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Effects of Deficit Irrigation on Canopy Temperature Dynamics and Physiology of Landscape Groundcovers

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Abstract. **Identifying the irrigation-induced cooling effects from a particular plant species used for urban groundcovers while optimizing the rates of irrigation applications is important in regions with hot and dry summers. A 2-year (2020–21) study was conducted in Riverside, CA, USA, to evaluate the effect of irrigation rates on the canopy temperature dynamics of 10 urban groundcovers. Four reference evapotranspiration (ET_o)-based irrigation treatments (20%, 40%, 60%, and 80% ET_o) and 10 groundcovers were laid in a randomized complete block design and replicated three times. The effect of irrigation rates on the difference between canopy–air temperature (ΔT), leaf area index (LAI), and stomatal conductance (g_s) were evaluated. All response variables were collected between May and October 2020 and 2021. The crop water stress index for five groundcovers was also computed. The ΔT was affected ($P < 0.05$) by irrigation rates, and groundcovers, including *Rhagodia spinescens* and *Baccharis* × 'Starn Thompson', maintained the canopy temperature less than the ambient air temperature for all irrigation rates imposed. For most of the groundcovers, the ΔT yielded a strong relationship with LAI (r = –0.41 to –0.73), and g_s (r = –0.35 to –0.60). Crop water stress index also showed a strong correlation to normalized difference vegetation index (r = 0.42 to –0.72) and g_s (r = –0.57 to –0.64). Irrigation-included cooling was evident in most groundcovers irrigated at higher rates; however, *Rhagodia spinescens* and *Baccharis* × 'Starn Thompson' were found to perform well in cooling ability and maintaining the canopy growth as evidenced by LAI. Our study showed that proper plant selection and irrigation management could help maintain green spaces and mitigate the urban heat island effect while conserving irrigation water.**

Lawn and landscape irrigation uses a substantial portion of urban water in the United States, particularly in arid and semiarid regions during the summer (Yue et al. 2022), and the irrigation demand is increasing as a result of urban expansion due to increased population (Bouwer 2000; Hartin et al. 2018). Moreover, there is growing competition for freshwater supply in agriculture, industry, and cities (Anderson 2003). Global warming, climate change, and frequent drought further limit freshwater resources while increasing the irrigation demand (Döll 2002; Haddeland et al. 2014). Therefore, the importance of irrigation water conservation cannot be overlooked. Various irrigation water conservation strategies include the use of recycled water (Niu and Rodriguez 2006; Niu et al. 2007), deficit irrigation that purposely stresses the plant by providing less water than its potential transpiration rate (Haghverdi et al. 2021b; Nazemi Rafi et al. 2019; Pittenger et al. 2001), and planting of drought-tolerant species (Lockett et al. 2002).

The urban green space provides several ecosystem services, including cooling benefits on warm days (Masoudi et al. 2021). Evapotranspiration (ET) is the underlying cooling mechanism in the urban ecosystem (Cheung et al. 2022) and even a small vegetated area can reduce the land surface temperature by up to 6 °C during the day (Ossola et al. 2021). In contrast to water conservation, the use of irrigation water comes with potential cooling benefits; for example, irrigation-induced cooling was found to reduce the ground surface temperature by ~4.9 °C (Cheung et al. 2022), decrease the air temperature by up to 1.4 °C (Gao et al. 2020), and have helped between 0.79 and 1.29 billion people from being exposed to extreme temperatures around the year 2000 (Thiery et al. 2020). However, the impact of varying irrigation rates to maintain cool canopies compared with the surrounding air temperature is not well studied for ornamental groundcovers. Also, we do not know to what extent different irrigation regimes impact the cooling benefits of native and nonnative ornamental groundcovers.

Plant growth and productivity is greatly affected by water stress condition. Water stress in plants affects stomatal activity. It closes stomata and decreases stomatal conductance (g_s), which then affects photosynthesis and growth of plant (Osakabe et al. 2014; Romero et al. 2004). Stomatal closure also reduces plant's evaporative cooling potential, increasing leaf temperature and enhancing evaporative demand (Buckley 2019). Similarly, leaf area index (LAI), which evaluates plant canopy cover (Chen and Black 1992; Chen et al. 1997; Liu et al. 2018), is another important measurement affected by water stress conditions (Bréda 2003). Water stress conditions will change the canopy structure and productivity of the plant, and hence there will be a change in LAI values (Bréda 2003). In addition, plants under severe water stress conditions will have fewer leaves than those under non–water-limiting conditions (Karamanos 1978; Yegappan et al. 1982). These differences in the number and size of leaves will result in decreased transpiration and lower evaporative cooling rates. Overall, monitoring g_s and LAI help us understand how deficit irrigation impacts the total transpiration rate and cooling potential of a canopy.

Monitoring canopy temperature is a nondestructive approach to assess the water stress in plants (Andrews et al. 1992; Henson et al. 2006; Irmak et al. 2000; Nazemi Rafi et al. 2019; Taghvaeian et al. 2014). Whenever the canopy (T_c) and air (T_a) temperature difference ($\Delta T = T_c - T_a$) is close to or less than 0 °C, the plants are not in water-stress conditions and are transpiring efficiently (Henson et al. 2006). This phenomenon is based on two assumptions 1) non–water-stressed plants transpire at their full potential and hence maintain leaf temperature lower than air temperature, and 2) when plants are in water-stressed condition, transpiration process decreases and hence increases leaf temperature relative to the air temperature (Andrews et al. 1992; Jackson 1982). Moreover, the impact of limited irrigation on the canopy temperature of groundcovers is not well studied, but it is necessary because it helps to evaluate the trade-offs between water conservation and irrigation-induced cooling in urban areas (Haghverdi et al. 2021a).

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The crop water stress index (CWSI) is another important temperature-based parameter that is centered on a linear relationship between ΔT and the vapor pressure deficit (VPD) under non–water-stress conditions (Idso et al. 1981). It is measured on a scale of 0 to 1, where 0 indicates plants are transpiring at their full potential, and 1 represents nontranspiring conditions (Irmak et al. 2000). The CWSI has been estimated to evaluate water stress in many agronomic crops (Alghory and Yazar 2019; Irmak et al. 2000; Taghvaeian et al. 2014), turfgrasses (Haghverdi et al. 2021a; Jalali-Farahani et al. 1993), and fruits (Andrews et al. 1992; Park et al. 2017). However, the CWSI has not been widely studied and estimated for groundcovers, and its potential to evaluate the performance of groundcovers at varying irrigation rates has not been well documented.

The main objective of this study was to evaluate the trade-offs between water conservation and the cooling potential of irrigated groundcovers in semiarid inland Southern California. The specific objectives of this study were to 1) evaluate the effect of irrigation on the canopy temperature, g_s and LAI of groundcovers species and 2) develop CWSI and assess its variability under different irrigation scenarios over time for the selected groundcovers.

Materials and Methods

Study area

A 2-year (2020–21) study was done at the agricultural experiment station (lat. 33°55′ N, long. 117°19′ W, 307 m elevation) at the University of California Riverside, Riverside, CA, USA. The study was conducted in a year-old established field. The soil at the experimental site is classified as Hanford coarse sandy loam (websoilsurvey.sc.egov.usda.gov), and the climate in the region is semiarid. During the experimental season (May to October) in 2020 and 2021, the reference evapotranspiration (ET_o) was up to 9% higher than the long-term average (948 mm; 1992 to 2021) with no to minimal rainfall. Pre-emergent herbicide Pendulum AquaCap (38.7% pendimethalin, applied at 10 $L \cdot ha^{-1}$) was applied in 2019 before planting to control weeds. After groundcovers were planted, weed control consisted of spraying alleyways periodically with herbicide Makaze (41.0% glyphosate, applied at 1.5% v/v) and hand weeding the groundcover plots. In the beginning of the experimental setup and plant establishment, fertilizer 15–5–8 microgreen was top-dressed at 49 $kg \cdot N \cdot ha^{-1}$.

Groundcover species selection, experimental design, and irrigation treatments

Landscape groundcovers [Fig. 1; Sapkota et al. (2023)] of different plant types, including woody, herbaceous, and succulent, were selected for the study. These groundcovers are either California native (*Eriogonum fasciculatum* 'Warriner Lytle' and *Baccharis* × 'Starn Thompson') or nonnative drought-tolerant species. The experiment was laid in two adjacent randomized complete block designs totaling 10 groundcover species and four irrigation treatments replicated three times. Out of 10 groundcovers included in this study, six were acquired (*Rhagodia spinescens*, *Eriogonum fasciculatum* 'Warriner Lytle', *Baccharis* × 'Starn Thompson', *Eremophila glabra* 'Mingenew Gold', *Ruschia lineolata nana*, and *Oenothera stubbei*) in 1-gallon containers (#1 container) and planted at the density of 12 to 16 plants per plot. The remaining four groundcovers were purchased in trays with a dimension of the 10-cm deep pots.

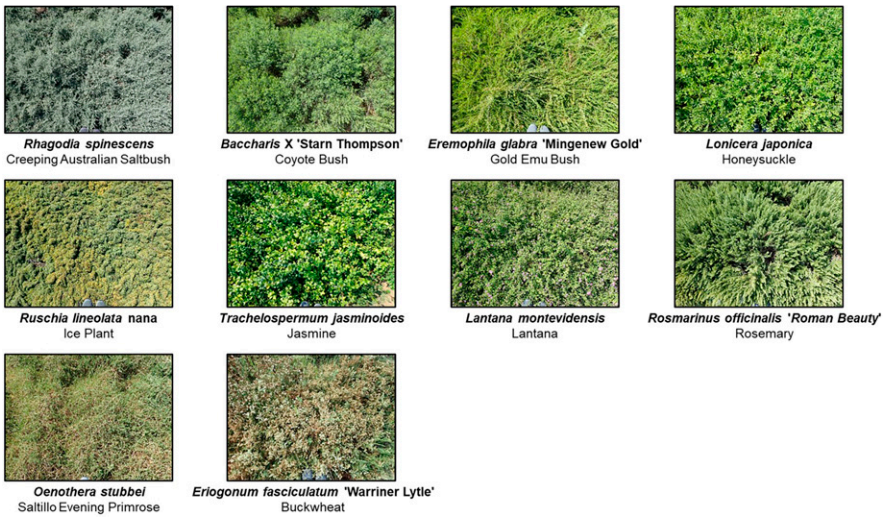

Fig. 1. Canopy pictures, the scientific names (italic and bold) and the common name of landscape groundcovers selected in this study. Adapted from Sapkota et al. (2023).

Experimental plots were ~3-m × 3-m with an alley of 1.2-m between the neighboring plots. Irrigation at each experimental plot was controlled independently using a solenoid valve (Hunter PGV-101G; Hunter Industries, San Marcos, CA, USA). Each plot was irrigated using four 300-mm tall (~600 mm tall while working) quarter-circle pop-up heads with pressure-compensating 254-mm precision series spray nozzles (TORO 570Z series; TORO CO., Bloomington, MN, USA). The irrigation scheduling was done using a smart irrigation controller (Weathermatic SmartLine SL4800; Weathermatic, Garland, TX, USA). The watering days were limited to 3 to 4 d per week to avoid light irrigation applications. The four evapotranspiration-based irrigation treatments were 20%, 40%, 60%, and 80% ET_o. The programmed irrigation rates in the controller were adjusted based on the efficiency of the irrigation system. The irrigation controller followed the programmed watering days with slight overirrigation in 2020 and 2021 by an average of 7.7% (range: 7.5% to 8.7%) and 4.7% (range: 3.2% to 7.1%), respectively (Sapkota et al. 2023). Table 1 shows the irrigation treatments, programmed irrigation rates, and actual irrigation applications by the controller. The controller employed temperature data measured on-site and latitude-based solar radiation estimates to calculate ET_o using the Hargreaves equation (Hargreaves and Samani 1985). The calculated ET_o was used by the controller to determine the daily water deficit at midnight (irrigation application = plant type × ET_o). For each treatment, the plant type value was computed as the percentage of ET_o divided by the irrigation system's efficiency. The subsequent irrigation was administered according to the water deficit accrued since the previous irrigation event for each treatment. The controller transformed the irrigation application into irrigation runtime values, guided by the user-defined estimated precipitation rate of the irrigation system. The water deficit was reset to zero by the controller upon the completion of watering. To prevent light irrigation, the controller was configured to employ the default deficit threshold (3.81 mm) as the requisite deficit amount before any irrigation operation occurred (Haghverdi et al. 2021b). More details on the experimental design and irrigation treatments are presented in Sapkota et al. (2023).

Data collection

Canopy temperature, air temperature, and canopy–air temperature difference. The T_c was measured using an infrared thermometer (Fluke 64 Max; Fluke Co., Everett, WA, USA) held at waist height and hovered over the plot keeping the trigger engaged to get a representative and average T_c for each plot.

Table 1. Irrigation treatments, expressed at the percentage of reference evapotranspiration (ET_o), implemented in the study in 2020 and 2021.

	Irrigation	Percentages of ET_o			
2020	Treatment	20	40	60	80
	Programmed[i]	23	47	70	93
	Applied[ii]	25	51	75	99
2021	Treatment	20	40	60	80
	Programmed	23	47	70	93
	Applied	24	49	75	96

[i] Programmed irrigation is equal to treatment levels divided by irrigation efficiency of 86%.
[ii] Applied irrigation is equal to actual irrigation applications based on the precipitation rates of the irrigation system and flowmeter data.

Precision psychrometer (Extech RH300; Extech Instruments, FLIR Systems, CA, USA) was used to measure T_a, and relative humidity (RH) simultaneously from each experimental plot.

The Infrared sensor was held at ~1 m high and hovered over the center of the plot to get the representative readings, and an average canopy temperature was recorded. Canopy temperatures were collected at solar noon on cloud-free days. The canopy–air temperature ($T_c - T_a$), was computed for each measurement day to determine how stressed the plants were under varying irrigation rates (Henson et al. 2006). In both years (2020 and 2021), the canopy temperature data were collected on 12 dates (mostly every other week) during the experimental season (May to October). Normalized difference vegetation index (NDVI) was also collected on the same day and time using the GreenSeeker (Trimble, Sunnyvale, CA, USA) from each of the experimental plots. More details on how different rates of irrigation impact the visual quality ratings and NDVI of landscape groundcovers are presented in Sapkota et al. (2023).

Stomatal conductance and LAI

Stomatal conductance was measured using porometer (SC-1 Leaf Porometer; Meter Group, WA, USA) with 0 to 1000 mmol·m^{-2}·s^{-1} range, 0.1 mmol·m^{-2}·s^{-1} measurement resolution and ± 10.0% accuracy. The g_s of only six groundcovers with flat or broad leaves were measured, including *Rhagodia spinescens*, *Eremophila glabra* 'Mingenew Gold', *Lonicera japonica*, *Trachelospermum jasminoides*, *Lantana montevidensis*, and *Oenothera stubbei*. Groundcovers with succulent and needle-like leaves only partially covered the aperture of the sensor causing erroneous readings, hence were excluded from the study. The g_s readings from three leaf samples were recorded for each of the six groundcovers and four irrigation treatments. Data collection was done on a cloud-free day within ± 2 h of the solar noon. A young, disease-free, fully developed leaf that was exposed to the sun was selected for the measurement. When leaves were small and close to the stem, and it was difficult to get them to hold on to the sensor, they were detached from the stem with a petiole, and the g_s was measured immediately. The g_s measurement was made five times in 2020 and seven times in 2021, and we tried to record these readings about every 15 d.

LAI was measured using ceptometer (Accu-PAR LP-80, Meter Group) with an external PAR sensor. Four measurements were made in each plot from one experimental block and an average value was reported. The Accu-PAR LP-80 sensor accurately measures intercepted PAR on days of fluctuating radiation levels. The LAI of *Ruschia* was not measured due to its low-growing, creeping succulent structure preventing to insert the sensor probe into the canopy. The LAI measurement was done eight times in 2020 and nine times in 2021 during the experimental period.

CWSI

Idso et al. (1981) developed a CWSI that is independent of the environmental variability and suggested that the canopy minus air temperature difference from the non–water-stressed plants will have a linear relationship with the VPD (Idso et al. 1981). The following equation was used to compute the CWSI:

$$\text{CWSI} = \frac{(T_c - T_a)_m - (T_c - T_a)_{lb}}{(T_c - T_a)_{ub} - (T_c - T_a)_{lb}} \quad [1],$$

where T_c = canopy temperature (°C); T_a = air temperature (°C); m = measured; lb = lower limit baseline (non–water-stressed baseline); ub = upper limit baseline (water-stressed baseline).

The non–water-stressed baseline $[(T_c - T_a)_{lb}]$ was computed as:

$$(T_c - T_a)_{lb} = a(VPD) + b \quad [2],$$

where a = slope and b = constant of the fitting equation.

The VPD is the difference between the saturated vapor pressure at air temperature and the actual vapor pressure.

$$VPD = e_s(T_a) - e_a \quad [3],$$

where $e_s(T_a)$ = saturated vapor pressure (kPa) and e_a = actual vapor pressure (kPa). They were calculated as:

$$e_s(T_a) = 0.6108 * exp\left(\frac{17.27 \times T_a}{237.3 + T_a}\right) \quad [4]$$

$$e_a = \left(\frac{RH}{100}\right) * e_s(T_a) \quad [5]$$

For each landscape groundcover, the no-water-stress baseline was established using the mean canopy temperature, air temperature, and relative humidity data collected on the day of irrigation from the plots with the highest irrigation (i.e., 99% ET_o). Among data collected from 12 d between May and October, it included all data collected between June and September (except the data collected on 19 Aug) in 2020. In 2021, data were primarily collected on days when the highest irrigation rates were not triggered; therefore, those data were not included. This is based on the assumption that data collected on clear and sunny days after significant irrigation or precipitations should be used to establish a non–water-stressed baseline (Taghvaeian et al. 2014).

The upper-limit baselines for water-stressed plants were determined following Katimbo et al. (2022), who suggested a maximum observed $(T_c - T_a)$ to be considered as the upper limit (Katimbo et al. 2022). A $(T_c - T_a)_{ub}$ was determined for each groundcover from the lowest irrigation treatments (i.e., 25% ET_o, 24% ET_o irrigation treatments and rainfed plots in 2020, 2021, and 2022, respectively). Therefore, a constant $(T_c - T_a)_{ub}$ was used for each groundcover when computing the CWSI.

Statistical analysis

The difference in the canopy and air temperature ($T_c - T_a$) and LAI data were

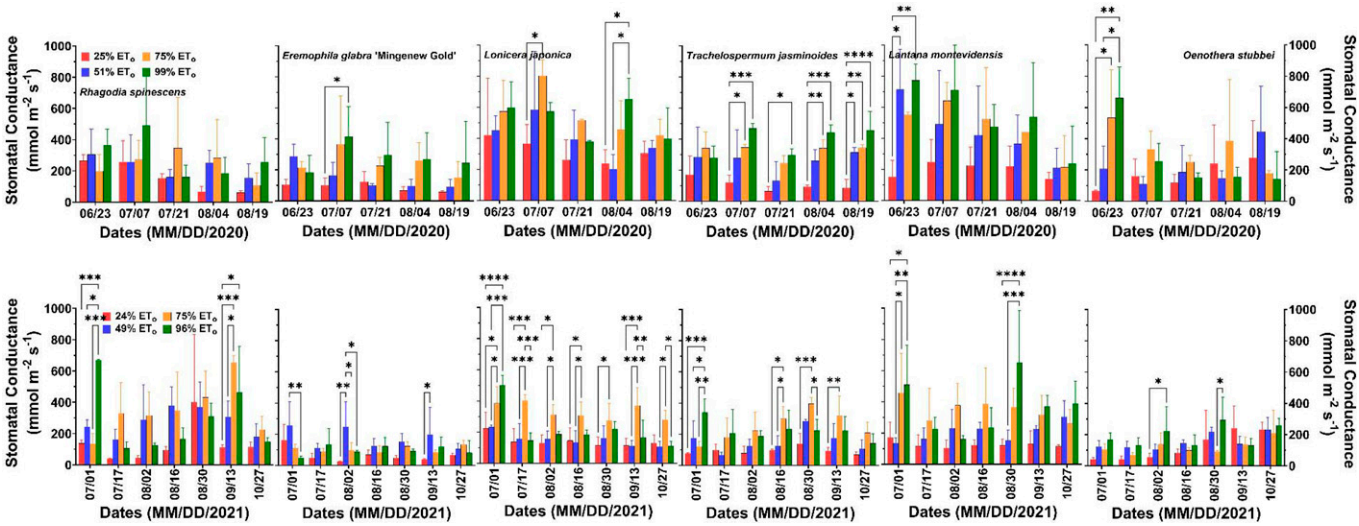

Fig. 2. Effect of irrigation on the stomatal conductance of six groundcovers. The top row represents 2020 and the bottom row represents 2021 data. ET_o = reference evapotranspiration. *, **, ***, ****P values <0.05, <0.01, <0.001, and <0.0001, respectively.

analyzed using the PROC GLIMMIX procedure in SAS (2014, Version 9.4; SAS Institute, Cary, NC, USA). When 2-year data were pulled together, there were significant year effects, so data for 2020 and 2021 were analyzed separately. Also, a significant difference was observed among the groundcovers; therefore, data for each groundcover were analyzed independently (Pittenger et al. 2001). Groundcover *Baccharis* was pruned before the data collection on days 22 May, 14 Oct, and 27 Oct in 2021; therefore, data from these dates for *Baccharis* were not included in the analysis. Also, the groundcover *Eriogonum* was not well established in 2020; hence, only the data from 2021 are presented for this groundcover. Irrigation rates, data collection dates, and their interactions were used as fixed effects. Block and its interaction with irrigation rates were used as random effects during the analysis. To identify the significant differences among treatments, the LSMEANS option LINES statement was used for pairwise least square mean comparisons, and treatment effects were considered significant at $\alpha \leq 0.05$. Ordinary two-way analysis of variance was done using the GraphPad Prism (Version 9.3.1, GraphPad Software, San Diego, CA, USA) for the g_s, and the statistical significance was checked using the Tukey test. Relationships among different variables were also determined by computing the Pearson correlation coefficient. Graphs were made using the GraphPad Prism (Version 9.3.1, GraphPad Software). A simple linear relationship between ΔT and irrigation (% ET_o) was also established for 10 groundcovers using the 2-year data (only the data from 2021 for *Eriogonum*) from the experiment. Applied irrigation rates (Table 1) from both years were pooled together for each groundcover. Change in the canopy temperature for each irrigation treatment and groundcover was averaged for each data collection day and used in establishing the linear relationship.

Results

Effect of irrigation management on g_s and LAI. Figure 2 shows the effect of irrigation rates on the g_s of six groundcovers at different dates of measurement in 2020 and 2021. Except for *Lonicera* and *Trachelospermum*, the effect of irrigation on g_s was significant only in a few of the measurement dates in either year. Irrigation affected the g_s of *Lonicera* in both years (Fig. 2). We observed that the g_s for 75% ET_o irrigation was higher in *Lonicera* in 2021 as compared with the other irrigation treatments. For other species, the g_s was inconsistent between irrigation rates; however, the highest irrigation yielded numerically greater g_s (in most cases) as the rate of irrigation increased.

Table 2 shows the effect of irrigation, data collection date, and their interaction on the LAI of different groundcovers in 2020 and 2021. The LAI of groundcovers *Rhagodia* (7.56 to 9.69) and *Baccharis* (2.39 to 3.31) was not impacted by irrigation rates in either

Table 2. Analysis of variance (ANOVA) table presenting the effect of irrigation treatments, date of data collection, and their interaction on the difference between canopy and air temperature (ΔT) and leaf area index (LAI) of different groundcover species in the years 2020 and 2021.

	Rhagodia spinescens		*Baccharis* × 'Starn Thompson'		*Eremophila glabra* 'Mingenew Gold'		*Lonicera japonica*		*Ruschia lineolata* nana		*Trachelospermum jasminoides*		*Lantana montevidensis*		*Rosmarinus officinalis* 'Roman Beauty'		*Oenothera stubbei*		*Eriogonum fasciculatum* 'Warriner Lytle'	
2020 ET_o (%)	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI	ΔT	LAI
25	−1.67 a	8.49	−0.01 a	3.11	4.61 a	3.30 b	3.74 a	5.31 bc	5.55 a	—	9.47 a	0.75 b	7.38 a	2.71 b	3.27 a	3.62	3.27 a	3.93 b	—	—
51	−2.23 a	7.56	−1.37 ab	3.13	2.52 a	3.34 b	3.88 a	4.89 c	3.91 a	—	5.36 b	1.93 a	2.88 b	5.81 a	2.08 a	4.33	3.47 a	3.73 b	—	—
75	−5.62 b	8.38	−2.67 bc	2.91	−0.26 b	3.27 b	−0.67 b	7.66 a	−0.53 b	—	0.74 c	1.43 ab	−0.98 c	5.99 a	−0.51 b	5.67	−0.48 b	6.54 a	—	—
99	−7.12 b	8.48	−3.78 c	3.14	−2.20 b	4.69 a	−0.84 b	6.08 b	−3.42 c	—	−1.31 c	2.31 a	−4.23 d	8.30 a	−3.37 c	5.04	−3.34 c	7.20 a	—	—
SE	0.44	0.55	0.64	0.30	0.68	0.42	1.21	0.75	0.56	—	0.83	0.31	1.22	1.44	0.43	0.67	0.67	0.55	—	—
P values																				
Irrigation (I)	0.001	0.629	0.024	0.935	0.003	0.018	0.006	0.001	<0.0001	—	<0.0001	0.025	0.000	0.015	0.000	0.148	0.001	0.011	—	—
Date (D)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.000	<0.0001	<0.0001	—	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.687	<0.0001	<0.0001	—	—
I × D	<0.0001	0.756	0.066	0.745	<0.0001	0.241	0.000	0.141	0.001	—	<0.0001	0.249	<0.0001	0.115	<0.0001	0.999	<0.0001	0.030	—	—
2021 ET_o (%)																				
24	−2.19 a	9.69	−0.10 a	2.39	3.72 a	3.17 c	3.39 a	3.34 b	8.58 a	—	11.89 a	0.44 b	6.25 a	1.81 c	3.17 a	3.93 b	8.61 a	0.87 b	4.08 a	3.02
49	−5.00 b	9.06	−3.58 b	3.19	−1.83 b	4.39 b	1.53 b	3.28 b	4.39 b	—	3.78 b	2.14 ab	2.08 b	3.49 bc	−0.14 b	5.82 a	4.31 b	1.40 b	1.50 b	2.55
75	−6.44 c	9.2	−2.06 ab	2.74	−1.72 b	4.68 b	−1.86 c	6.65 a	1.83 bc	—	0.86 b	2.65 ab	−1.53 c	5.31 b	0.03 b	6.21 a	−0.94 c	3.14 a	−1.47 c	2.91
96	−4.83 b	8.73	−4.32 b	3.31	−1.72 b	6.28 a	−0.67 c	5.71 a	0.45 c	—	0.42 b	3.94 a	−2.55 c	7.94 a	−0.69 b	6.56 a	−0.47 c	3.92 a	−0.86 bc	2.63
SE	0.58	0.71	0.77	0.29	0.87	0.44	0.51	0.43	1.18	—	1.34	0.88	1.33	0.87	0.77	0.60	1.04	0.62	1.01	0.71
P values																				
Irrigation (I)	0.001	0.717	0.039	0.185	0.012	0.003	0.002	0.003	0.005	—	0.002	0.046	0.003	0.002	0.026	0.031	0.003	0.013	0.004	0.953
Date (D)	0.006	<0.0001	0.000	<0.0001	0.001	<0.0001	<0.0001	<0.0001	<0.0001	—	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
I × D	0.039	0.988	0.296	0.076	0.228	0.800	0.340	0.014	0.101	—	0.063	0.027	0.013	0.059	0.005	0.272	0.000	0.003	0.132	0.039

For each year, a different letter assignment within a column represents statistical significance at $\alpha = 0.05$.
SE = standard error of the means for each groudcover for a specific year; ET_o = reference evapotranspiration; ΔT = difference between canopy and air temperature; LAI = leaf area index.

year. Irrigation rates also did not affect the LAI of *Rosmarinus* (3.62 to 5.67) in 2020 and *Eriogonum* (2.55 to 3.02) in 2021. In 2021, *Rosmarinus* had the lowest LAI for 24% ET_o irrigation, whereas it was significantly ($P < 0.05$) the same for the other three irrigation treatments (Table 2). *Oenothera* in both years showed a similar effect of irrigation on the LAI. Compared with the top two irrigation treatments, the lower two irrigation rates decreased LAI values (0.87 to 3.93) for *Oenothera*. *Oenothera* seems not to withstand water deficit conditions and may not recover fully after the water stress condition. Therefore, we observed a significant decline in LAI of *Oenothera* in 2021 compared with 2020. *Eremophila*, *Trachelospermum*, *and Lantana* always had the highest LAI for irrigation rates ≥96% ET_o and lower LAI for irrigation rates ≤25% ET_o. On the other hand, *Lonicera* had the highest mean LAI value (7.66) for irrigation treatment 75% ET_o in 2020. In 2021, the mean LAI value was 6.65 for irrigation treatment with 75% ET_o and was statistically similar to the 96% ET_o (LAI = 5.71).

All groundcovers showed a decreasing trend (Fig. 3) in LAI values, regardless of irrigation treatments, as the summer progressed in 2020 and 2021, with an exception for *Rosmarinus* in 2020, which was unaffected by the data collection date ($P = 0.69$). The LAI for *Oenothera* dropped for irrigation rates 25 and 51% ET_o in 2020 compared with the other two irrigation rates. *Oenothera* also followed a similar trend in 2021 (Fig. 3; Table 2). In 2021, the interaction of irrigation rates and data collection date was significant for *Lonicera*, *Trachelospermum*, and *Eriogonum*. Groundcover *Lonicera* maintained the LAI consistently high at 75% ET_o

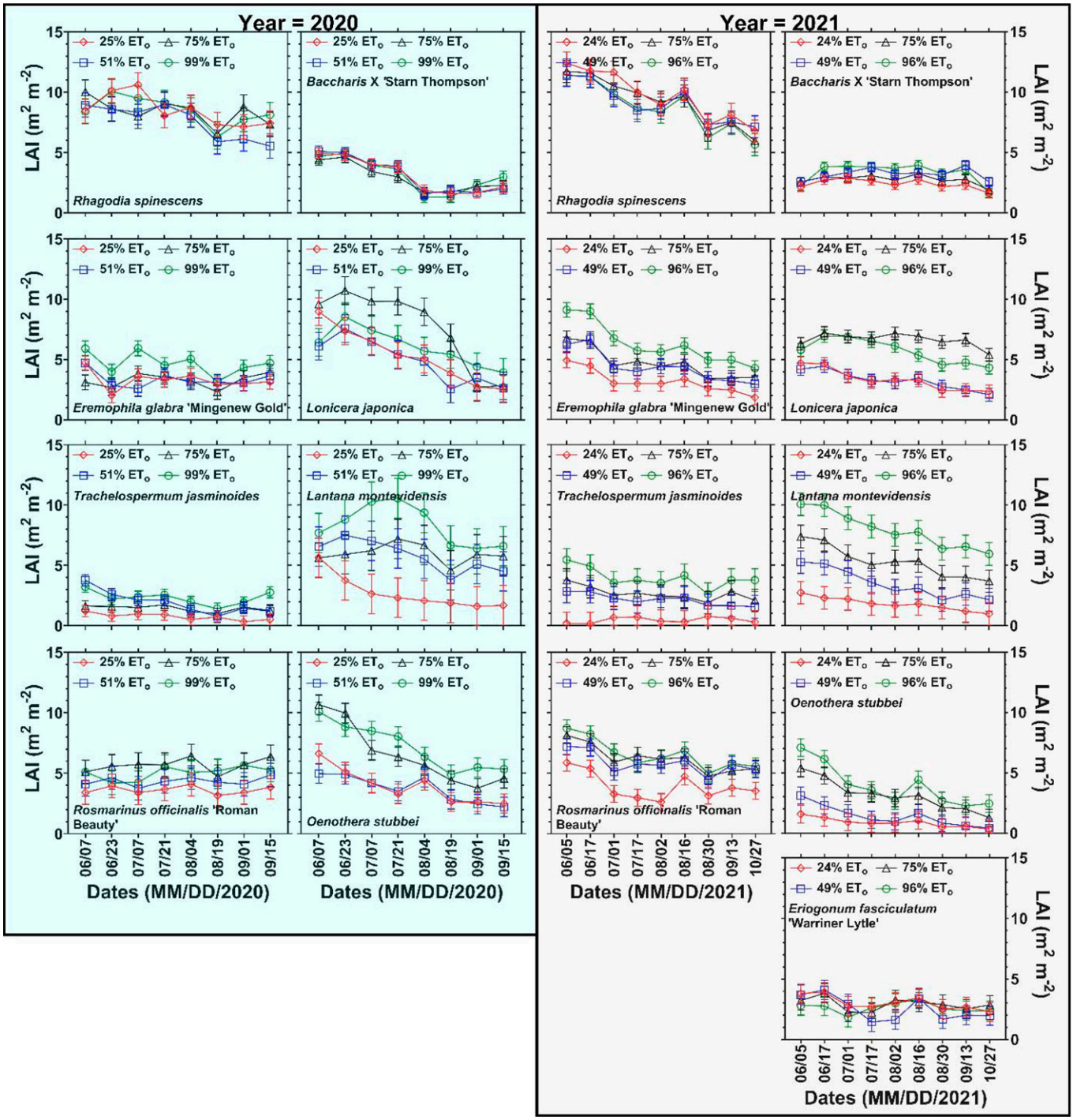

Fig. 3. Effect of irrigation on the leaf area index (LAI) of different groundcovers in 2020 (left) and 2021 (right). Error bars are the standard error of the means for each specific groudcover during the growing season. ET_o = reference evapotranspiration.

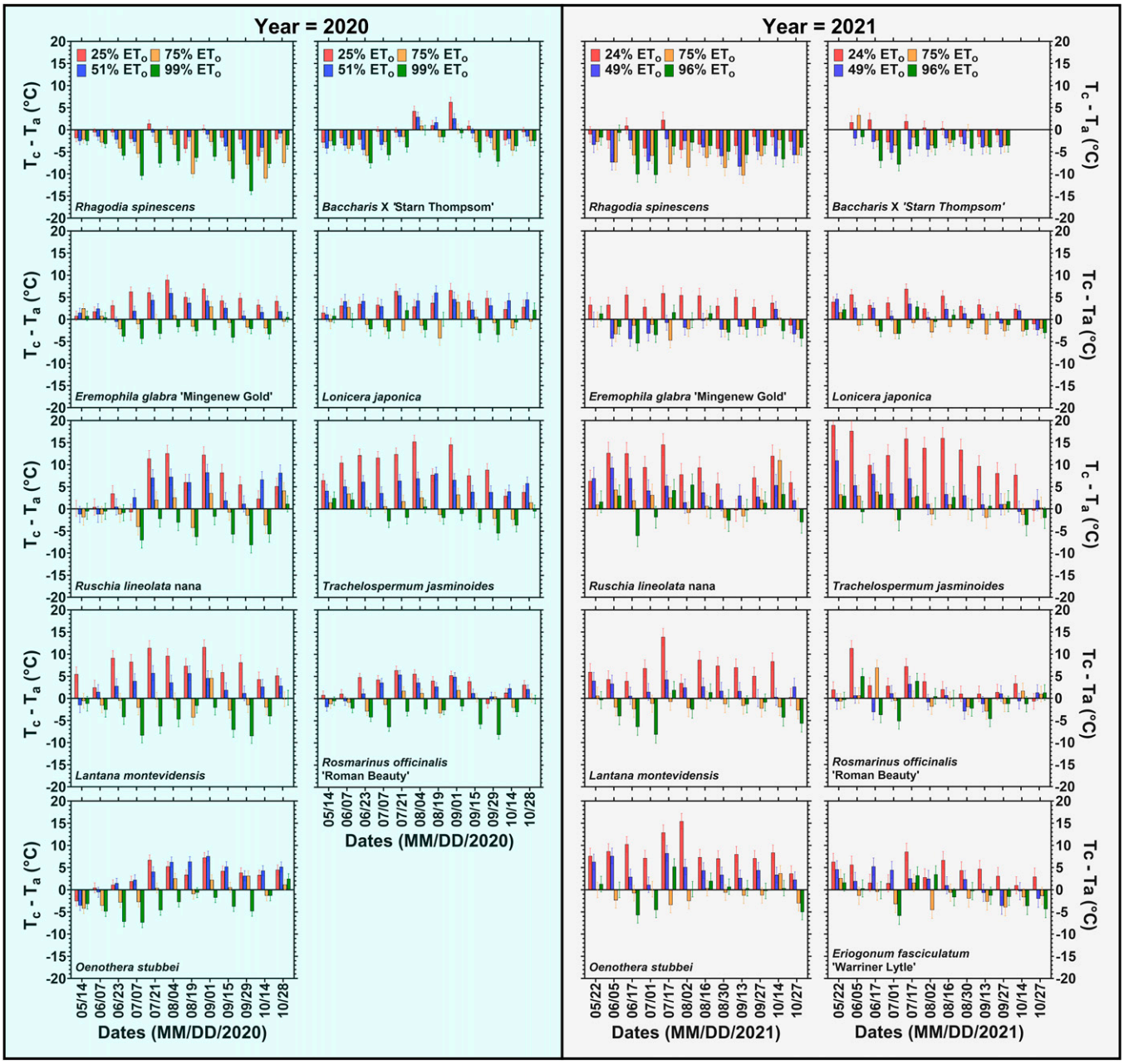

Fig. 4. Effect of irrigation on the canopy temperature of different groundcovers in 2020 and 2021. T_c = canopy temperature, T_a = air temperature. Error bars are the standard error of the mean. ET_o = reference evapotranspiration.

(Fig. 3; Table 2) compared with the other three irrigation rates.

Canopy–air temperature: the cooling potential of urban groundcovers. Table 2 presented how irrigation rates, data collection dates, and their interaction impacted the canopy (T_c) minus air (T_a) temperature ($T_c - T_a = \Delta T$) of the groundcover species in the 2020 and 2021 experimental periods. The groundcover *Rhagodia* mostly maintained the ΔT near 0 °C or less for all the irrigation rates in both years (Fig. 4). Except for August 2020 and June 2021, the groundcover *Baccharis* also had the ΔT close to 0 °C or less for all irrigation rates in both years. The groundcover *Rhagodia* also maintained a cool canopy among all the groundcovers; its mean ΔT during the experimental period ranged from –1.67 to –7.12 °C in 2020 and –2.19 to –6.44 °C in 2021 (Table 2) for all the irrigation rates.

Groundcovers *Eremophila* and *Rosmarinus* had a ΔT less than 0 °C for irrigation rates ≥75% ET_o in 2020 and the canopies were cool ($P < 0.05$) compared with the irrigation treatments ≤49% ET_o (Table 2). In 2021, the ΔT was near 0 °C or less for all the irrigation rates ≥49% ET_o (Table 2) for both the groundcovers *Eremophila* and *Rosmarinus*. Groundcover *Eriogonum* also had cool canopies with ΔT close to 0 °C or less for irrigation rates ≥ 49% ET_o (Table 2; Fig. 4).

The effect of irrigation rates on ΔT was similar for groundcovers *Lonicera*, *Lantana*, and *Oenothera*. In both years and for most of the days of data collection, the mean ΔT was close to or less than 0 °C for irrigation treatments ≥75% ET_o (Table 2). *Ruschia* had a ΔT less than 0 °C for irrigation treatments 75- and 99-% ET_o only in 2020 (Table 2). Limited irrigation applications severely impacted the groundcover *Trachelospermum*, resulting in the highest canopy temperature and maximum mean ΔT among all the species throughout the study (Fig. 4).

Table 3 shows the linear relationship established between ΔT and irrigation (% ET_o). The ΔT of all groundcovers decreased with increased irrigation rates (Fig. 5). *Rhagodia* (native to Australia) followed by *Baccharis* (native to California) were the top two species maintaining cooler canopies than the air temperature at nearly all irrigation levels greater than 20% ET_o. *Lonicera, Eriogonum, Eremophila,* and *Rosmariuns* had similar

Table 3. Relationship between the difference of canopy (T_c) and air (T_a) temperature ($\Delta T = T_c - T_a$) and applied irrigation expressed in percentage of reference evapotranspiration (ET_o) for ten groundcovers measured in 2020 and 2021.

Landscape groundcovers	R^2	ΔT
Rhagodia spinescens	0.28	$-0.0601ET_o - 0.6768$
Baccharis × 'Starn Thompson'	0.21	$-0.0483ET_o + 1.147$
Eremophila glabra 'Mingenew Gold'	0.47	$-0.0806ET_o + 5.3658$
Lonicera japonica	0.45	$-0.0695ET_o + 5.3538$
Ruschia lineolata nana	0.45	$-0.1209ET_o + 10.059$
Trachelospermum jasminoides	0.62	$-0.1535ET_o + 13.38$
Lantana montevidensis	0.71	$-0.1413ET_o + 9.8914$
Rosmarinus officinalis 'Roman Beauty'	0.36	$-0.0697ET_o + 4.7857$
Oenothera stubbei	0.52	$-0.1168ET_o + 9.0172$
Eriogonum fasciculatum 'Warriner Lytle'[i]	0.39	$-0.0749ET_o + 5.3845$

[i] Data from 2021 only were used for this groundcover.
ΔT = difference between canopy and air temperature.

slopes and responses to irrigation treatments. *Ruschia* and *Trachelospermum* could only keep their canopy cool at irrigation levels greater than 80% ET_o.

Crop water stress index (CWSI). Figure 6 shows the relationship between $T_c - T_a$ and the VPD. Only five groundcovers (*Rhagodia, Ruschia, Trachelospermum, Lantana*, and *Rosmarinus*) yielded a statistically significant ($P < 0.05$) and strong relationship ($r^2 \geq 0.75$) when establishing the lower baseline [i.e., ($T_c - T_a$) vs. VPD]. Therefore, CWSI was computed only for these five groundcovers. The $(T_c - T_a)_{ub}$ for five groundcovers, including, *Rhagodia*, *Ruschia*, *Trachelospermum*, *Lantana*, and *Rosmarinus* were 2.92, 18.50, 18.94, 13.89, and 11.30 °C, respectively.

Figure 7 shows the change in CWSI over time for all irrigation treatments for the five groundcovers in the years 2020 and 2021. The mean CWSI for the lowest irrigation treatments (25% ET_o in 2020 and 24% ET_o in 2021) remained higher than other irrigation treatments. In 2020, the mean CWSI for the highest irrigation rate (99% ET_o) was close to 0 for all five groundcovers. The mean CWSI remained close to 0 in 2021 for groundcovers *Lantana* (0.09 ± 0.17) and *Trachelospermum* (0.08 ± 0.14), while it increased to 0.18–0.20 for groundcovers *Rhagodia, Ruschia,* and *Rosmarinus*.

Based on the minimum NDVI established for each groundcover in our recently published study (Sapkota et al. 2023) and the relationship between CWSI and NDVI obtained here (Table 4), a maximum CWSI threshold to be water-stressed has been identified for five groundcovers to maintain the minimally acceptable quality. The maximum CWSI values for groundcovers *Rhagodia, Ruschia, Trachelospermum, Lantana*, and *Rosmarinus*, are 0.41, 0.47, 0.23, 0.34, and 0.39, respectively (a shaded green region in Fig. 7). Above these CWSI values, the respective groundcovers may show signs of water stress.

Rhagodia maintained a cool canopy (Fig. 4) for all irrigation treatments and in both years. However, CWSI suggests that *Rhagodia* experienced water stress for the 25- and 51-% ET_o irrigation treatments in 2020 and 24% ET_o irrigation in 2021. This shows that *Rhagodia* can withstand water-stress conditions while maintaining its growth. Furthermore, it has been evident from the stomatal conductance data (Fig. 2) and LAI (Table 2; Fig. 3) that none of the physiological parameters were affected by irrigation ($P > 0.05$) for the groundcover *Rhagodia*.

Groundcovers *Ruschia*, *Trachelospermum*, and *Lantana* showed a similar trend in terms of CWSI. They all showed no sign of stress for irrigation treatments ≥75% ET_o for both years. Groundcovers *Trachelospermum* and *Lantana,* showed noticeable water-stress signs based on CWSI for the irrigation treatments 24% to 51% ET_o. *Rosmarinus*, on the other hand, showed signs of water stress only for the lowest irrigation (24% ET_o) in 2021, while it was stressed for two irrigation treatments (25- and 51-% ET_o) from mid to late summer in 2020 (Fig. 7).

Relationship between ΔT, NDVI, LAI, g_s, and CWSI. Table 4 presents the Pearson correlation coefficient obtained for parameters including ΔT, NDVI, LAI, g_s, and CWSI for different groundcovers. When the linear relationship of NDVI was compared between the T_c and ΔT, ΔT was found to have a better correlation ($-0.70 \leq r \leq -0.50$) for six groundcovers (*Baccharis*, *Eremophila*, *Lonicera*, *Trachelospermum*, *Lantana*, and *Oenothera*). *Ruschia* and *Rosmarinus* showed a comparable and similar relationship between ΔT and T_c with NDVI (Table 4). Groundcover *Rhagodia* and *Eriogonum* had an insignificant correlation ($r = -0.21$ or -0.02, respectively) between NDVI and ΔT or T_c.

The relationship between the ΔT and LAI was also determined. Other than for *Rhagodia* ($r = 0.05$) and *Rosmarinus* ($r = -0.24$), there was a moderate to strong correlation between ΔT and the LAI ($-0.73 \leq r \leq -0.41$) (Table 4). CWSI, which uses ΔT as one of its parameters, yielded a strong correlation with one another for five groundcovers whose CWSI was computed ($0.76 \leq r \leq 0.97$). A strong relationship between NDVI and LAI was also established, with r ranging from 0.46 to 0.90 for eight groundcovers. *Eriogonum* yielded the weakest relationship between NDVI and LAI, and the relationship for *Ruschia* was not determined (Table 4).

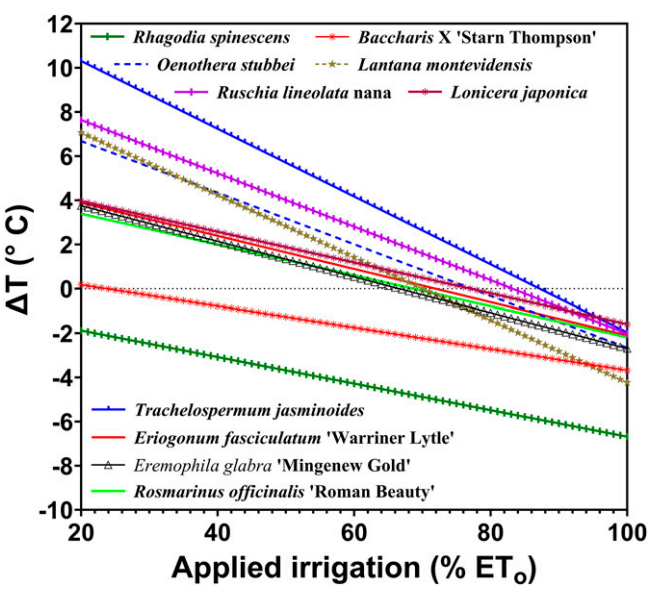

Fig. 5. Effect of irrigation rates on keeping the canopy cooler than the air temperature for 10 groundcovers. ΔT = canopy (T_c) minus air (T_a) temperature (°C); ET_o = reference evapotranspiration.

Discussion

Water stress and canopy temperature dynamics in landscape groundcovers. In this study, all groundcovers maintained a canopy temperature less than the air temperature at the irrigation levels ≥75% ET_o for both years except for *Ruschia* (in 2021) and *Trachelospermum* (in 2020 and 2021). This was in line with the findings reported in Colorado, USA, and Mashhad, Iran (Henson et al. 2006; Nazemi Rafi et al. 2019). Five irrigation rates ranging from 0% to 100% ET_o were applied to 17 annual herbaceous ornamentals and Kentucky bluegrass (*Poa pratensis* L.), eight of which maintained the cool canopy at irrigation levels ≥75% ET_o, and none of the plant species included had a canopy temperature less than air temperature for irrigation levels ≤50% ET_o (Henson et al. 2006). Similarly, when four herbaceous

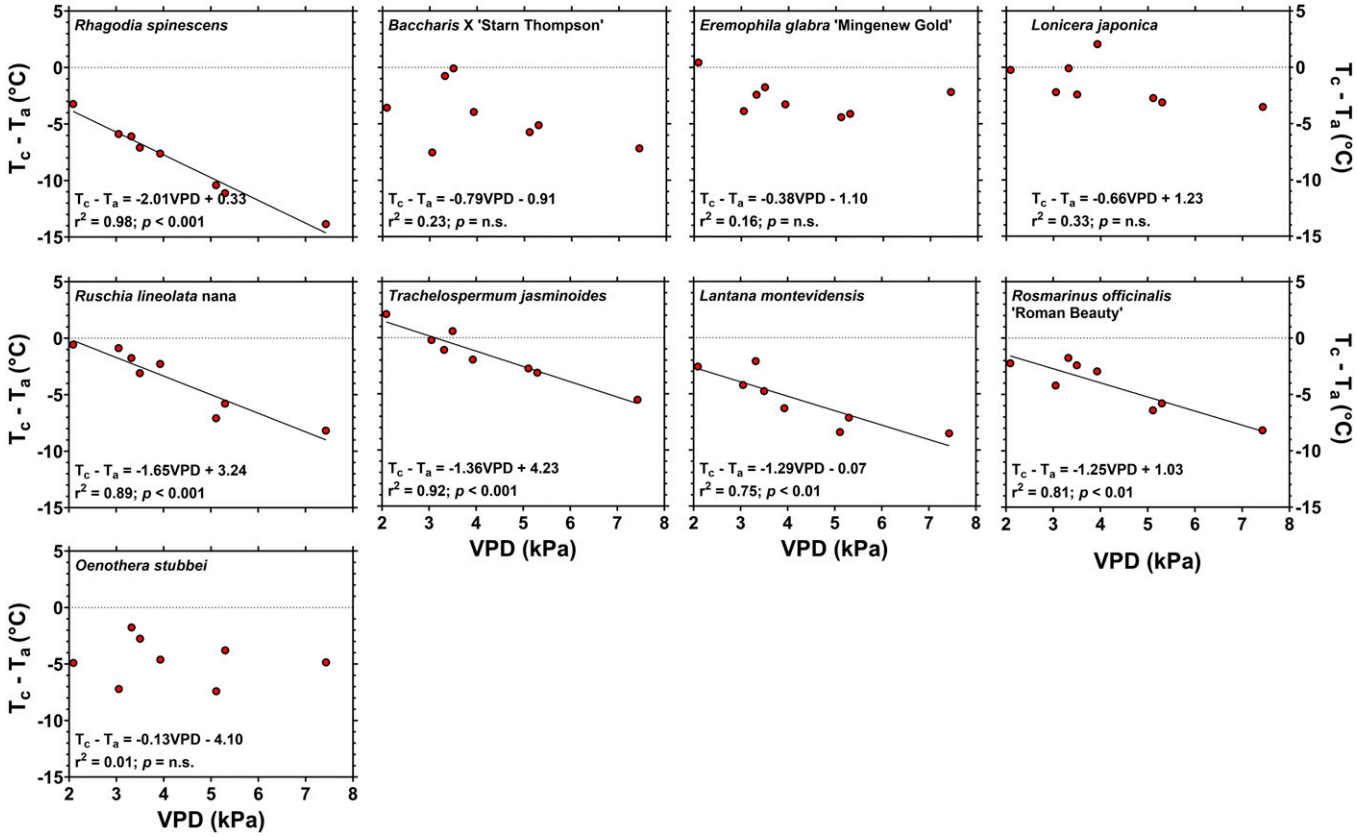

Fig. 6. Establishing a lower baseline (non–water-stressed) for groundcovers to calculate crop water stress index. T_c = canopy temperature; T_a = air temperature; VPD = vapor pressure deficit.

ornamentals were treated with four irrigation rates ranging from 25% to 100% ET_o in Mashhad, Iran, only one species (*Rudbeckia hirta)* maintained ΔT less than 0 °C for irrigation level ≥50% ET_o (Nazemi Rafi et al. 2019).

The process of total transpiration rate of a canopy, which is directly affected by the LAI, helps in the cooling process of the canopy of the groundcovers (Zhang 2020). When plants show signs of water stress, their leaf transpiration significantly decreases, reducing the ability of evaporative cooling and increasing the canopy temperature (Kimball and Bernacchi 2006). In our study, deficit irrigation did not reduce the LAI and g_s of the top-performing groundcovers (*Rhagodia* and *Baccharis*) that maintained their dense canopies even at lower irrigation rates (Table 2). Hence, they could keep a cool canopy even with minimum irrigation. In this study, groundcovers other than *Rhagodia* and *Baccharis* showed signs of water stress at varying irrigation rates, evident from low visual quality ratings and low NDVI values (Sapkota et al. 2023) or through the low LAI, high CWSI, and positive ΔT. Therefore, groundcovers that showed signs of

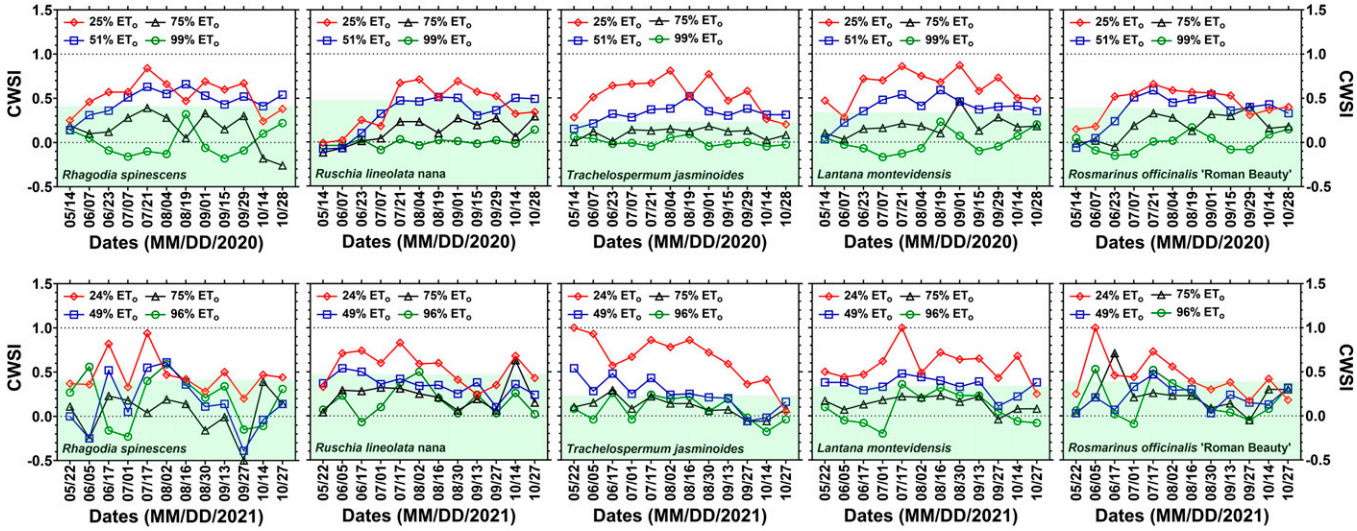

Fig. 7. Changes in crop water stress index (CWSI) over the growing season in 2020 (top row) and 2021 (bottom row). ET_o = reference evapotranspiration. The light green shaded region shows that the groundcovers would maintain their acceptable quality whenever the CWSI falls in that region.

Table 4. Relationship between different response variables that were impacted by the irrigation rates.

Landscape groundcovers	ΔT vs. NDVI	T_c vs. NDVI	ΔT vs. LAI	NDVI vs. LAI	CWSI vs. g_s	ΔT vs. CWSI	CWSI vs. NDVI	g_s vs. LAI	ΔT vs. g_s
					r				
Rhagodia spinescens	−0.21	−0.46	0.05	0.46	−0.57	0.76	−0.42	−0.02	−0.55
Baccharis × 'Starn Thompson'	−0.64	−0.28	−0.62	0.90	—	—	—	—	—
Eremophila glabra 'Mingenew Gold'	−0.69	−0.56	−0.45	0.55	—	—	—	0.16	−0.48
Lonicera japonica	−0.50	−0.30	−0.41	0.82	—	—	—	0.80	−0.35
Ruschia lineolata nana	−0.52	−0.56	—	—	—	0.92	−0.61	—	—
Trachelospermum jasminoides	−0.70	−0.56	−0.58	0.65	−0.61	0.96	−0.71	0.29	−0.60
Lantana montevidensis	−0.69	−0.55	−0.73	0.91	−0.64	0.97	−0.72	0.75	−0.57
Rosmarinus officinalis 'Roman Beauty'	−0.41	−0.43	−0.24	0.62	—	0.92	−0.50	—	—
Oenothera stubbei	−0.74	−0.71	−0.66	0.85	—	—	—	0.55	−0.37
Eriogonum fasciculatum 'Warriner Lytle'	−0.02	−0.27	—	0.28	—	—	—	—	—

ΔT = difference between canopy and air temperature; NDVI = normalized difference vegetation index; T_c = canopy temperature; LAI = leaf area index; CWSI = crop water stress index; g_s = stomatal conductance.

water stress with decreased irrigation rates could not maintain the cool canopies. Not all the groundcovers that have a dense canopy necessarily keep cool canopies. For example, *Ruschia* had a full groundcoverage and dense canopy but could not maintain the cool surface, especially in 2021, even at the highest irrigation rates (Fig. 4). *Ruschia* has a succulent leaf, and the succulence behavior is well known for storing water in living cells. In succulent plants, evaporative cooling through transpiration is avoided because of their morphology and physiology (Griffiths and Males 2017). The size and density of the leaves of *Ruschia*, and their water storage for future use increased the thermal capacity. Hence, *Ruschia* has a higher canopy temperature than air temperature during noon (Griffiths and Males 2017). Therefore, planting *Ruschia* in water-scarce urban areas of arid regions may not yield any cooling benefits. The LAI of *Eremophila*, *Lonicera*, and *Oenothera* decreased over the summer (Fig. 3), and LAI, in most cases, is associated with cool canopies (Zhang 2020). Therefore, these groundcovers could not maintain their cool canopies and may not be a good fit to grow in the urban green spaces of arid regions like Riverside, CA, USA.

LAI is a dimensionless quantity representing the canopy of ecosystems, the one-sided area of leaf tissue per unit area, and changes in its values alter the stand productivity (Bréda 2003). Various factors, including frost, storm, defoliation, drought, and management practices, affect the LAI (Bréda 2003). Our results align with the literature reporting that leaf area decreases under water-stressed conditions (Gómez-del-Campo et al. 2002) and irrigation significantly impacts the LAI (Çakir 2004; Kalaydjieva et al. 2015). On the other hand, top-performing groundcovers (e.g., *Rhagodia* and *Baccharis*) withstood severe deficit irrigation and maintained acceptable and cool canopies. This is because the process of transpiration is directly affected by LAI, and the higher LAI helps in the cooling process of the canopy of the groundcovers (Zhang 2020). *Lonicera*, which grows well when irrigated (Larson et al. 2007), did not do well at the highest irrigation rates in both years. Above 75% ET_o irrigation, their growth and physiologic performances started deteriorating, evident from the LAI and g_s values. It can be because *Lonicera* arrays their leaves horizontally (Larson et al. 2007); as the canopy gets dense, the horizontal leaf orientation may intercept the irrigation water, eventually decaying the leaves. Overall, the effect of irrigation on the LAI of groundcover was significant. Groundcover, which maintained its LAI for all irrigation levels, were found to have acceptable quality and irrigation-induced cooling potential.

The range of CWSI's lower baseline for five groundcovers in this study was in line with the results reported in studies in the past for agricultural crops (Idso et al. 1981; Irmak et al. 2000; Katimbo et al. 2022; Sammis and Jernigan 1992). The CWSI helped detect water stress, but that did not necessarily match the groundcovers' quality and cooling potential. For example, CWSI indicated that deficit irrigation (≤51% ET_o) stressed *Rhagodia*, but LAI, ΔT (Fig. 7), NDVI, and visual quality ratings (Sapkota et al. 2023) were unaffected by the lower irrigation rates. Also, the CWSI did not accurately indicate the negative effect of lower irrigation rates on *Ruschia*'s cooling potential. The minimum irrigation treatments decreased *Ruschia*'s ΔT, but CWSI stayed above the minimum established threshold of 0.47. CWSI has advantages as it normalizes the canopy temperature considering VPD, but ΔT is a more direct indicator of groundcovers cooling potential. Additional studies that focus on developing CWSI for urban groundcovers are needed.

Importance of groundcover selection and irrigation management to save water and maintain irrigation-induced cooling. This study showed that groundcovers respond differently to water stress, and their irrigation requirements were different to maintain growth and quality. For example, groundcover *Rhagodia* and *Baccharis* performed well at all irrigation levels, whereas others needed increased irrigation. Comparing ΔT and visual rating values (Sapkota et al. 2023) also revealed that the minimum irrigation levels to maintain aesthetic values and cool canopy were not always the same. For seven species, the minimum water needed to maintain the aesthetic value was insufficient to keep ΔT <0. Therefore, we need to develop plant-specific irrigation recommendations and move toward hydrozoning (Kjelgren et al. 2016; Sun et al. 2012) in the future, where each hydrozone consists of groundcovers with similar irrigation requirements and is irrigated separately.

Irrigation-induced cooling was directly related to the level of water received by the plants and the type of groundcover species. Some groundcovers (e.g., *Rhagodia* and *Baccharis*) successfully maintained the canopy cooler than the air temperature, even in limited irrigation scenarios. However, most groundcovers required significant irrigation (>70% ET_o, Fig. 5) to keep the plant canopy lower than the surrounding air temperature. Plant radiative properties depend on leaf color, texture, type, and age. Silver-leaved plants reflect sunlight because of higher albedo. Their bright color also protects the plants from drying and has improved resilience to dry conditions (Baumann et al. 2019). For example, *Rhagodia* with silver-green leaves maintained a canopy temperature cooler than the air temperature. Additionally, lighter color leaves maintain a lower temperature than dark ones, which absorb more energy (Dahanayake et al. 2017). More studies are necessary to see if other silver-leaved plants show similar canopy temperatures under limited irrigation applications. Native plants are typically favored over nonnative species in semi-arid and arid regions where water conservation is required. They are known to be low-input plants that require little maintenance and irrigation (Reid and Oki 2008). However, the top performing species in our study was a nonnative, *Rhagodia*, suggesting that their potential to help achieve water conservation goals should not be overlooked.

Conclusion

A 2-year (2020–21) field study evaluated the effect of deficit irrigation on the physiological performance and canopy temperature dynamics of 10 groundcovers in inland Southern California. The following are the major conclusions:

1. Not all drought-tolerant groundcovers performed well under minimum irrigation applications, and it is important to select a plant that withstands severe deficit irrigation while maintaining a cool canopy. For example, groundcovers *Rhagodia* and *Baccharis* maintained a canopy temperature cooler than the air temperature for all the deficit irrigation rates.
2. The difference in the canopy and air temperature (ΔT) showed a negative correlation with quality (NDVI, r = –0.50 to –0.74) and growth (LAI; r = –0.24 to –0.73) for most groundcovers. ΔT was also strongly correlated with g_s and CWSI.
3. Overall, plants needed equal or more water to maintain a cool canopy than the minimum water required to keep their aesthetic values. Therefore, applying the minimum irrigation to drought-tolerant species may negatively impact their role in helping mitigate the urban heat island effect in semiarid regions.

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