Greenhouse Irrigation Systems Affect Growth of 'TAM-Mild Jalapeño-1' Pepper Seedlings

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Abstract. Two studies were conducted to determine how greenhouse irrigation systems alter root elongation, root morphology, shoot growth, and water status of 'TAM-Mild Jalapeño-1' pepper (*Capsicum annuum* L.) seedlings. Transplants were grown in containerized trays for 48 days in a greenhouse. Irrigation systems were 1) flotation (FI), 2) 28 days FI plus 14 days overhead (OI; FI + OI), 3) alternate OI and FI (OI-FI), and 4) OI. FI and OI-FI transplants maintained a uniform lateral root length increase between 20 and 41 days after seeding (DAS). In FI + OI and OI transplants, lateral root elongation tended to plateau at ≈ 31 DAS; however, by increasing the number and length (33%) of basal roots, OI transplants had a total root growth compensation during the remaining growth period. At 41 DAS, OI transplants had a higher shoot : root ratio (S : R = 5) and maintained a higher shoot water potential ($\Psi_{\text{stem}} = -0.58$) than FI transplants (S : R = 3; $\Psi_{\text{stem}} = -0.69$ MPa, respectively). In the second study, OI transplants maintained higher Ψ_{stem} than FI transplants. The latter had a lower stomatal conductance and photosynthesis rate than OI and FI + OI transplants. FI may be used to lower the S : R ratio and promote hardiness in jalapeño transplants.

Recent years have brought a marked increase in the consumption of pungent peppers used in southwestern ethnic food products or Mexican cuisine in the United States. Texas ranks first in processing pungent peppers, with 27% of the total U.S. market, estimated at \$660 million for 1993 (Texas Pepper Conference, Weslaco, unpublished). Of processed pepper products, $\approx 90\%$ include 'TAM Mild Jalapeño-1', which was the first multiple-virus-resistant, mildly pungent pepper developed by the Texas Agriculture Expt. Station, Uvalde (Villalón, 1983). Transplant growth of 'TAM-Mild Jalapeño-1' pepper (a single-stem genotype) generally is characterized by fast stem elongation that may result in thin, weak seedlings with little ability to withstand stresses caused by strong winds and high temperatures after transplanting.

Most containerized vegetable transplants grown in greenhouses are overhead-irrigated; however, subirrigation [flotation or ebb-and-flow] systems produce high-quality bell pep-

per seedlings if grown with minimal nutrient and water stress (Leskovar and Cantliffe, 1993). When drought stress and root pruning methods were used to harden and prevent stem elongation in fresh-market tomato (*Lycopersicon esculentum* Mill.) transplants grown with flotation, there was an increase in lateral root elongation and a decrease in shoot : root ratio (S : R) (Leskovar et al., 1994).

Root development is a dynamic process, responding to several stress stimuli, probably as an adaptive mechanism (Klepper, 1991). Roots sensing water stress synthesize chemicals and transport a signal to the shoots, thus influencing stomatal behavior, gas exchange characteristics, and ultimately growth (Davies et al., 1990). Induced drought or abscisic acid application, used to control shoot growth in bell pepper plants in greenhouses, alters dry-matter partitioning and stomatal behavior (Berkowitz and Rabin, 1988; Leskovar and Cantliffe, 1992; Watts et al., 1981).

Transplant shock occurs when transpiration exceeds water uptake, resulting in sudden or severe plant water deficit (Nitzsche et al., 1991). Information on seedling root and shoot morphological and physiological responses to water management in the greenhouse would be beneficial to optimize production strategies of high-quality, jalapeño pepper transplants with the ability to withstand shock on transplanting. Our purpose was to determine how seedling root elongation, root morphology, shoot growth, and gas exchange characteristics are influenced by irrigation systems in greenhouse-grown, containerized jalapeño pepper transplants.

Transplant growth, Spring 1991. 'TAM-Mild Jalapeño-1' pepper transplants were grown in polystyrene trays with 200 inverted pyramid cells [2.5 long (square side) $\times$ 7.2 cm deep; 18 cm²]. Seeds were sown on 15 Feb. 1991 in a tobacco peat-lite mix (Speedling, Sun City, Fla.) with a water-holding capacity 4.4 times greater than its own weight and covered with 1.25 ml of vermiculite grade 2-3-4 (W.R. Grace & Co., Cambridge, Mass.). Trays were held in a growth chamber at $25 \pm 1^\circ\text{C}$ and 98% relative humidity for 4 days and then transferred to a greenhouse held at $18/30^\circ\text{C}$ minimum/maximum. Seedlings were irrigated every 2 or 3 days using the following watering systems: 1) flotation (FI), 2) 28 days FI plus 14 days overhead (OI; FI + OI), 3) alternate OI and FI (OI-FI), and 4) OI. Irrigation was provided to maintain medium water content between 50% and 20% of water-holding capacity (w/w). In FI, trays were suspended on metal wires attached 6 cm above the base of a wooden frame ($48 \times 84 \times 10$ cm) sealed with clear polyethylene. In each irrigation, water was raised to the level of the container, maintained for 15 to 30 min and then released through a drainage system placed at the base of the wooden frame. For OI systems, seedlings were watered in three passes using a boom similar to those used in commercial nurseries. A soluble fertilizer (Plantex Plantco, Branton, Ont., Canada) at 60, 26, and 50 mg N, K, and Ca/ha, respectively, was applied at 5 and 7 days after seeding (DAS). Thereafter, a combination of $\text{Ca}(\text{NO}_3)_2$ and KNO_3 (ratio 7:3) was applied at 60, 59, and 50 mg N, K, and Ca/liter, respectively, every 3 days until 42 DAS. A supplemental fertilization of 180, 78, and 150 mg N, P, and K/liter, respectively, was applied at 35 and 42 DAS.

Root elongation. Three seedlings per replication were sampled on 7, 14, 21, and 28 Mar. 1991 (20, 27, 35, and 42 DAS, respectively). Seedlings were removed from the trays with forceps and shoots were cut off at the crown surface. Roots were washed in water, blotted, placed in polyethylene bags, and stored at 7°C for 1 or 2 days. Stem diameter and length and leaf area were measured immediately after cutting; dry weights of stems and leaves were determined as described by Leskovar and Cantliffe (1992). Fresh roots were partitioned into their components [taproot (of embryonic origin), laterals (arising from the taproot), and basals (arising from the basal region of the hypocotyl)] and were stained for 24 h using 3 ml of staining stock solution (1% methyl base violet in methyl alcohol) in 100 ml deionized water. Root lengths were measured using a digital image analysis system with a 512×488 -pixel spatial resolution and a MicroSoft DOS 3.3, AgImage Plus software (Decagon Devices, Pullman, Wash.). To increase accuracy and avoid errors resulting from roots overlapping, large (>250 cm long) root samples were divided into subsamples and total lengths were added. At 42 DAS, water potential at the base of the stem (Ψ_{stem}) was measured with a pressure chamber (Soilmoisture Equipment,

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Santa Barbara, Calif.) on 12 seedlings per treatments between 1300 and 1430 HR.

Field root growth. Transplants grown in the greenhouse during Spring 1991 were planted on a Uvalde silty clay loam (fine-silty, mixed, hyperthermic Aridic Calciustoll) soil at the Texas A&M Univ. Center, Uvalde, on 29 Mar. 1991. Beds, 20 cm high, were spaced 1.8 m center to center. A preplant fertilizer blend (45, 15, 30 kg N, P, and K/ha, respectively) was broadcasted and incorporated in the center of the bed. The herbicide *N,N*-diethyl-2-(1-naphthalenyloxy)-propionamide (21.8% a.i.) was sprayed at 4.1 liters·ha⁻¹ on the beds and incorporated with a disk along with the fertilizer. Beds were covered with either black or white polyethylene photodegradable mulch (0.04 mm thick). Transplants were set in two rows per bed and with 0.3-m between-row and 0.3-m within-row spacing in 7-m long plots. Plant water requirements of 25 to 40 mm/week were supplied using drip irrigation to keep the soil water potential between -20 and -50 kPa, as measured by tensiometers placed 20 cm deep. Drip tubing was positioned at the soil level in the center of the bed, 15 cm to the sides of the plants. A flow rate of 340 liters·h⁻¹ per 100 m of bed at 55 kPa was provided by a turbulent twin-wall tape (Chapin Watermatics, Watertown, N.Y.), with emitters spaced every 30 cm. Additional fertilization at 8, 12, and 6 kg N, P, and K/ha, respectively using NH₄NO₃, H₃PO₄, and KNO₃ was applied weekly through the drip system for the first 6 weeks following transplanting.

Three plants per replication were sampled destructively on 20 May 1991. Shoots were excised at the surface; partitioned into stems, leaves, and fruit; oven-dried at 65°C for 5 days; and then weighed. Roots were excavated to a 30-cm depth with a shovel in a 30 × 30-cm area, with the plant in the center of the square. Soil-root samples were gently shaken to remove the adhering soil and washed by soaking in water using a 20-liter container. This technique did not collect small, higher-order lateral roots that were lost during washing and is reflected in the data presented. Roots were partitioned into taproot, basal, and lateral roots. The number of large and medium (>7 and <7 to >2 mm in diameter, respectively) basal or lateral roots and small (<2 mm in diameter) basals roots were counted. Taproot length was measured and dry weights for each component were determined. Marketable fruit at the mature-green stage were harvested from 30 plants per replication on 5 and 18 July and 8 and 21 Aug., and fruit weights were measured.

Transplant growth, Spring 1992. 'TAM-Mild Jalapeño-1' seeds were sown on 28 Apr. 1992 and seedlings were grown for 44 days in a greenhouse held at 25/36°C minimum/maximum. Irrigation treatments and growing conditions were similar to Spring 1991, except for the nutrient levels and frequency of irrigation. Fertilizer was applied at 120, 52, and 100 mg N, P, and K/liter, respectively. Irrigation was provided at 2-day intervals until 36 DAS, followed by daily waterings until 42 DAS, and then returning to the 2-day intervals between 42 and 49 DAS to stimulate seedling harden-

ing. Vegetative growth of three seedlings per replication was determined on 27 May and 10 June (28 and 42 DAS, respectively). Removing seedlings, washing roots, and measuring root and shoot components were performed as previously described.

Water status and gas exchange. Water potential at the base of the stem of transplants was measured between 1300 and 1430 HR with a pressure chamber on 26 May 1992 and continued after 1 day of irrigation at 2- or 3-day intervals. Four randomly selected seedlings per replication were excised at the base of the stem, and within 30 sec of excision, they were inserted into a pressure chamber. Water potential at the base of the stem was measured by standard procedures. On 11 June (44 DAS), diurnal gas exchange was measured with an infrared gas analyzer (model LI-6250; LICOR, Lincoln, Neb.) using a portable leaf photosynthesis meter (model LI-6200; LICOR) on the newly expanded leaves of transplants in the greenhouse.

A randomized complete-block design with irrigation systems replicated four times was used for all experiments. Shoot and root growth, fruit yield, water potential, and gas exchange characteristics data were subjected to analysis of variance and orthogonal contrasts (SAS Institute, Cary, N.C.). Means were separated by least significant difference at $P \leq 0.05$. Significant irrigation systems × time interactions were partitioned for sampling time.

Results and Discussion

Spring 1991 study. Lateral root elongation for FI and OI-FI transplants increased linearly between 20 and 41 DAS (Fig. 1A). OI and FI + OI transplants had a linear increase between 20 and 31 DAS, reaching a plateau thereafter (Fig. 1A). The number of lateral roots (>1 cm long) was independent of irrigation systems, with a mean of 22 roots per seedling and a linear increase during the growing period (data not shown). Between 28 to 42 DAS, basal root elongation was greater for OI and OI-FI transplants than for FI and FI + OI transplants (Fig. 1B).

Although water content of the medium was not measured directly, based on our observations, OI may have provided uniform moisture levels around the hypocotyl, promoting more basal than lateral root elongation in OI transplants, whereas FI (e.g., in FI and OI-FI transplants) promoted early lateral root growth at distal regions from the hypocotyl. In FI + OI transplants, basal root growth was initiated when OI was imposed (28 DAS). The newly emerged basal roots may be a strong sink for assimilates and can constitute important growth components on transplanting in the field, where FI + OI transplants had 30% more basal root weight than FI transplants at 52 days after transplanting (Table 1). This increase in root weight resulted primarily from an increase in large basal roots, which represented 63% of

Fig. 1. (A) Lateral and (B) basal root elongation of jalapeño pepper seedlings in response to greenhouse transplant irrigation [flotation (FI), 28 days FI plus 14 days overhead (OI; FI + OI), alternate OI and FI (OI-FI), and OI] systems, Spring 1991. Vertical bars represent a mean (n = 12) ± SE. Where there are no error bars, SE was smaller than the mean indicator symbol.

the total basal root weight. The importance of basal roots on plant growth and development has been emphasized in bell peppers (Leskovar and Cantliffe, 1993), paprika peppers (Kahn, 1985), black beans (*Phaseolus vulgaris* L.) (Stoffella et al., 1979), and tomato (Zobel, 1975). Root dry weight allocation for large and total lateral root growth was greater for plants growing under black rather than white mulch (Table 1). Soil temperatures under the black mulch during the daytime are generally 3°C higher at 5 cm than under white mulch (Lamont, 1993). However, mulch color did not significantly affect basal, taproot, and total root dry weight.

Jalapeño transplants receiving OI–FI had a larger leaf area and higher leaf dry weight than FI and FI + OI transplants (Table 2), but stem diameter, stem height, leaf count, root components, and total root dry weight were unaffected by irrigation systems (data not shown). During mid-development of transplants (27 to 34 DAS), the S : R ratio approached 3 for all irrigation treatments; however, at 41 DAS, OI transplants had an S : R ratio of 5.1 compared to 2.8 for FI transplants (Fig. 2). In addition, Ψ_{stem} with OI transplants was higher than with FI transplants (Table 2). The higher S : R ratio for OI transplants may be due to an increase in leaf growth. Recent studies have reported higher leaf dry weights resulting from OI on bell peppers and tomato transplants grown in commercial transplant production systems using the same Speedling trays and with about the same nutritional regimes used in this study (Leskovar and Cantliffe, 1993; Leskovar et al., 1994). Early and the pooled fruit yields from four harvests were similar for all irrigation treatments (data not shown). In Leskovar and Cantliffe's (1993) study, OI promoted more basal rather than lateral root elongation in bell peppers early in development. However, in that study, those differences were minimized in the field after transplanting, and total fruit yields were similar as we have reported for jalapeño peppers.

Spring 1992 study. OI transplants had a significantly higher Ψ_{stem} than FI transplants at 28 DAS, approaching –0.55 and –0.85 MPa for OI and FI transplants, respectively, at 34 DAS (Fig. 3). OI–FI and FI + OI transplants had minor Ψ_{stem} changes (average –0.75 MPa) between 28 and 36 DAS (data not shown). At 42 DAS, the time at which the irrigation frequency was decreased from 1 to every 2 days, transplants from all irrigation regimes had a Ψ_{stem} decrease (from –0.9 to –1.1 MPa). Water uptake on OI transplants might initially be greatest at the proximal end of basal roots colonizing the upper part of the medium in the container cells. Conversely, lateral roots in FI transplants, particularly root apicals, are more prone to suffer from root volume restriction, thus reducing water uptake. Stoffella et al. (1988) showed that the S : R ratio was reduced when sucrose was added to the root medium of bell pepper seedlings, and this response was attributed to a lower water content or higher dry weight accumulation in roots.

Stomatal conductance (g_s) was low for all irrigation treatments when measured at dawn

Table 1. Root component dry weights (in grams) of jalapeño pepper transplants as affected by irrigation systems and mulch color, Spring 1991.

Variables	Basal ^z				Lateral			Taproot	Total
	L	M	S	Total	L	M	Total		
Irrigation systems									
Flotation (FI)	141	83	25	249	13	12	25	328	601
FI + overhead (OI)	205	95	24	324	37	11	49	352	724
Alternating (OI–FI)	175	69	24	268	33	10	44	379	690
OI	192	79	34	304	40	9	49	433	787
LSD _{0.05}	60	---	---	71	17	---	20	81	142
Mulch									
White	198	83	23	304	23	13	36	373	713
Black	159	80	30	268	38	9	47	372	688
Significance ^y	NS	NS	NS	NS	*	NS	*	NS	NS

^zL = large, M = medium, S = small.

^yIrrigation systems × mulch interactions were not significant. Data were collected 52 days after transplanting.

NS, *Nonsignificant or significant by F test at $P \leq 0.05$, respectively.

but increased steadily during the morning in FI + OI, OI, and OI–FI transplants and peaked at $\approx 0.35 \text{ mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ at 1100 HR for FI + OI and at 1300 HR for OI transplants (Fig. 4A). All transplants had a slow increase in g_s during the morning with a decline in mid-afternoon. The g_s was much lower in FI transplants than in any others. Transpiration rates followed the same trends as the g_s (data not shown). Photosynthesis (P_n) was higher for OI transplants at 0700 and 0900 HR and for FI + OI transplants at 1100 and 1300 HR compared with P_n for FI transplants (Fig. 4B).

Gas exchange measurements indicated that irrigation systems altered net P_n , g_s , and transpiration. The g_s reduction and transpiration in FI transplants may be valuable for seedling acclimation (hardening) and shock alleviation under water deficit conditions on transplanting. Decrease in g_s is a response associated with drought stress, increase of endogenous abscisic acid (ABA) levels, or exogenous application of an antitranspirant or ABA (Berkowitz and Rabin, 1988; Davies et al., 1990; Watts et al., 1981). Although FI transplants had low g_s , Ψ_{stem} measured at the same time (44 DAS) as g_s was similar to that of FI +

OI and OI–FI (data not shown) transplants but lower than that of OI transplants (Fig. 3). Gollan et al. (1992) reported that g_s decreased in sunflower (*Helianthus annuus* L.) plants exposed to drying soil, even when no decrease in shoot water potential occurred.

Total root elongation was similar for all irrigation treatments at 42 DAS. However, basal root length was greater for OI than for FI transplants, but lateral root length was greater for FI than for OI transplants (Table 3). The FI transplants also exhibited more stem elongation and leaf area than OI transplants. The

Table 2. Influence of irrigation systems on leaf growth and stem water potential (Ψ_{stem}) of jalapeño pepper transplants, Spring 1991.^z

Irrigation systems	Leaf		Ψ_{stem} (MPa)
	Area (cm ²)	Dry wt (mg)	
Flotation (FI)	12	12	–0.69
FI + overhead (OI)	12	13	–0.64
Alternating (OI–FI)	19	16	–0.61
OI	16	17	–0.58
LSD _{0.05}	6	2	0.07

^zPooled data between 20 and 41 days after seeding. Means of 48 seedlings.

Fig. 2. Shoot : root ratio of jalapeño pepper seedlings in response to greenhouse transplant irrigation [flotation (FI), 28 days FI plus 14 days overhead (OI; FI + OI), alternate OI and FI (OI–FI), and OI] systems, Spring 1991. Vertical bars represent a mean ($n = 12$) $\pm$ SE.

Fig. 3. Xylem water potential of jalapeño pepper seedlings irrigated (arrows) with the following systems in Spring 1992: flotation (FI) and overhead (OI). Vertical bars represent a mean ($n = 12$) $\pm$ SE. Where no error bars are shown, SE was smaller than the mean indicator symbol.

Fig. 4. (A) Diurnal leaf conductance and (B) leaf photosynthesis of jalapeño pepper seedlings in response to greenhouse transplant irrigation [flotation (FI), 28 days FI plus 14 days overhead (OI; FI + OI), alternate OI and FI (OI-FI), and OI] systems, Spring 1992. Vertical bars represent a mean ($n = 12$) $\pm$ SE. Where no error bars are shown, SE was smaller than the mean indicator symbol.

Table 3. Influence of irrigation system on shoot growth and root elongation of jalapeño pepper transplants, Spring 1992.^a

Irrigation systems	Stem length (cm)	Leaf area (cm ²)	Root length	
			Basal (cm)	Lateral (cm)
Flotation (FI)	15.6	34	121	199
FI + overhead (OI)	15.6	31	146	176
Alternating (OI-FI)	13.8	30	158	172
OI	12.6	29	169	151
LSD _{0.05}	1.2	3	29	29

^aMeasurements taken 42 days after seeding.

number of basal and lateral roots and the leaf count were unaffected by irrigation systems (data not shown). Nutrient levels seemed to have a major influence, judging by the plant size differences between OI and FI transplants for the Spring 1991 and 1992 experiments (Tables 2 and 3). Nutrient concentration in the medium most likely did not remain constant throughout the experiment. Nutrition often has a strong influence on plant growth and many processes may have been influenced long before changes in root or shoot growth were measured. For example, Ca^{2+} in the root cap seems to play a major role in modification of root growth. Different water conditions at the root tip may affect the root responsiveness to Ca^{2+} (Takahashi et al., 1992).

Based on the high Pn for OI transplants (Fig. 4B), we also would have expected more shoot growth compared to FI transplants; however, that response did not occur (Table 3). Root branching and root color at 42 DAS indicated that OI transplants had relatively more basal and younger lateral roots, compared to fewer basal and older lateral roots, than FI transplants. In many species, 30% to 60% of photosynthates produced each day are lost in respiration, with a significant portion of these losses occurring in roots. These values tend to decline with increasing seedling age (Lambers et al., 1981). Whether younger, actively growing roots (e.g., from OI transplants) are a major sink for photosynthates but with a significant portion lost through root respiration is unknown.

The differential provision of water to the roots influenced the morphology, dry-matter partitioning, and physiological responses of jalapeño pepper transplants. For 'TAM-Mild Jalapeño-1' pepper transplant, FI may be used to improve water-use efficiency, reduce the S : R ratio, and promote hardiness. These characteristics ultimately will determine the transplant quality at the time of planting and its ability to withstand stress after transplanting.

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