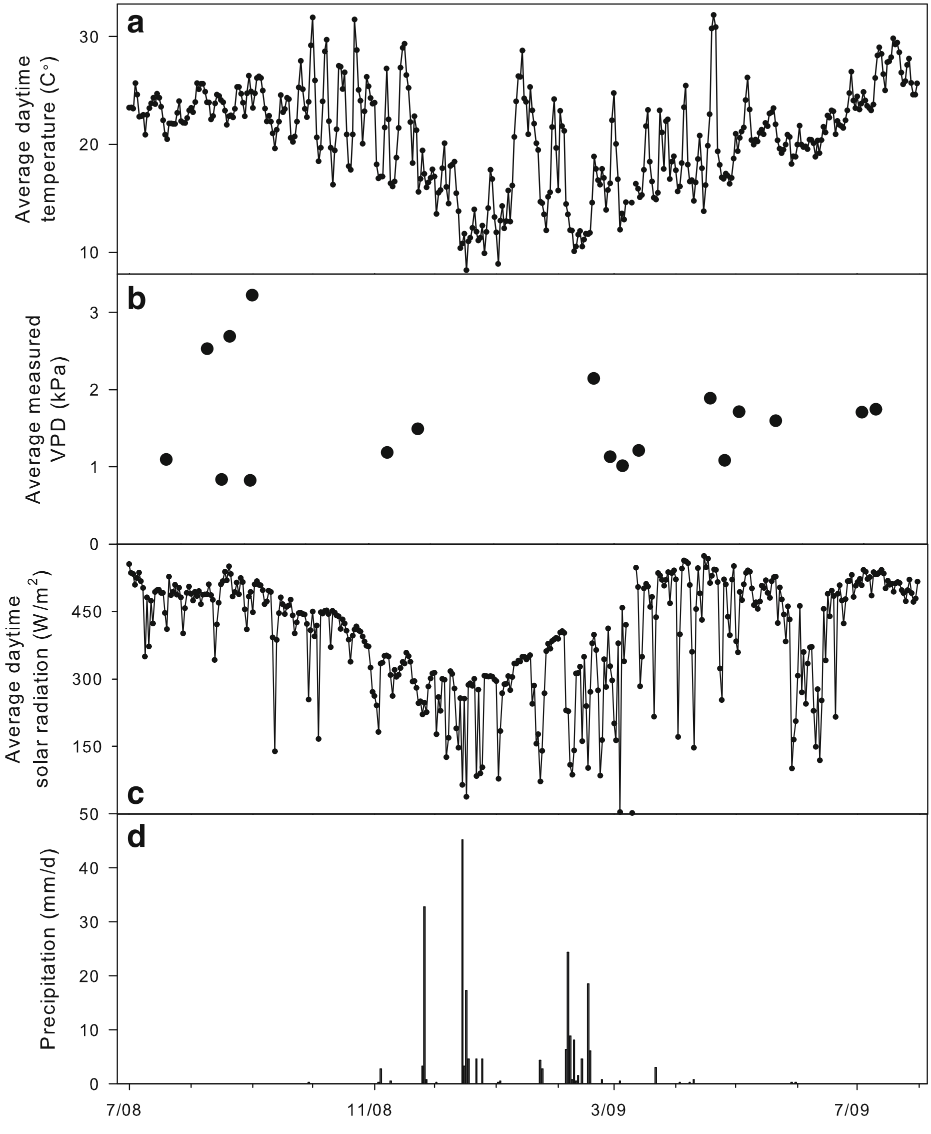

Fig. 2 Average values of environmental variables during the study period: **a** daytime temperature, **b** daytime above-canopy VPD, **c** daytime solar radiation (I_o), and **d** precipitation

Measured and modeled daily average ET were similar ($p>0.05$), and showed similar seasonal trends (Fig. 7a, b). ET was highest in July 2009 at ~4 mm/day, and was lowest between November and February at ~1 mm/day. Measured ET was indistinguishable among lawns due to high spatial variability (Fig. 7a). Variability in modeled ET was lower, which enabled significant differences in lawn ET to be observed. There was significantly lower ET in paspalum compared to fescue and sedge on four dates (November 10, 2008, and February 19,

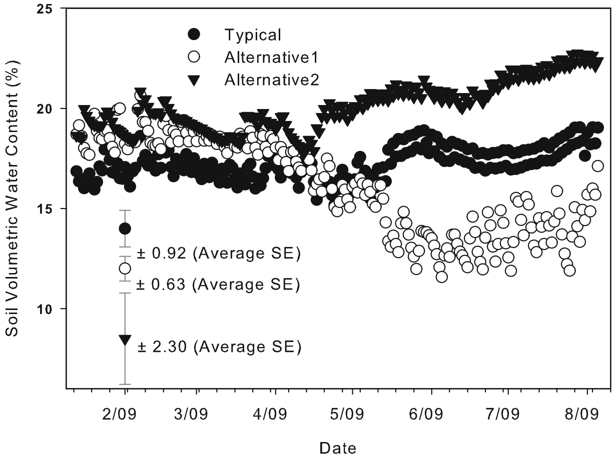

Fig. 3 Time series of soil volumetric water content (VWC) with SE from 0 to 15 cm, 20 cm, 25 cm depth for Typical, Alternative1, and Alternative2 landscapes, respectively. There were no differences in the soil moisture of landscapes until May 2009, when the Alternative1 landscape became marginally drier than the Typical landscape (*p*=0.0607)

March 5, and April 24, 2009) (Fig. 7). Integrated measured ET from July 2008 to July 2009 was 834 ± 67 mm, 770 ± 68 mm, 970 ± 86 mm for the Typical, Alternative1, and Alternative2 landscapes, respectively. Integrated annual modeled ET from July 2008 to July 2009 was 821 ± 42 mm, 570 ± 28 mm, 876 ± 39 mm for the Typical, Alternative1, and Alternative2 landscapes. Chamber ET measurements were lower than calculated CIMIS ET_0 by 67 ± 26 %, 64 ± 19 %, and 80 ± 23 %, for the Typical, Alternative1, and Alternative2 landscapes. Modeled ET estimates were lower than calculated CIMIS ET_0 by 80 ± 27 %, 56 ± 10 %, and 87 ±26 %, for the Typical, Alternative1, and Alternative2 landscapes. VPD and I_o were significantly correlated with chamber ET and explained 50-57 % of the variation when

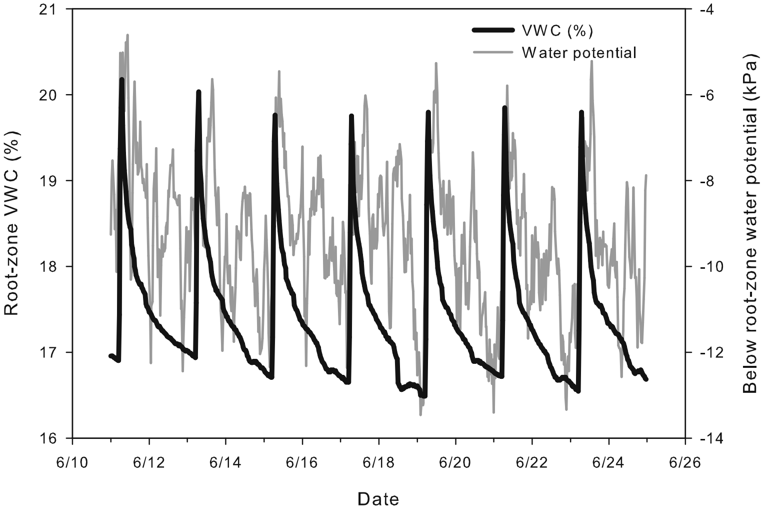

Fig. 4 Time series of soil volumetric water content (VWC) in the root zone, and water potential below the root zone

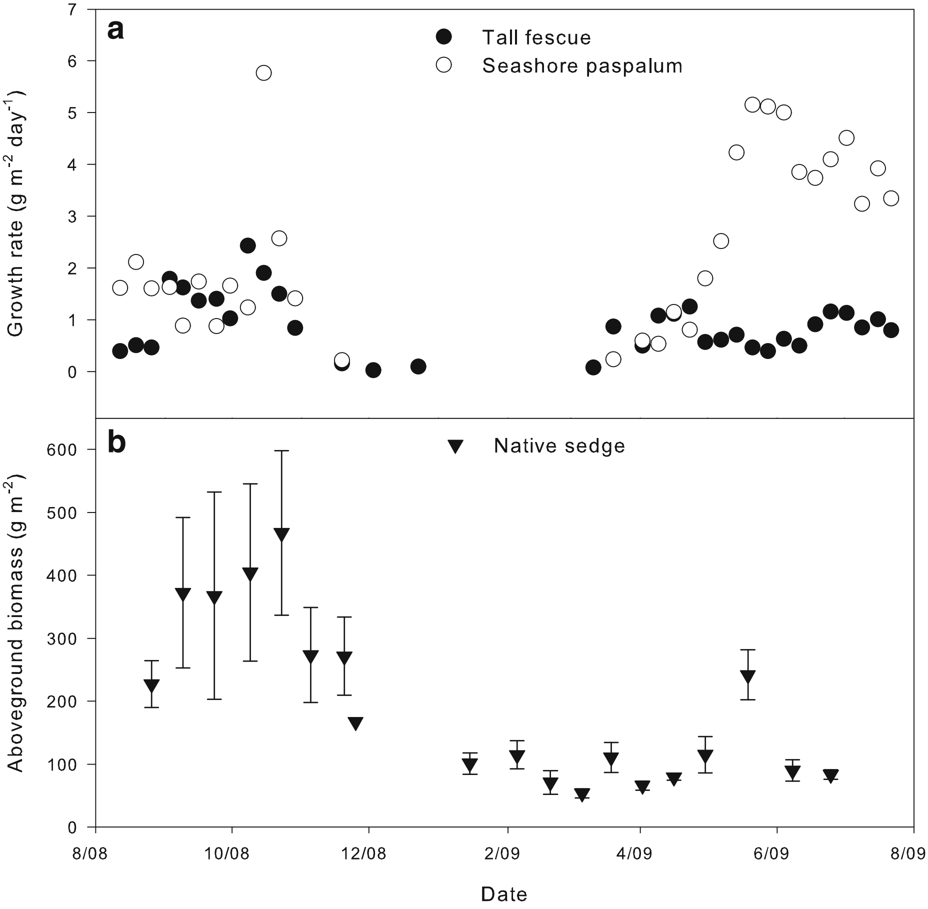

Fig. 5 Time series of **a** growth rate for tall fescue and seashore paspalum **b** aboveground biomass for native sedge

modeled with equation (1) (Table 2). Model residuals were not related to VWC at 0–5 cm soil depth nor to root zone VWC at 0 to 15 cm, 20 cm, and 25 cm depth for the Typical, Alternative1, and Alternative2 landscapes, respectively (p>0.1).

The annual water application from irrigation for the Typical landscape was 288 ± 22 cm (2880 ± 220 L/m^2 or 379,037 ± 28,954 L) (Fig. 8). Spray loss via evaporation from sprinkler head to the landing point tested on a summer day in June ranged from 0.6 to 1.4 % in the Typical sprinklers. Applying this range to the entire year would lead to spray losses between 2274 and 5306 L; this was assumed to be negligible in the calculated water budget as these

Table 1 Leaf properties: stomatal conductance, specific leaf area (SLA), and one-sided leaf area index (LAI) for each species

Species	Stomatal conductance (mmol/m^2/s)	SLA (cm^2/g)	One-sided LAI
Tall fescue	138±61	232±33	6.8±2.4
Seashore paspalum	162±88	313±46	5.9±1.8
Native sedge	116±65	150±32	8.7±3.9

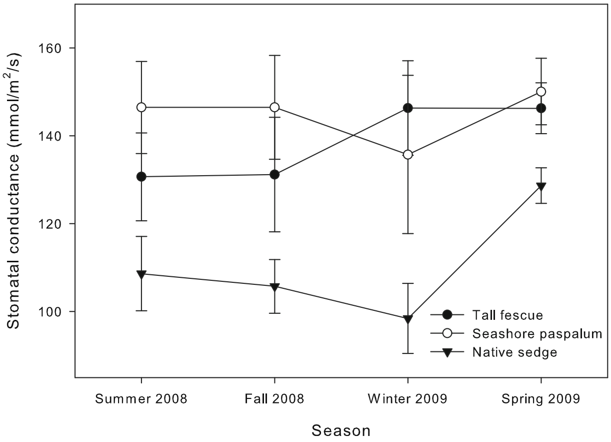

Fig. 6 Time series of seasonally averaged stomatal conductance for each species with SD

losses were relatively small compared to other water flows. Water budgets calculated using the chamber and Penman-Monteith methods were similar (Fig. 8a, b). For the one-year period

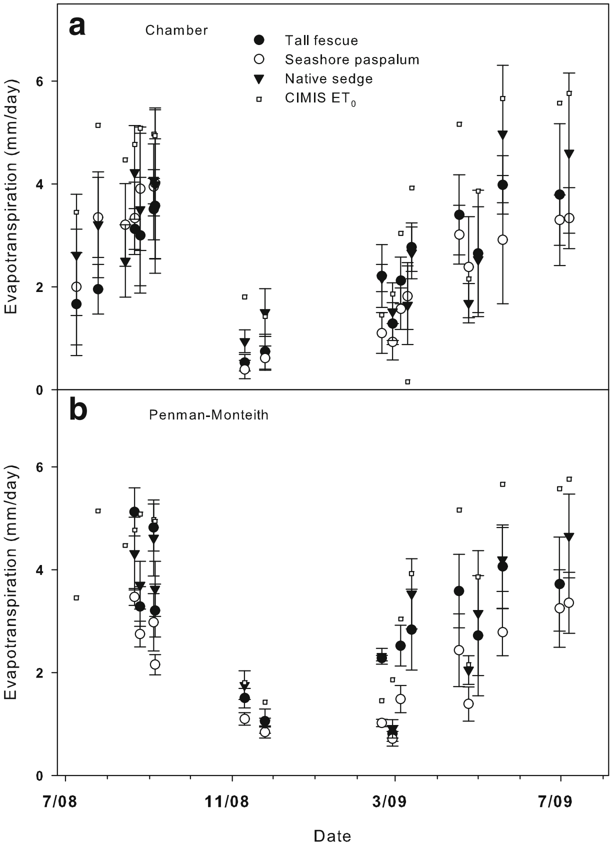

Fig. 7 Time series of (**a**) measured ET and (**b**) modeled ET for each landscape and ET$_0$ measurements calculated by CIMIS

Table 2 Mean model parameters (±1 standard error) describing canopy ET ($mg/m^2/s$) in relation to light (W/m^2) and vapor pressure deficit (kPa)

Species	R^2	y_0	a	b
Tall fescue	0.56	16.4±7.2	37.2±5.3	0.0922±0.01412
Seashore paspalum	0.65	0.2±6.5	26.3±3.8	0.1341±0.0125
Native sedge	0.52	24.7±7.8	42.6±5.9	0.1018±0.0152

starting July 9, 2008, Typical landscape IE was only 28–31 % based on the chamber and Penman-Monteith methods (Fig. 8a, b). Drainage accounted for more than half the water applied to the landscape (62 – 65 %). Runoff accounted for 7 ± 1 % of applied water. Soil water storage did not change during this period.

Irrigation was 770 ± 100 mm (101,340 ± 13,161 L), 355 ± 20 mm (15,098 ± 851 L), and 583 ± 64 mm (31,499 ± 3,458 L) for the Typical, Alternative1, and Alternative2 landscapes between March 14, 2008 and July 22, 2008 (Fig. 9). Water budgets calculated using the chamber and Penman-Monteith methods were similar (Fig. 9). During this period, the Alternative1 landscape had the highest IE (86 - 97 %), the Alternative2 was intermediate (78 - 80 %), and the Typical landscape was lowest (57 - 58 %). Drainage was highest in the Typical landscape (40 - 42 %) (Fig. 9a, b). 20 - 21 % of applied water was lost to drainage in the Alternative2 landscape (Fig. 9e, f), and there was little or no drainage in the Alternative1 landscape (0.6 ± 12 % calculated using the chamber, and 14 ± 15 % with Penman-Monteith) (Fig. 9c, d). Runoff was 1.6 ± 0.2 %, 0.2 ± 0.0 %, and 0.2 ± 0.0 % for the Typical, Alternative1, and Alternative2 landscapes (Fig. 9). Soil water storage did not change significantly in the Typical and Alternative2 landscapes during this period, but in the Alternative1 landscapes, soil water loss was 9.4 mm or 2.6 % of irrigation.

Precipitation was 0.6 %, 1.3 %, and 0.9 % of total water input for the Typical, Alternative1, and Alternative2 landscapes, respectively, between March 14, 2008 and July 22, 2008 (Fig. 9).

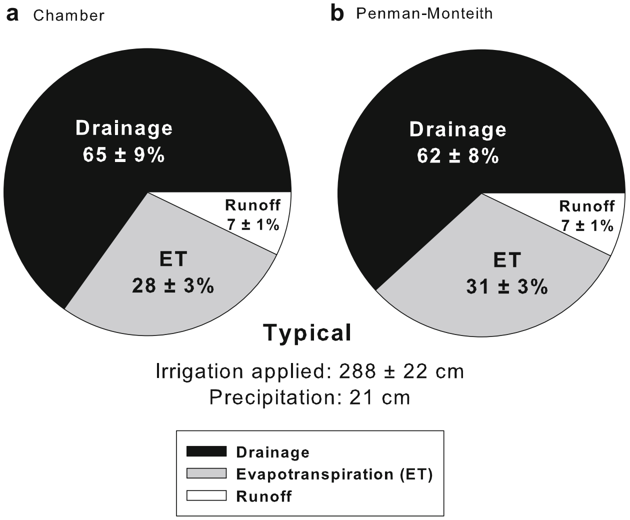

Fig. 8 The annual water budget as a percentage of irrigation applied to the Typical landscape using (**a**) the chamber method (**b**) and Penman-Monteith method. Amount of irrigation applied and precipitation for this time period is indicated beneath the pie chart

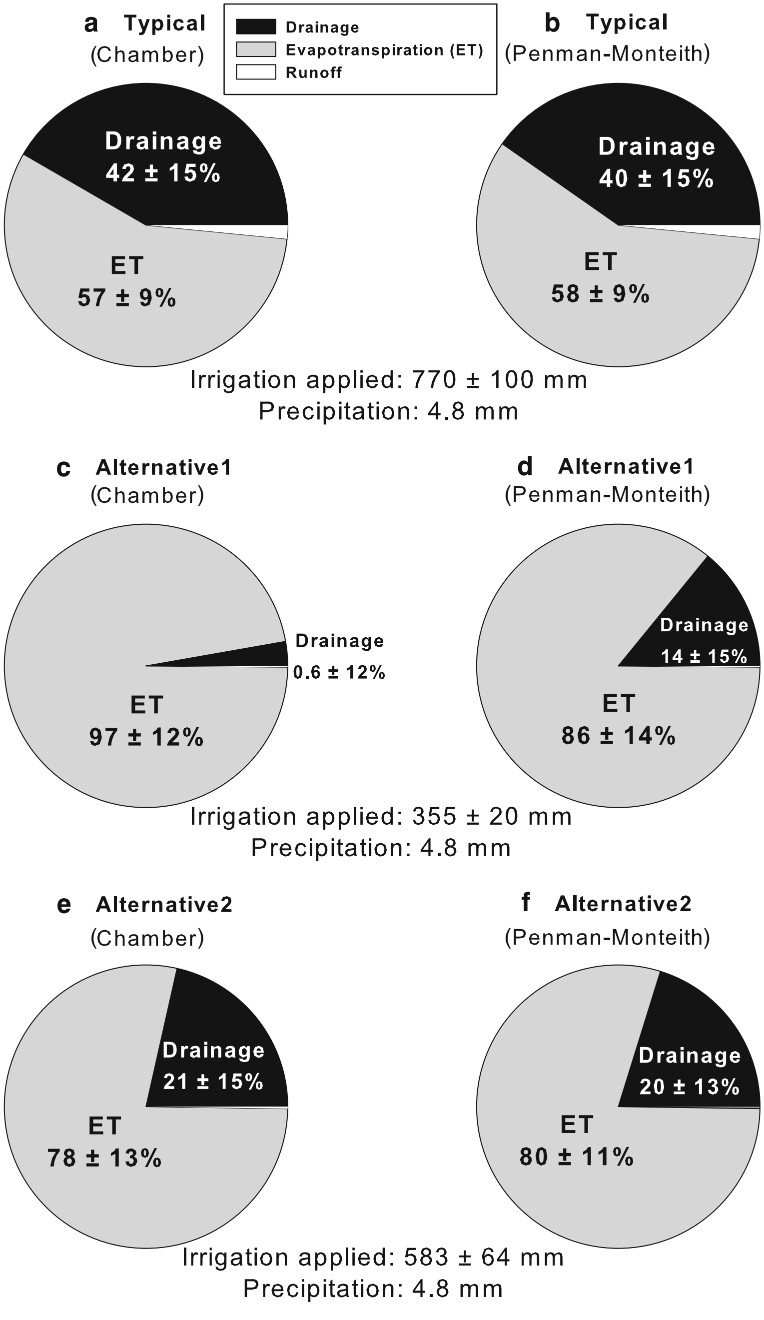

Fig. 9 The water budget as a percentage of irrigation applied to each landscape from March 14, 2009 to July 22, 2009 using the chamber method (**a**, **c**, **e**) and Penman-Monteith (**b**, **d**, **f**). Amount of irrigation applied and precipitation for this time period is indicated beneath each pie chart

There was only a small amount of total runoff from this period from the landscapes (less than 2 % of applied irrigation and precipitation). The runoff from the Alternative1 and Alternative2 landscapes was mostly due to rain events rather than irrigation. In the Alternative1 landscape, measurable runoff occurred only on one day, March 22, with a rainfall event of 3 mm. For the other rain events, daily rainfall was less than 0.8 mm and there was no measurable runoff in the Alternative1 landscape. 76.7 % of the runoff from the Alternative2 landscape occurred on days with rain events. In contrast, irrigation played a larger role in causing runoff on the Typical landscape, as only 20.3 % of the runoff from the Typical landscape was from days with rain events. The majority (65.8 %) of runoff from the Alternative2 landscape was due to the March 22 rainfall event, and 11.4 % of runoff from the Typical landscape was due to this event. In contrast, there was measurable runoff from the Typical landscape after every rain event.

Discussion

The role of irrigation method

Landscapes with automatic timed controllers may use 47 % percent more water than those without (Mayer et al. 1999). Baum-Haley et al. (2007) found substantial over-irrigation relative to plant water demand using homeowner scheduled automatic timed irrigation in Florida, and found a water savings of 30 % when the controllers were set based on historical ET. Smart controllers have also been shown reduce landscape water application (Hunt et al. 2001; Devitt et al. 2008; McCready et al. 2009; Davis et al. 2009). Weather-based smart controllers in Irvine, California reduced outdoor water use by 16 % compared to previous water use (Hunt et al. 2001). Devitt et al. (2008) found that weather-based smart controllers reduced water consumption by 20 % compared to time-based irrigation treatment in Las Vegas; similarly, Davis et al. (2009) observed 43 % water savings in Florida. Both studies found that controllers did not alter turf quality. A study by McCready et al. (2009) in Florida found water savings of 7–30 % for rain sensor-based controllers, 25–62 % for weather-based controllers, and 0–74 % for soil moisture-based controllers compared to a time-based irrigation treatment; however, turf quality was impacted at the higher end of the range. Soil-moisture based controllers in Florida have been shown to reduce irrigation by 42 % to 72 % in rainy periods and between −1 % and 64 % in dry periods, compared to automatic timed systems (Cardenas-Lailhacar and Dukes 2012). These studies concur with our findings, as the automatic timed controller in the Typical landscape applied about twice as much irrigation (116 %) as the soil moisture-based smart controller in the Alternative1 landscape, and 32 % more water than the weather station-based smart controller in the Alternative2 landscape. Greatest water savings have been observed in irrigation systems that use soil moisture based technology compared to other types of irrigation systems (Baum-Haley 2011). Our results support this finding, and not our hypothesis, as the Alternative1 landscape rather than the Alternative2 received the least amount of water during the study period.

The CIMIS online database of reference ET is considered a guide for properly scheduling irrigation. Our results showed that typical management may result in water use greater than CIMIS recommendations, while properly planned alternative management may result in water use similar to or much lower than CIMIS recommendations. For the one-year period starting July 9, 2008, CIMIS ET_0 was 128 cm, and the irrigation applied to the Typical landscape was more than double, 288 ± 22 cm. The CIMIS ET_0 during the March 14 – July 22, 2009 period was 610 mm (Irvine station #75). The Typical landscape, which received 770 ± 100 mm during this time, was overwatered relative to CIMIS ET_0. The Alternative2 landscape, which received 583 ± 64 mm, was watered near CIMIS ET_0 (it was set to water at 80 % of on-site ET_0). The Alternative1 landscape, which received 355 ± 20 mm, was watered at nearly half CIMIS ET_0.

Irrigation rates of landscapes likely influenced soil moisture, but not turf quality. As a result of their higher watering rates, soil moisture in the root zone was similar in the Typical and Alternative2 landscapes (Fig. 3). However, the Alternative1 landscape, which received less irrigation than the other two landscapes, experienced a decline in soil moisture due to an imbalance between summer evaporative demand and irrigation (Fig. 3). A study of St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze) in Florida showed that the use of a soil moisture based controller reduced turf quality during dry periods (McCready et al. 2009), but turf quality was not altered in this study as there was no decline in paspalum ET during this period nor an influence of soil moisture on paspalum ET ($p > 0.1$).

The role of turfgrass species

Warm-season grasses such as big bluestem (*Andropogon gerardii* Vitman) and switchgrass (*Panicum virgatum* L.) have been shown to have a higher growth rate than a variety of cool-season grasses during summer months in the semi-arid climate of Utah (Robins 2010). We also found that the warm-season paspalum had a higher growth rate than the cool-season fescue in the warmer spring and summer months, as hypothesized (Fig. 5a). The C_4 photosynthetic pathway in paspalum supported a higher growth rate than the C_3 fescue with a similar level of stomatal conductance (Fig. 5a, 6), as expected for a warm season species.

Although stomatal conductance was similar in fescue and paspalum, it was lower in native sedge (Fig. 6). Our values of stomatal conductance for fescue were within previously observed laboratory values, although lower than well-watered fescue under laboratory conditions (~400 mmol/m^2/s) (Zhao et al. 2008; Swarthout et al. 2009). Stomatal conductance of native sedge was within the observed range for *Carex* species grown in drained soils (Busch and Lösch 1998). We did not find previous estimates of stomatal conductance in paspalum.

Measurements of leaf area were similar to other studies. Our measured SLA was within expected ranges (Volk et al. 2000; Bijoor et al. 2008; Liang et al. 2009) for sedge and fescue; previous values were not available for paspalum. Our values of LAI are similar to Lee (2008), who reported LAI up to 9 for various turfgrasses. Our estimated LAI of mowed material was similar to Bijoor et al. (2008), although these values depend on mowing height.

ET and water balance

Several studies have shown that ET measured by a chamber is similar to ET determined using other methods. In our study, ET measured by the chamber and calculated by the Penman-Monteith methods were similar (Fig. 7). Consequently, the water budgets estimated by the two methods were similar (Figs. 8 and 9). Pauwels and Samson (2006) also found good agreement between measured ET and Penman-Monteith modeled ET in grass, though they used Bowen ratio energy balance and the eddy correlation methods for measurements. However, Shi et al. (2008) found some discrepancy between these methods in forest ecosystems. Other studies have compared chamber ET to other methods. For example, Steduto et al. (2002) and McLeod et al. (2004) have shown good agreement between the daily ET obtained with chamber systems and the Bowen ratio method. Another study found good agreement with the chamber technique and eddy covariance (Balogh et al. 2007). Teitel et al. (2011), using a greenhouse as an open chamber, found measurements to be in agreement with leaf-level gas exchange. However, both of these measurements resulted in slightly lower estimates than lysimeter measurements. Some studies have found ET measured by chambers to be higher than other techniques, for example 25 % higher than the gravimetric method (Grau 1995) and ~26 % higher than eddy-covariance (Stannard and Weltz 2006). Most studies have compared chamber

ET to eddy covariance, Bowen ratio methods, or gravimetric methods. Centinari et al. (2009) found a good match between open chamber measurements and lysimeter measurements, as well as with calculations using the Penman-Monteith equation. This is the first study of which we are aware which has compared ET measured by a closed portable chamber to Penman-Monteith modeled ET using direct measurements of stomatal conductance. The similarity in results between the two methods in this study provides confidence in our estimates of landscape ET.

Our study shows that lawn uses more water than irrigated urban forests. ET values for urban irrigated forests in southern California have been found to be up to 2 mm/d (Pataki et al. 2010). Our ET values for turfgrass were higher than irrigated forest ET reported by Pataki et al. (2010) and showed high spatial and temporal variance, possibly caused by differences in turf density, light, temperature, or wind (Fig. 7). Our lawn ET measurements were within expected ranges, as they were lower on average than calculated CIMIS ET_0 by 67-80 %, and 80-87 % for cool-season fescue and sedge, and 56-64 % for warm-season paspalum. This is consistent with Meyer et al. (1985), who determined that turfgrass can be maintained for optimum performance by watering at 80 % and 60 % of ET_0 for cool-season and warm-season grass, respectively.

It is commonly assumed that warm-season turfgrasses will transpire less than cool-season turfgrasses (Meyer and Gibeault 1986). Although it was not possible to distinguish between the water use of species using the chamber technique due to the high spatial variability in daily ET (Fig. 7a), ET of paspalum was lower than the ET of the C_3 species on some days using the Penman-Monteith method (Fig. 7b). Other studies have also found lower water use in paspalum relative to C_3 species (Feldhake et al. 1983; Huang and Fry 2000). Our analysis also showed that ET was not related to soil moisture in the root zone or surface (0–5 cm), where most roots were concentrated (Table 2; $p>0.1$). Thus, it is likely that our measured rates of stomatal conductance represent maximum values, which did not differ between fescue and paspalum (Fig. 6). There is a general consensus that native grasses have a low transpiration rate. However, in our study, while leaf-level stomatal conductance was lowest for the native sedge (Fig. 6), this did not scale-up to a lower plot-scale ET (Fig. 7) as sedge had a higher LAI (Table 1).

Soil evaporation probably played a small role in ET and therefore in the total water budgets. The high VPD inside the short grass canopies suggests that soil evaporation was low, as within-canopy VPD did not exceed 0.6 kPa even during a hot summer afternoon in August. The low within-canopy VPD (<0.6 kPa) indicates a high boundary layer resistance, as would be expected for a lawn (Schulze et al. 2005).

Conventional landscape management with a timer-based system resulted in low irrigation efficiency, while landscapes with smart irrigation technology were more irrigation efficient. The annual water budget of the Typical landscape, irrigated with an automatic timer-based system, showed a low IE (28 - 31 %), and more than half the water applied drained below the root zone (62 – 65 %) (Fig. 8). The Typical landscape water budget was compared to the water budgets of landscapes with the smart controllers from March 14, 2009 to July 22, 2009 (Fig. 9). During this time, the smart controllers in the Alternative1 and Alternative2 landscapes were more irrigation efficient relative to the timer-based controller in the Typical landscape. Differences in IE between landscapes were due mainly to the amount of irrigation applied, since the volume of water application varied more than species water use. The Typical landscape was associated with a high level of drainage water loss (40 – 42 %) and low IE (57 – 58 %) (Fig. 9a, b). The Alternative1 landscape was highly irrigation efficient (86 – 97 %), with negligible drainage (Fig. 9c, d). The Alternative2 landscape had a slightly lower irrigation efficiency of 78 - 80 %, with a small amount of drainage (Fig. 9e, f). There was slight over-irrigation relative to ET by the weather-based smart controller in the Alternative2 landscape (up to 21 ± 15 % according to the chamber method). Similarly, Pittenger et al. (2004) found over-irrigation by a weather-based controller in southern California. Other studies have also found over-irrigation in drought adapted vegetation, due to lack of irrigation adjustment (Cook et al. 2012 and references therein). Soil moisture-based irrigation may be more sensitive to plant water needs than the weather station based systems, which utilize atmospheric conditions rather than plant available water.

Drainage losses were a large component of the Typical landscape water budget. They were 62 - 65 % of the total water budget annually (Fig. 8), and 33 - 37 % for spring/summer (Fig. 9a, b). Our inferred rates of drainage are supported by the below-root soil water potential, which showed rapid increases in water potential coincident with irrigation events (Fig. 4). Other studies have also shown high rates of drainage in loamy sand soils (Prunty and Greenland 1998; Roy et al. 2000; Ochoa et al. 2007). Saffigna et al. (1977) used drainage lysimeters for potato crops in loamy sand soils and showed that more than half of the total water inputs were lost to drainage using conventional irrigation scheduling. Loamy sand is known to have a high saturated hydraulic conductivity (Maidment 1993), which increases in the presence of turfgrass (Roy et al. 2000).

Runoff was not an important component of the water budget in any of the landscapes (Figs. 8 and 9).Runoff was the highest in the Typical landscape, possibly due to the concrete hardscape, as the driveways in the other landscapes were made of permeable materials. Runoff may have been higher and drainage lower if the experiment had been conducted in finer textured soils, which should be evaluated with additional experiments.

Conclusions

We evaluated the water budgets of three turfgrass landscapes that utilized varying degrees of water conservation measures. We found that smart irrigation controllers conserve water relative to timer-based controllers. The amount of irrigation applied was highest in the Typical landscape which had an automatic timer-based irrigation controller, intermediate in the Alternative2 landscape which had a weather-based irrigation controller, and lowest in the Alternative1 landscape which had a soil-moisture based irrigation controller. This shows the effectiveness of the soil-moisture based system in conserving water, although this will likely vary depending on the threshold for watering set by the user (25 kPa at 25 cm depth in this study). Weather-based or automatic timed controllers may be similarly effective in conserving water if settings were changed to apply less water. Other studies have stressed the importance of proper programming for irrigation controllers in order to achieve water savings (Pittenger et al. 2004; Davis and Dukes 2010; Baum-Haley and Dukes 2012).

As a result of their higher watering rates, there was no significant difference in soil moisture between the Typical and Alternative2 landscapes, while the Alternative1 landscape was slightly drier in the spring/summer. The stomatal conductance of sedge was lower than the other two species. However, the ET of sedge was not lower than the other species due to a higher leaf area index. We used two methods to estimate ET: a chamber-based measurement approach and a Penman-Monteith modeling approach based on weather data collected on-site and direct measurements of grass stomatal conductance. There was good agreement between average daily ET estimated from each method. ET of each landscape was not distinguishable with the chamber based approach due to large spatial variability, while the Penman-Monteith method revealed lower ET by C_4 paspalum relative to C_3 species on some days, as was expected.

The Alternative1 landscape, which was equipped with a soil moisture sensor-based irrigation system and was planted with a warm-season grass, had the highest IE (86 – 97 %); thus nearly all the applied water was utilized for ET. This was followed by the Alternative2 landscape, which utilized a weather station-based drip irrigation system and had a native sedge lawn (78 - 80 %). The Typical landscape was equipped with a standard timer-based irrigation system and a cool season fescue lawn, and had the lowest IE (57 – 58 %). A priori, the Alternative2 landscape was expected to have the highest IE, as it utilized the most recommended water conservation measures. Differences in IE were largely due to the amount of irrigation applied, since water application varied more than ET among species. Thus, reduced water application as a result of irrigation technology was more important in influencing water budgets than choice of turfgrass species. The timer-based irrigation system resulted in large annual drainage losses (62 – 65 %). These drainage losses may have been reduced if rates were adjusted daily based on ET estimates. In addition, our estimates of ET were 56 – 87 % of CIMIS ET_0, confirming that watering turf at ET_0 can result in over-irrigation. We expect irrigation efficiencies similar to those found in this study in actual residences with similar soils and management in arid/semi-arid areas. However, the proportion of runoff relative to drainage would likely be higher in finer textured soils. This study should be replicated in other soil, climatic, and landscape conditions, but shows the importance of direct measurements of the components of water balance for determining effective irrigation rates and water conservation strategies.

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