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Response of Landscape Groundcovers to Deficit Irrigation: An Assessment Based on Normalized Difference Vegetation Index and Visual Quality Rating

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Abstract. **Developing water conservation strategies for urban landscape groundcovers grown in hot and dry summers like inland Southern California, USA, is crucial because they are one of the largest residential water users. A 2-year (2020–21) study was conducted in Riverside, CA, to assess the effect of irrigation rates on the growth of landscape groundcovers as evaluated by visual quality ratings (VR) and normalized difference vegetation index (NDVI). Relationships between VR and NDVI were also established to obtain the minimum threshold values of NDVI for each groundcover. Lastly, the groundcover water response function was developed to estimate groundcover response to irrigation rates over time. Four reference evapotranspiration (ET_o)-based irrigation treatments ranging from 24% to 99% ET_o and 10 landscape groundcovers were laid in a randomized complete block design and replicated three times. Data were collected from May to October in 2020 and 2021. The irrigation controller overirrigated the plots on average by 7.7% and 4.7% in 2020 and 2021, respectively. A significant relationship ($P < 0.05$, $0.35 \le R^2 \le 0.82$) between NDVI and VR for each landscape groundcovers was found. On the basis of the NDVI values and VR, it was found that three landscape groundcovers, including *Rhadogia spinescens*, *Baccharis* × 'Starn' Thompson, *Eriogonum fasciculatum* 'Warriner Lytle' can withstand water stress and can maintain their growth and visual quality at 24% ET_o irrigation. Groundcovers *Ruschia lineolate* nana, *Rosmarinus officinalis* 'Roman Beauty', and *Eremphila glabra* showed the potential to perform well with as low as 49% ET_o irrigation, whereas *Lantana montevidensis*, *Oenothera stubbei*, and *Lonicera japonica* required 75% ET_o or more.**

Water-efficient horticultural alternatives to turfgrass are recommended in many urban areas where water is scarce. Predominant among these recommended alternatives are perennial groundcovers, which are low-growing plants that form a continuous soil covering (Davison 1999). They vary significantly in shape, size, texture, and color, with heights typically ranging from 7.5 cm to 1 m (Davison 1999; Pittenger et al. 2001). However, the assumption that groundcovers consume less water (Pittenger et al. 2001) is mainly anecdotal because few studies have assessed the response of groundcovers to deficit irrigation (Costello and Jones 2014; Garcia-Navarro et al. 2004; Nazemi Rafi et al. 2019; Pittenger et al. 2001). Moreover, the quality assessment of groundcovers is mostly based on the visual ratings (Nazemi Rafi et al. 2019; Pittenger et al. 2001), and the potential use of quantitative quality predictor, including normalized difference vegetation index (NDVI) has not been studied for landscape groundcover.

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Visual quality rating (VR) is a dominant and traditional method to assign a numerical value to plant appearance. Nevertheless, estimating groundcover quality based on visual methods can be time-consuming and requires a skilled and trained evaluator (Wang et al. 2022). Even a well-trained person may introduce bias because the VR process is subjective and prone to rater's fatigue (Horst et al. 1984; Luscier et al. 2006; Wang et al. 2022). The relationship between VR and the NDVI, widely used indicator of vegetative health (Easterday et al. 2019; Haghverdi et al. 2021c), has been studied in turfgrass plots (Fitz-Rodríguez and Choi 2002; Haghverdi et al. 2021b, 2021c; Leinauer et al. 2014). In turfgrass research, some studies suggested the use of NDVI as an alternative to visual rating because it provides consistent and reliable evaluation of turfgrass quality in less time compared with visual quality (Bell et al. 2009; Fitz-Rodríguez and Choi 2002; Haghverdi et al. 2021c). In contrast, some studies in turfgrass highlighted the practical limitations of using NDVI for the quality assessment (Bremer et al. 2011; Leinauer et al. 2014). However, studies evaluating the potential of NDVI values to assess the quality of landscape groundcovers are yet to be done.

Haghverdi et al. (2021c) introduced the turfgrass water response function as an empirical regression-based model to estimate the response of turfgrass to extreme drought and limited irrigation scenarios. These models were developed using data from turfgrass fields in southern and central California along with long-term weather data obtained from nearby weather stations (Haghverdi et al. 2021b, 2021c). Development of these models can be helpful in irrigation management as they estimate the quality (based on NDVI values) of plants for different rates of irrigation. Because the water requirements of landscape groundcovers can significantly differ among species, development of a species-specific water response function model [hereafter called groundcover water response function (GCWRF)] can help predict the quality of groundcovers based on NDVI values at varying rates of irrigation. This in turn can be helpful in optimizing irrigation rates while maintaining the quality of groundcovers.

Evapotranspiration (ET)-based smart irrigation controllers with on-site weather measurements can be used for autonomous landscape irrigation management. These controllers have been reported to reduce irrigation water by 40% to 61% in plot studies and 28% to 32% in residential studies (Dukes 2020). However, few studies evaluated their performance for landscape groundcovers (Shober et al. 2009; US Bureau of Reclamation 2008), particularly in arid and semiarid regions such as inland Southern California, where keeping plants alive with minimum water application is often required (Haghverdi et al. 2021c; Serena et al. 2020). Efficient irrigation scheduling using ET-based controllers depends on the availability of science-based plant factor information for each landscape species and the accuracy of the ET_o estimations by the irrigation controller (Haghverdi et al. 2021a). Hence, the objectives of this study were to 1) evaluate the effect of irrigation rates on VR and NDVI of 10 landscape groundcovers; 2) examine the strength of linear relationships between VR and NDVI for each groundcover species, 3) estimate the response of groundcover species to multiple irrigation regimes under extremely low, high, and mean atmospheric evaporative demand using GCWRFs; and 4) determine the reliability of the Weathermatic smart ET-based controller for autonomous irrigation scheduling.

Materials and Methods

Study area. A 2-year (2020–21) study was conducted in a year-old established field at the Agricultural Experimental Station, Riverside (lat. 33°58′ N, long. 117°19′ W, 307 m. elevation) at the University of California–Riverside, Riverside, CA. The experimental field had a soil classified as Hanford coarse sandy loam (websoilsurvey.sc.egov.usda.gov). The climate in Riverside is semiarid. The ET_o demand during the experimental season (May–October) was higher than the long-term average in both years, while precipitation was negligible (Table 1). Fertilizer 15–5–8 microgreen (Simplot Turf & Horticulture, San Diego, CA) was top-dressed at 49 $kg \cdot ha^{-1}$ nitrogen (N) and the soil was treated with preemergent herbicide in 2019 to control weeds. The experimental plots were hand-weeded during the study, and alleyways were sprayed with herbicides. Fast-growing groundcovers were pruned to maintain 38 cm height. Similarly, the lateral growth of the groundcover was always confined within the designated plot size (3.05 m × 3.05 m) by trimming the excess growth.

Experimental design, groundcover species selection, and irrigation application. Ten woody, herbaceous, and succulent landscape groundcovers, including some native and widely grown species in California with different growth habits and water requirements, were planted in 2019 (Fig. 1). Two other plant species (*Delosperma cooperi* 'John Profitt' and *Frankenia thymifolia*) did not grow well and were not included in this study. *Eriogonum* did not become fully established in the first year after planting, so results for it are presented only for 2021. For six species (i.e., *Rhagodia, Eriogonum*, *Baccharis*, *Eremphila*, *Ruschia*, and *Oenothera*), 12 to 16 plants per plot were acquired in 2.8-L (1 gallon) containers. For the remaining species, 10-cm pot plants in full trays were obtained and planted at a higher density to ensure proper plot coverage and plant establishment. Four irrigation treatments (80%, 60%, 40%, and 20% ET_o) replicated three times were laid in two adjacent randomized complete block designs totaling 144 individual experimental plots. Each plot was ∼3 m × 3 m, with a 1.2-m alley between the neighboring plots. Four 300-mm tall quarter-circle pop-up heads (Toro 570Z series; The Toro Company, Bloomington, MN, USA) with pressure-compensating precision series spray nozzles (Model 0-10-Q, The TORO Company) were used to irrigate each plot. Each plot was independently controlled using a Hunter PGV-101G solenoid valve (Hunter Industries, Inc., San Marcos, CA). In addition, a pressure regulator was installed in the field to maintain steady water pressure.

The automatic irrigation scheduling was done by a Weathermatic SmartLine SL4800 smart irrigation controller (Weathermatic, Garland, TX, USA). The controller works in the principle of the Hargreaves and Samani (1985) equation, which uses on-site temperature data and latitude-based solar radiation to estimate ET_o. The SmartLine irrigation controller was connected to an SLW1 weather sensor and a Badger Meter Recordall Turbo flowmeter (Badger Meter, Inc., Milwaukee, WI, USA). Flowmeter was calibrated using field-based flow test data. The low half distribution uniformity of the system (86%) was determined at the beginning of the experiment using a catch-cans test. The irrigation controller was programmed to apply the desired ET_o level divided by the irrigation frequency for each treatment. Therefore, programmed irrigation rates were 93%, 70%, 47%, and 23% ET_o (Table 2). The controller initiates the irrigation whenever the minimum deficit irrigation threshold is reached, can irrigate multiple times a day until the desired level is reached; however, it does not irrigate outside of the pre-defined irrigation window. Plots were irrigated between midnight to 8 AM to avoid evaporative water loss. The smart controller automatically performed run-soak cycles to eliminate runoff. The maximum runtime and minimum soak time between the irrigation event were set to be 10 and 30 min, respectively. The irrigation trial ran from early May to late October in 2020 and 2021, and uniform nonlimiting (80% ET_o) irrigation was applied from November to April.

The performance of the ET-based irrigation controller was evaluated using CIMIS-ET_o rates obtained from the nearby California Irrigation Management Information System (CIMIS #44). The irrigation runtime data for each treatment were retrieved from the controller, converted to CIMIS-ET_o, and compared with the programmed ET_o values at the beginning of the trial.

Data collection. The effect of irrigation rates on the landscape groundcovers was evaluated by measuring the NDVI and VR. The NDVI is a widely used index for vegetation assessment (Huang et al. 2021) as it correlates strongly to green coverage, aboveground biomass, and plant vigor (Easterday et al. 2019; Garg et al. 2022).

The NDVI data were collected using handheld GreenSeeker (Trimble Inc., Sunnyvale, CA) close to solar noon on cloud-free days. The GreenSeeker was held at waist height and hovered over the plot (∼3 m^2) in an inverse Z-shape keeping the trigger engaged to get a representative and average NDVI value from each experimental plot. Data were collected during solar noon in a cloud free day. In both years, the NDVI data were collected on 12 dates during the experimental season (May to October).

Canopy pictures from each experimental plot were captured on the same day of NDVI data collection using a 12-megapixel Olympus digital camera (TG-5; Olympus Korea Co., Ltd., Seoul, Korea). The canopy pictures were obtained for VR. A scale of 1 to 9 was used to rate the visual appearance of the groundcovers, where 1 = dead or dying plants, 6 = minimally acceptable, and 9 = ideal or optimum quality (Pittenger et al. 2001). Ground coverage, plant vigor, and color were taken into consideration during the rating process (Pittenger et al. 2001). In 2020, images from six data collection dates and in 2021, canopy pictures from 12 different data collection dates were used for the visual quality assessment. To maintain the consistency of rating, one person rated all the pictures using the same screen for all the images obtained in both years. Simple linear regression models were developed for all the species to evaluate the relationships between NDVI and VR. The models were subsequently used to identify minimum NDVI thresholds for each species equivalent to the VR value of six.

Statistical analysis. Data were analyzed using PROC GLIMMIX in SAS ver 9.4 (SAS Institute Inc., Cary, NC, USA). When data

Table 1. Growing season monthly, seasonal, and 30-yr average reference evapotranspiration (ET_o), precipitation, and air temperature obtained from the nearby California Irrigation Management Information System (CIMIS) weather station (CIMIS #44).

	ET_o (mm)			Precipitation (mm)			Air temp (°C)		
Month	2020	2021	1992–2021	2020	2021	1992–2021	2020	2021	1992–2021
May	184	164	157	0	0	5	20	18	18
Jun	163	188	174	1	4	2	21	22	21
Jul	208	206	189	0	3	2	24	25	24
Aug	197	181	183	0	0	2	27	25	25
Sep	161	149	142	0	0	3	25	23	23
Oct	122	102	103	0	11	8	22	18	19
Season	1,035	990	948	1	18	22	23	22	22

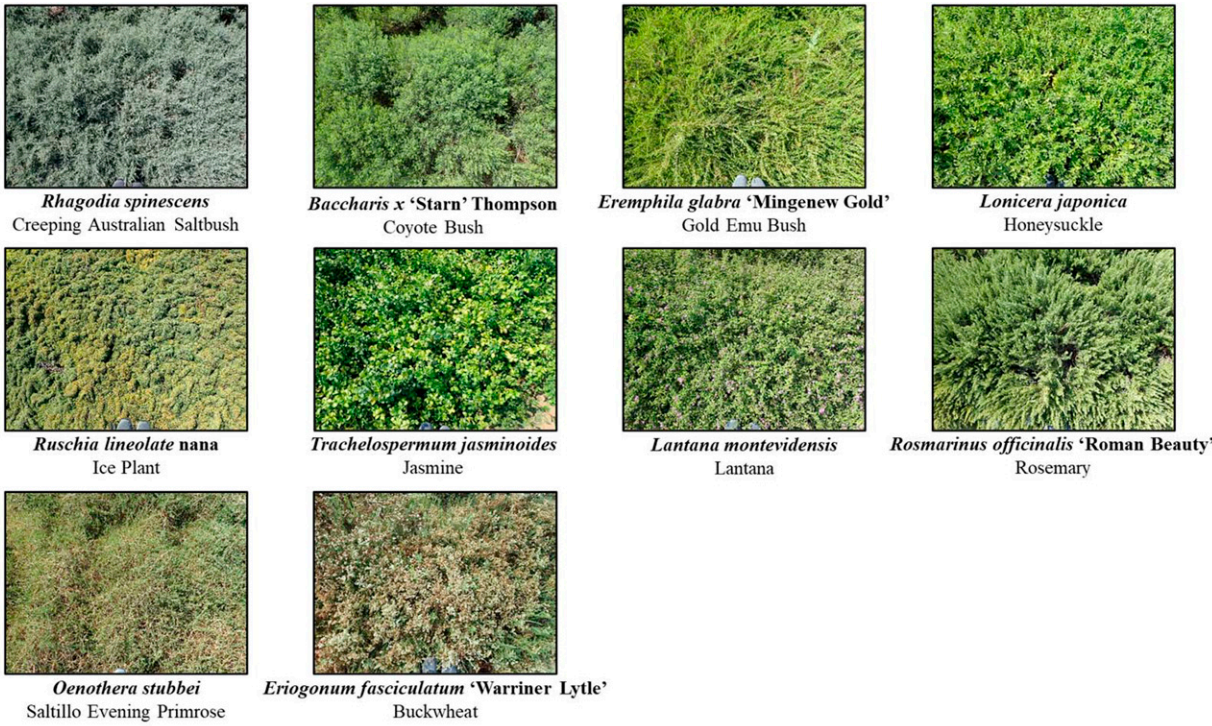

Fig. 1. Canopy pictures, the scientific name (italic and bold) and the common name of landscape groundcovers selected in this study.

from 2020 and 2021 were combined, there was a significant year effect. Also, the meteorological information, including precipitation, ET_o, and air temperature (Table 1), differed considerably between the 2020 and 2021 experimental seasons. Therefore, data were analyzed separately for each year. Also, because there were significant differences between species, each landscape groundcover was individually analyzed (Pittenger et al. 2001). The landscape groundcover *Baccharis* × 'Starn' Thompson was pruned just before the data collection on 22 May, 14 Oct, and 27 Oct in 2021; data from these dates for this specific plant were not included in the analysis because it would have skewed the results. Also, the groundcover *Eriogonum fasciculatum* 'Warriner Lytle' did not grow well in 2020, so data from 2021 were only included for this groundcover in the analysis. Irrigation treatments, data collection date, and interaction were used as fixed effects for the response variables. Block and its interaction with irrigation treatment were random effects. The LSMEANS option LINES statement was used for pairwise least square mean comparisons, and treatment effects were considered significant at $\alpha = 0.05$.

Table 2. Irrigation treatments 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.

ET_o = reference evapotranspiration.

Data in 2020 and 2021 for each groundcover (only from 2021 for *Eriogonum fasciculatum* 'Warriner Lytle') were pulled together to determine the relationship between NDVI and VR. The mean value of NDVI and VR for each species were obtained for all four irrigation treatments and each day of data collection. The regression option from the data analysis tool in Microsoft Excel 2016 was used to compute the regression statistics, identify the relationship's significance, and get the coefficients of slope and intercepts for the linear regression equation. Graphs were made using GraphPad Prism version 9.3 (GraphPad Software, LLC, San Diego, CA, USA).

A simple linear regression-based GCWRF model for each groundcover was developed using 2 years of experimental data. Applied irrigation amount (percentage of ET_o), atmospheric evaporative demand (cumulative ET_o), and their interaction were used as predictor variables, and the NDVI was the response variable. The significant difference between the models was determined using the analysis of variance function in SAS. Long-term ET_o data (30 years) from CIMIS station 44 was used to identify minimum, mean and maximum daily ET_o values for six months (1 May–31 Oct). Then GCWRFs were used to estimate the response of groundcovers to four irrigation levels (80%, 60%, 40%, and 20% ET_o) under extremely low (minimum daily ET_o), high (maximum daily ET_o), and mean (mean daily ET_o) atmospheric evaporative demands. The performance of models was evaluated using the coefficient of determination (R^2; Eq. [1]), mean absolute error (MAE; Eq. [2]), mean biased error (MBE; Eq. [3]), and the root mean square error (RMSE; Eq. [4]).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(M_i - E_i)^2}{\sum_{i=1}^{N}(M_i - \bar{M})^2} \quad [1]$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|E_i - M_i| \quad [2]$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(E_i - M_i) \quad [3]$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - M_i)^2} \quad [4]$$

where N is the total number of observations, M_i is the measured and E_i is the predicted value of i^{th} observation, and $\bar{M}$ is the mean of the measured values.

Results

Performance of the ET-based smart irrigation controller. Table 2 summarizes the irrigation treatment values, programmed irrigation rates, and the actual irrigation applied as percentages of CIMIS-ET_o. The irrigation controller overirrigated the landscape groundcovers by an average of 7.7% (range: 7.5% to 8.7%) in 2020 and 4.7% (range: 3.2% to 7.1%) in 2021. The controller closely followed the programmed watering days (irrigation frequency).

Impact of irrigation on the VR of landscape groundcovers. In 2020, the data collection date (i.e., time of the season) significantly affected ($P < 0.01$) the VR (Table 3, Fig. 2) of

Table 3. Analysis of variance table presenting the effect of irrigation treatments, date of data collection, and their interaction on the normalized difference vegetation index (NDVI) and visual rating (VR) of different groundcover species in the years 2020 and 2021.

		Rhagodia spinescens		*Baccharis* × 'Starn' Thompson		*Eremphila glabra* 'Mingenew Gold'		*Lonicera japonica*		*Ruschia lineolate nana*		*Trachelospermum jasminoides*		*Lantana montevidensis*		*Rosmarinus officinalis* 'Roman Beauty'		*Oenothera stubbei*		*Eriogonum fasciculatum* 'Warriner Lytle'	
	ET_0 (%)	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR	NDVI	VR
2020	25	0.48 c[1]	6.94 b	0.50 a	6.56 a	0.51 c	5.5 c	0.51 c	5.28 b	0.55 b	6.56 b	0.34 c	3.56 b	0.36 c	4.17 c	0.50 b	5.67 b	0.43 c	5.72 ab	-	-
	51	0.49 bc	7.61 ab	0.50 a	6.33 a	0.57 b	6.28 bc	0.59 b	5.94 b	0.66 a	8.39 a	0.49 b	5.44 ab	0.58 b	5.78 b	0.63 a	7.89 a	0.43 c	5.06 b	-	-
	75	0.54 ab	8.61 a	0.52 a	6.89 a	0.61 b	6.94 ab	0.69 a	7.61 a	0.68 a	8.72 a	0.60 ab	5.67 a	0.64 ab	6.72 b	0.66 a	8.39 a	0.54 b	7.17 ab	-	-
	99	0.56 a	7.89 ab	0.55 a	6.39 a	0.66 a	7.78 a	0.71 a	7.56 a	0.71 a	8.72 a	0.69 a	6.78 a	0.68 a	8.06 a	0.66 a	8.22 a	0.64 a	8.00 a	-	-
	SE	0.01	0.34	0.01	0.23	0.01	0.22	0.04	0.42	0.02	0.35	0.05	0.53	0.04	0.47	0.02	0.41	0.02	0.74	-	-
												P values									
	Irrigation (I)	0.031	0.059	0.178	0.411	0.001	0.003	0.0018	0.003	0.005	0.009	0.001	0.034	0.0006	0.0008	0.001	0.02	0.002	0.144	-	-
	Date (D)	<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	0.003	<0.0001	<0.0001	<0.0001	<0.0001	-	-
	I × D	<0.0001	0.257	<0.0001	0.709	00.0001	0.003	0.0004	0.041	<0.0001	<0.0001	<0.0001	0.022	<0.0001	0.002	<0.0001	0.0004	<0.0001	0.055	-	-
2021	24	0.51 a	8.64 a	0.53 b	7.74 a	0.46 b	7.19 b	0.51 b	6.33 b	0.46 b	6.33 b	0.22 b	2.28 b	0.34 d	4.14 c	0.48 b	6.33 b	0.26 b	3.86 b	0.47 a	7.72 a
	49	0.50 a	8.53 a	0.58 ab	7.89 a	0.65 a	8.86 a	0.52 b	6.42 b	0.62 a	8.61 a	0.51 a	6.36 a	0.46 c	6.03 b	0.68 a	8.86 a	0.34 b	5.19 b	0.49 a	8.06 a
	75	0.54 a	8.86 a	0.58 ab	7.93 a	0.65 a	8.89 a	0.79 a	8.69 a	0.66 a	8.78 a	0.56 a	7.11 a	0.60 b	7.83 a	0.68 a	8.83 a	0.55 a	7.53 a	0.53 a	7.69 a
	96	0.53 a	8.69 a	0.63 a	8.22 a	0.70 a	8.97 a	0.72 a	8.53 a	0.67 a	8.50 a	0.66 a	7.83 a	0.66 a	8.67 a	0.67 a	8.89 a	0.60 a	8.28 a	0.53 a	7.25 a
	SE	0.02	0.12	0.01	0.21	0.03	0.26	0.04	0.19	0.03	0.42	0.06	0.66	0.03	0.35	0.01	0.17	0.03	0.55	0.02	0.51
												P values									
	Irrigation (I)	0.564	0.353	0.106	0.635	0.001	0.008	0.008	0.0003	0.006	0.010	0.003	0.001	<0.0001	0.0005	<0.0001	<0.0001	0.0008	0.003	0.151	0.570
	Date (D)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.001	<0.0001	<0.0001	<0.0001	0.0002	0.013	0.358	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.198
	I × D	0.999	0.538	0.0002	0.966	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.058	0.133	0.0002	<0.0001	<0.0001	<0.0001	0.151	<0.0001	0.195	0.502

[1] For each year, different letter assignment within the column represents statistical significance at $\alpha = 0.05$.

SE = standard error of the mean.

all nine groundcovers (*Eriogonum* was not included in 2020). Irrigation rates and their interaction with data collection dates also had significant ($P \leq 0.05$; Table 3) impacts on the VR of six groundcovers except for *Rhagodia*, *Baccharis*, and *Oenothera.* In 2021, the effect of data collection dates on the VR was significant ($P \leq 0.001$; Table 3) for eight landscape groundcovers during the experimental season except for *Trachelospermum* ($P = 0.358$) and *Eriogonum* ($P = 0.198$). In addition, the varying irrigation rates also significantly ($P < 0.01$) affected the VR of seven groundcovers other than *Rhagodia*, *Baccharis*, and *Eriogonum* ($P > 0.05$). The interaction effect of irrigation and data collection date on VR was significant ($P < 0.001$; Table 3) for only six groundcovers excluding *Rhagodia*, *Baccharis*, *Trachelospermum*, and *Eriogonum*.

The mean VR values of *Rhagodia* for 75% and 99% ET_o irrigation treatments were above the minimum VR threshold (VR = 6) for the whole experimental period in 2020 (Fig. 2). The VR values dropped below 6 in mid-August for 51% and 25% ET_o irrigation treatments. In 2021, the lowest mean VR value was 7.33, and irrigation rates did not affect the VR values of this groundcover (Fig. 3). *Eriogonum*, which was evaluated only in 2021, was also not affected by irrigation rates (Table 3), and the VR values were above the minimum threshold of 6 (Fig. 3).

Groundcovers *Ruschia* and *Rosmarinus* had a similar trend in 2020 and 2021. Irrigation treatments ≥49% ET_o had significantly the same VR values and were well above the minimum threshold (Figs. 2 and 3). Only the plots with irrigation treatments <25% ET_o showed signs of water stress and VR values <6, mainly from August. In 2020, *Eremphila* had VR values <6 for irrigation treatments 51% and 25% ET_o (Fig. 2). In 2021, three irrigation treatments (≥49% ET_o) did not significantly affect the VR values (Fig. 3) and had VR values consistently above 6. *Eremphila* treated with 24% ET_o irrigation treatment had significantly different VR values than the other three irrigation treatments; however, the lowest mean VR values were 6, suggesting the plants still maintained acceptable visual quality.

Groundcovers such as *Lantana*, *Oenothera*, and *Lonicera* mostly had VR values above the minimum acceptable threshold (i.e., VR = 6; Figs. 2 and 3) for the irrigation rates ≥75% ET_o in both years. *Lonicera* once had VR <6 in September 2020 (Fig. 2). The VR values for the other two irrigation rates diminished as the experimental season progressed and dropped below the minimum acceptable threshold of 6.

Baccharis was not affected by any of the four irrigation treatments in 2020 and 2021, nor by the interaction effect of irrigation rates and data collection dates (Table 3, Figs. 2 and 3). In 2020, the VR values for all irrigation treatments started falling after the start of the experimental season. Beginning in August, VR values were mainly below the minimum threshold of 6 to be visually acceptable (Fig. 2). However, in 2021, for all irrigation rates and the whole experimental season,

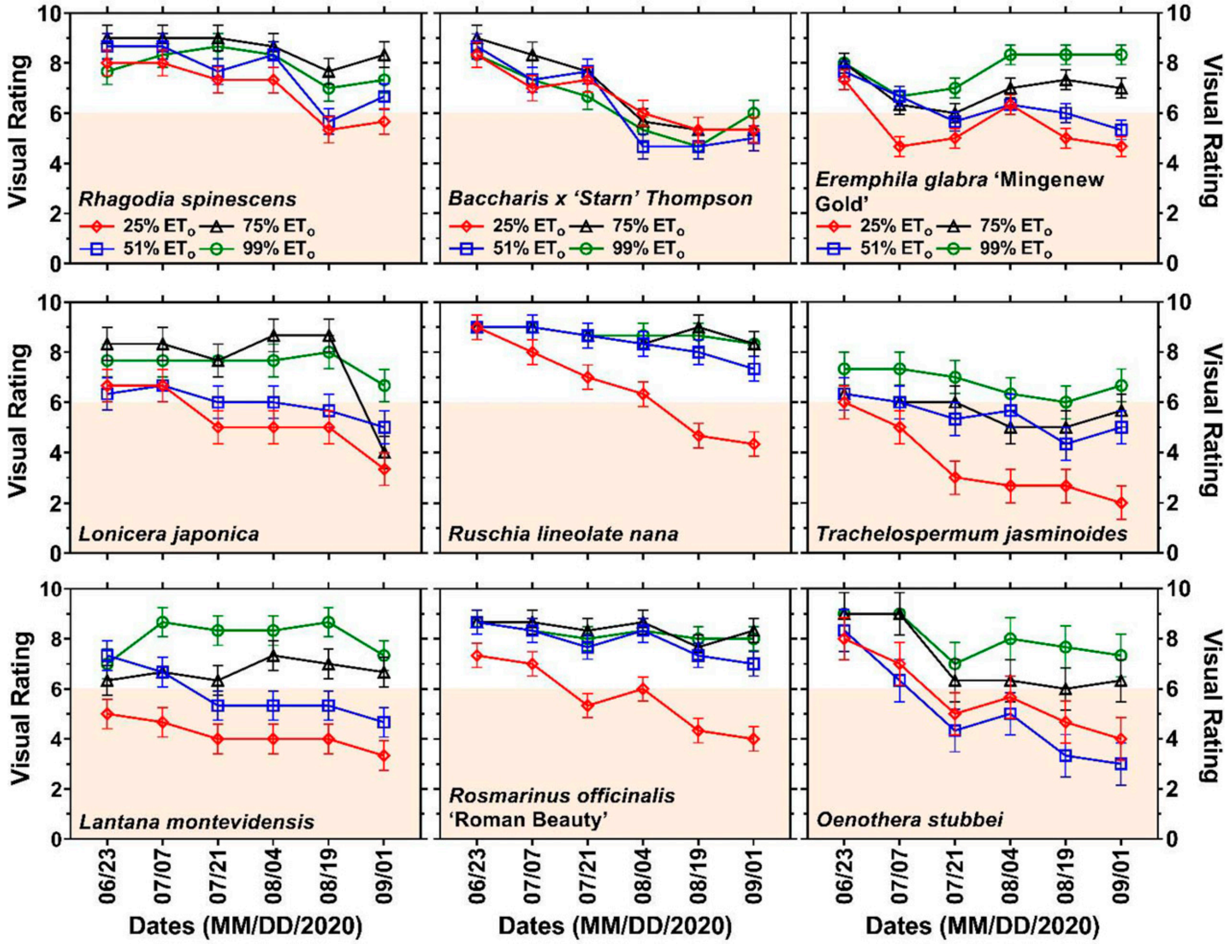

Fig. 2. Visual rating (VR) of multiple groundcover species over the growing season in 2020 as affected by varying irrigation rates (25%, 51%, 75%, and 99% ET_o). For each groundcover species, VR values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance (i.e., VR <6 on a scale of 1 to 9). Error bar represents the standard error of the means for each groundcover species during the growing season. ET_o = reference evapotranspiration.

the VR values for *Baccharis* remained at or above the acceptable threshold of six (Fig. 3). Unlike *Baccharis*, *Trachelospermum* was greatly affected by irrigation treatments. The mean VR values were above the minimum threshold of 6 only for irrigation levels ≥96% ET_o for the whole experimental period (Figs. 2 and 3). The VR values were as low as two for the irrigation rates ≤ 25% ET_o.

Relationship between NDVI and VR. Figure 4 shows the relationship between the VR and NDVI of multiple groundcovers in this study. Minimum NDVI values identified for each groundcover are presented in Table 4. A statistically significant ($P < 0.001$) linear relationship was established for nine landscape groundcovers. *Eriogonum* did not yield a significant relationship, so a minimum NDVI threshold value for this groundcover was not developed. However, based on the VR (Fig. 3), it had maintained the minimum acceptable VR ratings throughout the experimental period in 2021; therefore, all the NDVI values (0.40–0.67) were within the acceptable quality range for this groundcover. The relationship between NDVI and VR for three groundcover species, including *Trachelospermum*, *Rosmarinus*, and *Oenothera* showed a strong correlation with $R^2 \geq 0.80$. Landscape groundcovers, including *Baccharis*, *Lonicera*, *Ruschia*, and *Lantana*, showed a significant and robust correlation between NDVI and VR with $70 < R^2 < 80$ (Fig. 4). *Rhagodia* (R^2 = 0.35), and *Eremphila* (R^2 = 0.49) also showed a significant relationship between NDVI and VR (Fig. 4).

Impact of irrigation on NDVI of landscape groundcovers. In 2020, the data collection date (i.e., time of the season) significantly affected ($P < 0.001$) the NDVI readings (Table 3, Fig. 5) of all nine groundcovers (*Eriogonum* was not included in 2020). The effect of irrigation rates also was significant ($P \leq 0.03$; Table 3) on the NDVI values of all the groundcovers except *Baccharis* ($P = 0.178$; Table 3). The interaction between irrigation and the data collection date had significant ($P < 0.001$) effects on NDVI readings of all groundcovers in 2020. Like in 2020, the effect of data collection dates on the NDVI was significant ($P \leq 0.013$; Table 3) for all 10 landscape groundcovers in 2021 during the experimental season (Fig. 6). In addition, the varying irrigation rates also significantly ($P < 0.01$) affected the NDVI values of seven groundcovers except for *Rhagodia*, *Baccharis*, and *Eriogonum* ($P > 0.05$). The interaction effect of irrigation rates and data collection date was significant for six groundcover species and groundcovers, but *Rhagodia*, *Trachelospermum*, *Oenothera*, and *Eriogonum* were not significantly ($P > 0.05$) influenced by the interaction of irrigation rates and data collection dates.

Among all groundcovers, *Rhagodia* had slight variation of the NDVI values during the experimental season and between the irrigation treatments. *Rhagodia* with silvery green leaves had mean NDVI values ranging between 0.41 and 0.62 in 2020. On the basis of the fitted linear regression between NDVI and VR, the minimum NDVI threshold for *Rhagodia* was 0.46 (Table 4). For irrigation treatments ≥75% ET_o, this groundcover had NDVI values above the minimum threshold (0.46) throughout the experimental season in 2020. Additionally, for the irrigation rates of 25% and 51% ET_o, the NDVI values were on the threshold borderline from late July to October, as shown in the light orange shaded region in Fig. 5. However, in 2021, the mean NDVI values (ranged between 0.46 and 0.58) for all irrigation rates and data collection dates were at or well above the acceptable minimum threshold. Figure 6 shows the performance of *Rhagodia* in 2021 for four irrigation rates from May to October. *Baccharis*

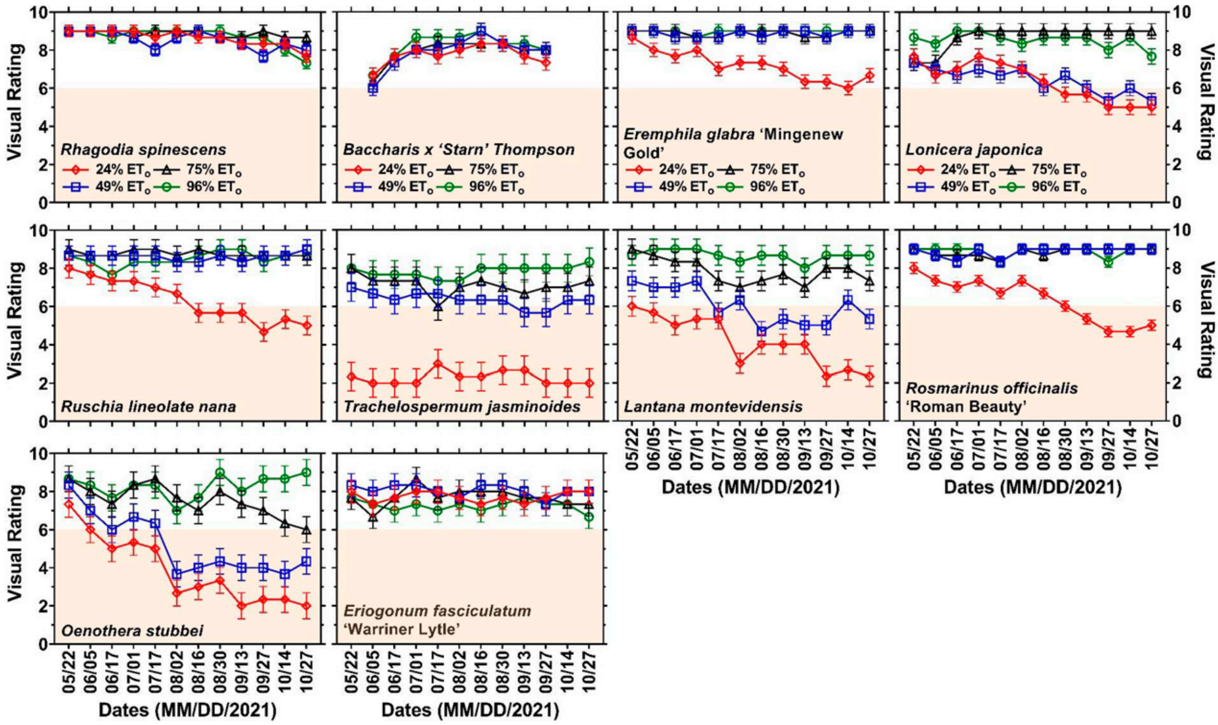

Fig. 3. Visual rating (VR) of multiple groundcover species over the growing season in 2021 as affected by varying irrigation rates (24%, 49%, 75%, and 96% ET_o). For each groundcover species, VR values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance (i.e., VR <6 on a scale of 1 to 9). Error bar represents the standard error of the means for each groundcover species during the growing season. ET_o = reference evapotranspiration.

mostly maintained its steady growth and health under all the irrigation rates in 2020 and 2021. However, the interaction effect of irrigation rates and data collection date was significant. In 2020, its mean NDVI values ranged from 0.27 to 0.78, with the lowest recorded in early to mid-August. Similarly, the mean NDVI ranged from 0.43 to 0.69 in 2021. Given the NDVI threshold of 0.41 (Table 4), *Baccharis* maintained its acceptable quality for all irrigation rates in 2021 (Fig. 6). However, in 2020, it fell below that threshold

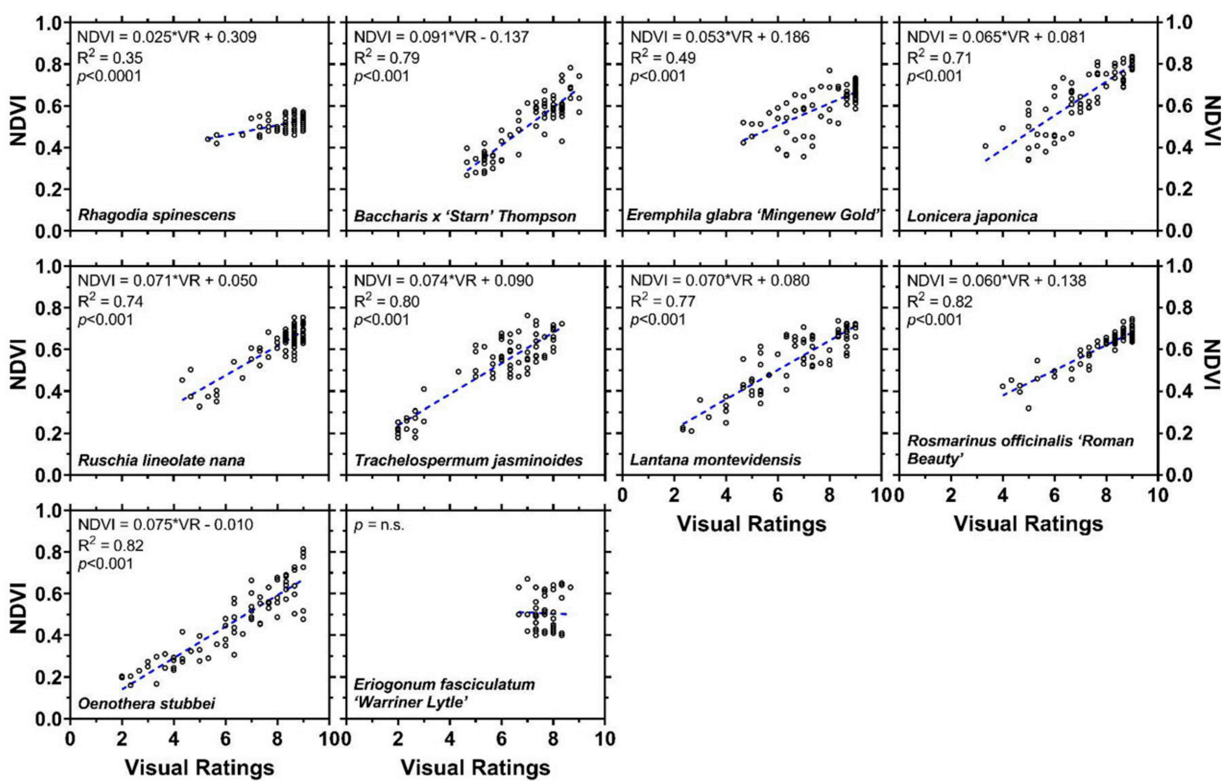

Fig. 4. Relationships between normalized difference vegetation index (NDVI) and visual rating (VR) of multiple groundcover species used in the study. Data in 2020 and 2021 for all groundcover (only from 2021 for *Eriogonum*) were combined to determine the relationship between NDVI and VR.

Table 4. Landscape groundcover water response functions and the minimum NDVI threshold developed for each groundcover to be minimally acceptable.

Scientific name	Minimum NDVI[i]	Water response function to estimate NDVI
Rhagodia spinescens	0.46	$0.55 + (2.73{*}10^{-4}{*}I^{ii}) - (1.47{*}10^{-4}{*}CET_o^{iii}) + (8.47{*}10^{-7}{*}I{*}CET_o)$
Baccharis × 'Starn' Thompson	0.41	$0.73 - (9.30{*}10^{-4}{*}I) - (4.26{*}10^{-4}{*}CET_o) + (3.10{*}10^{-6}{*}I{*}CET_o)$
Eremphila glabra 'Mingenew Gold'	0.50	$0.66 + (2.21{*}10^{-4}{*}I) - (3.78{*}10^{-4}{*}CET_o) + (3.95{*}10^{-6}{*}I{*}CET_o)$
Lonicera japonica	0.47	$0.77 + (3.70{*}10^{-4}{*}I) - (6.01{*}10^{-4}{*}CET_o) + (5.13{*}10^{-6}{*}I{*}CET_o)$
Ruschia lineolate nana	0.48	$0.71 + (2.58{*}10^{-4}{*}I) - (4.11{*}10^{-4}{*}CET_o) + (3.72{*}10^{-6}{*}I{*}CET_o)$
Trachelospermum jasminoides	0.53	$0.42 + (2.31{*}10^{-3}{*}I) - (4.07{*}10^{-4}{*}CET_o) + (5.10{*}10^{-6}{*}I{*}CET_o)$
Lantana montevidensis	0.50	$0.53 + (2.53{*}10^{-3}{*}I) - (4.59{*}10^{-4}{*}CET_o) + (3.30{*}10^{-6}{*}I{*}CET_o)$
Rosmarinus officinalis 'Roman Beauty'	0.50	$0.68 + (3.96{*}10^{-4}{*}I) - (3.43{*}10^{-4}{*}CET_o) + (3.14{*}10^{-6}{*}I{*}CET_o)$
Oenothera stubbei	0.44	$0.45 + (4.08{*}10^{-3}{*}I) - (3.95{*}10^{-4}{*}CET_o)$
Eriogonum fasciculatum 'Warriner Lytle'	—	$0.57 + (8.48{*}10^{-4}{*}I) - (2.08{*}10^{-4}{*}CET_o)$

[i] NDVI = normalized difference vegetation index.

[ii] I = irrigation percentage expressed in terms of reference evapotranspiration.

[iii] CET_o = cumulative evapotranspiration (millimeters).

in August, and irrigation treatments 51% and 25% ET_o struggled to rise above the threshold of 0.41 (Fig. 5).

Groundcovers *Ruschia* and *Rosmarinus* showed a similar trend of NDVI values in 2020 and 2021. Three irrigation rates (≥49% ET_o) had significantly the same NDVI values, and they were all above the minimum acceptable NDVI values of 0.48 and 0.50, respectively. Only the plots with ≤25% ET_o irrigation treatments showed signs of water stress, as reflected by the NDVI values. The NDVI values of both species deteriorated starting from late July and dropped below the minimum acceptable NDVI threshold. Groundcover *Eremphila* showed a similar trend in 2021. For three irrigation rates (≥49% ET_o), the NDVI values were significantly the same and were above the established minimum acceptable NDVI threshold of 0.50. For 24% ET_o irrigation treatments, the NDVI values dropped significantly below 0.5 starting in July (Fig. 6). In 2020, the NDVI values for *Eremphila* were above 0.50 minimum acceptable threshold only for two irrigation rates (75% and 99% ET_o). The NDVI values dropped significantly below the acceptable threshold starting in July for 25% ETo, and it remained at the borderline of the NDVI = 0.50 for the 75% ET_o irrigation treatment for most of the experimental season in 2020 (Fig. 5).

Until mid-August 2020 (Fig. 5) and early August 2021 (Fig. 6), *Lonicera* grew well for all four irrigations without showing signs of drought injury. After that, the NDVI values for deficit irrigation treatments ≤51% ET_o fell below the desired threshold value of 0.47 and showed signs of water stress. In 2020, for September (Fig. 5), NDVI values for 60% ET_o treatment were significantly dropped and came

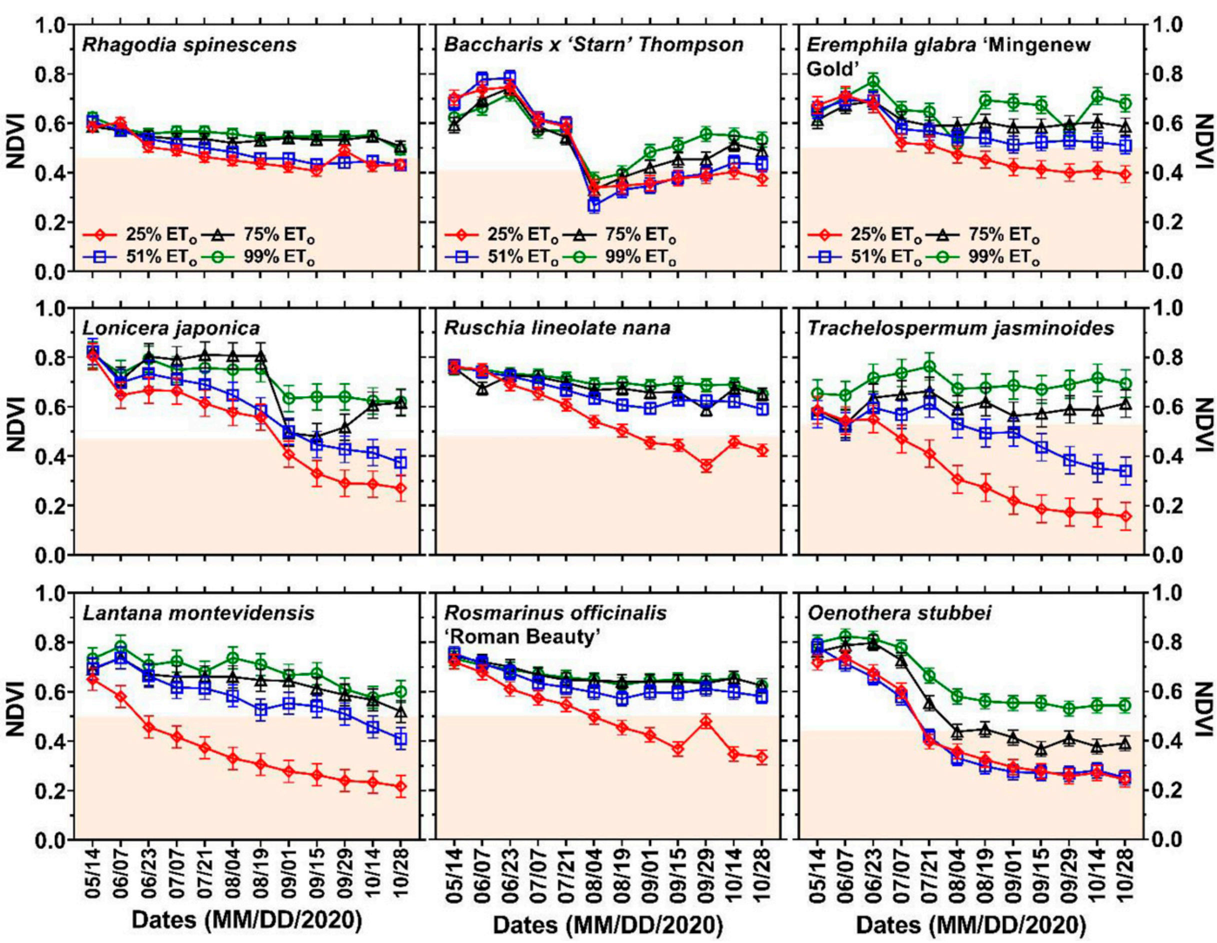

Fig. 5. The normalized difference vegetation index (NDVI) of multiple groundcover species over the growing season in 2020 under varying irrigation rates (25%, 51%, 75%, and 99% ET_o). For each groundcover species, NDVI values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance. Error bar represents the standard error of the means for each groundcover species during the growing season. ET_o = reference evapotranspiration.

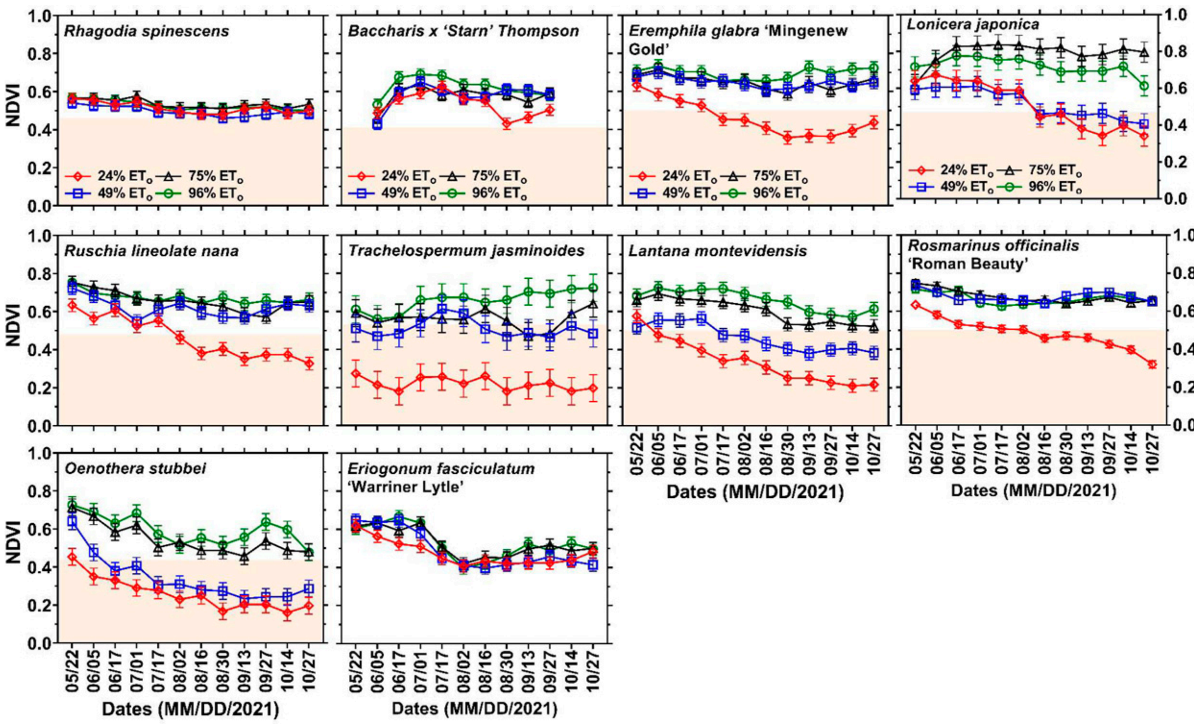

Fig. 6. The normalized difference vegetation index (NDVI) of multiple groundcover species over the growing season in 2021 under varying irrigation rates (24%, 49%, 75%, and 96% ET_o). For each groundcover species, NDVI values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance. Error bar represents the standard error of the means for each groundcover species during the growing season. ET_o = reference evapotranspiration.

close to the minimum threshold value of 0.47; however, groundcover *Lonicera* grew sufficiently for the 75% ET_o treatment, and NDVI values started getting better. In both years (except for September 2020), the NDVI values for $\geq$75% ET_o irrigation treatments were significantly the same, with mean NDVI values for 75% ET_o treatment being slightly more than that of $\geq$96% ET_o treatments (Figs. 5 and 6). For *Lantana*, in both years, irrigation treatments $\geq$75% ET_o had acceptable mean NDVI values above its NDVI threshold of 0.5 (Table 4). However, as the summer progressed, the NDVI values for all the irrigation rates decreased such that the NDVI values of the irrigation treatments $\leq$51% ET_o fell below the acceptable threshold showing visible water-stress symptoms. As a result, the minimum NDVI readings were only 0.22 and 0.21 for the lowest irrigation treatments in 2020 (Fig. 5) and 2021 (Fig. 6), respectively.

Oenothera maintained acceptable NDVI values (Figs. 5 and 6) for irrigation treatment $\geq$96% ET_o in both years. However, plants treated with irrigation treatments $\leq$51% ET_o showed signs of water stress and had mean NDVI values less than the NDVI threshold of 0.44 (Table 4). For 75% ET_o irrigation treatment, the groundcover maintained the NDVI values above the minimum threshold of 0.44 for the experimental season in 2021, whereas it was right below that threshold in 2020 starting from August.

The mean NDVI values of *Trachelospermum* were significantly affected by irrigation rates and data collection dates in both years (Table 3). However, the interaction effect of irrigation rates and data collection dates was significant ($P < 0.001$) only in 2020. In both years, the irrigation treatment $\geq$96% ET_o only had NDVI values well above the minimum required threshold (i.e., NDVI = 0.53; Table 4) for the whole experimental season (Figs. 5 and 6). The 75% ET_o irrigation treatment had NDVI values above the threshold in 2020, but it was not the case in 2021. Plants at <25% ET_o treatment always had the lowest NDVI values. Switching back to nonlimiting irrigation between Nov 2020 and Apr 2021 did not help this species regenerate from the water stress. Hence, NDVI values were relatively lower in 2021 than in 2020.

Eriogonum did not grow well in 2020, so only 2021 data were processed and presented for the results. The NDVI was not significantly affected by different irrigation rates and their interaction with the data collection date (Table 3). For all four irrigation treatments, the NDVI values followed the same trend (Fig. 6). The maximum mean NDVI value recorded was 0.67, whereas the minimum was 0.40.

Groundcover water response function. Table 4 shows the GCWRFs developed using 2-year data for all 10 groundcover species. The relationships between the measured and the GCWRFs-estimated NDVI are presented in Fig. 7. The strength and accuracy of the models developed were presented in terms of the coefficient of correlation (R^2), MAE, MBE, and RMSE.

The cumulative ET_o for scenarios minimum, mean, and maximum atmospheric evaporative demand based on long-term data were 403, 949, and 1302 mm, respectively, for the experimental period from May to October. All groundcovers maintained their growth and aesthetic values at 80% ET_o irrigation (Fig. 8) for all three scenarios except *Oenothera*, which only performed well under minimum atmospheric evaporative demand was minimum. A significant relationship between NDVI and VR was not obtained for *Eriogonum*. However, NDVI >0.4 were considered acceptable for this species because all their corresponding VR values were above the minimum threshold. The NDVI of *Baccharis* and *Lantana* under maximum evaporative demand dropped to values close to their thresholds toward the end of October.

Under 60% ET_o irrigation application, three landscape groundcover, including *Eremphila*, *Ruschia*, and *Rosmarinus* maintained their acceptable NDVI values for all weather scenarios (Fig. 9). Groundcovers *Rhagodia*, *Baccharis*, and *Lonicera* maintained their acceptable quality at 60% ET_o irrigation only under minimum and mean atmospheric evaporative demands. Groundcovers *Trachelospermum*, *Lantana*, and *Oenothera* had NDVI values below the minimum threshold at 60% ET_o irrigation rate for the scenario when the daily ET_o equals the mean or maximum of the long-term average (Fig. 9).

Rhagodia maintained its quality for all three atmospheric evaporation demand at 40% ET_o until early September, after which the quality of *Rhagodia* dropped below the acceptable threshold except for minimum atmospheric evaporative demand (Fig. 10). Groundcovers *Rosmarinus*, *Ruschia*, and *Baccharis* maintained NDVI above their thresholds at 40% ET_o except under the maximum atmospheric

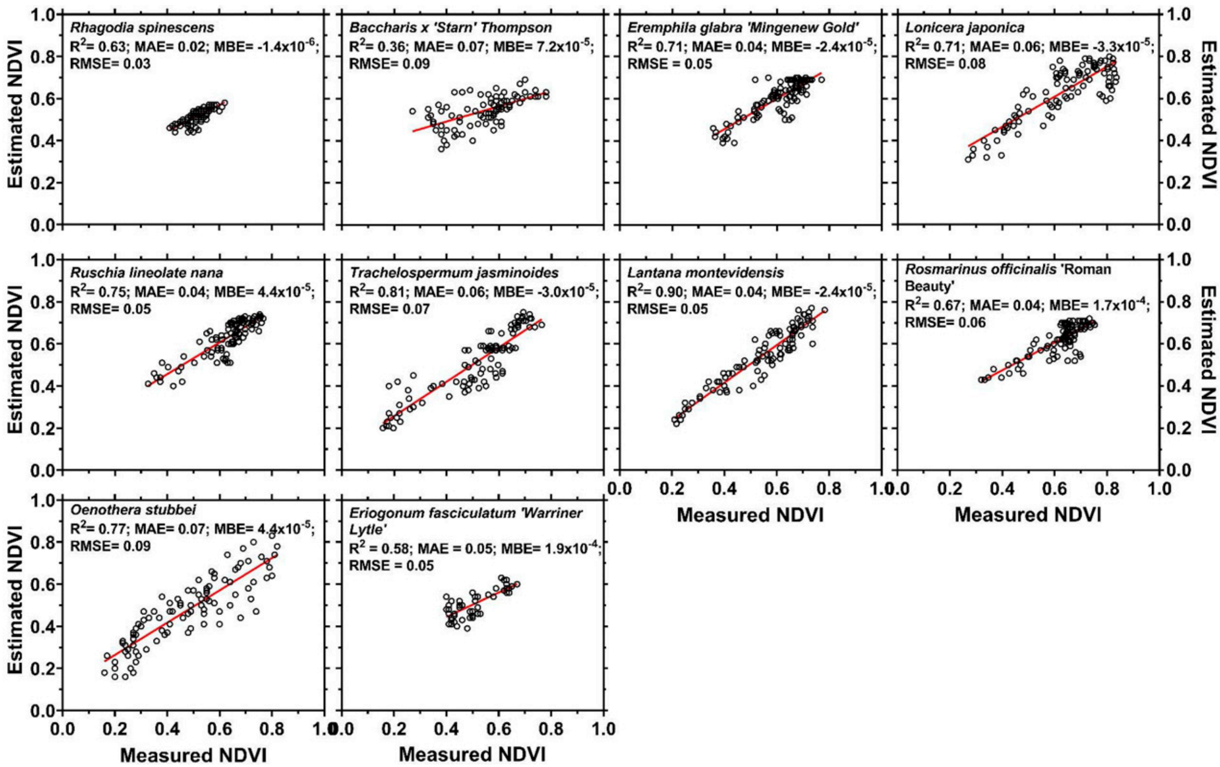

Fig. 7. Relationships between measured and estimated normalized difference vegetation index (NDVI) for multiple groundcovers obtained using landscape groundcover water response functions.

evaporative demand scenario. The NDVI for *Eremphila* and *Lonicera* fell below the acceptable threshold toward the end of the season under the mean atmospheric evaporative demand scenario. The groundcover *Trachelospermum* could not maintain the acceptable NDVI threshold at 40% ET_o and *Lantana* and *Oenothera* only held the acceptable NDVI values under the minimum atmospheric evaporative demand scenario.

Fig. 11 showed how groundcovers responded to 20% ET_o irrigation application

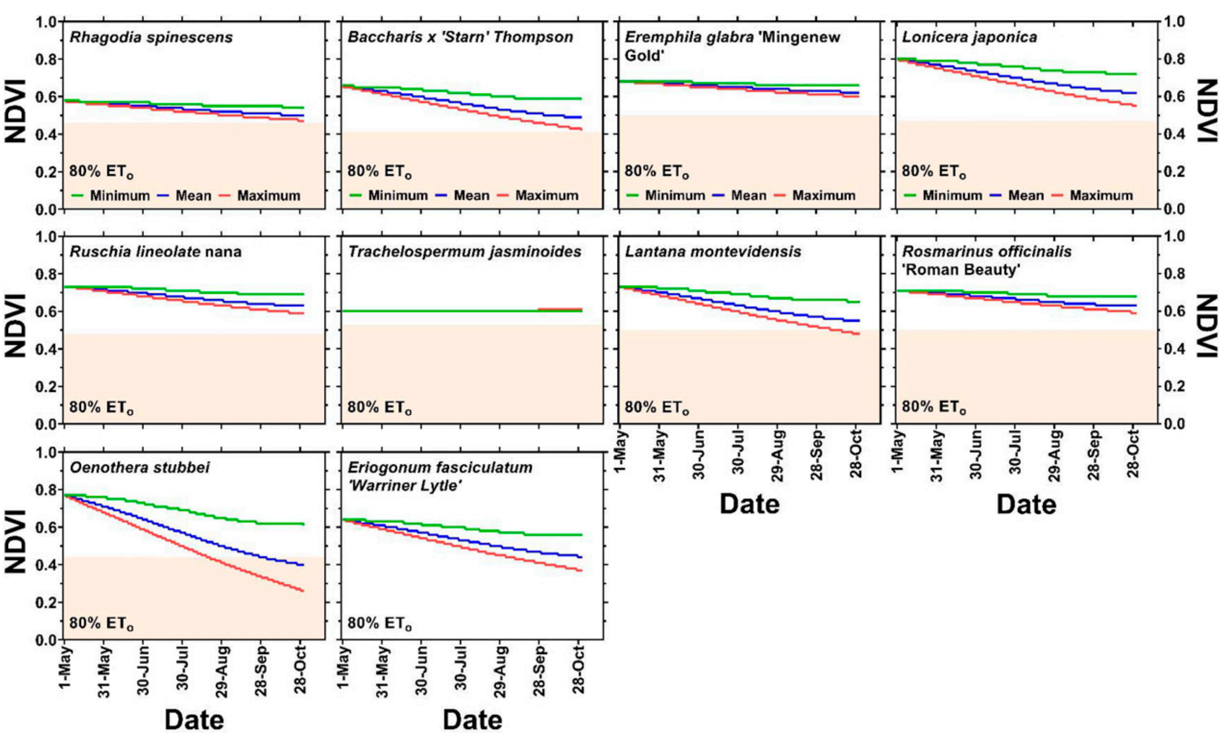

Fig. 8. Response of 10 landscape groundcovers to irrigation scenario equivalent to 80% reference evapotranspiration (ET_o) using the groundcover water response functions. The minimum, mean, and maximum scenarios represent minimum, mean, and maximum cumulative ET_o for that specific date based on the long-term weather data. For each groundcover species, NDVI values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance.

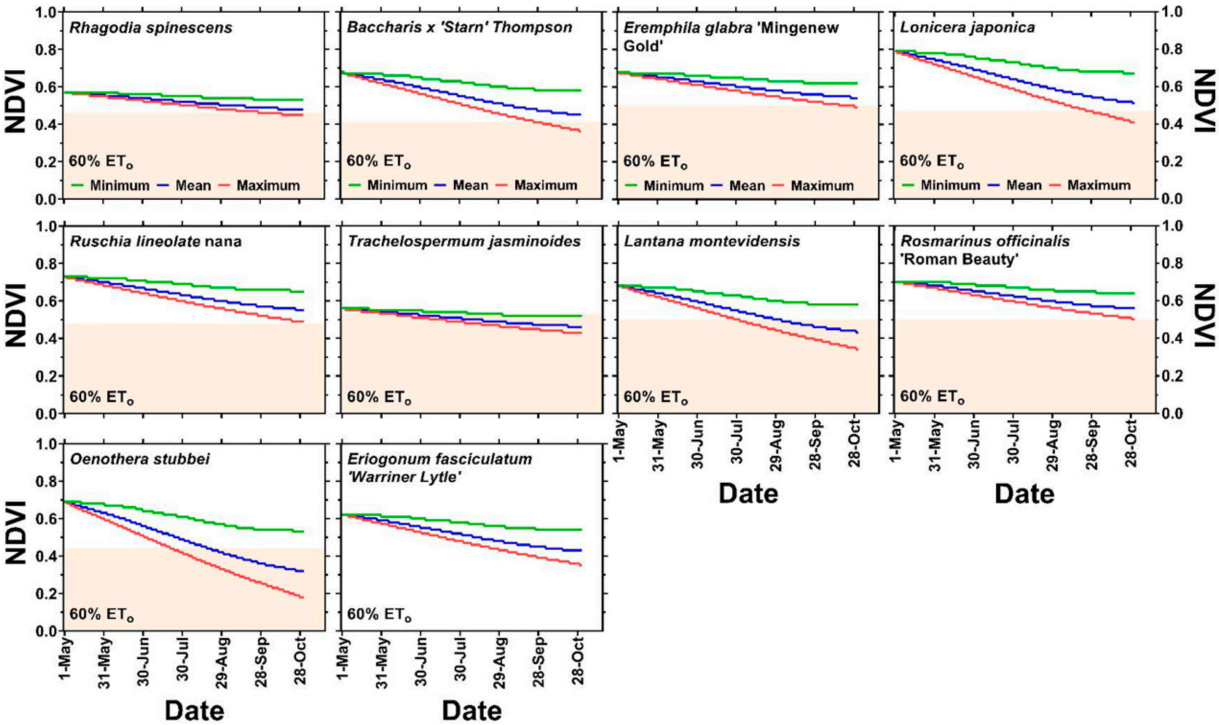

Fig. 9. Response of 10 landscape groundcovers to irrigation scenario equivalent to 60% reference evapotranspiration (ET_o) using the groundcover water response functions. The minimum, mean, and maximum scenarios represent minimum, mean, and maximum cumulative ET_o for that specific date based on the long-term weather data. For each groundcover species, NDVI values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance.

under minimum, mean and maximum atmospheric evaporative demand scenarios. All groundcovers, except *Trachelospermum*, *Lantana*, and *Oenothera*, performed well under the minimum atmospheric evaporative demand scenario. At 20% ET_o irrigation application and mean atmospheric evaporative demand, six groundcovers maintained the acceptable NDVI threshold early in the experimental season, yet their quality fell below the minimum threshold as the season progressed. A similar trend with a more pronounced reduction in NDVI values was observed under maximum atmospheric evaporative demand (Fig. 11). The NDVI values of groundcovers

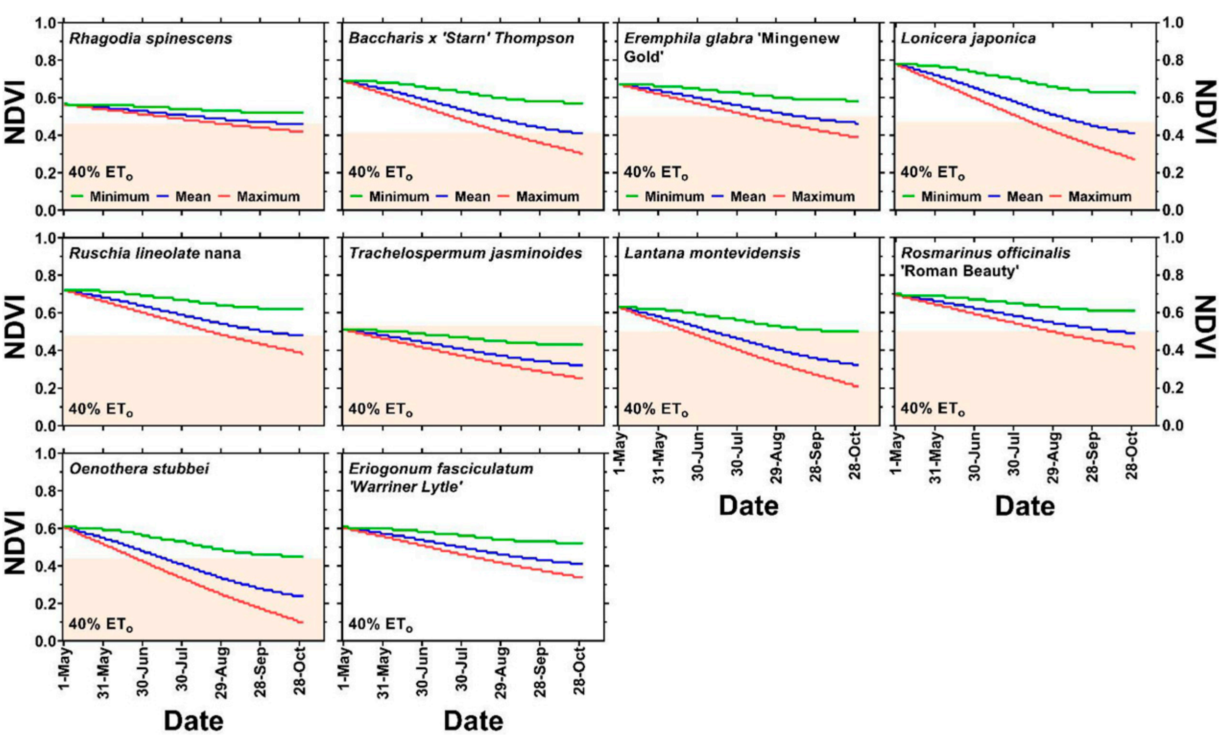

Fig. 10. Response of ten landscape groundcovers to irrigation scenario equivalent to 40% reference evapotranspiration (ET_o) using the groundcover water response functions. The minimum, mean, and maximum scenarios represent minimum, mean, and maximum cumulative ET_o for that specific date based on the long-term weather data. For each groundcover species, NDVI values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance.

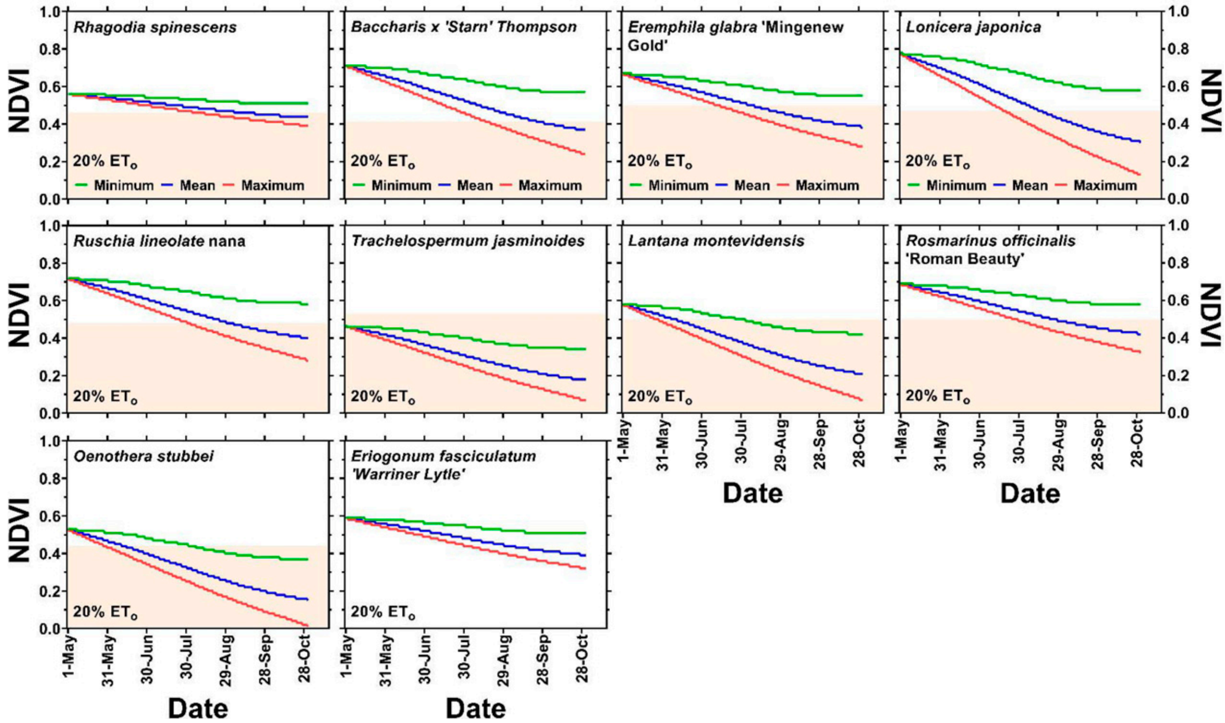

Fig. 11. Response of 10 landscape groundcovers to irrigation scenario equivalent to 20% reference evapotranspiration (ET_o) using the groundcover water response functions. The minimum, mean, and maximum scenarios represent minimum, mean, and maximum cumulative ET_o for that specific date based on the long-term weather data. For each groundcover species, NDVI values that fall in the light orange shaded region represent not meeting the minimal acceptance appearance.

Trachelospermum, *Lantana*, and *Oenothera* were severely decreased under the mean and maximum atmospheric evaporative demands.

Discussion

Performance of the smart irrigation controller. The overestimate of ETo by the Weathermatic SL4800 was similar to the 5% to 8% and 3% to 12% overestimation that we observed in two turfgrass irrigation trials in central and southern California, respectively (Haghverdi et al. 2021a, 2021c). A higher range of ET_o overestimation (9% to 33%) was reported in a study done in Gainesville and Wimauma, FL (Rutland and Dukes 2014), which could be attributed to their different climatic conditions. Our results suggest that the Weathermatic SL4800 controller is reliable for autonomous irrigation scheduling in summer months in semiarid environments. However, we recommend more studies to assess its accuracy in different climate regions based on long-term data. Also, the average ET_o for the study periods was within 9% of the 30-year average. Likewise, individual monthly average cumulative ET_o was within 18% of the long-term average (Table 1). Smart irrigation controllers showed better performance in estimating the irrigation needs; however, programming based on historical data also showed some potential but fluctuated sharply between months of the growing season.

NDVI as an indicator of groundcover growth and quality. The relationship between NDVI and VR was established for 10 landscape groundcovers in this study. We suggest NDVI as a proxy to quantify the growth and health of groundcovers in a fast and consistent manner, given its high correlation ($0.35 \leq R^2 \leq 0.82$) with VR for almost all the species in this study. The minimum NDVI threshold (equal to VR of 6) ranged from 0.41 to 0.53 among species. We recommend that NDVI thresholds are established for each species separately since the NDVI values are impacted by each species' unique leaf and flowering characteristics (Shen et al. 2009, 2010). We also observed that pruning substantially reduced the NDVI values, especially in the case of woody-type groundcovers. Summer flowering may also impact the NDVI readings of some species, such as *Eremphila*, which bears yellow flowers. Yellow flowers reduce the NDVI readings by increasing the red band canopy reflectance without apparent variation in near-infrared reflectance (Shen et al. 2009). These not water-stress-related fluctuations in the NDVI values should be considered for large-scale remote sensing studies when ground-truth data might not be readily available.

Water conservation potential of the groundcover species. In this study, groundcover *Rhagodia* and *Eriogonum* showed the highest potential for performing well under limited water application. *Rhagodia* and *Eriogonum* formed a dense canopy with almost complete coverage, resisting evaporative loss and conserving soil moisture (Huang 2008). This helped these species stay green and healthy and maintain the acceptable VR at an irrigation rate of 24% to 25% ET_o. This is roughly one-third of the minimum required irrigation application to sustain hybrid bermudagrass quality in the summer in inland Southern California (Haghverdi et al. 2021c). A slightly lower irrigation level (20% ET_o) was recommended for *Rhagodia* and *Eriogonum* in coastal southern California (Sisneroz et al. n.a.). The GCWRF estimations suggest that under extremely high atmospheric evaporative demand, the best performing groundcovers (*Rhagodia*, *Eremphilla*, *Ruschia*, and *Rosmarinus*) may require substantially higher irrigation applications (60% ET_o) to maintain the acceptable quality throughout the summer. Under the mean atmospheric evaporative demand scenario, however, the groundcovers (*Rhagodia*, *Baccharis*, *Ruschia*, and *Rosmarinus*) are expected to maintain their quality at the 40% ET_o irrigation application rate (Fig. 10).

A minimum of 49% ET_o irrigation was found to be sufficient for *Ruschia*, *Rosmarinus, and Eremphila* to keep the visually acceptable groundcover quality. A lower irrigation level of 20% ET_o was reported to maintain the acceptable quality by (Sisneroz et al. n.d.) for *Ruschia* species in Davis and Irvine, CA. This is attributed to differences in field and weather conditions between the two studies, including a) full sun in our study vs. 50% shade in (Sisneroz et al. n.d.) and b) little to no rain in our study vs. considerable rainfall (177 mm) reported by (Sisneroz et al. n.d.) from April to October in Irvine. The least performing species was *Trachelospermum*, with a longer establishment time than other species and visible water stress symptoms even at a 75% ET_o application rate. Overall, our results showed that groundcovers have irrigation water-saving potentials; however, not all groundcovers are drought-tolerant and perform at lower irrigation rates than the irrigation requirement of turfgrass species in the region. The use of NDVI to assess the quality of groundcovers might be a new normal, but it comes with challenges, and further research that identifies the time and frequency of data collection for homeowners and stakeholders to get reliable and meaningful results are needed.

Conclusion

A 2-year (2020–21) field study evaluated the effect of deficit irrigation on the NDVI and visual quality rating of 10 landscape groundcovers in inland Southern California. Following are the main conclusions drawn:

I The Weathermatic SL4800 smart irrigation controller showed a fair potential to schedule autonomous irrigation in summer in semiarid regions with slight overirrigation (on average 4.7% to 7.7%) compared with CIMIS-ET_o.

II Development of plant-specific plant factors for irrigation scheduling is needed because groundcovers respond differently to different irrigation scenarios, and not all groundcovers can be drought-tolerant and withstand severe deficit irrigation. Three landscape groundcovers, including *Rhadogia spinescens*, *Baccharis* × 'Starn' Thompson, *Eriogonum fasciculatum* 'Warriner Lytle' withstood water stress and maintained their growth and visual quality even at a 24% ET_o irrigation application. Groundcovers, *Ruschia lineolate* nana, *Rosmarinus officinalis* 'Roman Beauty', and *Eremphila glabra* have the potential to perform well with ≥49% ET_o irrigation. Landscape groundcovers *Lantana montevidensis*, *Oenothera stubbei*, and *Lonicera japonica* required 75% ET_o or more irrigation to maintain their growth and acceptable visual appearance. Results showed that *Trachelspermum jasminoids* require a more extended establishment period before deficit irrigation is imposed.

III NDVI showed a potential to monitor the growth and quality of landscape groundcovers in a fast and consistent manner; however, the growth stages and maintenance activities can affect the readings. Therefore, NDVI should be evaluated, and minimum thresholds should be established for each groundcover. In this study, a minimum NDVI threshold was identified for multiple landscape groundcovers which can be used as an alternative to VR.

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