The Effect of Substrate Moisture Content on Growth and Physiological Responses of Two Landscape Roses (*Rosa hybrida* L.)

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Abstract. A greenhouse study was conducted to quantify the irrigation requirements of two rose (*Rosa hybrida* L.) cultivars, RADrazz and Belinda's Dream, which are widely valued for their ease of maintenance in landscapes, grown at four constant volumetric substrate moisture contents (SMCs) of 10%, 20%, 30%, and 40%. In both cultivars, there were no differences in growth and physiological responses between 30% and 40% SMC. In 'RADrazz', shoot dry weight (DW) was reduced by 25% and 86%, root DW was reduced by 27% and 71%, and flower number was reduced by 27% and 86% at 20% and 10% SMC, respectively, compared with 30% SMC. Midday leaf water potential (ψ), photosynthesis (P_n), stomatal conductance (g_s), and transpiration (E) were highest at 30% and 40% SMC and they were lowest at 10% SMC. In 'Belinda's Dream', shoot DW was reduced by 30% and 87%, root DW was reduced by 35% and 81%, and flower number was reduced by 42% and 75% at 20% and 10% SMC, respectively, compared with 30% SMC. Midday ψ was least negative at 40% SMC, whereas it was most negative at 10% SMC. There were no significant differences in midday ψ between 20% and 30% SMC. P_n , g_s , and E were highest at 30% and 40% SMC and lowest at 10% SMC. In summary, plants at 30% and 40% SMC maintained the highest shoot and root DW, flower number, midday ψ , P_n , g_s , and E. Water applied at 30% and 20% SMC was reduced by 31% and 70% compared with 40% SMC with excellent performance at 30% SMC and acceptable growth and quality at 20% SMC. The 10% SMC led to significant growth reduction, poor quality, and 25% mortality.

Due to decreasing water resources and increasing population and urbanization, water conservation and development of more efficient irrigation systems are critical in greenhouse and landscape water management (Nicolas et al., 2008; Niu et al., 2006a). Additionally, many crops are overirrigated in greenhouse production, which results in runoff and leaching of water and nutrients from the greenhouse into the environment. To optimize water use in greenhouse production, a thorough understanding of the amount of water needed to produce quality plants is vital. Although water requirements of food crops and turfgrass have been enumerated, data quantifying the irrigation requirements

of ornamental landscape plants are minimal at present. By irrigating plants based on water requirements, water use could be reduced, and plants may be acclimated for drought tolerance in the landscape (Kozlowski and Pallardy, 2002).

Roses (*Rosa hybrida* L.) are some of the most popular garden plants in the world. RADrazz and Belinda's Dream rose cultivars are well adapted to various climatic and soil conditions and provide the consumers with garden plants that require minimum fertilizer, water, and pesticides while growing in gardens or landscapes (Aggie Horticulture, 2014; MacKay et al., 2008). However, there is little science-based knowledge about the minimal irrigation required for plant growth and their responses to different SMC. Most drought studies use the drydown method to determine drought tolerance. In a cyclic drought study by Cai et al. (2012), 'RADrazz' and 'Belinda's Dream' roses had significant

reductions in P_n , g_s , and E as SMC decreased from 20% to 10%. Plant responses to such cyclic drought stresses may differ from the responses to a continuous drought at stable SMC. The constant SMC could be maintained by the use of sensor technology in greenhouse production.

Conserving water and reducing the environmental impact of runoff are two important issues confronting container production in greenhouses and nurseries (Warsaw et al., 2009). With increasing cost of water and stringent legislation, and decreasing water availability, the development of efficient irrigation technology that conserves water and reduces runoff without adversely affecting crop quality is becoming increasingly important for success of container nurseries. Applying irrigation based on plant water requirements is a key concept in water-conserving irrigation scheduling (Warsaw et al., 2009). Using a real-time sensing technology to detect the substrate water status and control irrigation is a promising approach for improving sustainability of irrigation management (van Iersel et al., 2010).

The volumetric SMC is the most valuable environmental factor for automatic irrigation control (Jones, 2007). To study the growth and photosynthetic physiology of begonia (*Begonia semperflorens* L.) at six SMCs, Miralles-Crespo and van Iersel (2011) used time domain transmissometry sensors (TDTs) in multiple containers to control the irrigation based on container-specific SMC thresholds. The six SMCs ranged from 13.6% to 47.2%. The results showed that shoot DW of begonia increased as SMC increased, and plants had similar shoot DW at SMC higher than 34.8%. The total evapotranspiration increased linearly with SMC. With decreased SMC, begonia had significant reduction in leaf size, P_n , and g_s (Miralles-Crespo and van Iersel, 2011).

Burnett and van Iersel (2008) reported that there was an increase in water use efficiency and reduction in stem length and branch numbers of gaura (*Gaura lindheimeri* Engelm. & Gray) with decreasing SMC (45% to 10%). In a study by van Iersel et al. (2010), a substrate moisture sensor-controlled irrigation system was developed to quantify the daily water use of petunia (*Petunia xhybrida* Hort ex. Vilm) in SMCs from 5% to 40%. Lower SMC resulted in a decrease in shoot DW, leaf ψ , and ψ_s . There was only slight additional growth above 25% SMC. Similarly, at four constant SMCs (9%, 15%, 22%, and 32%), Nemali and van Iersel (2008) found that gas exchange, chlorophyll fluorescence, and leaf water potential were similar between 32% and 22% SMC for impatiens (*Impatiens wallerana* Hook.) and salvia (*Salvia splendens* Sell ex Roem. & Schult).

The objectives of the current study were to determine minimum water requirements and quantify the growth and physiological responses of two popular landscape roses, 'RADrazz' and 'Belinda's Dream', grown at four different SMCs using the TDT sensors in multiple containers to control the irrigation based on container-specific SMC thresholds.

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Materials and Methods

Plant materials and culture. Rooted cuttings of two landscape rose cultivars, RADrazz and Belinda's Dream, were purchased from Greenheart Farm (Greenheart, Arroyo Grande, CA) and transplanted to 23.5-L (28.1 cm wide, 45.7 cm long, 18.3 cm height) plastic containers (Iris USA Inc., Pleasant Prairie, WI) on 21 Jan. 2012 in a glass greenhouse at College Station, TX. Containers were filled with Fafard 52 mix (bark, Canadian sphagnum peatmoss, perlite, vermiculite, dolomitic limestone, wetting agent) (Fafard, Inc., Anderson, SC). The mix was evenly amended with 54 g of a slow-release fertilizer, 15N-3.9P-9.9K Osmocote (Peters Professional, Scotts-Sierra, Marysville, OH). After transplanting, plants were manually irrigated with reverse osmosis (RO) water to container capacity and drenched evenly with broad-spectrum fungicide (Banrot®; Scotts-Sierra Crop Protection Company, Marysville, OH) until runoff to prevent root rot. During the establishment stage (35 d), plants were pruned once a week to remove flower buds and improve plant shape.

Although the cultivars used for the study are relatively pest-free in the landscape, in this greenhouse study, plant foliage was washed with soapy water periodically to control spider mites. Greenhouse temperatures were controlled by a pad-and-fan cooling system during the summer and by a natural gas heating system during the winter. The average temperature in the greenhouse was 26.4 °C day/22.0 °C night, which was measured and logged by temperature sensors (HOBOs; Onset Computer Corp., Bourne, MA). The average daily light integral (DLI) and the average relative humidity (RH), measured using sensors (Watchdogs; Spectrum Technologies), were 27.5 mol·m⁻²·d⁻¹ and 70.0%, respectively.

Irrigation system. The irrigation system consisted of Acclima TDT sensors (5.4 cm wide, 20.3 cm long, 1.4 cm height) (Acclima Inc., Meridian, ID), solenoid valves, and a polyethylene header pipe placed in the center and down the entire length of the bench. The Acclima TDT sensors were placed in the center of the container, lying flat. Two dribble ring emitters were placed on top of the root substrate and around the plants and secured with pins. Polyethylene pipe (Silver-line Plastics, Asheville, NC) was cut to fit between the header and each container and attached to the header with a tee fitting (Lasco Fittings Inc., Brownsville, TN). A 10-cm section of pipe was attached to each tee with a polyvinyl chloride threaded male adapter (Lasco Fittings Inc.) and Teflon tape (LG Sourcing Inc., North Wilkesboro, NC) that was attached to the solenoid valve (N-100F-H; Weathermatic, Dallas, TX). Containers were arranged as completed randomized design in two 3 × 1-m greenhouse benches with 51 cm between containers. Two dribble ring emitters (61 cm lead, 15 cm diameter) (Dramm Corporation, Manitowoc, WI) were evenly spaced and

connected to the 25-cm polyethylene pipe by a microtube to deliver water to the plants. The garden hose was used to connect the system to a pressure regulator (25 PSI; Mister Landscaper, Dundee, FL) at the greenhouse water main faucet, which was the source of RO water. All sensors were placed and an extension cord (Chicago Electrical Power Tools, distributed by Harbor Freight Tools, Camarillo, CA) was cut into 86-cm pieces to connect each sensor. The irrigation system used in this greenhouse study measured SMC in multiple containers and irrigated the plants based on container-specific SMC thresholds. A laptop computer was connected to the irrigation system once a day to monitor the SMC and control for problems. When a sensor fails, the computer will be programmed to make the irrigation of that container depend on another Acclima sensor programmed to the same SMC. There were no sensor failures in this experiment.

Substrate moisture content treatment. The SMC is defined as V_w/V_T (V_w is the volume of water; V_T is the total volume of soil, water, and air space). Uniform plants of each cultivar were selected and divided into four SMC treatment groups: 10%, 20%, 30%, and 40%. The 40% SMC treatment corresponded to well-irrigated plant, whereas the 10% SMC treatment corresponded to drought stress. There were two cultivars in each container and four replications of the container (total 16 containers and 32 plants). SMC treatment was initiated on 13 Mar. and ended on 4 May 2012 (52 d). Before the initiation of the treatment, the Acclima sensors were calibrated. After calibration, the 10%, 20%, 30%, and 40% SMC treatments equaled to the Acclima readings of 1.1%, 8.2%, 15.2%, and 22.3%, respectively (Fig. 1). Once the SMC dropped below the set point in each treatment, the solenoid valves would stay open until the SMC reached the expected value. Due to severe drought at 10% SMC, two plants senesced in one container. Plants at 10% SMC were then irrigated manually to container capacity for recovery (Fig. 1).

The total amount of water applied in each container was determined by multiplying the flow rate by the total watering time from the beginning to the end of the experiment. The flow rates of the dribble ring emitters were determined by opening one valve and placing the two dribble rings into a bucket to collect the water. The amount of water emitted per second was calculated by measuring the ratio of the weight of the water to the time (in seconds) the dribble rings were on. After calculation, the flow rate of a dribble ring was 5.3 mL·s⁻¹.

Measurements. Midday leaf water potential was measured on young, fully expanded leaves using a pressure bomb (Soil Moisture Equipment Corp., Santa Barbara, CA) every other day after 4 weeks of the treatment. Instantaneous leaf gas exchange parameters (P_n , g_s , and E) were measured on four plants per cultivar per treatment every week during the treatment period. Between 1000 and 1200 HR, a young, fully expanded leaflet was put into the leaf chamber (cuvette) of a portable infrared gas exchange analyzer (LI-6400XT; LI-COR Inc., Lincoln, NE) with cuvette conditions set at 25 °C, 1000 μmol·m⁻²·s⁻¹ photosynthetic photon flux, and 400 μmol·mol⁻¹ CO₂. Data were recorded when the environmental conditions and gas exchange parameters in the cuvette became stable. At 52 days after treatment (DAT), flower number was recorded. DW of shoots and roots were determined after being oven-dried at 80 °C to constant weights.

Experimental design and statistical analysis. The experiment used a two-factorial experiment design (cultivar × SMC). A two-way analysis of variance procedure was used to test the effects of SMC and cultivar on plant growth and physiological responses. When there was an interaction between SMC and cultivars, means were separated into four SMC of each cultivar by Student-Newman-Keuls multiple comparison at $P = 0.05$. When the interaction was not significant, data were pooled across SMC or cultivar. All statistical analyses were performed using SAS (Version 9.1.3; SAS Institute, Cary, NC).

Fig. 1. Responses of the substrate moisture content (SMC) thresholds for the Acclima system at 10%, 20%, 30%, and 40% SMC treatments during experimental period. DAT = days after treatment.

Fig. 2. Total amount of water applied at 40%, 30%, 20%, and 10% substrate moisture content (SMC) treatments during the 2-month experimental period.

Fig. 3. Effect of substrate moisture content (SMC) (10%, 20%, 30%, and 40% SMC) on shoot dry weight (DW) of 'RADrazz' and 'Belinda's Dream'. Means within each cultivar with the same letter are not significantly different tested by Student–Newman–Keuls (SNK) multiple comparison at $P = 0.05$. Vertical bars represent SE.

Fig. 4. Effect of substrate moisture content (SMC) (10%, 20%, 30%, and 40% SMC) on root dry weight (DW) of 'RADrazz' and 'Belinda's Dream'. Means within each cultivar with the same letter are not significantly different tested by Student–Newman–Keuls (SNK) multiple comparison at $P = 0.05$. Vertical bars represent SE.

Substrate moisture content and total water application. Although there were increases in plant size and large fluctuations in DLI and RH, the capacitance automated irrigation system was able to maintain the stable SMC (Fig. 1), which has been reported by Nemali and van Iersel (2006) and van Iersel et al. (2010). However, due to severe drought at 10% SMC, two plants were dead in one container on at 27 DAT. All plants at 10% SMC were then watered manually to field capacity and allowed to dry down again (Fig. 1). At 14 DAT, the 20% and 40% SMC treatments slightly exceeded the thresholds (Fig. 1). This was caused by heavy rain resulting in some leakage through the greenhouse glazing into the containers before it was stopped. The total amount of water applied during the treatment period decreased with decreasing SMC (Fig. 2). There was no applied irrigation water leached from the containers. Burnett and van Iersel (2008), Nemali and van Iersel (2006), and van Iersel et al. (2010) also reported that the total irrigation volume increased with increasing SMC thresholds. During the 2-month treatment period, total water applied in each container was 5.7 L, 16.6 L, 39.3 L, and 57.2 L at 10%, 20%, 30%, and 40% SMC, respectively. Compared with 40% SMC, there was 90%, 71%, and 31% reduction in water application at 10%, 20%, and 30% SMC, respectively (Fig. 2).

Dry weight of shoots and roots and flower number. There were interactions between SMC treatment and rose cultivar for shoot and root DW and flower number. For both cultivars, there were no significant differences in shoot and root DW and flower number between 30% and 40% SMC (Figs. 3, 4, and 5). In 'RADrazz', shoot DW was reduced by 25% and 86%, root DW was reduced by 27% and 71%, and flower number was reduced by 27% and 86% at 20% and 10% SMC, respectively, compared with 30% SMC. In 'Belinda's Dream', shoot DW was reduced by 30% and 87%, root DW was reduced by 35% and 81%, and flower number was reduced by 42% and 75% at 20% and 10% SMC, respectively, compared with 30% SMC (Figs. 3, 4, and 5).

In both cultivars, shoot DW increased as the SMC increased from 10% to 30% with no significant effect at higher SMC set point (Fig. 3). Burnett and van Iersel (2008) reported that there was an increase in shoot DW as the SMC increased from 10% to 25% with no effects at higher SMC set points in gaura. van Iersel et al. (2010) found that there was a quadratic relationship between the SMC and shoot DW in petunia; shoot DW increased as the SMC increased from 5% to 25% with no additional increase at higher SMC. In a study by Niu et al. (2007), cut raceme yield and shoot and root DW of big bend bluebonnet (*Lupinus bavardii*) decreased as SMC decreased from 33% to 12% or 15%, and plants required 25% SMC or greater to maintain the maximum plant growth and cut flower production. In this study, at 20% SMC, lower

Fig. 5. Effect of substrate moisture content (SMC) (10%, 20%, 30%, and 40% SMC) on flower number of 'RADrazz' and 'Belinda's Dream'. Means within each cultivar with the same letter are not significantly different tested by Student–Newman–Keuls (SNK) multiple comparison at $P = 0.05$. Vertical bars represent SE.

Fig. 6. Responses of leaf net photosynthesis (P_n), stomatal conductance (g_s), and transpiration (E) to different substrate moisture contents (SMCs) (10%, 20%, 30%, and 40% SMC) in 'RADrazz' and 'Belinda's Dream' during the treatment period. Means within each cultivar followed by the same letter are not significantly different tested by Student–Newman–Keuls (SNK) multiple comparison at $P = 0.05$. DAT = days after treatment.

reductions of shoot and root DW and flower number were observed in 'RADrazz' compared with 'Belinda's Dream' (Figs. 3, 4, and 5), which was consistent with a previous study

in which 'RADrazz' had less growth reduction than 'Belinda's Dream' under drought stress (Cai et al., 2012). In a cyclic drought study (SMC decreased from 40% to 10%, then

increased to 40% after rewatering), Cai et al. (2012) reported that shoot DW was reduced by 21% and 36% and flower number was reduced by 41% and 47% in 'RADrazz' and 'Belinda's Dream', respectively, compared with control plants. Drought stress did not affect the root DW of 'RADrazz', whereas root DW of 'Belinda's Dream' was reduced by 42%. In the current study, shoot DW was reduced by 86% and 87%, flower number was reduced by 86% and 75%, and root DW was reduced by 71% and 81% in 'RADrazz' and 'Belinda's Dream', respectively, under continuous drought at 10% SMC.

Photosynthesis, stomatal conductance, and transpiration. There were interactions between SMC treatment and rose cultivar for P_n , g_s , and E . In 'RADrazz', there was no significant difference in P_n between 30% and 40% SMC at 17 DAT, whereas the P_n was reduced by 12% and 71% at 20% and 10% SMC, respectively, compared with 30% SMC (Fig. 6). At 24 DAT, P_n was highest at 40% SMC, and there was no significant difference in P_n between 20% and 30% SMC, whereas it was reduced by 78% at 10% SMC compared with 30% SMC. At 31 DAT, there was no significant difference in P_n between 30% and 40% SMC, whereas the P_n was reduced by 11% and 81% at 20% and 10% SMC compared with 30% SMC. At 38 DAT, P_n was highest at 40% SMC, and there was no significant difference in P_n between 20% and 30% SMC, whereas it was reduced by 74% at 10% SMC compared with 30% SMC. At 45 DAT, there was no significant difference in P_n between 30% and 40% SMC, whereas the P_n was reduced by 26% and 61% at 20% and 10% SMC, respectively, compared with 30% SMC (Fig. 6). In 'Belinda's Dream', there was no significant difference in P_n between 30% and 40% SMC during the treatment period, whereas the P_n was reduced by 10% to 29% at 20% SMC and by 53% to 91% at 10% SMC compared with 30% SMC (Fig. 6). The responses of g_s and E to different SMCs in two cultivars are similar to those of P_n (Fig. 6).

Decreasing moisture content causes reductions in plant gas exchange rates, which is one of the primary defense mechanisms protecting plants from desiccation (Chaves, 1991). In the current study, P_n , g_s , and E decreased as SMC decreased from 40% to 10% with little or no difference between 30% and 40% or 30% and 20% SMC in 'RADrazz' and 'Belinda's Dream' depending on time of measurement (Fig. 6). Reduced P_n was probably due to reduced g_s at decreasing SMC. In a study by Cai et al. (2012), they reported that P_n , g_s , and E for 'RADrazz' and 'Belinda's Dream' decreased quadratically as SMC decreased from 40% to 10%, and 'RADrazz' had greater P_n , g_s , and E than those of 'Belinda's Dream' during drying down. Similarly, in the current study, the P_n , g_s , and E were higher in 'RADrazz' than 'Belinda's Dream' under continuous drought at 10% SMC. In a study on four bedding plants [salvia 'Bonfire Red', vinca 'Cooler Peppermint' (*Catharanthus roseus* L. G. Don.), petunia 'Lavender White', and impatiens 'Cherry'],

Fig. 7. Effect of substrate moisture content (SMC) (10%, 20%, 30%, and 40% SMC) on midday leaf water potential (ψ) of 'RADrazz' and 'Belinda's Dream'. Means within each cultivar with the same letter are not significantly different tested by Student–Newman–Keuls (SNK) multiple comparison at $P = 0.05$. Vertical bars represent SE.

Nemali and van Iersel (2008) found that leaf P_n was lowest at 9% SMC and there was no difference in P_n among SMC of 15%, 22%, and 32%. Miralles-Crespo and van Iersel (2011) reported that leaf size, P_n , and g_s of begonia were lowest at 13.6% SMC as SMC decreased from 47.2% to 13.6% and there were no significant differences among the other SMCs (21%, 28.1%, 34.8%, 41.2%, and 47.2% SMC). Similarly, in the current study, P_n was lowest at 10% SMC, and there was no significant difference between SMC of 20% and 30% or between 30% and 40% SMC. Both cultivars can maintain the acceptable photosynthetic rates at 20% SMC (Fig. 6).

Midday leaf water potential. There were interactions between SMC treatment and rose cultivar for midday ψ . In 'RADrazz', midday ψ increased as SMC increased from 10% to 40%, and there were no significant differences in midday ψ between 30% and 40% SMC. Compared with 30% SMC, midday ψ was 0.25 MPa and 1.06 MPa lower at 20% and 10% SMC, respectively (Fig. 7). In 'Belinda's Dream', there were no significant differences in midday ψ between 20% and 30% SMC. Midday ψ was least negative at 40% SMC, whereas it was most negative at 10% SMC. Compared with 30% SMC, midday ψ was 0.45 MPa lower at 10% SMC (Fig. 7).

Leaf ψ is an important parameter to indicate the level of plant water stress. In the present study, midday ψ significantly decreased as SMC decreased from 20% to 10% in 'RADrazz' and 'Belinda's Dream', indicating severe drought stress at 10% SMC (Fig. 7). In a cyclic drought study, Cai et al. (2012) found that midday ψ decreased rapidly at SMC less than 20% in 'RADrazz' and 'Belinda's Dream'. Some studies have reported that 20% SMC may be the critical threshold to cause steep declines in leaf ψ in big bend bluebonnet, *R. hybrida* 'Dr. Huey', *R. fortuniana*, *R. multiflora*, and *R. odorata* (Niu et al., 2006b; Niu and Rodriguez, 2009). van Iersel et al. (2010) reported a quadratic relationship between SMC and leaf ψ in petunias. Leaf ψ increased as the SMC increased from 5% to 15% with no additional increase at higher SMC. In a study

by Nemali and van Iersel (2008), regardless of species (impatiens, petunia, salvia, and vinca), midday ψ was lowest at 9% SMC and did not differ among the other three SMC levels (15%, 22%, and 32% SMC). Similarly, there was no difference of midday ψ among the plants irrigated with amounts varying from 50% to 100% of evapotranspiration in olive (*Olea europea* L.) plants.

Conclusion

Drought stress caused reductions in plants' growth, which could be used as a cultural control method for excessive plant growth (Bailey and Whipker, 1998). It is important for commercial greenhouse growers to predict plant growth responses to different SMCs, thereby determining their minimal water requirement. In two landscape roses investigated, all plants survived at four SMCs ranging from 10% to 40% except for two plants in one container (one for RADrazz and one for Belinda's Dream) at 10% SMC. In both cultivars, plants at 30% and 40% SMC maintained the highest shoot and root DW, flower number, midday ψ , and P_n . However, as a result of excessive irrigation at 40% SMC, algal growth observed on substrate surfaces would negatively impact plant aesthetic appearance and cause other management issues. There was no significant difference in P_n between SMC of 20% and 30% and between 30% and 40%, which could be the result of the lack of differences in midday ψ among these SMCs. Total water applied at 30%, 20%, and 10% SMC was reduced by 31%, 70%, and 90%, respectively, compared with 40% SMC. Plants had excellent performance at 30% SMC and acceptable growth and quality at 20% SMC. The 10% SMC led to significant growth reduction, poor visual quality (leaf wilt and drop), and 25% mortality. Results showed that soil moisture sensor-based automatic irrigation systems may be used to conserve water consumption in greenhouse container production and quality plants of these two garden roses can be grown at reduced SMC during greenhouse production.

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