Climate-ready Landscape Plants: Garden Roses Trialed at Reduced Irrigation Frequency in Utah, USA

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Abstract. Increased urban and suburban populations in the arid western United States have resulted in more water demand; however, water availability in the region has become limited because of inadequate precipitation. Recent droughts have led to restrictions on irrigating landscape plants. Garden rose (*Rosa* ×*hybrida*) is commonly used as flowering plants in residential landscapes, but its drought tolerance has not been widely studied. The objective of this study was to determine the impact of reduced irrigation frequency on visual quality, plant growth, and physiology of five garden rose cultivars, including ChewPatout (Oso Easy® Urban Legend®), Meibenbino (Petite Knock Out®), MEIRIFTDAY (Oso Easy® Double Pink), Overedclimb (Cherry Frost™), and Radbeauty (Sitting Pretty™). Twenty-four plants of each rose cultivar were established in a trial plot at Utah Agricultural Experiment Station Greenville Research Farm (North Logan, UT, USA) in Summer 2021. Plants were randomly assigned to one of three deficit irrigation treatments for which irrigation frequencies were calculated using 80% reference evapotranspiration (ET_O) (high), 50% ET_O (medium), and 20% ET_O (low). The total volumes of irrigation water applied to each plant were 345.6, 172.8, and 43.2 L for the high, medium, and low irrigation frequencies, respectively, during the deficit irrigation trial from 12 May to 30 Sep 2022. Root zones were wetted more frequently as irrigation frequency increased from low to high irrigation frequencies. Decreased irrigation frequency increased the number of visibly wilted and damaged leaves on all rose cultivars. However, only 'Meibenbino' and 'MEIRIFTDAY' exhibited a reduction in overall appearance under decreased irrigation frequency. The relative growth indices of both 'Meibenbino' and 'MEIRIFTDAY' decreased by 6%, whereas the dry weights of their leaves decreased by 37% and 36%, respectively, as irrigation decreased from high to low frequencies. Roses in this study appeared to decrease stomatal conductance up to 51% when irrigation decreased from high to low frequencies, or when air temperature increased. 'Meibenbino' and 'MEIRIFTDAY' exhibited unacceptable overall appearance, growth reduction, and higher leaf–air temperature differences, and they were less tolerant to reduced irrigation. Although the 'Radbeauty' maintained plant growth under the reduced irrigation frequency, the large leaf size led to a more visibly wilted appearance and the potential for heat stress, thus impairing visual quality. 'ChewPatout' and 'Overedclimb' were most tolerant to deficit irrigation at 20% ET_O and maintained plant growth with acceptable visual quality and lower leaf temperatures when they received one irrigation during the growing season.

Landscape irrigation accounts for 70% of residential water use per capita in the western United States (Hayden et al. 2015). However, as extreme weather events challenge water supplies, water demands in the urban and suburban sectors have increased rapidly because of the increased population (Mini et al. 2014). Water scarcity has forced restrictions on irrigating landscape plants when drought occurs. For example, residents of North Logan, UT, USA, were limited to 2 irrigation days per week for trees, shrubs or bushes, flowers, and gardens to conserve water during drought in Jun 2022 (North Logan City 2022). Furthermore, during Summer 2022, landscape water restrictions in California allowed local homeowners to irrigate their landscape plants no more than three times per week because of insufficient precipitation (California Water Boards 2022). These restrictions have the potential to negatively affect the growth and greenness of urban vegetation. For example, landscape irrigation was prohibited during the California droughts between 2012 and 2016, thus reducing urban vegetation coverage from 45% to 35% in downtown Santa Barbara, CA, USA (Miller et al. 2020). Subsequently, new landscapes were required to be designed using drought-tolerant plants that require less irrigation (California Department of Water Resources 2023). For instance, the County of San Diego in California requires that landscape designs for residential areas contain water-efficient plants for 75% of the plant area, whereas nonresidential areas must install water-efficient landscape plants in 100% of the plant area (County of San Diego 2020).

Reference evapotranspiration (ET_O) calculated using local weather station data may be used to schedule irrigation frequency or determine the amounts of irrigation water applied to residential landscapes (Evans et al. 2022). However, when the irrigation frequency and amounts of irrigation water decrease, the visual quality of landscape plants may be impaired because of an increase in the number of necrotic leaves and a reduction in floral abundance (Hartin et al. 2018; Zollinger et al. 2006). Growth reduction under water stress can also impair visual quality by limiting leaf density

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0283	ft^{3}	m^{3}	35.3147
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
645.1600	inch^{2}	mm^{2}	0.0016
1	micron(s)	μm	1
1	mmho/cm	dS·m^{-1}	1
28.3495	oz	g	0.0353
1	ppm	mg·kg^{-1}	1
6.8948	psi	kPa	0.1450
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

and shoot uniformity (Cameron et al. 2006). When experiencing water stress, partial closure of stomata not only reduces carbon assimilation but also limits the effects of transpirational cooling, resulting in an increase in leaf temperature (Nobel 2020). Increases in leaf canopy temperatures, if large enough, can disturb the biochemical functions of enzymes and destabilize membranes and proteins, which can lead to the inhibition of photosynthesis and cell death (Taiz et al. 2015). Heat stress often becomes most severe during the late afternoon because of a large saturation deficit at that time, resulting in plants having the highest leaf temperatures and lowest stomatal conductance (Tuzet et al. 2003).

Plants can acclimate to water stresses by modifying their morphology and physiology. However, the capacity to adapt to drought stress is highly variable among plant species (Taiz et al. 2015). Plants may respond to drought stress by reducing leaf area to restrict transpirational water loss. For instance, carnation (*Dianthus caryophyllus*) defoliated to limit leaf surface area for transpiration when irrigation was decreased by 65% (Álvarez et al. 2009). Dormancy also allows plants to avoid drought and heat during summer months through leaf senescence and abscission (Newell 1991). The leaves of California buckeye (*Aesculus californica*) senesced and abscised before the dry season, allowing the plants to have leafless canopies during summer to avoid water stress (Newell 1991). Drought-resistant plants can also adjust stomatal conductance to limit water loss from the transpiration pathway (Chen et al. 2022). McCammon et al. (2006) reported that landscape designs containing drought-tolerant ornamental plants could maintain better visual quality compared with those with high water-use plants when a 5-week-long dry-down period was imposed. Reid and Oki (2008) reported that drought-tolerant landscape plants, including Van Houtte's columbine (*Aquilegia eximia*) and blue grama (*Bouteloua gracilis*), maintained acceptable appearances when the interval between irrigations increased from 13 to 58 d.

Roses (*Rosa* ×*hybrida*) are flowering plants often used in residential landscapes (Sagers 2012). In the United States, more than 24 million roses are sold annually, with an estimated sales value of $168 million, accounting for 24.9% of the total value of deciduous shrubs sold on the market in the United States (US Department of Agriculture 2020). The drought tolerance of rose is highly diverse among cultivars. Cai et al. (2012) reported that container-grown roses could use partial closure of stomata to acclimate to drought stress in a greenhouse. A deficit irrigation treatment of 20% $\mathrm{ET_O}$ resulted in a marginally acceptable visual quality of 'Aushouse' rose, but good aesthetic quality for 'Meijocos' rose grown in an open field in Davis, CA, USA (Reid et al. 2019). The drought tolerance of rose has not been widely studied, and morphological and physiological mechanisms that allow roses to maintain an aesthetic appearance under drought have been rarely investigated.

'ChewPatout' (Oso Easy® Urban Legend®) and 'MEIRIFTDAY's (Oso Easy® Double Pink) are disease-tolerant and heat-tolerant landscape roses that have compact and mounding canopies (Proven Winners 2023). The cultivar Meibenbino (Petite Knock Out®) is a miniature rose with pest tolerance, and Overedclimb (Cherry Frost™) is a climbing rose exhibiting excellent disease resistance (Star Roses and Plants 2023). 'Radbeauty' (Sitting Pretty™) has good disease resistance and is highly attractive to pollinators (Star Roses and Plants 2023). These cultivars are commercially available; however, their performance under deficit irrigation has not been investigated previously. This study aimed to investigate the effects of reduced irrigation frequency on the growth and morphological, physiological, and canopy temperature changes of the five rose cultivars. We hypothesized that decreased irrigation frequency (with the same application volume at each irrigation) would reduce floral abundance and dry weights of stems and leaves of rose cultivars and increase canopy temperatures and the proportion of leaves visibly wilted, and that rose cultivars would reduce stomatal conductance and leaf area when irrigation frequency decreases.

To test these hypotheses, the objectives of this research were to determine plant growth and morphological and physiological differences of five rose cultivars at three decreased irrigation frequencies in a field setting, and to investigate the relationship between the overall aesthetic of rose cultivars and their morphological and physiological modifications in response to reductions in irrigation frequency.

Materials and methods

PLANT MATERIALS AND FIELD LAYOUT. 'ChewPatout' and 'MEIRIFTDAY' roses donated by the Spring Meadow Nursery (Grand Haven, MI, USA) were received on 23 Mar 2021, and 'Meibenbino', 'Overedclimb', and 'Radbeauty' roses donated by the Star® Roses and Plants Nursery (West Grove,

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PA, USA) were received on 9 Apr 2021. The roses were transplanted to 2-gallon injection-molded polypropylene containers (no. 2B; Nursery Supplies, Orange, CA, USA) filled with a soilless substrate (Metro-Mix® 820; SunGro Horticulture, Agawam, MA, USA) once received. Plants were irrigated with Logan, UT, USA, potable water (electrical conductivity = 0.403 $dS \cdot m^{-1}$, pH = 7.88) until substrates reached the container capacity, and they were kept in a Utah Agricultural Experiment Station research greenhouse (Logan, UT, USA). High-pressure sodium lamps (Hydrofarm, Petaluma, CA, USA) were installed 1.5 m above the growing bench to provide supplemental light from 0600 to 2200 HR when light intensity inside the greenhouse was less than 500 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Ambient temperatures within the greenhouse were maintained at (mean ± *SD*) 24.9 ± 0.5 °C during the day and 21.6 ± 0.2 °C at night, and the daily light integral at the canopy level was 40.8 ± 6.7 $mol \cdot m^{-2} \cdot d^{-1}$.

On 19 May 2021, plants were transplanted to an experimental plot at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA (lat. 41°45′56.66″N, long. 111°48′37.00″W, elevation 1400 m), with 2.0 m between rows and 2.0 m between plants in full sun conditions. All plants were irrigated by pressure-compensating emitters (PCR4-36; Dramm Corp., Manitowoc, WI, USA) connected to dribble rings at a flow rate of (mean ± *SD*) 2.35 ± 0.03 $mL \cdot s^{-1}$ using secondary water (untreated, unfiltered water) (electrical conductivity = 0.373 $dS \cdot m^{-1}$; pH = 8.38). The soil in the experimental plot is a Millville silt loam, and the values of field capacity and permanent wilting point were estimated to be 0.24 and 0.06 $m^3 \cdot m^{-3}$ (Or 1990), resulting in a plant available water value of 0.18 $m^3 \cdot m^{-3}$ (O'Geen et al. 2017). The experimental plot was covered with large chunk bark mulch (Mountain West Products, Rexburg, ID, USA) to control weeds. Soil samples collected from the plot were submitted to the Utah State University Analytical Laboratory (Logan, UT, USA) for analysis, and the soil pH, salinity, and mineral contents are presented in Table 1. Weather data, including cumulative ET_O and precipitation, average and maximum air temperatures, daily light integral, and average vapor pressure, were recorded by a Utah Climate Center weather station (lat. 41°45′59.32″ N, long. 111°48′37.8″ W, elevation 1400 m) ~250 m away from the experimental plot.

Table 1. Characteristics of soils in the experimental plot at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA, for testing 'ChewPatout', 'Meibenbino', 'MEIRIFTDAY', 'Overedclimb', and 'Radbeauty' roses at high, medium, and low irrigation frequencies, which were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively, from 12 May to 30 Sep 2022. Soil pH, salinity, and mineral contents, including phosphorous (P), potassium (K), zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn), were analyzed at Utah State University Analytical Laboratory in Logan, UT, USA.

pH	Electrical conductivity	P	K	Zn	Fe	Cu	Mn
	$(dS \cdot m^{-1})^i$			$(mg \cdot kg^{-1})^i$			
7.87	0.75	17.77	149.67	2.39	6.20	0.74	7.96

[i] 1 $dS \cdot m^{-1}$ = 1 mmho/cm; 1 $mg \cdot kg^{-1}$ = 1 ppm.

Deficit irrigation and soil moisture contents. In 2021, roses were irrigated approximately once every 3 d by setting the adjusted irrigation at 80% ET_O for establishment. The experiment was initiated on 12 May 2022, and plants were randomly assigned to one of the three irrigation treatments after receiving 43.2 L of irrigation water. Cumulative ET_O and precipitation were used to calculate the irrigation thresholds for controlling the three irrigation treatments (high, medium, and low irrigation frequencies) according to the method described by Costello et al. (2000). In brief, the adjusted irrigations of the high, medium, and low irrigation frequencies were calculated based on 80%, 50%, and 20% of ET_O, respectively. For instance, if the ET_O for the day was 0.8 cm, then the adjusted daily irrigations for high, medium, and low irrigation frequencies were 0.64, 0.40, and 0.16 cm, respectively. A targeted root zone for each plant was defined as a cylinder with a diameter of 100 cm and depth of 50 cm. Irrigation was applied when the cumulative adjusted irrigation minus cumulative precipitation for each treatment was ≥50% of plant available water in the target root zone, which was 4.6 cm within the top 50 cm of the Millville silt loam at the Utah Agricultural Experiment Station Greenville Research Farm. We assumed runoff and deep percolation were zero, and the amount of water equal to 50% of plant available water within the target root zone (43.2 L of water) was applied to refill the depleted plant available water in the target root zone with each irrigation. The plants were maintained under the deficit irrigation treatments until the experiment ended on 30 Sep 2022. A soil moisture sensor (TDT®; Acclima, Meridian, ID, USA) was installed at the bottom of the targeted root zone (50 cm deep) of a 'Radbeauty' rose randomly selected from each treatment to monitor and record volumetric water contents and wetting fronts.

Data collection

Plants were evaluated to determine their growth, visual quality, and physiological responses according to the method developed by the University of California (2023).

Visual quality score. Leaf wilting was graded using a scale of 1 to 5 (1 = complete wilting with >65% of leaves wilted; 2 = severe wilting with 35%–65% of leaves wilted; 3 = moderate wilting with 10%–35% of leaves wilted; 4 = minor wilting, <10% of leaves wilted; 5 = plant was fully turgid) (Zollinger et al. 2006). Foliage appearance, flower abundance, and overall appearance were recorded monthly using a scale of 1 to 5 according to the methods of Reid et al. (2019). Foliage appearance was determined by the percentage of leaves that were visibly damaged (i.e., leaf edge burn, curling, necrosis, etc.) using a scale of 1 to 5 (1 = poor quality with >50% of leaves showing visible damage; 2 = unacceptable quality with 26%–50% of leaves showing visible damage; 3 = acceptable quality with 11%–25% of leaves showing visible damage; 4 = good quality with 1%–10% of leaves showing visible damage; and 5 = excellent quality with <1% of leaves showing visible damage). Flower abundance was rated based on the percentage of the canopy covered in open blooms using a scale of 1 to 5 (1 = up to 20% of the canopy in bloom; 2 = 21%–40% of the canopy in bloom; 3 = 41%–60% of the canopy in bloom; 4 = 61%–80% of the canopy in bloom; and 5 = 81%–100% of the canopy in bloom). The overall appearance was rated based on how the plant performed in the landscape using a scale of 1 to 5 (1 = plant close to death; 2 = unacceptable performance; 3 = acceptable performance; 4 = good performance but not quite optimal; and 5 = excellent performance with eye-catching, uniform, and healthy appearance).

PLANT GROWTH AND LEAF WIDTH. Plant height was measured monthly from the ground to the highest leaf, whereas length and width were measured monthly in perpendicular angles along the row (in a north–south direction) and across the row (in an east–west direction), respectively, using the outermost leaves in each direction. Plant growth indices were calculated as follows: {[height + (length + width)/2]/2} (Irmak et al. 2004). The relative plant growth index of each month was calculated using the ratio of the monthly plant growth index to the initial plant growth index (Reid et al. 2019), and the overall relative plant growth index was calculated by averaging the monthly relative plant growth indices. To determine leaf width at the termination of the experiment, three mature leaves were sampled from the second to the fifth node counting downward from the tip of the main shoot of four randomly selected plants of each cultivar within each treatment. The leaf width of a plant was estimated by averaging the width of the three mature leaves. Then, plant leaves and stems were harvested and oven-dried at 80 °C for 1 month to obtain the dry weights of leaves and stems.

PHYSIOLOGICAL RESPONSES. Gas exchange parameters, including leaf temperature, leaf-to-air vapor pressure deficit (VPD), stomatal conductance, and transpiration rate, were recorded using a porometer (LI-600; LI-COR Biosciences, Lincoln, NE, USA) using the auto mode setup on 6 Jun, 11 Jul, 23 Aug, and 20 Sep 2022. The parameters were recorded on the terminal leaflet of one healthy, fully expanded, full-sun compound leaf at the outer canopy of eight replications in each treatment at midday between 1100 and 1230 HR. Because stomata conductance became the lowest in the afternoon when air temperature reached the maximum (Pereira et al. 1987), a preliminary gas exchange measurement of roses was recorded at the high and low irrigation frequencies in the late afternoon from 1600 to 1730 HR on 11 Jul, whereas the gas exchange parameters of roses were recorded at the three irrigation frequencies during the same period on 23 Aug and 20 Sep 2022. Air temperature recorded by the onsite weather station was used to calculate leaf–air temperature differences via the deviation between ambient air and leaf temperatures measured by the porometer.

STOMATAL DENSITY. Four plants were randomly selected from each cultivar per treatment, and a mature and fully expanded leaf at the outer canopy was randomly selected on each plant on 6 Sep 2022. Wet dental putty (Affinis light body; Coltene, Cuyahoga Falls, OH, USA) was applied to the abaxial surface of each leaf and allowed to air-dry for 1 h. Clear nail polish (Sally Hansen, New York, NY, USA) was applied over the putty to obtain a surface impression of the leaf abaxial surface. Ten fields of view (0.12 mm^2) at 400× magnification were photographed of each impression using a transmitted/reflected light microscope (BX51 BF/DF; Olympus Corp., Tokyo, Japan) with a digital camera (DP 74, Olympus Corp.) and a differential interference contrast prism condenser (U-DPA40, Olympus Corp.) for the 40× microscope objective (UPlanFL N, Olympus Corp.). The image of each field of view was acquired and processed using cellSens Dimension (Olympus Corp.).

Before the analyses, each image was resized to 1831 × 1144 pixels, and 80 images were randomly selected and uploaded to StomataCounter (Fetter et al. 2019) to obtain the value of the threshold probability (0.88 in our research) with the lowest error count at which the Pearson correlation coefficient between human and automatic stomata counts was 0.81 ($P < 0.0001$) (data not shown). Thereafter, stomata on all images were automatically counted using the StomataCounter with a threshold probability of 0.88.

DATA ANALYSIS. The experiment had a completely randomized design with three deficit irrigation treatments and eight replications in each treatment of each cultivar. An analysis of variance procedure was used to test the effects of the irrigation treatment on all measured parameters and the effects of air temperature measured by the weather station on the stomatal conductance recorded by the porometer of rose cultivars. Means separation among treatments was adjusted using the Tukey-Kramer method at $\alpha = 0.05$. Means separation was not conducted among cultivars because of differences in the growth habits of plants. All statistical analyses were conducted using the PROC MIXED procedure and SAS Studio (version 3.8; SAS Institute Inc., Cary, NC, USA), with a significance level specified at 0.05.

Table 2. Cumulative (cum) reference evapotranspiration rate (ET_O) and precipitation and the average (avg) and maximum (max) air temperatures, daily light integral (DLI), and avg vapor pressure at the experimental plot testing 'ChewPatout', 'Meibenbino', 'MEIRIFTDAY', 'Overedclimb', and 'Radbeauty' roses at high, medium, and low irrigation frequencies, which were controlled using 80% ET_O, 50% ET_O, and 20% ET_O, respectively, from 12 May to 30 Sep 2022, at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA.

Time	Cum ET_O (cm)[i]	Cum precipitation (cm)	Avg air temp (°C)[i]	Max air temp (°C)	DLI ($mol \cdot m^{-2} \cdot d^{-1}$)[i]	Avg vapor pressure (kPa)[i]
12–31 May	8.4	3.8	12.2	29.8	47.4	0.7
1–30 Jun	16.8	1.8	18.2	34.2	55.5	0.9
1–31 Jul	20.2	0.1	25.0	37.1	58.7	1.1
1–31 Aug	14.4	7.3	22.3	34.2	45.3	1.4
1–30 Sep	11.4	4.5	18.4	35.8	40.2	1.0

[i] 1 cm = 0.3937 inch; (1.8 × °C) + 32 = °F; 1 kPa = 0.1450 psi.

Results

Weather and soil water content. The cumulative ET_O in June, July, and August were higher than those in May and September (Table 2). Monthly cumulative precipitation decreased from May to July; July was the driest month during this trial, with a cumulative rainfall of 0.1 cm (Table 2). Because of heavy rains, August had the highest cumulative precipitation (7.3 cm). The average air temperature increased from May to July, and the air temperatures in July and August were higher than those during other months. The highest ambient temperature during the experiment was recorded at 37.1 °C in July, whereas daily light integrals in June and July were greater than $50\ mol{\cdot}m^{-2}{\cdot}d^{-1}$. Average vapor pressure, which is related to air humidity, increased from May to August, and August had the highest average vapor pressure (1.4 kPa). During the trial (Fig. 1), the deficit irrigation treatments resulted in eight irrigation events, four irrigation events, and one irrigation event at the high, medium, and low irrigation frequencies, respectively. The total volumes of irrigation water applied to each rose were 345.6, 172.8, and 43.2 L at the high, medium, and low irrigation frequencies, respectively, during the trial from 12 May to 30 Sep 2022. A rapid increase in soil moisture content was observed after irrigation was triggered, indicating that the wetting front had passed the 50-cm depth of the soil profile (Fig. 1).

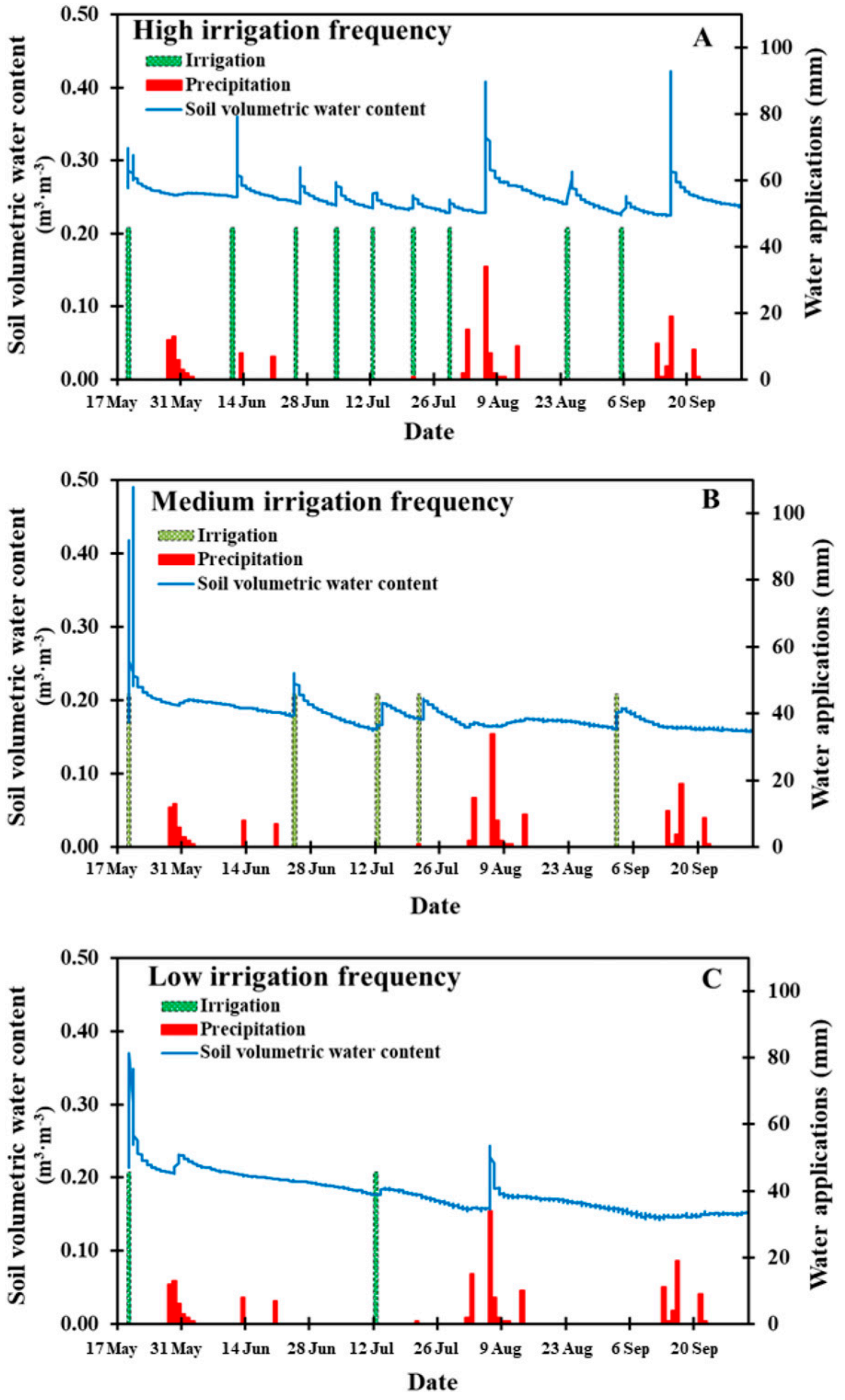

Fig. 1. Soil volumetric water contents estimated by soil moisture sensors (TDT®; Acclima, Meridian, ID, USA) installed at the bottom of the targeted root zone [depth of 50 cm (19.7 inches)] of a 'Radbeauty' rose at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA, with high [80% reference evapotranspiration (ET_O)] (A), medium (50% ET_O) (B), and low (20% ET_O) (C) irrigation frequencies from 12 May to 30 Sep 2022. 1 m^3 = 35.3147 ft^3; 1 mm = 0.0394 inch.

Visual quality

The proportion of leaves visibly wilted. For all three treatments, 'Chew-Patout' had minor wilting, with less than 10% of leaves wilted, and plants at the high and medium irrigation frequencies had a lower proportion of wilted leaves than those at the low irrigation frequency in July (Fig. 2A). The proportion of wilted leaves was less than 10% for 'Meibenbino' at the high and medium irrigation frequencies, except for those recorded in June, when 35% of the leaves were wilted (Fig. 2B). 'Meibenbino' at the low irrigation frequency exhibited a higher number of wilted leaves from August to September than those at the high and medium irrigation frequencies. Minor foliage wilting was discovered for 'MEIRIFTDAY' with all deficit irrigation treatments from May to July, but decreased irrigation frequency from the high to low irrigation frequencies resulted in an increased number of wilted leaves in August, with 35% of leaves wilted at the low irrigation frequency (Fig. 2C). The proportion of wilted leaves was less than 10% for 'Overedclimb' in the high irrigation frequency, but the medium and low irrigation frequencies

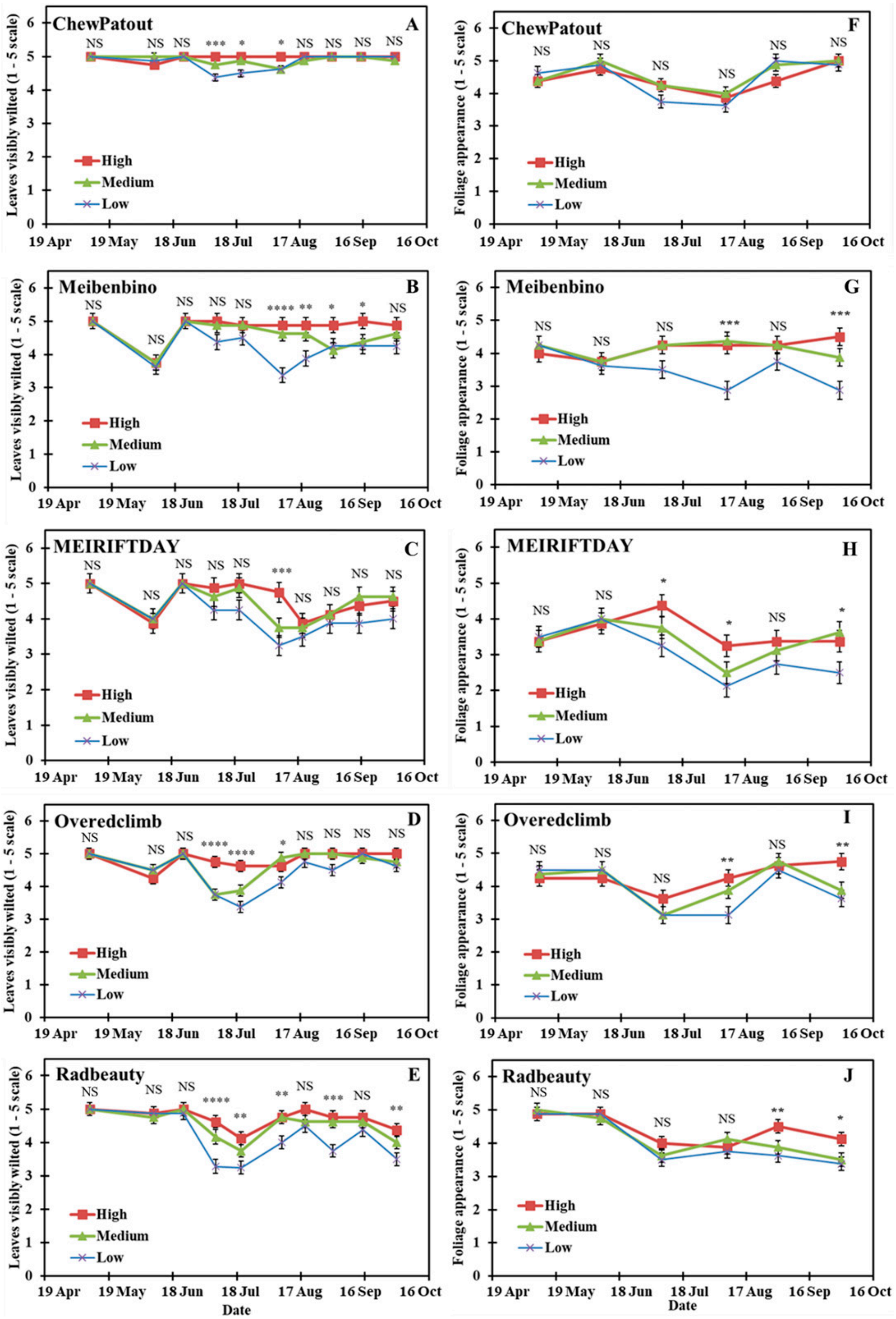

Fig. 2. Leaves visibly wilted (A–E) and foliage appearance (F–J) of ‘ChewPatout’, ‘Meibenbino’, ‘MEIRIFTDAY’, ‘Overedclimb’, and ‘Radbeauty’ roses at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA, with three irrigation frequencies (high, medium, and low) during this experiment from 12 May to 30 Sep 2022. The treatments comprising high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively. The proportion of leaves visibly wilted was rated using a scale of 1 to 5 (1 = >65% of the leaves wilted; 5 = plant was fully turgid) (Zollinger et al. 2006). Foliage appearance was determined by the proportion of foliage that was visibly damaged (i.e., leaf edge burn, curling, necrosis, etc.) using a scale of 1 to 5 (1 = poor quality and >50% of leaves showing visible damage; 5 = excellent quality with <1% of leaves showing visible damage) (Reid et al. 2019). Error bars represent the *SE* of eight plants. NS, *, **, ***, **** represent nonsignificant and significant at $\alpha \leq 0.05$, 0.01, 0.001, and 0.0001, respectively.

resulted in 35% of wilted leaves in July (Fig. 2D). Irrigation treatments did not affect the proportion of wilted leaves for 'Radbeauty' in May and June (Fig. 2E). However, the proportion of visibly wilted leaves for 'Radbeauty' increased in July, August, and September, when the irrigation frequency declined.

FOLIAGE APPEARANCE. Reduced irrigation frequency did not increase the proportion of damaged leaves for 'ChewPatout', resulting in foliage appearances equal to or better than the acceptable quality (Fig. 2F). 'Meibenbino' at the high and medium irrigation frequencies had a lower proportion of damaged leaves than those at the low irrigation frequency in July ($P = 0.09$), August, and late September (Fig. 2G). More than 25% of leaves of 'Meibenbino' under the low irrigation frequency were impaired by drought in August, leading to unacceptable foliage appearance. Additionally, increased irrigation frequency decreased the percentage of damaged leaves for 'MEIRIFTDAY', and plants irrigated at the high irrigation frequency had better foliage appearance than those at the medium and low irrigation frequencies in July, August, and late September (Fig. 2H). The low irrigation frequency also impaired the foliage appearance of 'Overedclimb' in August and late September, with leaf damage occurring in 25% of the canopy (Fig. 2I). Under the three irrigation treatments, 'Radbeauty' roses were able to maintain an acceptable foliage appearance throughout the trial, but an increased irrigation frequency enhanced the foliage appearance in September (Fig. 2J).

FLOWER ABUNDANCE AND OVERALL APPEARANCE. Rose cultivars in this study had two bloom peaks (Fig. 3). Bloom peaks of 'ChewPatout', 'Meibenbino', 'MEIRIFTDAY', and 'Overedclimb' occurred in July and September (Fig. 3A–D), whereas 'Radbeauty' had bloom peaks in July and August (Fig. 3E). Deficit irrigation treatments did not affect the flower abundance of all cultivars, except Meibenbino, which had a higher percentage of canopy covered in blooms under the high and medium irrigation frequencies than plants under the low irrigation frequency in August and September (Fig. 3B). The overall appearance of 'ChewPatout' did not decline at reduced irrigation frequency, and it exhibited acceptable or higher overall quality during the trial, with average scores of 3 or higher (Fig. 3F). 'Meibenbino' plants receiving the high and medium irrigation frequencies had better overall appearances than those at the low irrigation frequency from August to September (Fig. 3G). Increased irrigation frequency improved the overall appearance of 'MEIRIFTDAY' during early August and late September (Fig. 3H). 'MEIRIFTDAY' at medium and low irrigation frequencies had unacceptable overall appearances, with average scores of 1.9 and 1.8, respectively, in early August. 'Overedclimb' and 'Radbeauty' showed acceptable or better overall appearance throughout the trial regardless of irrigation frequency (Fig. 3I–J).

Plant growth responses

RELATIVE PLANT GROWTH INDEX AND LEAF WIDTH. The relative plant growth indices of 'Meibenbino' ($P = 0.02$) and 'MEIRIFTDAY' ($P = 0.09$) decreased as irrigation frequency declined, indicating that these plants will have smaller sizes under reduced irrigation frequencies (Table 3). However, the relative plant growth indices of 'ChewPatout', 'Overedclimb', and 'Radbeauty' were unaffected by reduced irrigation frequencies. 'Meibenbino' at the high and medium irrigation frequencies had significantly higher relative plant growth indices compared with those at the low irrigation frequency (Table 3). Similarly, the relative plant growth indices of 'MEIRIFTDAY' significantly decreased from 1.65 to 1.55, when the irrigation frequency was reduced from the high to the low irrigation frequency (Table 3). 'Meibenbino', 'MEIRIFTDAY', and 'Radbeauty' had narrower leaf widths as the irrigation frequency decreased from the high to the low irrigation frequency (Table 3). 'Meibenbino' had a leaf width reduction of 0.45 cm, 'MEIRIFTDAY' had a reduction of 0.69 cm, and 'Radbeauty' had a reduction of 0.33 cm under the low irrigation frequency compared with the high irrigation frequency (Table 3).

DRY WEIGHTS OF LEAVES AND STEMS. Leaf dry weights were affected by the reduced irrigation frequency of 'Meibenbino' and 'MEIRIFTDAY', whereas 'ChewPatout', 'Overedclimb', and 'Radbeauty' were unaffected (Table 3). 'Meibenbino' and 'MEIRIFTDAY' responded similarly to reduced irrigation by decreasing their leaf dry weights by 36% to 37% at the low irrigation frequency compared to that at the high irrigation frequency. 'ChewPatout', 'Overedclimb', and 'Radbeauty' maintained stem dry weights under reduced irrigation frequency, whereas 'Meibenbino' and 'MEIRIFTDAY' reduced stem dry weights as irrigation frequency declined. 'Meibenbino' had a 10% decrease in stem dry weight as the irrigation frequency decreased from the high to the low irrigation frequency, whereas 'MEIRIFTDAY' had 6% less stem dry weight at the low irrigation frequency than at the high irrigation frequency.

Physiological responses

STOMATAL CONDUCTANCE. Overall, stomatal conductance generally decreased as the irrigation frequency decreased (Fig. 4). In June, increased irrigation frequency did not increase stomatal conductance for all cultivars, except for Radbeauty. In July, although trends of decreased stomatal conductance were observed at midday, when irrigation frequency was reduced; they were not significantly different, except for those of 'ChewPatout'. However, all roses measured showed decreased stomatal conductance under reduced irrigation frequency during the late afternoon. In August, the reduced irrigation frequency did not affect the stomatal conductance of all cultivars at midday, but it reduced stomatal conductance during the afternoon for all cultivars except Overedclimb. In September, reduced irrigation frequency did not affect the midday or afternoon stomatal conductance of any cultivar. Additionally, a lower stomatal conductance was observed when the air temperature became higher from midday to late afternoon in July and August (all $P < 0.05$) (data not shown). This decreased trend was most significant for the roses under the low irrigation frequency, except for 'Meibenbino', which exhibited similar stomatal conductance at midday and late afternoon in August and September (both $P > 0.05$) (data not shown).

LEAF TEMPERATURE, GAS EXCHANGE PARAMETERS, AND STOMATAL DENSITY. The impact of reducing irrigation frequency on leaf temperature, leaf–air temperature difference, VPD, and transpiration rates was most pronounced during the afternoon in July and August (Table 4). In July, when the irrigation frequency was decreased from high to low, the leaf temperature of 'ChewPatout' and 'Radbeauty' increased by 2.2 and

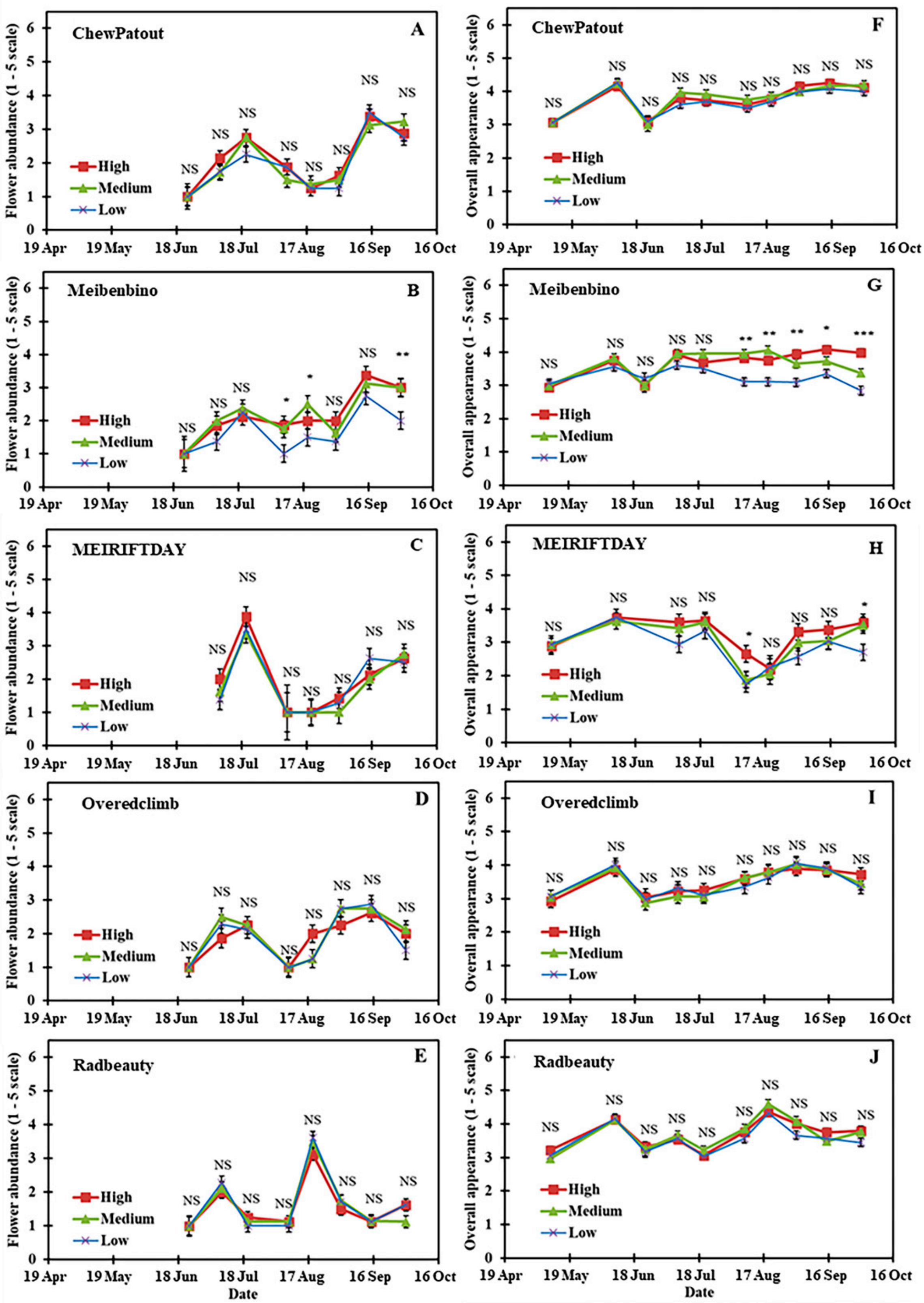

Fig. 3. The flower abundance (A–E) and overall appearance (F–J) of 'ChewPatout', 'Meibenbino', 'MEIRIFTDAY', 'Overedclimb', and 'Radbeauty' roses at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA, with three irrigation frequencies (high, medium, and low) during this experiment from 12 May to 30 Sep 2022. The treatments of high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively. Flower abundance was determined using the percentage of the canopy covered in open blooms, whereas the overall appearance was rated based on how the plant was performing in the landscape (Reid et al. 2019). Error bars represent the *SE* of eight plants; NS, *, **, *** represent nonsignificant and significant at $\alpha \leq 0.05$, 0.01, and 0.001 respectively.

Table 3. Overall relative plant growth indices, leaf width, the dry weights of leaves and stems of ‘ChewPatout’, ‘Meibenbino’, ‘MEIRIFTDAY’, ‘Overedclimb’, and ‘Radbeauty’ roses with three irrigation frequencies (high, medium, and low) at the termination of the experiment on 30 Sep 2022, at the experimental plot at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA. The treatments of high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively.

Cultivar	Irrigation frequency	Overall relative plant growth index[i]	Leaf width (cm)[ii]	Leaf dry wt (g)[ii]	Stem dry wt (g)
ChewPatout	High	2.09 a[iii]	1.78 a	596 a	1227 a
	Medium	2.07 a	1.78 a	552 a	1156 a
	Low	2.23 a	1.67 a	549 a	1201 a
Meibenbino	High	1.58 a	2.08 a	286 a	919 a
	Medium	1.58 a	2.38 a	220 ab	852 ab
	Low	1.48 b	1.63 b	181 b	826 b
MEIRIFTDAY	High	1.65 a	1.73 a	205 a	845 a
	Medium	1.61 ab	1.45 a	150 ab	812 ab
	Low	1.55 b	1.04 b	131 b	796 b
Overedclimb	High	2.37 a	2.91 a	619 a	1340 a
	Medium	2.21 a	3.19 a	460 a	1188 a
	Low	2.16 a	2.98 a	453 a	1086 a
Radbeauty	High	2.09 a	3.31 a	678 a	1255 a
	Medium	1.96 a	2.78 b	618 a	1199 a
	Low	2.04 a	2.98 b	623 a	1214 a

[i] The overall relative plant growth index was calculated by averaging monthly relative plant growth indices, which were determined by the ratio of the monthly plant growth index to the initial plant growth index, and the plant growth indices were calculated using the following equation: {[height + (length + width)/2]/2}.

[ii] 1 cm = 0.3937 inch; 1 g = 0.0353 oz.

[iii] Means with same lowercase letters within a rose cultivar and dependent variable are not significantly different among treatments according to the Tukey-Kramer method with a significance level specified at $\alpha \leq 0.05$.

2.7 °C, respectively, during the afternoon, resulting in greater leaf–air temperature differences and VPD. However, the leaf temperature, leaf–air temperature difference, and VPD of ‘Meibenbino’, ‘MEIRIFTDAY’, and ‘Overedclimb’ did not increase in response to the decreased irrigation frequency in July. All cultivars showed reduced transpiration rates from the high to the low irrigation frequency, except for ‘Meibenbino’, during the afternoon in July. In August, ‘ChewPatout’, ‘Meibenbino’, ‘MEIRIFTDAY’, and ‘Radbeauty’ increased their leaf temperature by 2.9, 3.0, 2.0, and 2.4 °C, respectively, under decreased irrigation frequency. Additionally, the leaf–air temperature difference and VPD of ‘ChewPatout’, ‘Meibenbino’, ‘MEIRIFTDAY’, and ‘Radbeauty’ increased from the high to the low irrigation frequency. Reduced irrigation frequency led to decreased transpiration rates of ‘ChewPatout’, ‘Meibenbino’, and ‘Overedclimb’. In August, decreased irrigation frequency decreased the transpiration rates of ‘MEIRIFTDAY’ and ‘Radbeauty’; however, the changes were not statistically significant.

The stomatal density of ‘Meibenbino’ ($P = 0.07$) and ‘Overedclimb’ ($P = 0.09$) increased as the irrigation frequency increased from the low to the high irrigation frequency (Table 5). However, ‘ChewPatout’, ‘MEIRIFTDAY’, and ‘Radbeauty’ did not show an increase in stomatal density as the irrigation frequency increased. At the high and medium irrigation frequencies, the abaxial leaf surface of ‘Meibenbino’ had 94 and 106 stomata/mm^2, respectively, whereas those at the low irrigation frequency had 92 stomata/mm^2 (Fig. 5). ‘Overedclimb’ at the low irrigation frequency had 67 stomata/mm^2, but those plants under the high and medium irrigation frequencies had 77 and 82 stomata/mm^2, respectively, on their abaxial surfaces (Fig. 5). Compared with other cultivars, Overedclimb had a significantly lower stomatal density, whereas MEIRIFTDAY and Radbeauty had the highest stomatal densities ($P < 0.05$) (data not shown).

Discussion

Low vapor pressure and high air temperature during the summer in Utah resulted in higher ET_O rates than those during other months (Mee et al. 2003) (Table 2). Solar radiation in the summer in Utah can exacerbate water loss through the transpiration pathway. Rainfall amounts are typically very low in the area during the growing season. For instance, Zollinger et al. (2006) reported that heavy precipitation was very uncommon at the Greenville Research Farm during the summer months. Historic cumulative precipitation (1960–2022) at the experiment site from June through September is 10.9 cm, but the cumulative ET_O is 62.2 cm (Utah Climate Center 2023). To maintain the growth and visual aesthetic quality of landscape plants, the gap between ET_O and precipitation is supplied by irrigation water in residential landscapes (Mee et al. 2003).

As irrigation became more frequent from the low to the high irrigation frequencies during this study, plant available water in the root zone was replenished more often with more wetting fronts passing the soil moisture sensor with the high irrigation frequency than with the low irrigation frequency (Fig. 1). A wetting front is an interface between the soil during the initial condition and the soil wetted by irrigation or infiltration (Stirzaker 2003). Wetting fronts form after irrigation is triggered, leading to an increase in soil moisture content after passing through a soil profile (Stirzaker 2003). If wetting fronts were not identified by our soil moisture sensors, which were at the bottom of the targeted root zone, then the targeted root zone may have been only partially wetted (Blonquist et al. 2006). Except for the monsoon rainfalls in August and September, wetting fronts were not detected after the rain events during this study, indicating that the precipitation was

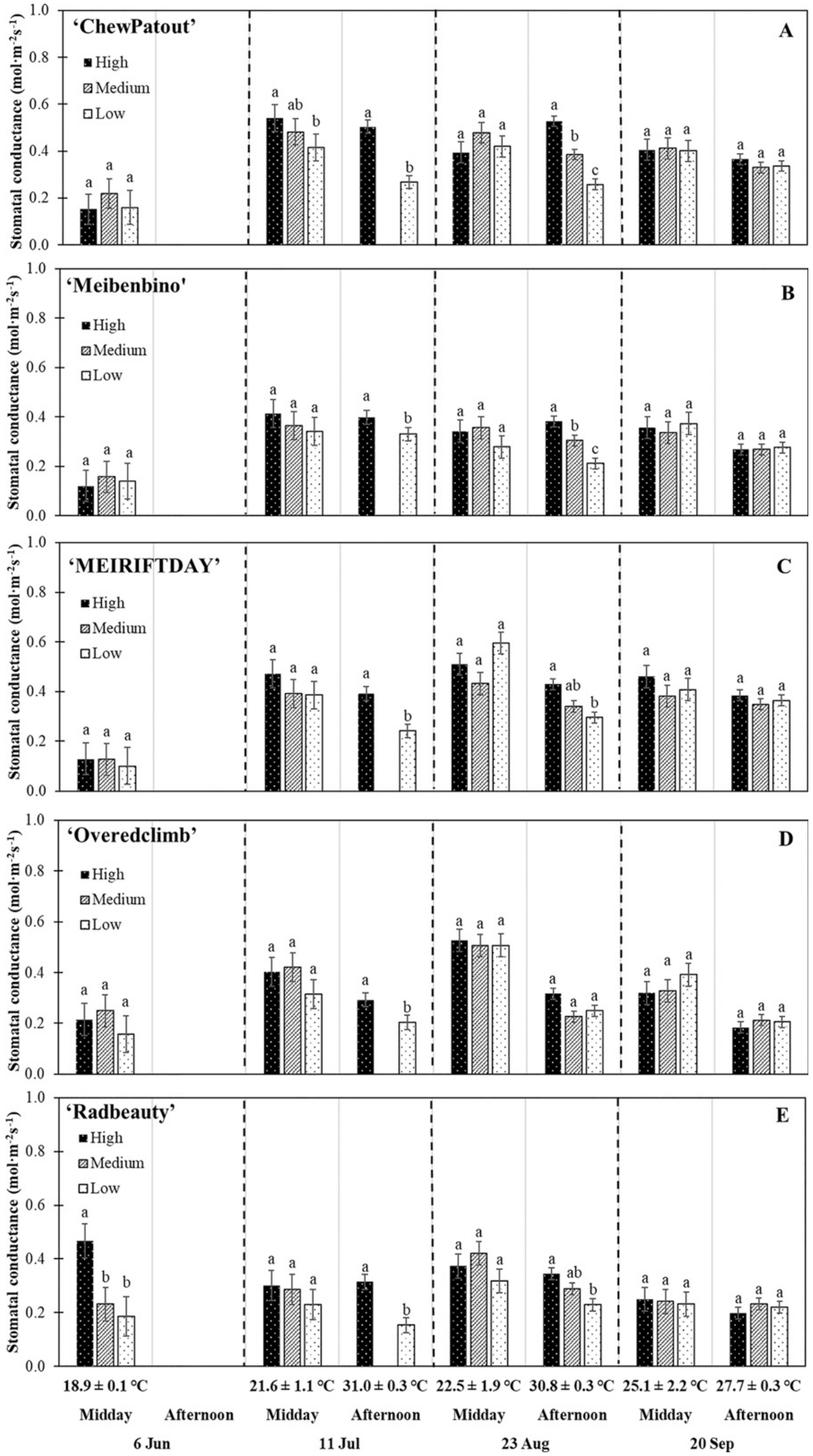

Fig. 4. Stomatal conductance of ‘ChewPatout’ (A), ‘Meibenbino’ (B), ‘MEIRIFTDAY’ (C), ‘Overedclimb’ (D), and ‘Radbeauty’ roses (E) at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA, with three irrigation frequencies (high, medium, and low) on 6 Jun, 11 Jul, 23 Aug, and 20 Sep 2022, with the mean and *SD* of air temperature during the measurements. The treatments of high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively. The midday conductance was recorded between 1100 and 1230 HR, whereas the afternoon conductance was recorded between 1600 and 1730 HR. Error bars represent the *SE* of eight plants. Treatments with the same lowercase letters within each species and the time of the day are not significantly different according to the Tukey–Kramer method, with a significance level specified at $\alpha \leq 0.05$. Stomatal conductance was only recorded at midday on 6 Jun, whereas afternoon stomatal conductance was recorded for roses under the high and low irrigation frequencies on 11 Jul 2022 (1.8 × °C) + 32 = °F.

Table 4. Leaf temperature, leaf–air temperature difference, vapor pressure deficit (VPD), and transpiration rate of 'Chew-Patout', 'Meibenbino', 'MEIRIFTDAY', 'Overedclimb', and 'Radbeauty' roses with three irrigation frequencies (high, medium, and low) from 1600 to 1730 HR on 11 Jul and 23 Aug 2022, at the experimental plot at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA. The treatments of high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively.

Cultivar	Irrigation frequency	Leaf temp (°C)[i]		Leaf–air temp difference (°C)		Leaf-air VPD (kPa)[i]		Transpiration rate ($mmol\cdot m^{-2}\cdot s^{-1}$)[i]	
		July	August	July	August	July	August	July	August
ChewPatout	High	31.2 b[ii]	31.8 b	−0.2 b	1.0 b	3.2 b	3.1 b	16.5 a	15.7 a
	Medium	[iii]	33.9 ab		3.1 ab		3.8 a		14.8 a
	Low	33.4 a	34.7 a	2.0 a	3.8 a	4.0 a	4.1 a	11.6 b	11.0 b
Meibenbino	High	31.5 a	32.7 b	0.6 a	1.9 b	3.3 a	3.4 b	13.6 a	13.6 a
	Medium		34.2 ab		3.4 ab		3.9 ab		12.3 ab
	Low	32.0 a	35.7 a	1.0 a	4.8 a	3.4 a	4.5 a	11.8 a	10.1 b
MEIRIFTDAY	High	33.3 a	33.1 b	2.3 a	2.3 b	3.8 a	3.5 b	15.7 a	15.3 a
	Medium		34.2 ab		3.4 ab		3.9 ab		13.7 a
	Low	33.7 a	35.1 a	2.8 a	4.7 a	4.0 a	4.1 a	10.5 b	12.8 a
Overedclimb	High	31.6 a	33.6 a	0.2 a	2.7 a	3.5 a	3.8 a	11.1 a	12.6 a
	Medium		33.8 a		3.0 a		3.9 a		9.4 b
	Low	32.9 a	34.3 a	1.5 a	3.7 a	3.9 a	4.0 a	8.7 b	10.7 ab
Radbeauty	High	32.0 b	33.2 b	0.9 b	2.3 b	3.6 b	3.6 b	12.1 a	13.2 a
	Medium		35.2 ab		4.4 ab		4.2 ab		12.9 a
	Low	34.7 a	35.6 a	3.7 a	4.9 a	4.5 a	4.4 a	7.7 b	10.8 a

[i] (1.8 × °C) + 32 = °F, 1 kPa = 0.1450 psi.

[ii] Means with same lowercase letters within a rose cultivar, dependent variable, and month are not significantly different among treatments according to the Tukey-Kramer method with a significance level specified at $\alpha \leq 0.05$.

[iii] Gas exchange parameters of the plant were recorded at the high and low irrigation frequency in the afternoon in July.

inadequate to wet the entire soil profile of the target root zone. However, soil water depleted by transpiration from June through July could be replenished by the heavy rainfalls of the monsoon season.

More frequent irrigation improved foliage quality by reducing the number of wilted leaves and leaf damage during this study (Fig. 2). However, the proportion of visibly wilted and damaged leaves varied among rose cultivars when the irrigation frequency was reduced (Table 6), indicating that roses tested during this research may have differing drought tolerance. The effects of reduced irrigation frequency on increased leaf wilting and impaired foliage appearance were most significant in July and August (Fig. 2). This may have resulted from insufficient plant available water and a hot and dry environment that caused the roses to lose turgor and damage to leaves. Therefore, some roses may require more irrigation water to sustain acceptable foliage visual quality. Zollinger et al. (2006) found that the hot and dry weather during summer and reduced irrigation could exacerbate canopy wilting and leaf burn of eastern purple coneflower (*Echinacea purpurea*) and blanketflower (*Gaillardia aristata*). After increasing the irrigation frequency, visual quality, especially for drought-sensitive species, was significantly improved (Zollinger et al. 2006). For instance, the foliage quality of 'Seascape' mat rush (*Lomandra confertifolia*), a drought-sensitive species, could be improved by increasing the irrigation frequency, but 'Tiny Tangerine' stalked bulbine (*Bulbine frutescens*), a xeric species, maintained acceptable quality regardless of irrigation frequency (Reid and Oki 2016). This may be related to the fact that drought-sensitive species lack mechanisms to limit water loss or promote water uptake. Therefore, they rely on irrigation to maintain plant growth and acceptable aesthetic quality

Table 5. Stomatal density of 'ChewPatout', 'Meibenbino', 'MEIRIFTDAY', 'Overedclimb', and 'Radbeauty' roses with three irrigation frequencies (high, medium, and low) on 6 Sep 2022, at the experimental plot at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA. The treatments of high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively.

Cultivar	Irrigation frequency	Stomatal density ($no./mm^2$)[i]
ChewPatout	High	107 a[ii]
	Medium	98 a
	Low	108 a
Meibenbino	High	94 ab
	Medium	106 a
	Low	92 b
MEIRIFTDAY	High	110 a
	Medium	121 a
	Low	112 a
Overedclimb	High	77 ab
	Medium	82 a
	Low	67 b
Radbeauty	High	117 a
	Medium	108 a
	Low	121 a

[i] 1 $stoma/mm^2$ = 645.1600 $stomata/inch^2$.

[ii] Means with the same lowercase letters within a rose cultivar are not significantly different among treatments according to the Tukey-Kramer method with a significance level specified at $\alpha \leq 0.05$.

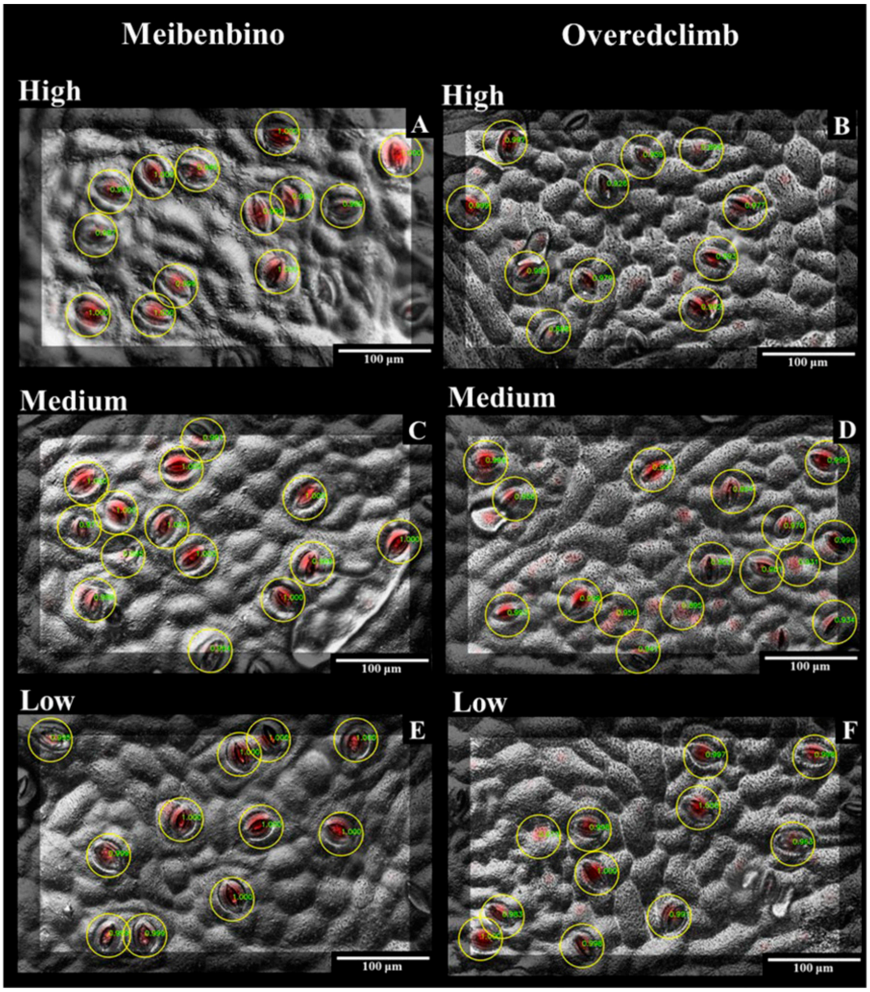

Fig. 5. Microscopy images of stomatal density of the leaf abaxial surface of 'Meibenbino' and 'Overedclimb' roses at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA, with high (A and B), medium (C and D), and low irrigation frequencies (E and F) on 6 Sep 2022. The treatments comprising high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration ($\mathrm{ET_O}$), 50% $\mathrm{ET_O}$, and 20% $\mathrm{ET_O}$, respectively. The number of stomata on each image was counted using a StomataCounter (Fetter et al. 2019) with a threshold probability of 0.88. 1 μm = 1 micron.

in highly evaporative environments (Kjelgren et al. 2009).

In addition to foliage quality, a reduction in flower formation was one of the main contributors impairing the overall visual appearance of flowering plants (Toscano et al. 2019). Reduced flower abundance of 'Meibenbino', for example, negatively affected its overall appearance during this study (Fig. 3). The quality of four landscape rose cultivars, including RADrazz, Belinda's Dream, Old Blush, and Marie Pavie, also declined when flower numbers decreased by 37% to 60% after irrigation frequency was reduced from three times per week to once per week (Cai et al. 2012). The flower abundance in a variety of herbaceous plants also decreased when the amount of irrigation water declined from 100% to 25% $\mathrm{ET_O}$ (Rafi et al. 2019). Drought-resilient ornamental plants, such as ivy leaf geranium (*Pelargonium peltatum*), sustained their flower numbers under deficit irrigation, but drought-sensitive species such as treasure flower (*Gazania rigens*), had a reduction in the size and number of flowers (Rydlová and Püschel 2020). In contrast, reducing irrigation from 80% to 20% $\mathrm{ET_O}$ did not reduce the number of flowers during a study of 10 different roses (Reid et al. 2019), indicating that the roses in this study may tolerate reduced irrigation rates. However, 'Meibenbino' showed decreased flower numbers under deficit irrigation during this study (Fig. 3, Table 6), indicating that 'Meibenbino' may not tolerate water stresses.

Overall appearance is also an important parameter that has been used to assess the impact of drought stress on the aesthetic quality of landscape plants (Rafi et al. 2019; Reid and Oki 2008). For instance, under deficit irrigation of 25% $\mathrm{ET_O}$, 'Imagination' South American mock vervain (*Glandularia tenuisecta*), a low water-use landscape plant, maintained an acceptable and better overall aesthetic quality than 'Tempo White' busy lizzy (*Impatiens walleriana*), a high water-use plant (Henson et al. 2006). Because 'Meibenbino' and 'MEIRIFTDAY' exhibited unacceptable overall appearances when the irrigation frequency was decreased from high to low during this study (Fig. 3, Table 6), these cultivars may be considered drought-sensitive and require higher amounts of irrigation to maintain acceptable overall quality during the growing season.

Leaf expansion and stem elongation are expansive growth features that are most sensitive to water stress (Hsiao 1990). The expansive growth of new stems and leaves of roses has been most susceptible to water stress because reductions in cell turgor under drought stress limited shoot elongation and leaf expansion (Jones 1992; Raviv and Blom 2001). Decreases in the water potential gradient between the growing substrate and roots limited the stem elongation rate of 'Kardinal' roses (Oki and Lieth 2004). Small plants under water stress have been observed on numerous ornamental plants (Cameron et al. 2008; Jafari et al. 2019). The relative plant growth indices (calculated the same way as during this study) of 'Korbin' rose were reduced from 3.1 to 2.4 when the irrigation rates were reduced from 80% to 20% $\mathrm{ET_O}$ (Reid and Oki 2016). Decreased relative plant growth indices were also observed for 'KORfloci01' and 'KORsixkono' under reduced irrigation rates (Reid et al. 2019). Because drought-sensitive plants cannot maintain turgor under water stress, they may exhibit more plant growth reduction than drought-tolerant plants (Cameron et al. 2006). For instance, a decrease in the soil water content of 50% reduced the plant height of 'Deep Rose' busy lizzy (*Impatiens walleriana*) by 7%, but the plant height of drought-tolerant ivy leaf

Table 6. Summary of the drought responses of 'ChewPatout', 'Meibenbino', 'MEIRIFTDAY', 'Overedclimb', and 'Radbeauty' roses when irrigation frequencies decreased from high to medium and low from 12 May to 30 Sep 2022, at Utah Agricultural Experiment Station Greenville Research Farm in North Logan, UT, USA. The treatments of high, medium, and low irrigation frequencies were controlled using 80% reference evapotranspiration (ET_O), 50% ET_O, and 20% ET_O, respectively.

Cultivar	Visual quality	Plant growth responses	Physiological responses
ChewPatout	Leaves visibly wilted (−)[i]	Plant growth responses were unaffected by reduced irrigation frequency.	Stomatal conductance (−); leaf temp (+); leaf–air temp difference (+); vapor pressure deficit (+); transpiration rate (−)
Meibenbino	Leaves visibly wilted (−); foliage appearance (−); flower abundance (−); overall appearance (−)	Relative plant growth index (−); leaf width (−); leaf dry weight (−); stem dry weight (−)	Stomatal conductance (−); stomatal density (−); leaf temp (+); leaf–air temp difference (+); vapor pressure deficit (+); transpiration rate (−)
MEIRIFTDAY	Leaves visibly wilted (−); foliage appearance (−); overall appearance (−)	Relative plant growth index (−); leaf width (−); leaf dry weight (−); stem dry weight (−)	Stomatal conductance (−); leaf temp (+); leaf–air temp difference (+); vapor pressure deficit (+); transpiration rate (−)
Overedclimb	Leaves visibly wilted (−); foliage appearance (−)	Plant growth responses were unaffected by reduced irrigation frequency.	Stomatal conductance (−); stomatal density (−); transpiration rate (−)
Radbeauty	Leaves visibly wilted (−); foliage appearance (−)	Leaf width (−)	Stomatal conductance (−); leaf temp (+); leaf–air temp difference (+); vapor pressure deficit (+); transpiration rate (−)

[i] (−) indicates the values of tested parameters reduced because of decreased irrigation frequency, whereas (+) suggests the values of tested parameters increased because of decreased irrigation frequency.

geranium was unaffected by the decreased soil moisture content (Chyliński et al. 2007). During this study, 'ChewPatout', 'Overedclimb', and 'Radbeauty' were able to maintain their growth under reduced irrigation frequency (Tables 3 and 6), indicating that they may be more drought-tolerant than 'Meibenbino' and 'MEIRIFTDAY'.

Decreased leaf and stem dry weights of 'Meibenbino' and 'MEIRIFTDAY' under deficit irrigation (Tables 3 and 6) may result from limited photosynthesis because partial stomatal closure can limit the amount of carbon dioxide available to the chloroplast (Taiz et al. 2015). The leaf dry weights decreased from the high to the low irrigation frequency during this study, which may also result from the defoliation of 'Meibenbino' and 'MEIRIFTDAY', leading to the reduced leaf surface area, transpiration, and light interception rates under drought stress (Kjelgren et al. 2009). Zollinger et al. (2006) reported similar results for purple coneflower and 'Alaska' shasta daisy (*Leucanthemum* ×*superbum*), which adapted to deficit irrigation conditions by drastically eliminating leaf area. Although 'Meibenbino' and 'MEIRIFTDAY' can defoliate to avoid drought stress, defoliation is not a favorable drought-tolerant trait because of the negative effects on visual quality and whole-plant photosynthesis efficiency (Bañon et al. 2006). In contrast, 'ChewPatout', 'Overedclimb', and 'Radbeauty' sustained their leaves under reduced irrigation frequencies (Tables 3 and 6) and, therefore, may be more suitable for low water-use landscapes.

According to our plant growth and visual quality data, rose cultivars with larger canopy sizes and leaf areas, such as ChewPatout and Overedclimb, were more tolerant of reduced irrigation frequencies than those with smaller canopies, including Meibenbino and MEIRIFTDAY. However, previous studies considered a species with a larger leaf area to be less drought-tolerant because they often require higher amounts of supplemental water to sustain transpiration (Bheemanahalli et al. 2021). For instance, Sun et al. (2012) found that the irrigation requirements of landscape vegetation to maintain turgor were positively correlated with leaf area. Despite the smaller canopy size, 'Meibenbino' and 'MEIRIFTDAY' exhibited reduced plant growth and unacceptable aesthetic qualities (Table 6). The size of their root system may also contribute to their drought sensitivity, as Schenk and Jackson (2002) found that a woody plant's root system volume is positively correlated with its aboveground size under drought conditions. The small aboveground size of 'Meibenbino' and 'MEIRIFTDAY' may suggest that these roses have smaller root systems that were disadvantageous for tolerating prolonged drought.

Partial stomatal closure may reduce transpirational water loss and protect plant tissues from further dehydration (Martínez-Vilalta and Garcia-Forner 2017) because stomatal conductance is correlated with plant water status (Zhang et al. 2013). Chapman and Augé (1994) reported a positive correlation between stomatal conductance and leaf water potential in swamp sunflower (*Helianthus angustifolius*), beebalm (*Monarda didyma*), and orange coneflower (*Rudbeckia fulgida*). Our observations of roses modifying stomatal conductance under deficit irrigation and high ambient temperatures (Fig. 4, Table 6) suggest that partial stomatal closure may be one of the strategies that roses use to cope with drought. Modifying stomatal conductance to regulate transpiration water loss is a favorable drought-resistance mechanism compared with defoliation, which significantly impairs visual aesthetics by eliminating leaf area (Zollinger et al. 2006). Additionally, partial stomatal closure may allow plants to have less negative internal water potential in the xylem, helping to avoid cavitation and maintain plant growth under prolonged drought (West et al. 2007). Although roses may close their stomata when experiencing water stress, the stomata of drought-tolerant roses have been shown to be more sensitive to environmental changes, resulting in a greater reduction in stomatal conductance when water availability became limited (Cai et al. 2012). Increased air temperatures from midday to late afternoon also created a greater water vapor flux in transpiration, exacerbating water stress (Mrad et al. 2019). All rose cultivars in this study modified their stomatal conductance in response to increased air temperatures (Fig. 4, Table 6), except for Meibenbino, which did not exhibit significant reductions in stomatal conductance that may have led to a reduction in growth and unacceptable visual quality.

Partial stomatal closure under reduced irrigation limited transpirational cooling, and leaf temperatures increased as transpiration rates declined during this study (Tables 4 and 6) (Nobel 2020; Tuzet et al. 2003). Heat stress resulting from increased leaf temperatures also led to increasing leaf–air temperature differences and VPD (Tables 4 and 6), which could exacerbate leaf wilting (Devi et al. 2015). A similar relationship was reported by Nelson and Bugbee (2015), who found that drought-stressed plants with stomatal conductance of 0.10 $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ had higher leaf temperatures than well-irrigated plants with a stomatal conductance of 0.50 $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. During this study, the narrower leaf widths of ‘Meibenbino’, ‘MEIRIFTDAY’, and ‘Radbeauty’ under reduced irrigation may indicate that leaf size was reduced to acclimate to drought conditions. Reduced cell expansion also limits leaf expansion, resulting in small leaves under water stress (Taiz et al. 2015). When water is insufficient, leaf energy is primarily balanced using sensible heat loss (Bowen 1926). Smaller leaves that have a lower boundary layer of resistance to sensible heat loss may also promote heat convection and conduction to sustain the leaf temperature close to the air temperature (Leigh et al. 2017). Previous research showed that ‘Torrey’ hybrid buffaloberry (*Shepherdia ×utahensis*) leaves were 51% smaller when the substrate volumetric water content decreased by 0.35 $\text{m}^3\cdot\text{m}^{-3}$ (Chen et al. 2022). During this study, Meibenbino, MEIRIFTDAY, and Radbeauty were the cultivars with the highest leaf–air temperature differences at the low irrigation frequency (Tables 4 and 6). Reduced leaf size may have helped these plants acclimate to heat stress when transpirational cooling was limited. The large leaf size of ‘Radbeauty’ may have resulted in less effective heat dissipation through sensible heat loss. However, under the hot and arid conditions of this experiment, ‘Radbeauty’ was still able to maintain plant growth but lost aesthetic quality because of an increased number of visibly wilted and damaged leaves.

Nelson and Bugbee (2015) concluded that leaf–air temperature >differences were within 2 °C of ambient temperature if plants did not experience water stress. Although only ‘MEIRIFTDAY’ and ‘Radbeauty’ under the low irrigation frequency showed leaf–air temperature differences greater than 2 °C in July, the leaf–air temperature differences of all rose cultivars were greater than 2 °C at the medium and low irrigation frequencies in August (Table 4). The increases in leaf–air temperature differences suggest that roses may suffer continuous water stress from July through August that worsens their water status. When experiencing water stress, roses adapted to hot and arid environments may exhibit fewer leaf–air temperature differences (Bheemanahalli et al. 2021). Rafi et al. (2019) reported that high mallow, a high water-use species, had a leaf–air temperature difference at 3.52 °C, but that drought-resilient hollyhock had a leaf–air temperature difference of −3.08 °C. Similar results were found during this study for ‘Meibenbino’ and ‘MEIRIFTDAY’, which had reduced growth, unacceptable overall appearance, and greater leaf–air temperature differences under reduced irrigation than drought-tolerant ‘ChewPatout’ and ‘Overedclimb’. Compared with ‘ChewPatout’ and ‘Overedclimb’, ‘Radbeauty’ had a greater leaf–air temperature difference (Table 4), which may have resulted from its large leaves. The heat stress could lead to an increase in visibly wilted leaves by ‘Radbeauty’ in July and August, even though no reduction in growth was observed.

In addition to stomatal closure, roses may have the capacity to modify stomatal density on the leaf in response to decreased soil water availability. Because low stomatal density may conserve more water and increase drought tolerance by limiting water loss (Caine et al. 2019), plants may decrease leaf stomatal density when experiencing drought stress (Chen 2022). This study showed that ‘Meibenbino’ and ‘Overedclimb’ reduced stomatal density as irrigation frequency was decreased (Fig. 5, Tables 5 and 6), indicating that their reduction in stomatal conductance under deficit irrigation may have resulted from a reduction in the number of stomata on the leaves. The low stomatal density of the ‘Overedclimb’ may be an advantageous characteristic for conserving water under drought stress. This may be the reason why ‘Overedclimb’ had fewer wilted leaves during the trial compared with ‘Radbeauty’, although both had large leaves. The findings of this research indicated that rose cultivars responded differently when irrigation frequency decreased, but they also were able to modify their morphology and physiology to tolerate drought stress (Table 6).

Conclusions

Reducing irrigation frequency can decrease the visual quality and restrict plant growth rates and photosynthesis efficiency of roses. Five rose cultivars tested during this study defoliated to reduce the surface area and closed their stomata to decrease transpirational water vapor flux under drought stress. Additionally, roses changed their stomatal density to limit stomatal conductance. Although the reduction in leaf size may mitigate heat stress, decreased irrigation frequency led to higher leaf temperatures and increased leaf–air temperature differences. Increased air temperature also exacerbated water stress of roses receiving the lowest irrigation frequency, and stomatal conductance declined under high temperatures.

Under the hot and arid conditions of this experiment, ‘ChewPatout’ and ‘Overedclimb’, which had smaller leaf sizes and lower stomatal densities, respectively, were able to maintain lower leaf temperatures and avoid reductions in plant growth and aesthetic quality. ‘ChewPatout’ and ‘Overedclimb’ may be recommended for low water-use landscaping because of their capacity to tolerate water stress. ‘Meibenbino’ and ‘MEIRIFTDAY’ may not be suitable for low water-use landscapes because they could not modify stomatal conductance in response to changing environmental conditions. Additionally, their small canopy sizes may have resulted in shallow root systems, which are disadvantageous for maintaining plant turgor at deficit irrigation. Under reduced irrigation, 'Radbeauty' roses maintained their growth, but their large leaf size could have resulted in more visibly wilted leaves because of heat stress.

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