Evaluation of Compensated Root Water Uptake Pattern of Greenhouse Drip Irrigated Chile

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Abstract
We evaluated comparative effects of the compensated (under water stress conditions using drip-irrigated partial root zone drying (PRD) techniques) and non-compensated (no water stress) root water uptake pattern of chile plants (NuMex Joe Parker; *Capsicum annuum*). The greenhouse pot experiments were conducted with three drip irrigation treatments: (1) control or non-compensated (fully irrigated), (2) PRD using vertically split-root system where the top 37% of the root zone system was exposed to water stress, and (3) PRD using two-compartment or lateral split-root system with alternately wetting and drying to impose water stress in the lateral part of the root zone. Results suggest that chile plants under these two drip-irrigated PRD treatments could compensate for water stress in one part of the vertical or lateral root zone profile by taking up water from less water–stressed parts of the vertical or lateral root zone regions, without affecting transpiration or photosynthetic rates to meet peak water demand. No significant differences were noted in the root length distributions and plant heights between PRD treatments and control. Either of the two drip-irrigated PRD techniques has a great potential to be adopted as water saving practices in chile production especially for environments with limited water.

Introduction

Water stress is one of the most critical factors that can decrease crop productivity across arid and semi-arid agricultural areas of New Mexico and the southwestern US. Water stress is exacerbated in these areas as a result of low rainfall, high evapotranspiration, and limited availability of irrigation water. However, a compensation mechanism within the crop root zone that balances reduced water uptake from one part of the rhizosphere by increased uptake in another less-stressed region of the root zone, while decreasing the loss of water due to evaporation can be beneficial for managing efficient use of irrigation water (Deb et al., 2011a). Partial root zone drying (PRD) is a potential water saving irrigation strategy where at each irrigation only a part of the rhizosphere is wetted with the remaining part left to dry to impose soil water stress. Although the hydraulic lift concept was proposed by Gardner in 1960, yet, there is still limited experimental evidence that plants under PRD can compensate for water stress in one part of the root zone by taking up available water from other parts of the root zone. In particular, the question remains unresolved whether chile plants under drip-irrigated PRD can compensate for water stress in one part of the root zone by taking up water from less-stressed parts of the root zone. The objective was to evaluate comparative effects of the compensated (under drip-irrigated PRD) and control or uncompensated (no water stress, fully irrigated) root water uptake pattern (or transpiration rate) of greenhouse drip irrigated chile plants. We hypothesized that (1) the response of chile plants to soil water stress compensation mechanism can be characterized from the drip-irrigated PRD experiments, and (2) compensated transpiration rate and plant growth under PRD will be similar to or greater than those without compensation.

Materials and methods

Experimental setup and irrigation treatments

The PRD experiment was carried out on chile plants in a greenhouse at New Mexico State University Fabian Garcia Science Center (latitude 32° 16′ 48″ N, longitude 106° 45′ 18″ W, elevation 1185 m). Seeds of New Mexican pod type chile (NuMex *Joe E. Parker*; *Capsicum annuum* L.) were sown in germinating tray until the appearance of the fifth leaf. At that stage, on 13 June 2011, chile plants were transplanted to pots (29 cm diameter and 54 cm deep), containing a 1:1:2 (v/v) mixture of sand: soil: organic matter (hereafter referred to as the soil), to produce a split-root system. Loading and compaction of soil in the pot was manually performed in 5-cm incremental layers to obtain a homogeneous profile. Experimental design consisted of a drip irrigation system, with two drip emitters per pot each emitting about 2 L h^{-1}. The drip tubing with the emitter was connected to the drip mainline tubing, which delivered water from a PVC water reservoir tank to the emitter tubing. The pumping system of the water tank provided a stable pressure to avoid variations in flow rate, and steady water flow rate was maintained through the flow control system. The bottom of each pot was perforated and covered with loosely woven fabric to allow free drainage without soil loss.

For each pot, the chile was irrigated every day at 800 h for 30 min during the period from 14 June (2DAT; 2 days after transplanting) to 31 October (142 DAT) 2011. The experiment was performed by applying three drip irrigation treatments with three replications per treatment: (1) control or non-compensation treatment was irrigated with two drip emitters placed at the pot surface. (2) PRD or compensation treatment (PRD_{vert}) in which the root zone was vertically divided into two parts (vertically split-root system) with two subsurface drip emitters placed at 20 cm depth, i.e., the top 37% of the root system was exposed to soil drying (or water stress), and the remaining 63% irrigated with subsurface drip emitters, and (3) PRD or compensation treatment (PRD_{compt}) in which the root zone was divided into two-compartment split-root system, in which roots were evenly separated into two compartments with a divider such that water exchange between two compartments was prevented. Plants were irrigated alternately on the two compartments with a drip emitter placed at the soil surface, and irrigation was switched between the two compartments at two-week intervals. Additionally three pots per treatment were used for monthly root distribution observation. All plants were fertilized with slow-release fertilizer [Scotts Osmocote Classic 14% Nitrogen (N)–14% Phosphate (P_2O_5)–14% Soluble Potash (K_2O)].

Determination of soil properties

Prior to transplanting, soil physical properties were determined using standard laboratory methods (Dane and Topp, 2002). The mean bulk density and saturated hydraulic conductivity (K_s) of the soil-mix were 1.34±0.05 Mg m^{-3} and 0.18±0.03 cm min^{-1}, respectively. Soil-mix water retention was determined on cores using the pressure chamber method at pressures (ψ) of 0, –300, –500, –1000, –3000, –5000, –10,000 and –15,000 cm H_2O (Fig. 1a). The field capacity (for $\psi \approx -300$ cm H_2O) and wilting point ($\approx -15{,}000$ cm H_2O) water contents were 0.41±0.024 and 0.28±0.02 cm^3 cm^{-3}, respectively. Soil-mix core samples were collected down to 40 cm soil depth to determine thermal conductivity using the KD2 probe (Decagon devices, Inc., Pullman, WA) at ψ of 0, –300, –500, –1000, –3000, –5000, –10,000 and –15,000 cm H_2O (Fig. 1b).

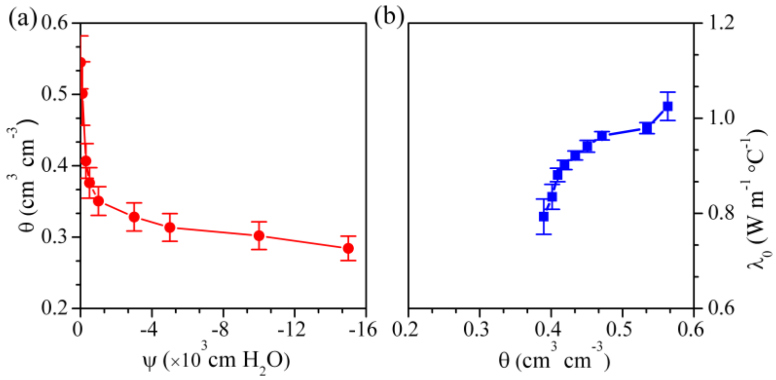

Fig. 1. (a) Water retention curve of the soil-mix (θ = volumetric water content and ψ = pressure head), and (b) thermal conductivity (λ_0) of the soil-mix as a function of the θ.

Measurement of soil water content, soil temperature, and microclimate

Two pots under each of the control and PRD_{vert} treatments were instrumented with two time domain reflectometry (TDR) sensors (CS640; Campbell Scientific, Inc., Logan, UT) and two temperature (TMC6–HD, Onset Computer Corp., Bourne, MA) sensors were installed at the depths of 5 and 25 cm to measure volumetric water content and soil temperature, respectively, at 10-min intervals. TDR and temperature sensors were installed at 5 cm on either compartment side of the PRD_{compt}.

Air temperature and relative humidity were measured using CS500 Temperature/Humidity sensors and net solar radiation using Q-7.1 Net Radiometer (Campbell Scientific, Inc., Logan, UT) inside the greenhouse. These measurements were made at 10–min intervals at 2 m above the soil surface of the greenhouse. To account for changes in evaporative demand inside the greenhouse, atmospheric vapor pressure deficit (VPD) values were calculated using Murray's equations (1967) using the hourly average air temperature and relative humidity data. The VPD outside the greenhouse were estimated using hourly average data obtained from Fabian Garcia Science Center weather station.

Measurement of plant photosynthetic and transpiration rates

Plant photosynthetic and transpiration rates and leaf temperature were measured between 700h and 900h on two fully expanded and exposed leaves per treatment. These measurements were made at two-week interval using LI-6400XT portable photosynthesis system (LI-COR Biosciences, Lincoln, NE).

Measurement of plant growth and root length density

Plant height was measured manually once every two weeks and canopy development was continuously monitored using garden cameras. Roots from control and treatment pots were manually washed and RLD distributions were determined four times during the period from 13 June to 31 Oct. 2011. Root images were acquired using EPSON V700 Photo Dual Lens System flatbed scanner (Epson America, Long Beach, CA). Following the procedure described by Deb et al. (2011b), analysis of the root length density (RLD) was performed with the WinRHIZO version 2008a (Regent Instruments Inc., Quebec, Canada).

Results and discussion

Soil water content and soil temperature

The trend and magnitudes of volumetric water content (θ) at 5 and 25 cm depths in the control were similar during a period from 2DAT to 142DAT, which varied between 0.34 and 0.47 cm^3 cm^{-3} at 5 cm, and 0.25 and 0.45 cm^3 cm^{-3} at 25 cm pot depth (Fig. 3a). As expected, the θ at 25 cm was consistently higher than that at 5 cm under PRD using vertically split-root system (PRD_{vert}) (Figs. 3b-c) because irrigation was applied with subsurface drip emitters placed at the 20 cm depth to impose water stress above 20 cm. For example, the θ varied from 0.25 to 0.38 cm^3 cm^{-3}, and 0.43 to 0.51 cm^3 cm^{-3} at 5 and 25 cm depths, respectively. The relatively higher values of θ could be explained by the water retention behavior and a much higher water holding capacity of the soil (Fig. 1a). The variations in θ at 5 cm under PRD_{vert} treatments (Figs. 2b-c) might be attributed to water extraction by roots above 20 cm depth. This also implies that water might be transported from the subsurface drip irrigation source at 20 cm to the surface (above 20 cm) by capillary rise. Either side of the two-compartment split-root system (PRD_{compt}) treatment had either a higher or a lower θ at 5 cm depending on whether it was being irrigated or not (Fig. 4a).

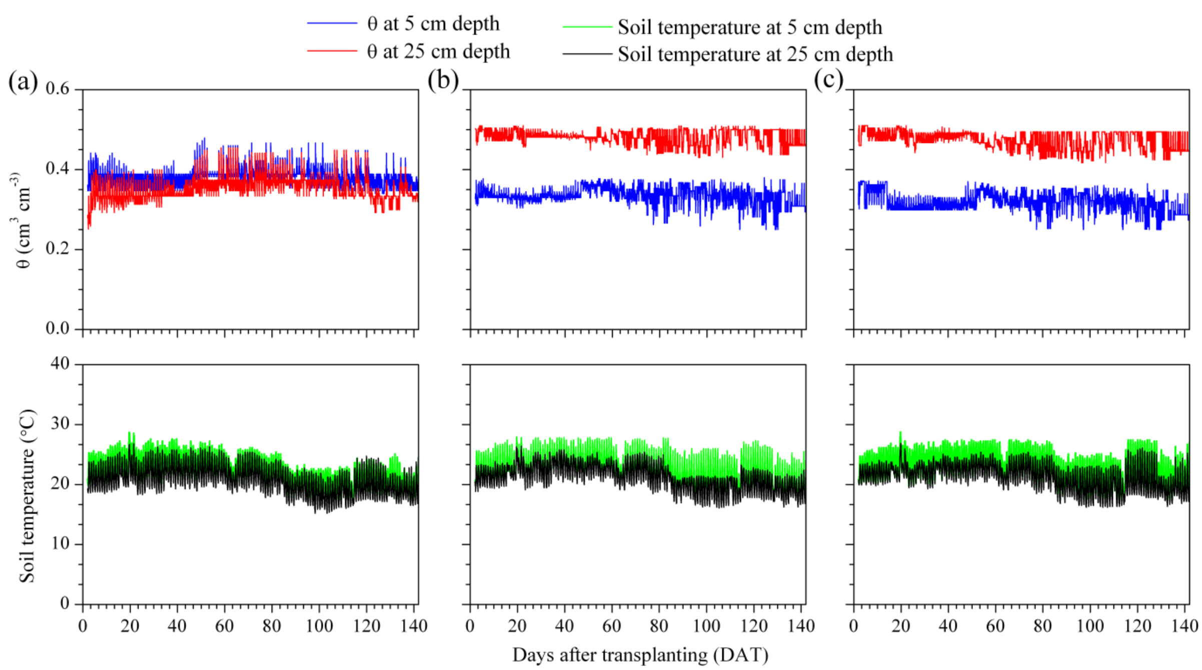

Fig. 3. Daily variations in volumetric water contents (θ) and soil temperatures at pot depths of 5 and 25 under (a) controls or non-compensation (no water stress, fully irrigated), and (b, c) drip-irrigated compensation or partial root zone drying (PRD) treatments using vertically split-root system (PRD_{vert}) during the period from 2 DAT (days after transplanting) to 142 DAT (14 June to 31 October, 2011).

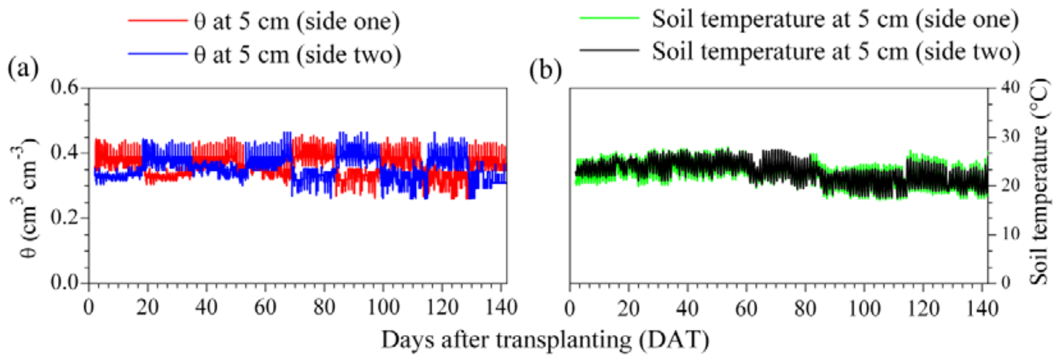

Fig. 4. Daily variations in (a) volumetric water contents (θ) and (b) soil temperatures at pot depth of 5 cm at each side of the drip-irrigated partial root zone drying treatment (PRD_{compt}) using two-compartment split-root system during the period from 2 DAT (days after transplanting) to 142 DAT (14 June to 31October, 2011).

Similar to temporal trends, magnitudes of soil temperatures at 5 and 25 cm pot depths did not noticeably vary among treatments (Figs. 3 and 4b). Soil temperatures at 5 and 25 cm depths in control and PRD_{vert} treatments (Fig. 3) showed a typical diurnal sinusoidal pattern, with decreasing amplitude with depth. Similar diurnal pattern was observed for soil temperatures at 5 cm depth for each side of the PRD_{compt} treatment (Fig. 4b).

Photosynthetic and transpiration rates and root length density

Photosynthetic and transpiration rates were unaffected by the applied irrigation treatments: control (Fig. 2a), PRD_{vert} and PRD_{compt} (Table 1). To meet the peak water demand, chile plants under both PRD treatments could compensate for water stress in one part of the vertical (PRD_{vert}) (above 20 cm depth; Fig. 2b-c) or lateral (PRD_{compt}) (Fig. 3a) root zone profile by taking up water from less-stressed (relatively higher θ) parts of the vertical or lateral root zone regions where water was available. During the period from 2DAT to 142DAT, the evaporative demand, expressed as atmospheric VPD inside the greenhouse (with climate control system), exhibited less fluctuation and was likely to be high (Fig. 5). For example, daily VPD values varied from 0.63 to 2.6 kPa inside the greenhouse compared with outside ones that varied from 0.52 to 3.5 kPa. The abrupt decrease in transpiration rates, particularly on 79DAT (Table 1), could be explained by the leaf temperature above that of the surrounding air. In general, leaf temperature was lower than that of air during photosynthesis and transpiration measurements (Fig. 5).

Table 1. Photosynthetic and transpiration rates, plant height, and root length density (RLD) in response to drip irrigation treatments: control or non-compensation (no water stress, fully irrigated), and two drip-irrigated partial root zone drying (PRD) treatments using vertically split-root system (PRD_{vert}) and two-compartment split-root system (PRD_{compt}).

Parameter	Treatment	Days after transplanting (DAT) on 13 June 2011*						
		37 (19 July)	51 (2 Aug.)	65 (16 Aug.)	79 (30 Aug.)	94 (14 Sep.)	114 (4 Oct.)	131 (21 Oct.)
Photosynthesis (μmol m^{-2} s^{-1})	Control	13.31a	15.70a	16.12a	10.13a	14.17a	8.98a	8.04a
	PRD_{vert}	13.33a	16.20a	16.11a	10.12a	14.00a	9.12a	8.06a

	PRD_{compt}	13.13a	16.16a	16.08a	10.11a	13.81a	10.03a	8.03a
Transpiration rate (mmol m^{-2} s^{-1})	Control	5.05ab	7.76a	6.18a	4.05a	4.81a	4.15a	3.22a
	PRD_{vert}	4.76b	7.73a	6.25a	4.00a	4.95a	4.13a	3.32a
	PRD_{compt}	5.474a	7.80a	6.13a	4.09a	4.90a	4.12a	3.20a
Plant height (cm)	Control	32.00a	46.03a	56.80a	59.14a	60.78a	66.05a	63.88a
	PRD_{vert}	30.05a	40.88a	51.23a	54.93a	57.53a	59.65b	62.90a
	PRD_{compt}	31.93a	47.78a	57.84a	60.86a	62.60a	65.65a	65.68a
RLD (cm root cm^{-3} soil)**	Control	0.071	-	0.083	-	0.085	-	0.071a
	PRD_{vert}	0.077	-	0.086	-	0.087	-	0.070a
	PRD_{compt}	0.068	-	0.085	-	0.088	-	0.072a

*Different letters within columns indicate significant differences by Tukey's Studentized range test at $P < 0.05$.
**On 37, 65, and 94DAT, one pot per treatment was sampled for RLD analysis, while on 131DAT, four pots per treatment were sampled.

No significant differences were noted in the root length distribution between PRD treatments and control (Table 1). Average plant height in all the treatments varied from 30 to 66 cm during the period from 2DAT to 142DAT. The difference in plant height between control, PRD_{vert} and PRD_{compt} treatments was not statistically significant (Table 1). Therefore, either of the two drip-irrigated PRD treatments has the potential to be adopted as water saving practices in chile production where limited water is available such as southern New Mexico.

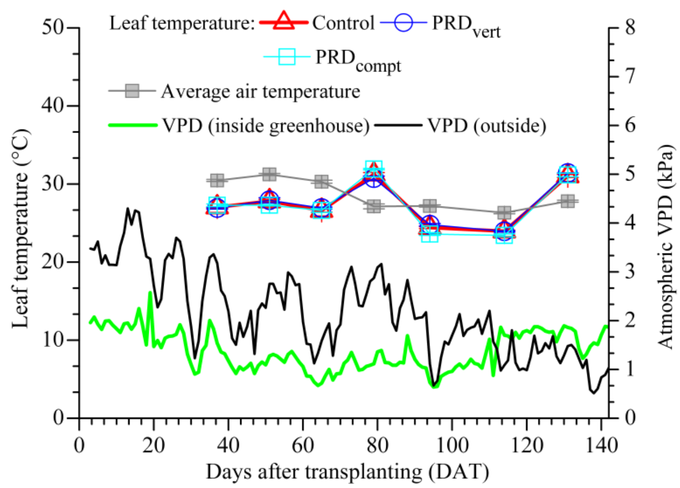

Fig. 5. Average air temperature, and leaf temperatures for control and two partial root zone drying (PRD) treatments using vertically split-root (PRD_{vert}) and two-compartment split-root (PRD_{compt}) systems during the time of photosynthesis and transpiration measurements (Table 1). Estimated daily atmospheric vapor pressure deficit (VPD) values inside and outside the greenhouse are shown during the period from 2DAT to 142 DAT (14 June to 31October, 2011).

Conclusions

Data obtained in this study suggest that both drip-irrigated PRD techniques have the potential to be adopted as water saving practices in chile production. Chile plants under PRD_{vert} and PRD_{compt} could compensate for water stress in one part of the vertical or lateral root zone profile by taking up water from less-stressed parts of the vertical or lateral root zone regions, without affecting root water uptake or transpiration or photosynthetic rates to meet peak water demand. No significant differences were noted in the root length distributions and plant heights between PRD treatments and the control. Although we evaluated PRD_{vert} and PRD_{compt} on greenhouse drip-irrigated chile plants grown in a soil-mix media and without the interference of rain, the application of these drip-irrigated PRD techniques to field-grown plants is expected to maintain similar advantages because chile is a deep rooted crop and therefore, roots will have a higher volume of soil to compensate for water stress. Further numerical assessment of compensatory root water uptake rates and their spatial distribution under PRD_{vert} and PRD_{compt} is recommended to extend the experimental findings.

Acknowledgments
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