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ORIGINAL PAPER

Sprinkler irrigation timing drives water loss tradeoffs in an urban, semi-arid environment

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Abstract

Nighttime scheduling of sprinkler irrigation is a widespread strategy to conserve water by reducing wind drift and evaporation losses (WDEL). Water intercepted by a canopy and evaporated during daytime irrigation events, however, may decrease gross water loss and ease heat stress, while microclimate changes from nighttime irrigation may be less consequential. The objectives were to determine whether water savings exist when comparing daytime versus nighttime irrigation with two urban crops by measuring (1) field water- and energy-balances to quantify WDEL, crop evapotranspiration (ET_c), and changes in soil moisture storage; (2) the response of microclimate and evaporative demand; and (3) crop response. A field study at the Greenville Research Farm in North Logan, Utah (41.77° N, 111.81° W), tested two sprinkler irrigation timings (daytime, 14:00–17:00, and nighttime, 02:00–05:00) with *Poa pratensis L.* 'Kentucky bluegrass' turfgrass and *Zinnia elegans L.* 'Benary's Giant Salmon Rose' cut flowers, in triplicate from 2019–2021, resulting in 126 paired events. The mean WDEL were 7% greater with daytime irrigation than with nighttime irrigation across both crops. Using the field water-balance method, the mean total seasonal $ET_{c,}$ was 13 mm greater with nighttime irrigation than with daytime irrigation for both crops. There were no significant differences in ET_c using the energy-balance method, nor was the response of either crop significantly different by day/night irrigation timing. Though recommendations may vary by climate and sprinkler design, landscape irrigation should avoid hours with wind speeds greater than 3 $m \cdot s^{-1}$ and not rely on nighttime irrigation as a sole water conservation approach.

Keywords Turfgrass · Cut flowers · Zinnia · Irrigation scheduling · Water balance · Energy balance

Abbreviations

CRD	Completely randomized design
CU	Coefficient of uniformity
D	Daytime irrigation timing treatment
DCGI	Dark green color index
DD	Deep drainage
Day × Turf	Daytime irrigation of turfgrass treatment
Day × Zinnia	Daytime irrigation of zinnia treatment
e	Vapor pressure
ET_c	Crop evapotranspiration
$ET_{c,BREB}$	Crop evapotranspiration, as calculated by the Bowen-ratio energy balance
$ET_{c.WB}$	Crop evapotranspiration, as calculated by the field water balance
ET_o	Reference evapotranspiration
G	Ground heat flux
I	Irrigation application as a depth
I_{cc}	Depth of irrigation water reaching the surface, as measured by catch cups
I_{fl}	Irrigation application as a depth, as measured by a flowmeter
N	Nighttime irrigation timing treatment
Night × Turf	Nighttime irrigation of turfgrass treatment
Night × Zinnia	Nighttime irrigation of zinnia treatment
P	Precipitation
R	Runoff
RH	Relative humidity
R_n	Net radiation
S	Soil moisture storage
T	Turfgrass vegetation treatment
T_a	Air temperature at a reference height
T_c	Canopy temperature

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T_s	Surface temperature
T_{soil}	Soil temperature
u	Wind speed
VPD	Vapor pressure deficit
WDEL	Wind drift and evaporative losses
Z	Zinnia vegetation treatment
z	Depth
γ	Psychrometer constant
θ_v	Volumetric water content
λ	Latent heat of vaporization

Introduction

Global trends in urbanization project rapid growth in the next decades, highlighting the need for water conservation and security amidst intensifying demand. In arid and semi-arid climates, landscape irrigation can account most of the urban water use. In Utah, the third-driest state in the U.S. (Sowby 2023), 60% of municipal and industrial water is used outdoors (UDWR 2021). One widespread strategy to promote water conservation is timing irrigation during night when meteorological conditions may reduce water loss from sprinklers to the atmosphere, making delivery to plants more efficient. In comparison to daytime, general nighttime environmental conditions include lower wind speed and air temperature, no solar radiation, and greater vapor pressure, all of which may reduce wind drift and evaporative losses (WDEL) (Cavero et al. 2016). Nighttime recommendations, however, consolidate the hours of peak water use, a challenge in Utah, as 90% of residents now live in urban and peri-urban areas (UDWR 2021). In considering a 24-hour irrigation schedule to balance increasing demand with limited system capacity, connecting irrigation timing to conservation tradeoffs within high-elevation, semi-arid climates, and urban crops will increase data-driven resource management.

For agronomic fields, WDEL typically accounted for the greatest fraction of water loss from sprinkler irrigation, and losses increased with wind speed. For one-hour events on bare soil, WDEL averaged 8.8 to 16.5% of the gross irrigation water applied at 2.3 to 3.2 m s^{-1} average wind speeds during the day (12:00 local time) and 3.3 to 7.4% at 0.8 to 2.3 m s^{-1} wind speeds at night (4:00 local time) in Zaragoza, Spain (41.724°N, 0.807°W, 225 m elevation, 298 to 330 mm annual precipitation) (Playan et al. 2005). In the same location with corn (*Zea mays* L.) and four- to six-hour irrigation events, the average WDEL were 20.2% at an average wind speed of 2.7 m s^{-1} during the day (12:00), and 8.5% at an average wind speed of 1.5 m s^{-1} at night (0:00) (Cavero et al. 2008). Alfalfa (*Medicago sativa L.*) irrigated at the same time, duration, and location as corn followed a similar pattern: WDEL averaged 3.0 to 19.6% with daytime irrigation and 0.0 to 6.5% with nighttime irrigation, with daytime wind speed averaging 2.5 m s^{-1} and nighttime averaging 1.4 m s^{-1} (Cavero et al. 2016). Irrigating during periods of lower wind speed consistently reduced WDEL across bare surfaces and agronomic crops.

The water intercepted by a canopy and subsequently evaporated decreased transpiration during and up to several hours after daytime irrigation events and thus may be subtracted from gross sprinkler losses (McNaughton 1981). For most crops and environments, net interception and evaporation were below 10% of the applied water (McNaughton 1981). In semi-arid Bushland, Texas (35.19°N, -192.06°W, 1166 m, 537 mm annual precipitation), the gross water loss from daytime sprinkler irrigation of corn averaged 10.7% per 15 to 25 mm event (Tolk et al. 1995). Modified microclimate and canopy interception and evaporation, however, suppressed transpiration by at least 50% during the events, resulting in net water losses of 2.7 to 3.9%, with lower losses on days of greater solar radiation (Tolk et al. 1995). Likewise, in semi-humid Lincoln, Nebraska (40.81°N, 96.70°W, 370 m elevation, 760 mm annual precipitation), 8% of the sprinkler-applied water evaporated during the daytime irrigation of corn, suppressing transpiration by 51.9% and soil evaporation by 24.8% (Thompson et al. 1993). Accounting for these decreases during daytime events, net water loss was 3.1%. Moreover, 24% of the net radiation during the irrigation events went toward the warming and evaporation of water droplets in flight, resulting in net sensible heat flux losses in both the canopy and soil surface environments (Thompson et al. 1993).

Sprinkler irrigation during hours of greater evaporative demand may decrease gross water loss to the environment and ease heat stress, while microclimate changes from nighttime irrigation were less consequential. Within a corn canopy, for example, the vapor pressure deficit (VPD) decreased by 1.2 kPa during the day and only 0.2 kPa during night irrigation, lasting up to three hours after the events (Cavero et al. 2009). At 1 and 2 m heights over alfalfa, the VPD decreased 0.3 to 4.4 kPa with daytime irrigation and by 0.1 to 0.5 kPa with nighttime irrigation (Cavero et al. 2016; Stambouli et al. 2012). Trends in air and canopy temperatures were similar: air temperature decreased by 1.5 °C and canopy temperature decreased by 3 °C during daytime irrigation, while air and canopy temperatures decreased by 0.5 °C and 1.5 °C, respectively, during nighttime irrigation (Cavero et al. 2009, 2016; Liu and Kang 2006).

Following the microclimate modification from daytime irrigation, measured crop evapotranspiration (ET_c) generally decreased, but less so than transpiration, while modelled ET_c simulated greater crop stress. For corn at full cover and irrigated around the times of the daily evaporative demand

maximum and minimum, average ET_c decreased from 1.99 to 1.35 mm and transpiration decreased from 2.03 to 0.86 mm from daytime irrigation (Martínez-Cob et al. 2008). During nighttime irrigation, transpiration decreased from 0.15 to 0.04 mm and ET_c increased from 0.07 to 0.28 mm, both negligible changes at night relative to plant-water dynamics (Martínez-Cob et al. 2008). Subtracting the changes from WDEL and interception, gross losses decreased from 19.3 to 17.5%, on average, for daytime irrigation and increased from 8.1 to 9.5% with nighttime irrigation (Martínez-Cob et al. 2008). Here, the modified microclimate from daytime irrigation helped satisfy the crop water demand by reducing transpiration, thereby improving the sprinkler efficiency during the day, but WDEL were still the greatest factor in reducing sprinkler efficiency. Continuous field measurements of soil moisture with irrigation events would enable a water-balance approach for linking aboveground dynamics to plant-water availability.

The efficiency of water delivery by irrigation timing may ultimately drive changes in yield, depending on crop type and conditions. In well-watered corn, yield was significantly greater by 1.6 Mg ha^{-1} with nighttime irrigation compared to daytime (Cavero et al. 2018), but the yield of alfalfa was not (Cavero et al. 2016). Conversely, in Texas (29.209°N, 99.750°W, 276 m elevation, 663 mm annual precipitation), the average grain yield of corn was significantly greater by 10% and plant height was significantly taller by 2% with evening (17:00 local time) compared to morning (8:00 local time) drip irrigation (Dong et al. 2016). In this study, the decrease in root zone soil temperature with the early evening irrigation (i.e., near daily temperature and evaporative demand maximums) may have increased root water uptake and decreased soil evaporation, increasing plant yield and growth (Dong et al. 2016). This again emphasizes the need for accounting for changes to the soil environment, as well as distinguishing hours of the day when considering irrigation timing, net losses, and plant stress.

Previous research on day versus night irrigation timings introduced water efficiency tradeoffs and complexity within the water balance beyond gross losses, through changes in above- and belowground microclimates and subsequent agronomic crop responses. To test the outcomes for urban water management at high-elevation, this study was the first to use field water-energy balance approaches to measure both net losses and microclimate modifications under sprinkler irrigation during the minimum and maximum evaporative demand and wind speed (2:00 to 5:00, and 14:00 to 17:00 local time). Moreover, it was the first to investigate prevalent residential and microfarm crops: lawn of Kentucky Bluegrass (*Poa partensis* L.) and beds of zinnia cut flowers (*Zinnia elegans* L.), which also represented different canopy architectures and seasonal growth habits.

Methods

Site description and management

The study was conducted at the Utah Agricultural Experiment Station – Greenville Research Farm in North Logan, UT (41.76°N, 111.81°W, 1404 m elevation, 501 mm annual precipitation) from 2019 to 2021. During the freeze-free growing season (May 15 to Sep 30) of these years, the average minimum and maximum air temperatures were 5 and 34 °C, respectively, and the mean annual reference ET for turfgrass, ET_o, was 715 mm (Utah Climate Center 2024). The soil is a Millville silt loam with 1.5% organic matter (NRCS 1998).

The site was established on a preexisting, 1.5-ha., turfgrass field with a solid-set sprinkler system. The sprinkler heads were spaced 15 m apart in a square-grid pattern. Six, adjacent irrigation zones (i.e., each zone was one group of sprinkler heads controlled as a unit) were selected for this study. Each of the six zones had two paired plots, resulting in 12 plots across the field site. Each plot was 5 × 5 m, centered within one set of four sprinkler heads, and the pair was randomly assigned an irrigation timing, Day or Night. Each plot within a pair was then randomly assigned a crop of Kentucky bluegrass (Turf) or zinnia Benary's Giant™ 'Salmon Rose' (Zinnia). Irrigation events occurred three times per week (Mondays, Wednesdays, and Fridays) unless a precipitation event of 10 mm or more occurred within 24 h of an event, in which case the irrigation event was skipped. Each pair of plots was irrigated at 80% of ET_o (Utah Climate Center 2024), which resulted in 20- to 60-minute irrigation event durations. The pairs were irrigated sequentially, such that Night occurred between 2:00 to 5:00 local time, and Day followed from 14:00 to 17:00. The order in which the pairs were irrigated within a timing treatment was alternated for each event.

The turfgrass and zinnias were fertilized based on annual spring soil test recommendations. Turfgrass was maintained at a 7.6 cm height (Kopp and Johnson 2011). Turfgrass quality was quantified by assessing the percent cover and dark green color index (DGCI) per plot using digital image quality rating software (Turf Analyzer program version 1.01) (Karcher and Richardson 2013) and by visual quality ratings in 2020 and 2021. Three digital images of each plot were captured each week using a lightbox (0.53 m W × 0.74 m L × 0.58 m H) with a compact fluorescent light bulb (9 W IS-09, UL, Camas, WA). Zinnia plots were divided into four beds, each 0.78 m wide and spaced 1.25 m on center. Pathways between the beds were covered with weed barrier landscape fabric (Dewitt, Weed Barrier, 116 g). Each bed contained two rows, spaced 0.6 m apart and was direct sown on June 03 to 05, 2019; May 19, 2020; and May 17,

2021. Plants were overseeded by 50% and then thinned to an in-row spacing of 0.30 m, for a total of 136 plants per plot. Yield as stems per m^2 was measured one to three times per week from 2019 to 2021. To assess quality, every stem was also graded. Stem lengths of 0.3 m or more were graded as marketable, while stems less than 0.3 m, diseased, or misshapen were graded as culls (Maughan et al. 2020). The bloom diameter to the nearest mm was also recorded for five randomly selected stems per plot per harvest.

Instrumentation

A weather station was located at the field site that measured precipitation (P) with a tipping bucket rain gauge (TR525, Texas Electronics, Dallas, TX, accuracy: ±1%) at a 6 m height, reference air temperature at a 3 m height (T_a), and wind speed ($u_{4.5}$) with a 4–blade propeller (05103, R.M. Young, Traverse City, MI, accuracy: ±0.3 m s^{-1}) at a 4.5 m height (Utah Climate Center 2024). To measure microclimate conditions near and within the plant canopy, each plot was equipped with an air temperature (T_c) and relative humidity (RH) sensor (CS215, Campbell Scientific Inc., Logan, UT, accuracy: ±2%) installed 0.14 m above the soil surface. The sensors remained stationary in the turfgrass plots. For Zinnia, the sensor height was incrementally increased to maintain position at half the canopy height, reaching a maximum height of 0.33 m at crop maturity. The surface temperature (T_s) was measured with one infrared radiometer centered in each plot at a 0.86 m height. For Zinnia, the sensor height was increased as needed to remain 0.06 m above the canopy (SI-411-SS, Apogee Instruments, Inc., Logan, UT, accuracy: 0.2 °C). Because the Turf root zone was 0.15 to 0.20 m and Zinnia ranged from 0.15 to 0.30 m, soil moisture (θ_v) and temperature (T_{soil}) were measured at 0.08 and 0.18 m depths in each plot with two volumetric water content sensors (TDR-310 H, Acclima, Inc., Meridian, ID, accuracy of θ_v and T_{soil} respectively: ±3% and ±0.25˚C). One soil moisture profile sensor (SoilVUE^{TM}10, Campbell Scientific Inc., Logan, UT, accuracy of θ_v and T_{soil} respectively: ±2% and ±0.15˚C) was installed per plot to measure volumetric water content and temperature and check for deep drainage (DD) at 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.75, and 1.0 m depths. Net, shortwave, and longwave radiation were measured in one replicate per treatment (i.e., four plots) in 2020 and 2021. Net radiometers (SN-500-SS, Apogee Instruments, Inc., Logan, UT, accuracy: ±3%) were mounted 0.15 m above the soil surface. For Zinnia, the height of the net radiometer increased throughout the season to remain 0.06 m above the canopy. Instruments scanned every 15 min, and hourly and daily averages were recorded with one datalogger (CR300, Campbell Scientific, Inc., Logan, UT) per pair of plots.

One magnetic flow rate meter (IM3000, Lindsay™, Omaha, NE, accuracy: ±2%) was installed per pair of plots to monitor the total volume of water applied per irrigation event in each sprinkler zone. To evaluate WDEL, nine 100-mL catch cups (Professional catch cups, USU CWEL, Salt Lake City, UT, accuracy: ±2 mL) were equidistantly spaced on the surface of each plot to manually measure the amount of water that reached the plots from each irrigation event. After the canopy of Zinnia covered approximately 75% of the soil surface, nine additional catch cups were installed above the canopy and adjusted with canopy height until reaching a maximum height of 1 m. The catch cups above the canopy were used to calculate WDEL, and the ground versus canopy catch cups were used to calculate canopy interception. In total, 162 catch cups were installed in the field. Water amounts from nighttime irrigation were measured by 6:00 am (i.e., within one hour of the last zone's irrigation event), while those from daytime events, occurring during peak evaporative demand, were measured immediately after each zone's event. Because of the sensor availability and time to establish the field in 2019, measurements began in late July and a total of 27 paired events (i.e., 27 Night and 27 Day) were monitored, whereas measurements began on June 1 in 2020 and 2021, for a total of 50 and 49 paired events per year, respectively.

Water- and energy-balance calculations

The irrigation volume from the flow meters represented water applied to the irrigation zone. To isolate the input to each 5 × 5 m^2 plot that was centered between the sprinkler heads (11% of the zone's area), a water audit was conducted in May 2019. The distribution and uniformity of application was assessed with 496 catch cups equidistantly spaced and irrigated across each zone for 20 min. From the depth of water recorded in each catch cup, 12.2 to 14.5% of the irrigation water applied reached each 5 × 5 m^2 plot. The water audit data, the sprinkler nozzle types (Size 6–14 of the Falcom 6504 series, Rainbird, Azusa, CA), and the degree of rotation per sprinkler head were used to calculate the irrigation depth (I, mm) per plot from the zone's irrigation volume. WDEL were calculated after Cavero et al. (2008), as:

$$WDEL\ (\%) = \left[\frac{I_{fl} - I_{cc}}{I_{fl}}\right] * 100 \quad (1)$$

$$WDEL\ (\mathrm{mm}) = [I_{fl} - I_{cc}] \quad (2)$$

where I_{fl} (mm) is the depth of water applied, measured by the flowmeter, and I_{cc} (mm) is the average depth of water collected across the catch cups per plot.

The change in soil moisture storage (ΔS) was calculated as the sum of two layers from the soil surface to an effective root zone depth of 0.3 m for each plot. At midnight each day, the volumetric water content (θ_v) at 0.08 m ($\theta_{v,0.08}$) was used to calculate the daily storage, S, from the 0 to a 0.16 m depth (z_1), while θ_v at 0.18 m ($\theta_{v,0.18}$) represented the 0.16 to 0.30 m depth (z_2) (adapted from Rahgozar et al. 2012):

$$S\,(\mathrm{mm}) = \theta_{v,0.08} \times z_{1+}\theta_{v,0.18} \times z_2 \tag{3}$$

The changes in daily S were then summed across days for weekly ΔS in mm. Below the root zone, DD was evaluated from θ_v at 0.3, 0.4, 0.5, 0.6, and 0.75 m depths at midnight each day. The changes in daily DD were then summed for weekly ΔDD in mm:

$$\begin{aligned} DD =& \theta_{v,0.3} \times 100 + \theta_{v,0.4} \times 100 + \theta_{v,0.5} \\ & \times 100 + q_{v,0.6} \times 100 + \theta_{v,0.75} \times 200 \end{aligned} \tag{4}$$

Weekly $ET_{c,\,WB}$ was calculated through the field water balance method (WB): precipitation (P) and irrigation (I), wind drift and evaporation loss (WDEL), change in root-zone soil moisture storage (ΔS), and change in deep drainage (ΔDD), with all units in mm (Pereira et al. 2020). Runoff (R) was considered negligible due to the semi-arid climate, irrigation rates at 80% of ET_o (Duong 2014), and level grade of the plots:

$$ET_{c,WB}\,(\mathrm{mm}) = P + I - WDEL - \Delta S - \Delta DD \tag{5}$$

To account for variability in water pressure, and hence variability in irrigation applied across plots and subsequent differences in $ET_{c,\,WB}$, several steps were used to normalize ET_c by irrigation applied as well as the irrigation amount per event. First, the ET_c of each plot was divided by the irrigation depth per plot to obtain the proportion of plot ET_c relative to the irrigation amount. The mean proportion of ET_c was then calculated for each irrigation timing × crop treatment. With the average irrigation depth across the field for each event, the mean proportion of ET_c per treatment was used with the average irrigation depth. If the irrigation depth in a plot was less than 80% of ET_o (mm) because of low water pressure in its zone, then the $ET_{c,\,WB}$ of that plot in that week was not included in the analysis. In mid-June to July 2021, this included one plot each of Night × Turf and Night × Zinnia.

The $ET_{c,\,BREB}$ was also quantified by the Bowen Ratio Energy Balance (BREB) method (Bowen 1926; Irmak et al. 2014):

$$ET_{c,BREB} = \frac{R_n - G}{\lambda\left(1 + \frac{\gamma\,(T_2 - T_1)}{e_2 - e_1}\right)} = \frac{R_n - G}{\lambda\,(1+\beta)} \tag{6}$$

where R_n is the net radiation and G is the ground heat flux (both in MJ m^{-2} d^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}), γ is the psychrometric constant (kPa°C^{-1}), T_2-T_1 (°C) is the air temperature difference between the upper (3 m) and lower measurements (0.35 m), and e_2 - e_1 (kPa) is the actual vapor pressure difference between the upper (3 m) and lower measurements (0.35 m). Two equations were used to validate $ET_{c,\,BREB}$ (mm). Hourly $ET_{c,\,BREB}$ were rejected when (Tanner et al. 1987; Payero et al. 2003):

$$\beta \approx -1 = (-1.25 < \beta < -0.75) \tag{7}$$

Data were also rejected when (Ohmura 1982; Payero et al. 2003):

$$\lambda\ (\Delta e + \gamma\,\Delta T)\,(R_n - G) < 0 \tag{8}$$

Based on these conditions across 2,928 h of data per plot per year (2020 and 2021), the ET_c was converted to 0 for an average of 38.3% (±4.0) of the hours, which largely occurred at night.

Statistical analysis of field data

The field study followed a split-plot design with three replications. The whole plot factor was the timing of irrigation with two levels (Day and Night), and the subplot factor was the crop type with two levels (Turf and Zinnia). Statistical analysis of covariance (ANCOVA) of WDEL in Day × Turf versus Night × Turf and Day × Zinnia versus Night × Zinnia was performed using SAS University Edition version 9.4 (SAS Institute, Cary, NC). Least Squares means (LSmeans), fixed effects, and difference of LSmeans of canopy vapor pressure, T_c, T_{soil}, θ_v, and T_s were estimated by repeated measures, where year was a random variable. In the model statement, the dependent variable was equal to the interaction of the crop type and irrigation event. Pairwise comparisons of the treatment least square means were adjusted with Tukey-Kramer's method for multiplicity. For WDEL analysis, WDEL in % or mm was used as a dependent variable and wind speed (m s^{-1}) was used as a covariate. Data were analyzed by ANCOVA with type 3 sum of squares and Tukey's pairwise comparisons to determine individual differences. Significance for all analyses was defined as $\alpha = 0.05$.

Results

Environmental conditions

The total P from May to Sep was 147 mm in 2019, 122 mm in 2020, and 58 mm in 2021, all of which were below the

30-year normal of 160 mm (1991–2020) (NOAA 2021). The mean daily (±SE) T_a from May to Sep was 18±0.4 °C in 2019, 18±0.4 °C in 2020, and 20±0.4 °C in 2021. The Day events occurred when the mean hourly T_a was 25±0.1°C (2019 and 2020) to 26±0.1°C (2021) and mean hourly $u_{4.5}$ was 1.6±0.02 m s^{-1} (2019 to 2021). For Night, the mean hourly T_a was 13±0.4°C (2019 and 2020) to 14±0.4°C (2021) and the mean hourly $u_{4.5}$ was 0.8±0.02 m s^{-1} (2019 to 2021). The mean maximum daily $u_{4.5}$ occurred at 14:00 (2.2±0.06 m s^{-1}), which was three times greater than the mean daily minimum at 6:00 (0.8±0.02 m s^{-1}). To view the 24-hour patterns, an example of these hourly trends is given for four consecutive, precipitation-free days in mid-August each year (Fig. 1).

WDEL and ET

The mean seasonal WDEL of Day × Turf were greater than Night × Turf by 3% in 2019 and 2021 and 13% in 2020, which was the only year that seasonal or monthly differences were significant ($p<0.0001$) (Table 1). In terms of depth of water loss, the mean seasonal WDEL across years were 103±18 mm for Day × Turf and 62±12 mm for Night × Turf; a mean difference of 44±16 mm between timings across years (Table 2). These differences were only significant in 2020, when losses were over two times greater with Day than Night (Table 2).

The mean seasonal WDEL ranged from 22 to 24% with Day × Zinnia and 15 to 16% with Night × Zinnia, which were significantly different in each of the three years ($p<0.05$) (Table 2). Differences in the mean monthly WDEL (%) by irrigation timing were most pronounced and significantly different later in the growing seasons, typically during the months of Aug and Sep (Table 1). The mean seasonal water losses in terms of WDEL were 121±16 mm for Day × Zinnia and 58±10 mm for Night × Zinnia; a mean difference of 63±14 mm between timings across years (Table 2).

Differences in the ET_c by irrigation timing × crop were not significant by either the field WB or BREB methods in any years ($p>0.05$) (Table 2). The total seasonal $ET_{c,\ WB}$ ranged from 533 to 593 mm in Night × Turf and 527 to 581 mm in Day × Turf, resulting in a mean difference of 10±4 mm between irrigation timings of turfgrass (Table 2; Fig. 2). The total seasonal $ET_{c,\ BREB}$ ranged from 558 to

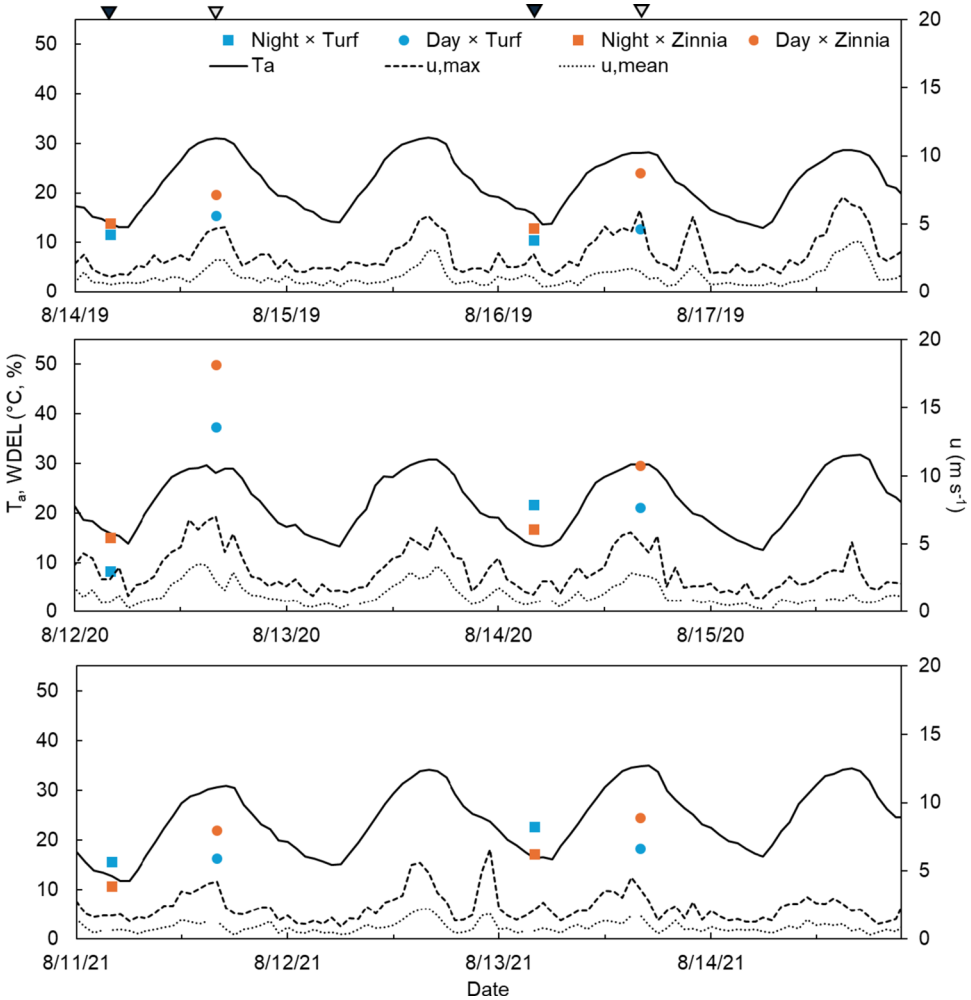


Fig. 1 Mean hourly air temperature (**T_a**,°C, solid line) and the wind speed at a 4.5 m height (**u**, m·s^{-1}) as an hourly maximum (max, dashed line) and mean (mean, dotted line) for the site. Mean wind drift and evaporative losses (**WDEL**, %) per event by irrigation timing × crop include nighttime irrigation of turfgrass (**Night × Turf**, blue square), daytime irrigation of turfgrass (**Day × Turf**, blue circle), nighttime irrigation of zinnia (**Night × Zinnia**, orange square), and daytime irrigation of zinnia (**Day × Zinnia**, orange circle). Four precipitation-free days, Wednesday through Saturday, of the second week of August are represented in 2019 (top panel), 2020 (middle panel), and 2021 (bottom panel). Irrigation on Wednesdays and Fridays is designated as nighttime (solid triangle) or daytime (open triangle) above the top panel

Table 1 Mean monthly (±standard error) wind drift and evaporation losses as a percentage (**WDEL**, %) with significant differences between nighttime (**Night**) versus daytime (**Day**) irrigations of turfgrass (**Turf**) and Zinnia (**Zinnia**) crops from 2019 to 2021

Year	Month	No. Events	Turf			Zinnia		
			Night	Day	*(p-value)*[a]	Night	Day	*(p-value)*[a]
			%			%		
2019	June[b]	–	–	–	–	–	–	–
	July	6	17 (3)	17 (3)	*1.0000*	18 (2)	18 (2)	*1.0000*
	Aug	13	12 (2)	14 (2)	*1.0000*	16 (1)	21 (1)	*0.6030*
	Sep	8	15 (3)	22 (3)	*0.8800*	14 (3)	28 (2)	*0.0260*
2020	June	11	12 (2)	24 (2)	*< 0.0001*	13 (1)	18 (1)	*0.5770*
	July	14	8 (2)	27 (2)	*< 0.0001*	16 (1)	22 (1)	*0.1760*
	Aug	13	9 (2)	24 (2)	*< 0.0001*	18 (1)	28 (1)	*< 0.0001*
	Sep	12	12 (2)	26 (2)	*< 0.0001*	18 (1)	28 (1)	*0.0000*
2021	June	12	20 (2)	20 (2)	*1.0000*	17 (1)	17 (1)	*0.9860*
	July	13	17 (2)	18 (2)	*1.0000*	15 (1)	19 (1)	*0.7990*
	Aug	11	18 (2)	25 (2)	*0.8530*	14 (1)	27 (1)	*0.0000*
	Sep	13	19 (2)	20 (2)	*1.0000*	16 (1)	24 (1)	*0.0020*

The number (No.) of events that were monitored per month is also given; each, with each event consisting of one paired nighttime versus daytime irrigation)

[a]$p<0.05$ is significant

[b]Data not available

Table 2 Seasonal summaries of 2019 – 2021 mean cumulative crop evapotranspiration rates ($\mathbf{ET_c}$, mm) with (±standard error) by the field water balance (**WB**) and Bowen ratio energy balance (**BREB**) methods, and mean cumulative and seasonal wind drift and evaporative losses (**WDEL**, mm and %)

Year[a]	Irrigation Timing	Turf				Zinnia			
		$ET_{c,WB}$	$ET_{c,BREB}$	WDEL	WDEL	$ET_{c,WB}$	$ET_{c,BREB}$	WDEL	WDEL
		mm			%	mm			%
2019	Night	–[c]	–[c]	27 (6)	14 (2)	–[c]	–[c]	31 (4)	16 (1)
	Day	–[c]	–[c]	40 (7)	17 (2)	–[c]	–[c]	61 (6)	22 (1)
	(p-value)[b]	–[c]	–[c]	*0.9850*	*0.4030*	–[c]	–[c]	*0.5284*	*0.0018*
2020	Night	594 (48)	558 (20)	62 (13)	11 (2)	627 (40)	592 (55)	71 (16)	16 (1)
	Day	581 (16)	546 (15)	143 (7)	25 (2)	614 (9)	546 (48)	161 (7)	24 (1)
	(p-value)[b]	*1.0000*	*1.0000*	*0.0163*	*< 0.0001*	*1.0000*	*0.981*	*0.0019*	*< 0.0001*
2021	Night	533 (35)	602 (28)	97 (7)	18 (2)	566 (32)	553 (20)	72 (10)	15 (1)
	Day	527 (11)	615 (40)	124 (22)	21 (2)	548 (30)	532 (43)	140 (11)	22 (1)
	(p-value)[b]	*1.0000*	*1.0000*	*0.7386*	*0.1300*	*0.9999*	*1.0000*	*0.0159*	*< 0.0001*

P-values are given for nighttime (**Night**) versus daytime (**Day**) irrigation by turfgrass (**Turf**) and zinnia (**Zinnia**) crops

[a]Data collected from July to Sep 2019, for a total of 27 paired events with each a nighttime and daytime irrigation; June to Sep 2020, for a total of 50 events; and Jun to Sep 2021 for a total of 49 events

[b]$p<0.05$ is significant

[c]Data are not available

602 mm in Night × Turf and 546 to 616 mm in Day × Turf across years (Table 2). For Zinnia, the total seasonal $ET_{c,WB}$ ranged from 566 to 627 mm in Night × Zinnia and 548 to 614 mm in Day × Zinnia, resulting in a mean difference of 16±3 mm between timings (Table 2; Fig. 3). The total seasonal $ET_{c,BREB}$ ranged from 553 to 592 mm with Night × Zinnia and 523 to 546 mm with Day × Zinnia (Table 2).

Microclimate

The mean decreases in maximum T_c and mean VPD during irrigation events were about half as great during Night than Day for both crops, as shown in the hourly trends for four consecutive, precipitation-free days in mid-August each year (Fig. 4). During irrigations across years, the mean seasonal decrease in hourly maximum T_c was 1.5±0.5 ˚C for Night × Turf and 2.5±0.8 ˚C for Day × Turf. The mean decrease in VPD was 0.03 to 0.06 kPa for Night × Turf and 0.05 to 0.08 for Day × Turf, which lasted up to two hours after irrigation for both timings (Fig. 4). The mean decrease in T_s was 0.7 to 1.0 ˚C with Night × Turf and 1.0 to 2.5 ˚C with Day × Turf.

For Night × Zinnia, the mean decrease in T_c during irrigations was 2.5±0.4 ˚C, while Day × Zinnia decreased by

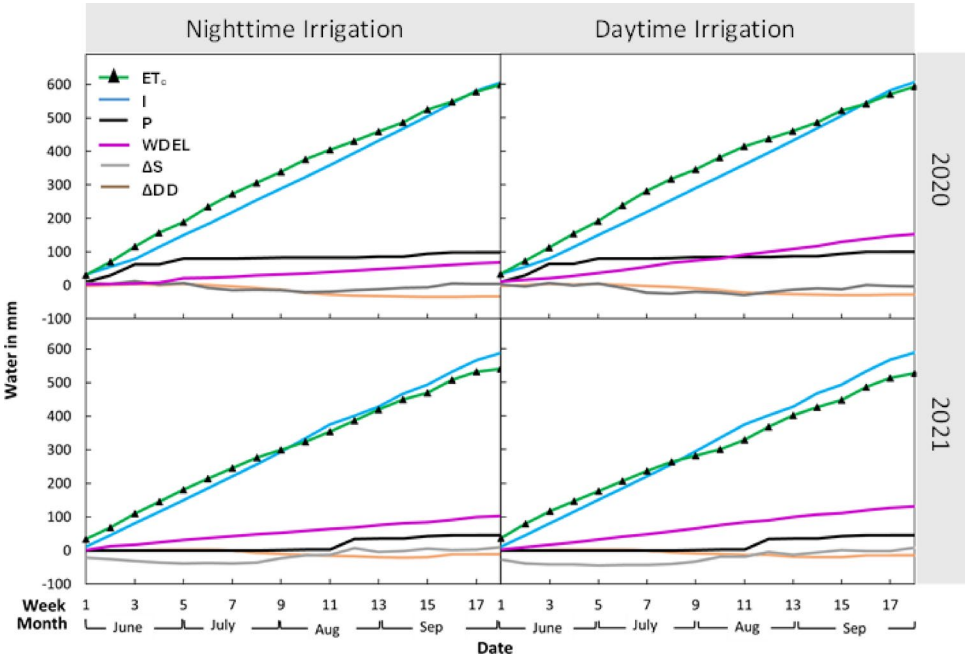


Fig. 2 Mean cumulative weekly water balance of Turf irrigated at Night (left panels) and during the Day (right panels) from June through September in 2020 (top panels) and 2021 (bottom panels). Components of the water balance in mm included crop evapotranspiration ($\mathbf{ET_c}$, black triangles and green line); irrigation applied (**I**, blue line); precipitation (**P**, black line); wind drift and evaporative losses (**WDEL**, pink line); soil moisture storage (Δ**S**, grey line); and deep drainage (Δ**DD**, orange line)

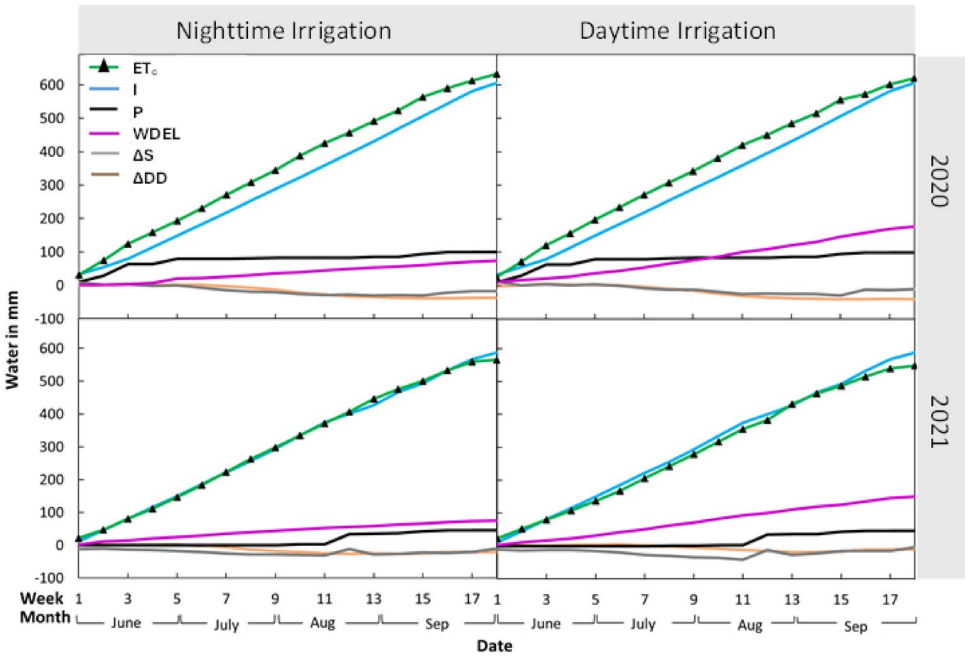


Fig. 3 Mean cumulative weekly water balance of Zinnia irrigated at Night (left panels) and during the Day (right panels) from June through September in 2020 (top panels) and 2021 (bottom panels). Components of the water balance in mm included crop evapotranspiration ($\mathbf{ET_c}$, black triangles and green line); irrigation applied (**I**, blue line); precipitation (**P**, black line); wind drift and evaporative losses (**WDEL**, pink line); soil moisture storage (Δ**S**, grey line); and deep drainage (Δ**DD**, orange line)

5.0 ± 1.4 ˚C, and the greatest decrease reached 8.5 ℃ with Day × Zinnia in Sep of 2020. For Night × Zinnia, the mean seasonal decrease in VPD during irrigation was 0.12 to 0.23 kPa, while Day × Zinnia was 0.61 to 0.80 kPa. These decreases lasted until the next irrigation event with Day × Zinnia, particularly after the canopy closed, but not with Night × Zinnia. During irrigation, the mean decrease in T_s was 1.4 to 1.6 ˚C for Night × Zinnia and 3.0 to 3.5˚C for Day × Zinnia.

Soil environment

Overall, $\theta_{v,0.08}$ and $\theta_{v,0.18}$ were greater in soils with Day compared to Night across crops (Fig. 5). On 01 Jun, the initial mean daily $\theta_{v,0.08}$ was 0.28 m^3 m^{-3} in Day × Turf and 0.26 m^3 m^{-3} in Night × Turf in 2020, and 0.28 and 0.24 m^3 m^{-3}, respectively, in 2021. After an irrigation event of either timing for Turf, $\theta_{v,0.08}$ increased by a mean of 0.03 ± 0.02 m^3 m^{-3} in 2020 and 0.04 ± 0.04 m^3 m^{-3} in 2021, and between irrigation events, $\theta_{v,0.08}$ remained greater in Day × Turf than Night × Turf. The mean daily $\theta_{v,0.08}$ was greater in Day ×

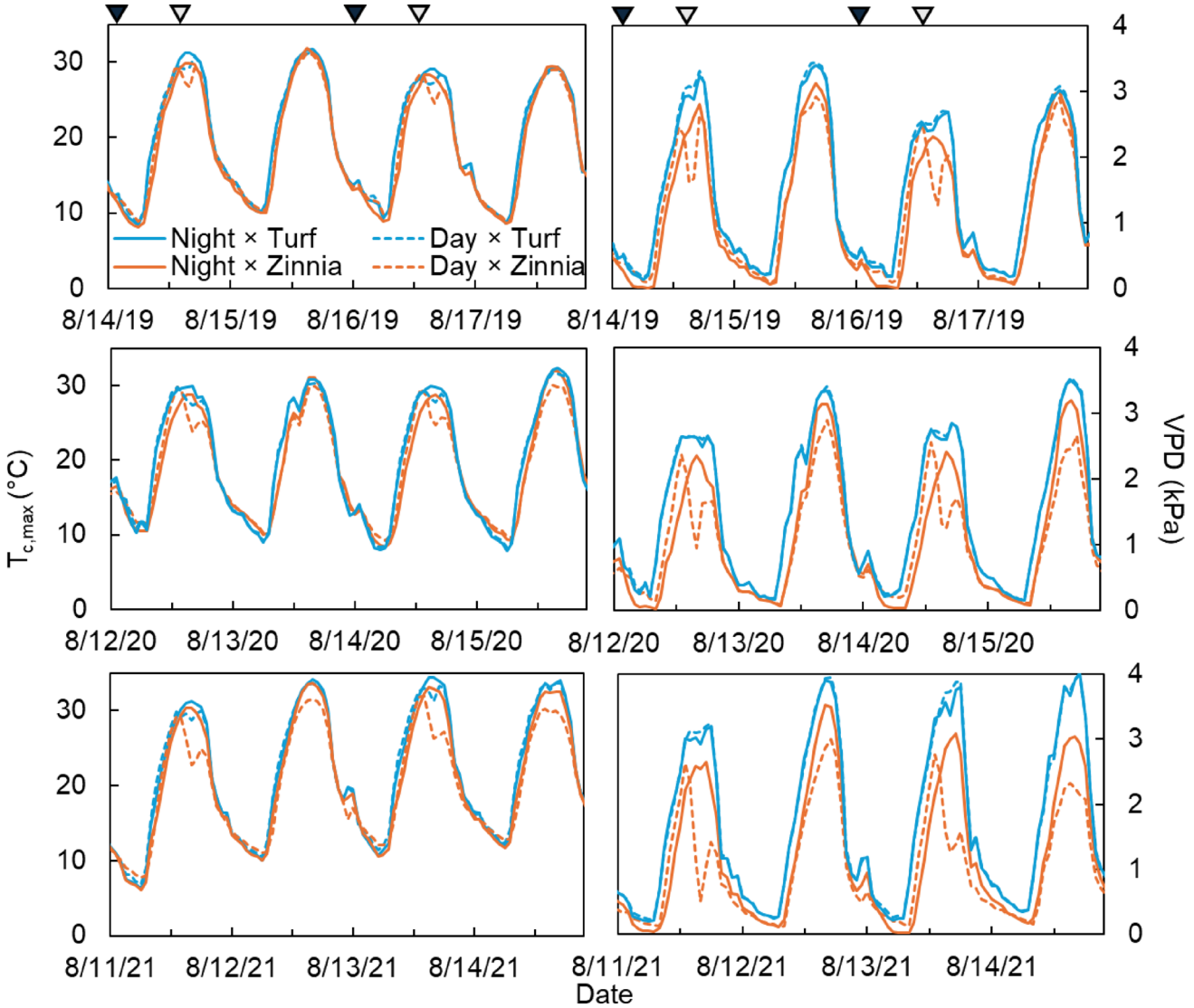


Fig. 4 Mean maximum hourly canopy temperature ($\mathbf{T_{c,\ max}}$, ˚C, left panels) and mean hourly vapor pressure deficit (**VPD**, kPa, right panels) by irrigation timing × crop: nighttime irrigation of turfgrass (**Night × Turf**, solid blue line), daytime irrigation of turfgrass (**Day × Turf**, dashed blue line), nighttime irrigation of zinnia (**Night × Zinnia**, solid orange line), and daytime irrigation of zinnia (**Day × Zinnia**, dashed orange line). Four precipitation-free days, Wednesday through Saturday, of the second week of August are represented in 2019 (top panels), 2020 (middle panels), and 2021 (bottom panels). Irrigation on Wednesdays and Fridays is designated as nighttime (solid triangle) or daytime (open triangle) above the top panels

Turf than Night × Turf for 66.7% of the days from 01 Jun to 30 Sep in 2020, and 70.5% of these days in 2021, while the mean maximum daily $\theta_{v,0.08}$ was greater with Day × Turf than Night × Turf for 72.0% of days in 2020 and 74.6% in 2021 (Fig. 5). The $\theta_{v,0.18}$ was generally greater with Day × Turf than Night × Turf by 0.07 ± 0.02 $m^3\ m^{-3}$ in 2020 and 0.10 ± 0.04 $m^3\ m^{-3}$ in 2021. The total ΔDD for Night × Turf was 12 mm in 2020 and 15 mm in 2021, while ΔDD was 19 mm in both 2020 and 2021 of Day × Turf. The mean hourly $T_{soil,0.05}$ of Night × Turf was 20.5 ± 1.8 ˚C from 01 Jul to 30 Sep 2019, 20.1 ± 1.6 ˚C from 01 Jun to 30 Sep 2020, and 20.8 ± 1.6 ˚C from 01 Jun to 30 Sep 2021. With the same date ranges by year, the mean $T_{soil,0.05}$ of Day × Turf was 21.2 ± 1.9 ˚C in 2019, 20.7 ± 1.6 ˚C in 2020, 21.4 ± 1.5 ˚C in 2021.

On 01 Jun, the initial mean daily $\theta_{v,0.08}$ was 0.19 $m^3\ m^{-3}$ in Day × Zinnia and 0.18 $m^3\ m^{-3}$ in Night × Zinnia in 2020, and 0.16 and 0.15 $m^3\ m^{-3}$, for each respectively, in 2021. The mean increase in $\theta_{v,0.08}$ from an irrigation event was 0.08 ± 0.03 $m^3\ m^{-3}$ in Day × Zinnia and 0.07 ± 0.03 $m^3\ m^{-3}$ in Night × Zinnia across years. The mean daily $\theta_{v,0.08}$ was greater in Day × Zinnia than Night × Zinnia for 100% of the days in 2020, and 75.4% of the days in 2021, while the mean maximum daily $\theta_{v,0.08}$ was greater in Day × Zinnia

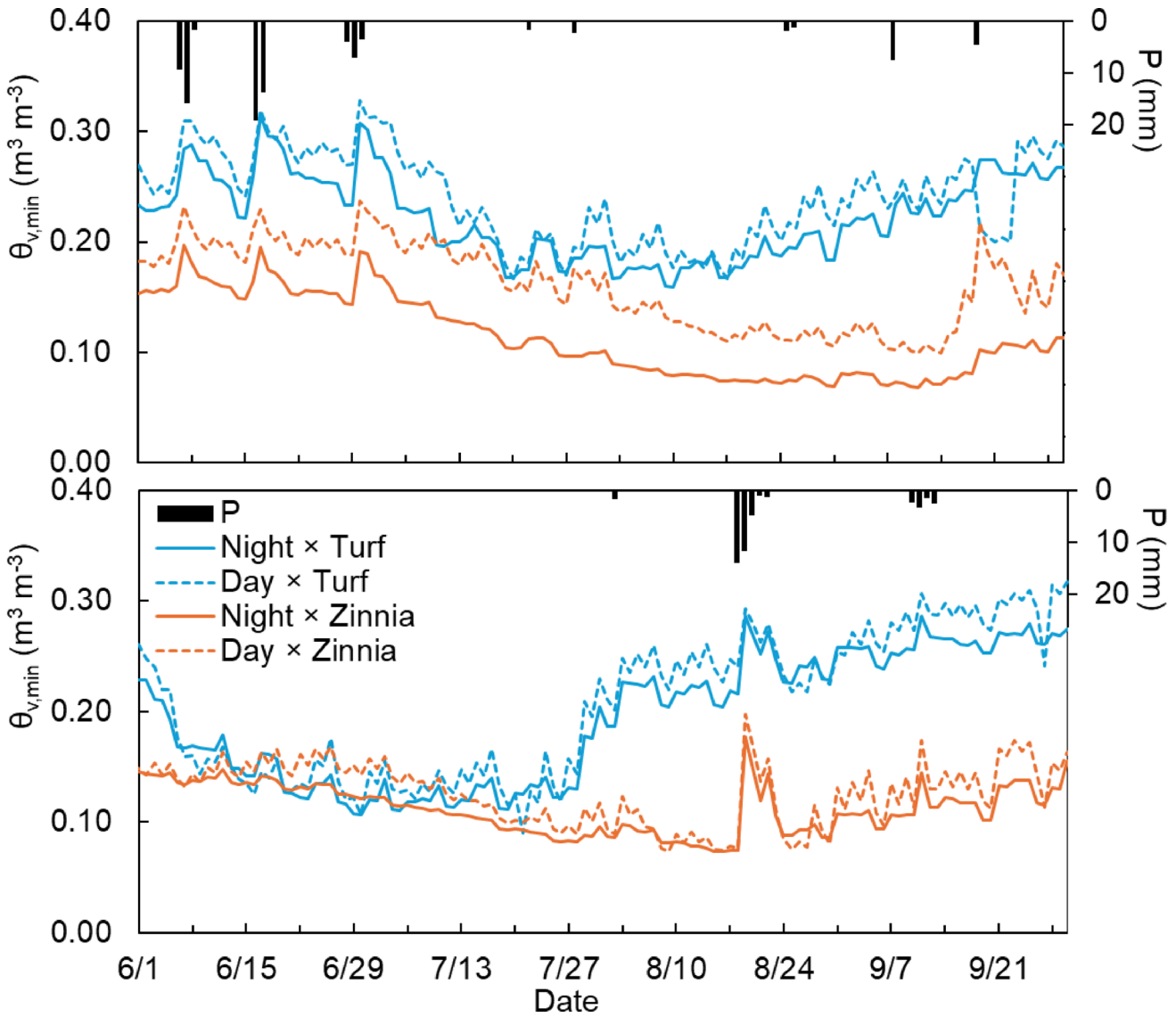


Fig. 5 The mean daily minimum soil volumetric water content ($\theta_{v,min}$, m^3 m^{-3}) at 0.08 m depth by irrigation timing × crop: nighttime irrigation of turfgrass (**Night × Turf**, solid blue line), daytime irrigation of turfgrass (**Day × Turf**, dashed blue line), nighttime irrigation of zinnia (**Night × Zinnia**, solid orange line), and daytime irrigation of zinnia (**Day × Zinnia**, dashed orange line) from June through September in 2020 (top panel) and 2021 (bottom panel). Total daily precipitation (**P**, mm) is also shown (bars)

than Night × Zinnia for 99.2% of days in 2020 and 89.3% in 2021 (Fig. 5). The $\theta_{v,0.18}$ in Day × Zinnia was greater than that of Night × Zinnia by a mean of 0.02±0.01 m^3m^{-3} in 2020, and 0.03±0.01 m^3 m^{-3} in 2021. The total ΔDD was 45 mm in 2020 and 30 mm in 2021 in Night × Zinnia, and 37 mm in 2020 and 22 mm in 2021 in Day × Zinnia. The mean hourly $T_{soil,0.05}$ of Night × Zinnia was 19.6±2.8 ˚C from 01 Jul to 30 Sep 2019, 19.3±2.3 ˚C from 01 Jun to 30 Sep 2020, and 20.5±2.9 ˚C from 01 Jun to 30 Sep 2021. For the same date ranges by year, the mean $T_{soil,0.05}$ of Day × Zinnia was 19.7±2.8 ˚C in 2019, 19.3±2.3 ˚C in 2020, 20.1±2.6 ˚C in 2021.

Crop growth, quality, and yield

The DGCI ranged from 0.34 to 0.41 in Night × Turf and 0.35 to 0.41 in Day × Turf across years, with only the 2020 growing season having significant differences ($p<0.05$) (Table 3). The mean cover was significantly greater for Day × Turf compared to Night × Turf in 2020 and 2021, with the greatest differences occurring in Aug and Sep 2020 and Jul 2021 ($p<0.05$) (Table 3). Specifically, mean cover was 93.0±0.2% with Night × Turf and 96.0±0.2% with Day × Turf in 2020, and 83.0±0.8% with Night × Turf and 86.0±0.7% with Day × Turf in 2021.

Table 3 Mean seasonal (gray shading) and monthly (no shading) turfgrass quality with (±standard error) as quantified by dark green color index (**DGCI**), and percent cover for turfgrass (%), with significance levels for nighttime (**Night**) versus daytime (**Day**) irrigation from 2019 to 2021

Year	DGCI (−)			Cover (%)		
Month	Night	Day	*(p-value)*[a]	Night	Day	(p-value)[a]
2019	_[b]	_[b]	_[b]	_[b]	_[b]	_[b]
June	_[b]	_[b]	_[b]	_[b]	_[b]	_[b]
July	_[b]	_[b]	_[b]	_[b]	_[b]	_[b]
Aug	_[b]	_[b]	_[b]	_[b]	_[b]	_[b]
Sep	_[b]	_[b]	_[b]	_[b]	_[b]	_[b]
2020	0.39 (0.0)	0.40 (0.0)	*0.0116*	93 (3)	96 (1)	*< 0.0001*
June	0.39 (0.1)	0.39 (0.1)	*0.9812*	97 (1)	99 (0)	*0.9108*
July	0.40 (0.1)	0.41 (0.1)	*0.7353*	97 (1)	99 (0)	*0.6322*
Aug	0.41 (0.1)	0.42 (0.1)	*0.0297*	93 (3)	97 (0)	*0.0001*
Sep	0.37 (0.1)	0.37 (0.1)	*1.0000*	86 (5)	92 (2)	*< 0.0001*
2021	0.36 (0.0)	0.36 (0.0)	*0.2852*	83 (4)	87 (2)	*0.0417*
June	0.36 (0.2)	0.36 (0.2)	*0.9978*	90 (3)	91 (1)	*1.0000*
July	0.34 (0.2)	0.35 (0.2)	*0.7733*	74 (15)	85 (7)	*0.0068*
Aug	0.35 (0.2)	0.35 (0.2)	*0.9993*	82 (6)	83 (3)	*1.0000*
Sep	0.37 (0.2)	0.37 (0.2)	*0.9909*	86 (3)	88 (2)	*0.9997*

There were 199 observations for DGCI and Cover across each Night and Day timing in 2020, and 124 in 2021

[a]$p<0.05$ is significant

[b]Data are not available

DGCI dark green color index; Night, nighttime irrigation; Day, daytime irrigation

No differences were found in crop height, marketable or total yield, or bloom diameter between Night × Zinnia and Day × Zinnia in any year of the study ($p>0.05$). The mean monthly height was 0.41 ± 0.2 m in July, 0.64 ± 0.01 m in Aug, and 0.81 ± 0.02 m in Sep across 2019 to 2021. At flowering (i.e., maturity), the mean height across years was 0.68 ± 0.02 m with Night × Zinnia and 0.69 ± 0.02 m with Day × Zinnia. The mean marketable yield per season (in stems per m^2) was 30 ± 7 with Night × Zinnia and 31 ± 8 with Day × Zinnia in 2019, 18 ± 6 with Night × Zinnia and 21 ± 3 with Day × Zinnia in 2020, and 36 ± 5 with Night × Zinnia and 37 ± 2 with Day × Zinnia in 2021. The mean total yield (i.e., marketable plus cull stems, in stems per m^2) was 67 ± 9 with Night × Zinnia and 77 ± 4 with Day × Zinnia in 2019, 83 ± 2 with Night × Zinnia and 92 ± 2 with Day × Zinnia in 2020, and 77 ± 2 with Night × Zinnia and 97 ± 2 with Day × Zinnia in 2021. The mean bloom diameter across years was 78 ± 2 mm with Night × Zinnia and 80 ± 2 mm with Day × Zinnia.

Discussion

In monitoring 126 paired Night and Day irrigation events across three study years (27 in 2019, 50 in 2020, and 49 in 2021), WDEL were greater with daytime than nighttime irrigation for both urban crops. The wind speed was nearly double during late afternoon, averaging 1.6 m s^{-1}, than 0.8 m s^{-1} in the early morning. Losses were up to 25% of the gross water applied for Day and up to 18% for Night. This was greater than WDEL measured in Spain, though the mean wind speeds during events were similar (Cavero et al. 2016; Cavero et al. 2008; Cavero et al. 2009; Martínez-Cob et al. 2008; Playán et al. 2005). Previously, sprinkler irrigation was avoided when wind speed exceeded 3.5 m s^{-1} (Cavero et al. 2008). In Northern Utah, the high-elevation valley and canyon-wind environment had a relatively low mean wind speed, but the average maximum wind speeds exceeded 3.5 m s^{-1} in 71.4% of Day and 22.4% of Night events. The frequency of brief, heightened wind speeds highlight the environmental variability, challenges to mitigating urban water losses, and potential for smart irrigation technologies paired with automated sprinkler systems in residential landscapes.

Wind drift and evaporative losses increased with crop height, particularly when wind speeds were greater during Day. Zinnia germinated by June, reached 75% canopy cover by mid- to late-July, and had mean heights of 0.64 m by Aug and 0.81 m by Sep of each year, two months when WDEL were particularly elevated during daytime irrigation events and the differences between timings were most frequently significant. Conversely, turfgrass canopy height was maintained at 0.075 m and differences in WDEL were significant between irrigation event timings in one of three study years. Moreover, the early-season WDEL in Zinnia tended to be similar (2019 and 2020) or lesser (2021) than those of Turf, while the later-season WDEL in Zinnia were typically greater (all years). Agronomic crops with taller canopies,

such as corn, were also associated with greater WDEL, than alfalfa (Cavero et al. 2008, 2016). The plots of Zinnia within the turfgrass field, much like gardens within a residential property or rows on an urban farm, likely also behaved as small disruptive fragments that altered wind velocity, thereby increasing air turbulence and drift over, around, and through the canopy (Miri and Webb 2022). Heterogeneous plant communities are prevalent in urban landscapes, making WDEL during peak windy hours a key consideration for water conservation in yards to microfarms.

Sprinkler irrigation modified the microclimate by decreasing T_c, T_s, T_{soil}, and VPD, all of which lowered the local evaporative demand and maintained S. These decreases were more pronounced and consequential during Day than Night events, as also found by Cavero et al. (2008), Cavero et al. (2009), Lui and Kang (2006), and Martinez-Cob (2008). Changes within the microclimate from sprinkler irrigation typically lasted four hours after Day and up to 12 h after Night events, which mitigated plant stress from both summer drought conditions and WDEL. Microclimate effects from sprinkler irrigation, however, have been documented to persist to several days (Liu and Kang 2006; Steiner et al. 1983). The limited extent of the effects in this study may be due to differences in water droplet size, the semi-arid and mountainous environment, the shorter-duration of application (up to 60 min per event) with a higher flow rate, and lesser water amounts applied (80% of ET_o, typically 10 mm per event), as previous studies applied irrigation for three to six hours (i.e., Cavero et al. 2008; Cavero et al. 2009; Cavero et al. 2016; Martínez-Cob et al. 2008; Yacoubi et al. 2010).

Though short-term, the cooling and humidifying effects of daytime irrigation coincided with daily maximum temperatures and evaporative demand, decreasing ET_c and maintaining θ_v throughout the growing season each year. The greatest decreases in T_c and VPD occurred during periods of greater air temperature. Most pronounced with Zinnia, the T_c with Day decreased by an average of 1.7 to 3.0 °C and a mean maximum decrease of 4.6 °C, while VPD decreased by 1.2 kPa. In response, ET_c for Zinnia was up to 34 mm lower with Day than Night in 2020 and 2021. Though Day was consistently lower than Night, ET_c estimates varied across the WB and BREB methods, with BREB tending to underestimate values in hot and dry environments (Irmak et al. 2014). Rejection rates that approach 40% and mainly occur at night are also well-established for semi-arid climates (Gavilán and Berengena 2007). Though ET_c is lowest during this period, error is nonetheless introduced (Gavilán and Berengena 2007). Error in the BREB may also reflect the limited net raditation measurements, which are central to energy partitioning, with only four net radiometers in this study (i.e., one replication per irrigation timing × crop treatment).

The decrease in ET_c did not negate greater WDEL from Day, but mitigated plant stress, and was reflected by soil moisture. Day soils remained above permanent wilting point (PWP, 8% θ_V) for all days in 2020 and dropped below PWP for eight days in 2021, while Night soils were below PWP for 34 days in 2020 and seven days in 2021. The emphasis on changes in S, measurements of which were fully replicated across plots, also underscores the advantage of the WB method. In response to a moderated microclimate and reduced drawdown of θ_V, crop productivity and quality were consistently, though not significantly, greater for Day × Zinnia than Night × Zinnia each year. The length of the freeze-free growing season resulted in annual variability in yield. The longest growing season was in 2021, as the sow date was later in the 2019 establishment year, and an early-September windstorm with frost damage shortened the season and increased late-season culls in 2020. Per m^2, the mean marketable yields of Zinnia were one to three stems greater and total yields were 9 to 20 stems greater with Day than Night, while plants at bloom were an average of 13 mm taller. This greater productivity, paired with greater measured θ_V, shows the lower ET_c from Day was not a result of reduced uptake from water or temperature stress, as was simulated for tomato (Yacoubi et al. 2010). Instead, the yield was elevated from the moderated microclimate of Day and may be an economic consideration for urban microfarms, inherently limited for space and water, as zinnia cut flowers command wholesale pricing of $1.00 per stem or more on local markets (Maughan et al. 2020). Nighttime irrigation also increased disease risk, as powdery mildew (*Golovinomyces cichoracearum*) emerged throughout one of the Night plots in September 2021, and is well associated with low θ_V in dry regions (Mieslerová et al. 2022).

For Turf, the differences in microclimate, ET_c, and θ_V by irrigation timing were lower than with Zinnia. Canopy temperature decreased by an average of 1.0 to 1.4 °C and VPD by only 0.1 kPa with Day, while Night reduced the temperature by 0.3 to 0.6 °C and VPD by less than 0.1 kPa. Similarly, differences in ET_c between irrigation timings were 13 mm and 6 mm through the WB and BREB, respectively. The dense, but short canopy of turfgrass, maintained at a 0.075 m height, likely had less capacity to intercept and evaporate water to provide a surface cooling effect to mitigate plant stress. These aboveground measurements were also limited by sensor placement, as T_c and RH sensors were 0.14 m aboveground due to the height of the radiation shield and mounting hardware. Similarly, differences in θ_V were also subtle. The mean θ_V was 1 to 2% greater with Day than Night, with neither timing resulting in values below PWP

in any of the study years. Instead, both irrigation timings remained near field capacity (FC, 24% θ_V).

The quality of the turfgrass, in particular the percent cover, was greater with Day than Night in each month of the two measurement years (2020 and 2021). Differences were greatest in the last two months of 2020, and percent cover was the lowest in July 2021, the hottest month of the year. The percent cover for both irrigation timings was considered acceptable, as they were both greater than a 70% threshold (Powlen et al. 2019). Dark green color index was significantly greater in 2020 with Day compared to Night; however, the result was not significant in 2021 when turfgrass was likely stressed from the above-average heat regardless of irrigation timings.

Conclusion

Scheduling sprinkler irrigation at night instead of during the day is a longstanding, recommended practice for saving water in urban landscapes, particularly in Utah and the desert southwest. However, the consolidated hours of application, paired with a rapidly growing population and demand for water, have introduced challenges with system capacity and questions of efficiency that highlighted the need for local data in urban systems. This study targeted two urban crops with contrasting canopy architectures and seasonal growth habits, quantified losses due to wind drift and evaporative losses (WDEL) and crop evapotranspiration (ET_c) with water and energy balance approaches, and measured soil moisture storage, microclimate, and plant productivity. Irrigation occurred during the hours of the daily minimum (nighttime events) and maximum (daytime events) evaporative demand. Wind drift and evaporative losses dominated the water balance and were 7% lower with nighttime than daytime irrigation, as a function of wind speed. Conversely, both the water and energy balances estimated lower ET_c with daytime irrigation, which decreased the evaporative demand during the hours of maximum daily air temperature and plant stress, compared to nighttime events. Differences in crop productivity and quality were largely not significant but tended to be greater with daytime irrigation applications because of the cooling and humidifying effect during peak daily heat and greater soil moisture.

Recommendations for future research include testing additional landscape scenarios and timings outside of the hours of peak daily wind speed. For example, monitoring irrigation applications in the late morning compared to evening near sundown could capture the environmental cooling effects that lower plant stress and disease incidence. The water conservation potential of nighttime irrigation was shown to be limited in the semi-arid region of this study. As residential irrigation controllers can delay or skip events in response to precipitation, wind speed thresholds (e.g., wind speeds greater than 3.0 m s^{-1}) should be incorporated to reduce water losses, while increasing time available for irrigation and alleviating peak demand issues for water suppliers. The main hours in which the wind speed exceeded these thresholds were between 13:00 to 16:00 local time at this study site. Additional opportunities for residential water conservation may include performing water pressure checks and sprinkler uniformity adjustments, reducing overall water-use through more drought-tolerant plant varieties or other ground covers, and using drip-irrigation for row crops.

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Data availability Data are provided within the manuscript. Additional data may be provided by the authors upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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