Low Nitrogen Fertigation Promotes Root Development and Transplant Quality in Globe Artichoke

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Abstract. Effective nutrition and irrigation are important nursery strategies to produce high-quality seedlings able to withstand heat and drought stress in the field. The objectives of this study were 2-fold, first to identify the influence of two nitrogen (N) levels (75 and 150 mg·L⁻¹) and two fertigation (FR) methods, overhead (OH) and flotation (FL) of artichoke (*Cynara cardunculus* cv. Green Globe Improved) transplants on root/shoot growth and leaf physiology during the nursery period. A repeated greenhouse experiment was conducted and morphophysiological measurements were determined at 4 and 7 weeks after seeding (WAS). The second objective was to determine the impact of the nursery treatments (FR method and N level) on the subsequent crop growth and yield under three field irrigation methods [surface drip, subsurface drip, and overhead-linear system (OH-L)]. Field measurements were conducted at 50 and 150 days after field transplanting (DAT) during Fall–Winter 2015. Transplants fertilized with 75 mg·L⁻¹ N (low N) had improved root components as compared to those with 150 mg·L⁻¹ N (high N), especially at 4 WAS. The low N transplants had higher root surface area, root length, root branching, thinner root diameter, and less shoot area than the high N transplants. Wilting for low N transplants was 13.5% less than that for high N at 5 DAT, with a total yield similar or slightly higher than those of high N. Although growth of OH and FL transplants was statistically similar at transplanting, those irrigated with OH (greenhouse) had a 10% higher yield than FL irrigated transplants, regardless of the field irrigation method evaluated. Overall, low N level (75 mg·L⁻¹ N) applied with OH irrigation in the nursery positively improved the transplant root system and transplant quality of artichoke seedlings.

Transplant shock is very common in globe artichoke [*C. cardunculus* (L.) var. *scolymus* L. (Fiori)] grown in semiarid regions of the United States, such as southwest Texas. High air temperatures and drought stress after transplanting can delay root and shoot growth and significantly reduce marketable yield (Leskovar and Xu, 2013). Therefore, effective nutrition and irrigation management strategies must be used during artichoke growth and development in the nursery period.

Containerized transplants have been widely used to improve stand establishment, control plant spacing, produce uniform plants, provide crop earliness, and increase total marketable yield (Leskovar and Xu, 2013; Russo, 2005). Several pretransplant conditioning methods have been used in the nursery to improve transplant quality, which include growth regulators such as abscisic acid (ABA), antitranspirants, water

deficit stress, media inoculation with mycorrhizal fungi, and temperature control (Campanelli et al., 2014; Garner and Björkman, 1996; Shinohara and Leskovar, 2014). Exogenous ABA induced stomatal closure and enhanced drought tolerance; however, film-forming antitranspirants were not effective in mitigating drought stress in artichoke transplants (Shinohara and Leskovar, 2014). Moreover, mycorrhizal fungi (*Glomus viscosum*) improved stomatal conductance (g_s) and chlorophyll content index (SPAD) of micropropagated globe artichoke (Campanelli et al., 2014).

About 50% of N applied as fertilizer is used by plants whereas the remaining 50% is emitted to the atmosphere (≈25%), leached or depleted to aquatic systems (≈20%), and stored in soils (≈5%) (Galloway et al., 2004). In containerized transplants, proper N level can markedly reduce N leaching from the growing media and improve transplant growth and development (Soundy et al., 2005). Fertigation techniques can also potentially impact transplant quality. For example, FR using FL irrigation can lead to salt accumulation in the upper layer of media in the cells of the tray (Liu et al., 2012) and reduce transplant quality. Since there is little runoff from the growing medium when FL or subirrigation is used, a recommended fertilizer guideline is to reduce fertilizer (20N–10P–20K) concentration in the

irrigation water when FL system is used in petunia (*Petunia ×hybrida*) (Klock-Moore and Broschat, 2001). However, FR of ornamental pepper [*Capsicum annuum* (L.)] using OH and subirrigation revealed that subirrigated plants should not be fertilized with lower N than OH irrigated plants (Kang et al., 2004). Overhead irrigation can better control salt accumulation in the container than FL because the excess water can leach out salts and prevent buildup in the growing medium (Liu et al., 2012); however, nutrient deficiency and low water use efficiency are still concerns.

In the field, subsurface irrigation delivered through drip systems placed deep in the soil (e.g., 30-cm depth) could lead to water deficit in the top soil surface due to slow capillary movement of water (Rowe et al., 2014). When water fronts radiating from the surface and subsurface drip emitters do not merge, they can leave dry regions between emitters (Rowe et al., 2014). Conversely, OH irrigation delivers water by gravity, distributing more uniformly over the planted area (Rowe et al., 2014). However, using preconditioned transplants could provide an adaptive mechanism to withstand microclimate shock in the field (Franco and Leskovar, 2002). This is because transplant root growth in the field is related to management practices (e.g., N level supplied) during the transplant stage in the greenhouse (Liptay and Nicholls, 1993). The use of FL fertigation system in the nursery period allowed muskmelon [*Cucumis melo* (L.)] to adapt to hot and dry weather and showed a trend of increased yield when compared with OH fertigation (Franco and Leskovar, 2002). In fact, FL fertigation maintained a uniform lateral root development in jalapeno pepper transplants and is recommended for promoting transplant hardiness (Leskovar and Heineman, 1994).

Root growth and development is significantly affected by management strategies impacting water and nutrient levels, but the underlying mechanisms are poorly understood (Zhang et al., 1999), especially for containerized vegetable transplants. In *Arabidopsis*, nitrate and phosphorus (P) levels can alter root system architecture (Linkohr et al., 2002). Increasing nitrate concentration in growing media reduced primary root length, while it increased with increasing P supply (Linkohr et al., 2002). In addition, lateral root elongation was suppressed by high nitrate and P levels (Linkohr et al., 2002). Although reduced N fertilization is effective to control transplant height, this approach can significantly limit other growth characteristics such as stem diameter and root volume (Liu et al., 2012). For example, dry matter allocation to roots increased by 7.5% and 12% after 72 and 120 h of N deprivation in rice [*Oryza sativa* (L.)] transplants, but the hydraulic conductivity of the same N-deprived plants was reduced by 24% of that in the control after 48 h (Ishikawa-Sakurai et al., 2014).

The objectives of this study were to 1) identify the impact of N level (low vs. high) and FR technique (OH vs. FL) based on changes in root/shoot growth and leaf level physiological

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responses, and to 2) determine if the FR method and N level used in the nursery significantly modifies the early vegetative growth or yield when grown under surface, subsurface, and OH linear irrigation. Information from this study will be useful to better understand the importance of N and irrigation strategies on improving transplant quality and stand establishment of globe artichoke when transplanted in hot and drought-prone environments.

Materials and Methods

Greenhouse experiment

Plant material and greenhouse setup. A repeated experiment was conducted in a greenhouse at the Texas A&M AgriLife Research and Extension Center, Uvalde, TX (long. 29°12'57.6" N, lat. 99°45'21.6" W). In Cycle I (Sept.–Oct. 2014), mean minimum and maximum temperatures in the greenhouse were 22 and 27 °C, relative humidity 30%–60%, and average light intensity during daytime was 960 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$. In Cycle II (Nov.–Dec. 2014), mean minimum and maximum temperatures were 20 and 25 °C, relative humidity 35% to 72%, and average light intensity during daytime was 640 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$. ‘Green Globe Improved’ artichoke seeds were sown in Speedling trays containing 128 cells (3.2 × 3.2 cm square and 6.4-cm deep) using a Can-Duit seeder (Blackmore Company, Belleville, MI). A black peat and Styrofoam bead mix (8:2) was used as the planting medium. Seeded trays were incubated in a germinator chamber at 22 °C in darkness for 4 d and then placed in the greenhouse where they were grown for 8 weeks each cycle (experiment).

Treatments. One week after seeding, artichoke transplants were fertigated weekly using two levels of N, 75 and 150 $\text{mg}\cdot\text{L}^{-1}$ (herein considered low and high N levels) applied using two irrigation systems, OH and FL. Fertilizers 20N–8.8P–16.6K and 32N–0.0P–0.0K were used as a N source for the first 6 weeks while calcium nitrate (2N–0.0P–0.0K) and 32N–0.0P–0.0K were used during weeks 7 and 8. The composition of 20N–8.8P–16.6K was NH_4^+ , 4%; NO_3^- , 6%; urea-N, 10%; P_2O_5 , 20%; K_2O , 20%; ferric ethylenediaminetetraacetic acid, 0.1%; Mn, 0.05%; B, 0.02%; and Cl, 0.025%. Calcium nitrate (2N–0.0P–0.0K) composition was Ca^{2+} , 3.2%; NO_3^- , 2%; Mg^{2+} , 1.2%; and Fe (chelated Fe), 0.1%.

Nitrogen was supplied through FR treatments using OH and FL irrigation methods. Additional irrigation was applied between FR as needed and based on $\approx 50\%$ of volumetric water content of the media. For trays allocated to OH irrigation, both N fertilizer treatments were applied using a CO_2 backpack sprayer at a speed of 2 min per tray. For FL irrigation, $1.60 \times 0.75 \times 0.15$ m wood beds covered with 0.1 μm thickness polyethylene film were used. After the beds were filled with the N solutions (75 and 150 $\text{mg}\cdot\text{L}^{-1}$) to a depth of 10 cm, the trays were maintained in the floatbeds for 2 h.

Field experiment

Plant material, soil sampling, and weather conditions. The field experiment was conducted

during Oct. 2014 to June 2015 at the Texas A&M AgriLife Research and Extension Center in Uvalde. Transplants (8-week old) grown with the low and high N levels, and using OH and FL irrigation from the first greenhouse cycle experiment were used for the field study. Soil cores of 30-cm depth were collected before planting and at the end of the experiment, soil physical and chemical properties were determined and summarized as shown in Table 1. During the experimental period, mean minimum and maximum temperatures were 16 and 22 °C, relative humidity 74% and 93%, and total rainfall 550 mm.

Cultural practices. Total N, P, and K applied during the field experiment was 150, 100, and 100 $\text{kg}\cdot\text{ha}^{-1}$, respectively. Fertilizers (4N–4.4P–8.3K and 32N–0.0P–0.0K) were applied in five split doses. Gibberellic acid (GA_3 , 4%; CP Bio, Inc., Chino, CA) was sprayed twice at 20 ppm, the first at the fourth leaf stage and the second 10 d after the first application. Seedlings were transplanted in three beds 1.5 m apart, using a single row per bed at a spacing of 0.9 m between plants. The outside rows were used as buffer rows and the middle one was used for evaluation. During the vegetative growth, periodic applications of esfenvalerate (Asana XL, 8.4% by weight; DuPont, Wilmington, DE) at 70 $\text{mL}\cdot\text{ha}^{-1}$ were conducted to control cucumber beetle (*Diabrotica undecimpunctata*) and cut worms. During harvesting, calcium (5%) and zinc (5%) (Tracite, Helena Chemical Co., Fresno, CA) were applied weekly to prevent head atrophy, a physiological disorder typically associated with calcium deficiency.

Treatments. Three irrigation systems (surface, subsurface, and OH-L) were randomized using 90-m-long beds. For surface and subsurface irrigation systems, drip tape was installed at 7.6- or 15-cm depth, respectively. Drip tape used had emitters spaced every 30 cm with a flow rate of 0.91 $\text{L}\cdot\text{h}^{-1}$ at 0.07 MPa (06SLF15636.2-12 Model; Netafim, Fresno, CA). The linear irrigation system was established using a Zimmatic lateral irrigation system (FieldBasic Z300-P; Lindsay Co., Omaha, NE). That system was equipped with fixed sprinklers 1 m above soil surface, 1.5 m between nozzles, and with sprinkler coverage of 6 m^2 at

0.07 MPa. The total irrigation was 140 mm applied in 10 irrigation events. During the season, plants received a total of 10 irrigations, two in Oct. and Dec. 2014, and Mar. 2015, and one irrigation in Nov. 2014, and Jan., Feb., and Apr. 2015. In addition, the linear irrigation time was synchronized with that of surface and subsurface irrigation. Soil moisture sensors (EC-5; Decagon Devices, Pullman, WA) were installed in the low N-OH plots (surface, subsurface, and OH-L) at 15-, 30-, and 45-cm depths and data were recorded hourly. Plant measurements were determined at 50 and 150 DAT.

Plant physiological measurements

Greenhouse. Photosynthetic rate (P_n , $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ CO_2), g_s ($\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ H_2O), and transpiration [E , ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ H_2O)], SPAD, shoot and root morphology, and leaf area were measured 4 and 7 weeks after N application in both cycles. Morphophysiological measurements were conducted between 1100 and 1300 hr from two fully expanded leaves. Sixteen transplants from each treatment (low and high N, OH, and FL) were used for measurements. Photosynthesis and gas exchange were determined using a portable photosynthesis system (LI-6400XT; LI-COR Biosciences, Lincoln, NE). Transplant root components were determined using a WinRHIZO image analysis system (V5.0, Regent Instruments, Quebec, Canada). Chlorophyll content index was measured using a chlorophyll meter (SPAD-502 Plus, Minolta, Japan), and leaf area with a leaf area meter (LI-3100C Area Meter; LI-COR Biosciences). At the end of the second cycle, shoot and root N, transplant pulling force and success %, and stomatal number were determined. Transplant pulling force and success % were determined using a digital force gauge (DFS II; Chatillon Inc., Largo, FL). The gauge was attached to a vertical motorized force tester (LTCM-100; Chatillon Inc.) and then each transplant was pulled from the stem base using seizing forceps with rubber jaws. The total number of pulled transplant without breakage and pulling force from individual transplants were recorded. The transplant pulling success % was calculated using the procedure of Soundy et al. (2005).

Table 1. Soil physical and chemical properties of the field experiment conducted at Uvalde, TX, during 2014–15. The base soil analysis was determined 2 weeks before the study, Sept. 2014. Soil samples were also collected from the 75 $\text{mg}\cdot\text{L}^{-1}$ N-overhead fertigation plots in the surface drip, subsurface drip, and overhead-linear irrigation treatments at the end of the experimental period, June 2015.

Soil properties	Base analysis	End of expt. ^a		
		Overhead-linear	Surface	Subsurface
Sand (%)	25	—	—	—
Clay (%)	41	—	—	—
Silt (%)	34	—	—	—
pH	8.1	8.4	8.4	8.4
Conductivity ($\mu\text{mho}\cdot\text{cm}^{-1}$)	559	362	339	345
$\text{NO}_3\text{-N}$ (ppm)	58.5	8.0	4.75	6.25
P (ppm)	54.5	42.5	51.3	40.6
K (ppm)	810	658	658	683
Ca^{+2} (ppm)	12,939	14,465	14,453	14,372
Mg^{+2} (ppm)	333	313	324	321

^aSoil chemical analyses (conductivity, $\text{NO}_3\text{-N}$, P, K, Ca^{+2} , Mg^{+2}) were not significant ($P < 0.05$) between overhead-linear, surface and subsurface at the end of the experiment. Number of replicates per treatment, $n = 4$. N = nitrogen.

Stomatal number was determined using the nail polish technique (Voleniková and Tichá, 2001). The abaxial side of the leaf (1 cm²) was nail polished for 2 h. The dry polish layer was removed, placed in glass slides, and then stomata number was counted using a binocular electron microscope (CX23; Olympus Optical Inc., Tokyo, Japan). Transplants total Kjeldahl N was determined using a Discrete Analyzer (Easy Chem. Plus; Analytical Technologies, Anagni, Italy). Shoot and root samples were collected, oven dried for 3 d at 65 °C and total N was determined.

Field. Transplant wilting and survival % were determined at 5 and 25 DAT, respectively. Wilting plants had bent leaves with angles between the ground level to less than 20° from the central shoot during the noon time (1100–1300 HR). Leaf area index (LAI) was measured using a ceptometer (LP-80; Decagon Devices, Pullman, WA) between 900 and 1100 HR. The ceptometer probe was placed under the plant and the average of two measurements was recorded. Photosynthesis, leaf gas exchange, and SPAD were determined on two fully mature leaves, fully exposed to the sun between 1100 and 1300 HR.

Artichoke harvests were conducted between 7 Apr. and 10 May 2015. Marketable and unmarketable yield (t·ha⁻¹), head, and heart weight (g) were determined. A head was considered marketable when its diameter was higher than 7 cm and without tipburn and/or open bracts. The artichoke heart and lower part of the head were fleshy after the external bracts were removed.

Statistical analysis

For the greenhouse study, a randomized complete block design with four replications and two factors (N levels, low and high) and FR (OH and FL) was used. Each tray was considered an experimental unit and four transplants per replication were used for measurements. The field experiment was allocated using a split-plot design with three main plots (surface, subsurface, and linear) and four subplots; two N levels (75 and 150 mg·L⁻¹ applied during the transplant stage) and two FR (OH and FL used during the transplant stage). Each plot had a total of 24 plants with three rows each with eight plants per row. The middle row was used for yield and physiological measurements. The analysis of variance in SAS (Version 9.4 for Windows; SAS Institute, Cary, NC) was used to identify differences between N levels, irrigation systems, and their interactions.

Results and Discussion

Root growth components—greenhouse experiments. Low N level (75 mg·L⁻¹ N) significantly improved root growth components and development (Table 2). Transplants fertigated with 75 mg·L⁻¹ N had higher root length, root surface area, root branching (forks), and thinner root diameter than those fertigated with 150 mg·L⁻¹ N after 4 weeks of FR in both cycles (Table 2). Specifically, comparing high to low N, the latter increased root length by 58% in Cycle I

and 42% in Cycle II; root surface area by 46% in Cycle I and 29% in Cycle II; and root forks number by 65% and 43% in Cycle I and II, respectively, when measured at 4 WAS. Root components also increased with low N during late development (7 WAS), 7% (Cycle II) to 39% (Cycle I) in root length, 5% (Cycle II) to 29% (Cycle I) in root surface area, and 10% (Cycle II) to 44% (Cycle I) in fork number. Therefore, seedlings exposed to the low

N level were able to maintain an increase in root development until transplant maturity.

Root plasticity and development are sensitive to nutrient availability within the soil profile including N (Zhang and Forde, 1998). Low N level in the root medium induces carbon assimilates allocation to the roots (Ishikawa-Sakurai et al., 2014). Conversely, high levels of nitrate in the growing medium inhibited early lateral root development,

Table 2. Root components of artichoke transplants fertigated with 75 and 150 mg·L⁻¹ N and with flotation and overhead systems measured in two experimental cycles.

Cycle no.	Week	Treatment	Root components			
			Length (cm)	Surface area (cm ²)	Avg diam (mm)	Forks no.
I	4	Nitrogen	75	152	19.3	0.41
			150	96.3	13.2	0.44
			<i>P</i> value ^z	<0.0001	0.0001	<0.0001
	7		75	843	90.7	0.34
			150	607	70.4	0.37
			<i>P</i> value	0.003	0.010	0.01
II	4		75	227	29.9	0.42
			150	159	23.2	0.46
			<i>P</i> value	0.039	0.080	0.001
	7		75	768	86.5	0.36
			150	716	82.7	0.37
			<i>P</i> value	0.360	0.580	0.41
I	4	Fertigation	Flotation	129	16.7	0.42
			Overhead	120	15.9	0.43
			<i>P</i> value	0.220	0.430	0.30
	7		Flotation	729	79.6	0.35
			Overhead	721	81.6	0.36
			<i>P</i> value	0.890	0.760	0.24
II	4		Flotation	179	24.7	0.44
			Overhead	206	28.4	0.44
			<i>P</i> value	0.360	0.300	0.830
	7		Flotation	686	75.3	0.35
			Overhead	798	93.9	0.38
			<i>P</i> value	0.060	0.020	0.030

^zIrrigation × nitrogen level interaction was not significant (*P* = 0.05).

N = nitrogen.

Table 3. Shoot components (leaf area, shoot length, and stem diameter), chlorophyll content (SPAD), photosynthesis rate (*P*_n, μmol·m⁻²·s⁻¹ CO₂), stomatal conductance (*g*_s, mol·m⁻²·s⁻¹ H₂O) of artichoke transplants fertigated with 75 and 150 mg·L⁻¹ N and with flotation and overhead irrigation systems.

Cycle no.	Week	Treatment	Leaf area (cm ²)	Shoot length (cm)	Stem diam (mm)	SPAD	<i>P</i> _n	<i>g</i> _s
I	4	Nitrogen	75	13.8	8.4	37.4	14.6	0.36
			150	15.7	8.9	36.5	15.4	0.34
			<i>P</i> value ^z	0.02	0.15	0.32	0.49	0.71
	7		75	30.1	21.2	34.2	17.2	0.34
			150	42.3	23.9	39.5	16.6	0.26
			<i>P</i> value	0.0002	0.0007	0.56	0.0002	0.72
II	4		75	19.0	10.5	33.4	15.0	0.70
			150	22.6	12.1	33.3	17.4	0.60
			<i>P</i> value	0.001	0.001	0.93	0.08	0.007
	7		75	32.5	26.5	31.9	28.4	0.64
			150	46.9	32.3	37.9	32.3	0.60
			<i>P</i> value	<0.0001	<0.0001	0.005	<0.0001	0.014
I	4	Fertigation	Flotation	14.2	8.4	37.8	13.9	0.35
			Overhead	15.3	8.9	36.1	16.1	0.35
			<i>P</i> value	0.14	0.18	0.07	0.048	0.97
	7		Flotation	34.5	22.4	36.6	15.8	0.30
			Overhead	37.9	22.8	37.0	18.0	0.31
			<i>P</i> value	0.18	0.55	0.007	0.71	0.83
II	4		Flotation	21.3	11.6	35.0	16.0	0.61
			Overhead	20.2	11.0	31.7	17.0	0.66
			<i>P</i> value	0.19	0.15	0.27	0.05	0.27
	7		Flotation	37.8	29.8	34.7	28.2	0.66
			Overhead	41.5	29.0	35.1	32.5	0.58
			<i>P</i> value	0.13	0.21	0.15	0.75	0.009

^zFertigation × N level interaction was not significant (*P* = 0.05).

N = nitrogen.

specifically after they emerged from the primary root, by postponing the activation of the lateral root meristem (Zhang et al., 1999). In grey alder [*Alnus incana* (L.)], plants exposed to low N, P, or S flux density allocated more carbohydrates to the roots than at higher flux densities (McDonald et al., 1996). In our study, the increase in root length and surface area, together with thinner root diameters and higher number of forks in the 75 mg·L⁻¹ N compared with 150 mg·L⁻¹ N support the hypothesis that low level of N enhance fine-root development and change the root architecture in artichoke transplant.

Although root growth and development are significantly affected by nutrient level, the mechanisms that regulate these processes are poorly understood (Zhang et al., 1999). Gan et al. (2005) found that the development of lateral roots is downregulated by high nitrate status which induced metabolism reprogramming as well as growth and development adaptation, such as changes in gene expression. The *ANR1* gene has been identified as a key component that regulates lateral root growth in *Arabidopsis thaliana* in response to external nitrate concentration in the growing medium (Zhang and Forde, 1998). Although low nitrate-N levels induced the expression of *ANR1* gene rapidly and enhanced lateral root growth, this root-expressed gene is downregulated under high N levels (Gan et al., 2005). Plant growth processes depend on environmental conditions and are strongly regulated by long- and short-distance signaling (Brackmann and Greb, 2014). During the greenhouse study, root N% from 75 mg·L⁻¹ N transplants was significantly lower than those from the 150 mg·L⁻¹ N (Table 4). Low level of N in the root tissues could induce changes in gene expression that triggered the development of lateral roots in transplants fertigated with 75 mg·L⁻¹ N. Accordingly, molecular sensing of nitrogen signaling will potentially improve our understanding of artichoke root growth and development in response to N supply.

Irrigation method can alter nutrient availability, pH, and root distribution in the growing medium. For example, subsurface irrigation (also known as ebb-and-flow, FL, or subirrigation) concentrates soluble salts and N in the top level of the root medium (Morvant et al., 1997). Conversely, OH irrigation distributes salts and nutrients evenly across the root zone, resulting in improved root distribution and more uniform pH of the root medium (Morvant et al., 1997). Because subirrigation holds more soluble salts in the growth medium and leaches less nutrients than OH, subirrigated plants may be more susceptible to salt injury than those under OH irrigation (Cox, 2001). Accordingly, plants growing under subirrigation systems require less fertilizer than those with OH irrigation (Cox, 2001). In addition, plants under subirrigation use less water as compared with OH irrigation. For example, although shoot and root fresh weights were statistically similar in both OH and subsurface irrigation systems, water use and irrigation efficiency was about 9% for OH and 77% for subsurface irrigation (Neal and Henley,

1992). Leskovar and Heineman (1994) found that pepper transplants grown with FL irrigation had lower g_s , P_n , and higher total root and stem water potential than OH irrigated transplants. In our study, no differences were found in root components (length, surface area, diameter, and fork number) between the FR systems, except for root surface area and diameter in Cycle II Week 7.

Shoot growth components—greenhouse experiments. Transplants grown with 150 mg·L⁻¹ N had a significantly increased leaf area, shoot length, SPAD, P_n (Table 3), transplant pulling force (less negative), and total N concentration in roots and shoots (Table 4) at 7 WAS as compared with those grown at 75 mg·L⁻¹ N. Leaf area increased by 30% and shoot length by 15% when exposed to high

Table 4. Abaxial stomatal number, shoot and root total nitrogen (N) and pulling force of artichoke transplants fertigated using 75 and 150 mg·L⁻¹ N and with flotation and overhead systems. Measurements were collected from Cycle II, 7 weeks after seeding.

Treatment	Stomatal no. (mm ⁻²)	Shoot N (%)	Root N (%)	Pulling force (N)
Nitrogen	75	83.13	1.67	1.73
	150	71.58	2.47	2.21
	<i>P</i> value ^z	0.090	<0.0001	<0.0001
Fertigation	Flotation	85.25	1.95	1.86
	Overhead	63.33	2.19	2.08
	<i>P</i> value	0.0002	0.0020	<0.0001

^zFertigation × N level interaction was not significant (*P* = 0.05).

Fig. 1. Irrigation, rainfall, and volumetric soil moisture percentage of irrigation systems at 15-, 30-, and 45-cm soil depths.

vs. low N levels. Overhead FR increased leaf area ($P = 0.14$ Cycle I and 0.13 Cycle II), stem diameter ($P = 0.007$ Cycle I and 0.15 Cycle II), and P_n at the end of both transplant cycles (Table 3). But, shoot length and g_s from OH and FL were inconsistent. Interestingly, transplants grown with OH fertigation had higher total N concentrations in the roots and shoots and lower abaxial stomatal number than FL (Table 4). However, the percentage of artichoke transplants that were pulled from the trays without any breakage was 100% at both N levels under both irrigation methods (data not shown). Higher shoot volumes at high levels of N could be attributed to higher root hydraulic conductivity (Ishikawa-Sakurai et al., 2014) which might induce shoot expansion. It is known that plants subjected to high N levels increased the expression of water channel (aquaporin) genes in the root, whereas N deficiency suppressed their expression (Ishikawa-Sakurai et al., 2014). Aquaporin channels control the passive water movement across cell membranes and play a key role in hydraulic conductivity in plants (Ishikawa-Sakurai et al., 2014; Maurel et al., 2008).

Field experiment. The total rainfall and irrigation were 550 and 140 mm, respectively (Fig. 1). During the study, the soil moisture level was kept between 60% and 80% of soil water holding capacity. All the three irrigation systems used in the field (OH-L, surface, and subsurface drip) delivered similar amounts of water and at the same frequency of application. During the experimental period, all field irrigation treatments had similar soil N and nitrate content at 30-cm depth (Table 1) and volumetric soil moisture percentage (Fig. 1). Soil moisture of OH-L irrigation ranged from 22% to 48% at 15-cm soil depth, 27% to 40% at 30 cm, and 35% to 50% at 45 cm. Surface drip irrigation for volumetric soil moisture was between 25% and 45% at 15-cm depth, 30% and 42% at 30 cm, and 35% and 45% at 45 cm. Soil moisture of subsurface irrigation ranged from 22% to 45% at 15-cm depth, 27% to 42% at 30 cm, and 35% to 48% at 45-cm soil depth. The difference in volumetric soil moisture percentage between irrigation systems was less than 10% across soil depths and over the experimental period. In addition, soil chemical analyses collected from the low N-OH plots (surface, subsurface, and OH-L) at the end of the experiment were statistically similar (Table 1).

Nitrogen level and FR system during transplant development in the nursery did not affect plant gas exchange, SPAD, height, width, and LAI after transplanting in the field conditions (Table 5). However, FR with the low N level significantly improved transplant stress tolerance as no signs of shoot wilting was recorded at 5 DAT. This response can be attributed to the bigger root system of transplants produced with 75 mg-L^{-1} which may help mitigate early transplant shock. Transplant root growth and development in the field is correlated with greenhouse management practices during the nursery stage (Liptay and Nicholls, 1993). Franco and

Leskovar (2002) found that transplant preconditioning during the transplant stage could provide an adaptive mechanism to withstand weather shock in the field. However, transplant survival from all treatments was 100% when measured at 25 DAT (data not shown).

Field irrigation systems significantly impacted artichoke morphophysiological measurements (Table 5). Plant height and LAI of OH-L irrigation was lower than subsurface drip. But leaf-level transpiration rates from OH-L irrigation were higher than those measured from subsurface drip. In addition, transplant shoot wilting % from OH-L was significantly higher than surface and subsurface drip irrigation at 5 DAT.

Marketable yield was similar among all treatments (Table 6). A slight numerical increase was noticed with transplants fertigated with the low level of N (4%) and with the OH-L irrigation (8%). Although OH-L produced lower unmarketable yield than surface and subsurface drip, the marketable yields from field irrigation systems were statistically similar (Table 6). However, the total yield (marketable and unmarketable) from subsurface was statistically higher ($P < 0.0001$) than surface and OH-L irrigation (Table 6). In bell pepper, subsurface drip irrigation had higher yield and root length density and less water consumption than surface irrigation (Kong et al., 2012). Subsurface irrigation

had the capacity to produce more heads than surface and OH-L systems but 29% of the heads did not reach the marketable grading standards, a response that can be related to a higher competition for assimilates into the developing heads and the increase in spring temperatures limiting the size of the heads.

Conclusions

This is the first study in globe artichoke that addressed the impact of pretransplant management of N and FR system on transplant quality and subsequent growth, physiology, and yield responses under three distinctive field irrigation systems. Low level N (75 mg-L^{-1}) FR regime improved root length and surface area and produced shorter and compact transplants, resulting in seedlings more tolerant to field stresses after transplanting in the field. Moreover, transplants with low level N did not exhibit a reduction in yields as compared with those grown with high N level when evaluated under linear, surface, and subsurface drip irrigation. This study demonstrated the importance of N level on improving the overall transplant root system and growth components of globe artichoke containerized transplants and the subsequent adaptation to irrigated field conditions in a semiarid environment.

Table 5. Mean shoot wilting (%), plant height and width, SPAD, LAI, photosynthesis (P_n , $\mu\text{mol-m}^{-2}\text{-s}^{-1} \text{ CO}_2$), gas exchange [stomatal conductance (g_s , $\text{mol-m}^{-2}\text{-s}^{-1} \text{ H}_2\text{O}$)], and transpiration (E , $\text{mmol-m}^{-2}\text{-s}^{-1} \text{ H}_2\text{O}$) of artichoke fertigated using 75 and 150 mg-L^{-1} N and with flotation and overhead systems at transplant stage, and irrigated using overhead (linear), surface and subsurface irrigation systems in the field. Morphophysiological measurements conducted at 50 and 150 d after planting. Shoot wilting evaluation determined 5 d after transplanting.

		Shoot wilting (%)	Plant ht (cm)	Plant width (cm)	SPAD	LAI	P_n	g_s	E
N	75	0.0	78.3	168.0	54.6	3.9	26.9	0.55	2.6
	150	13.5	83.2	169.2	53.8	3.9	26.7	0.49	2.5
	<i>P</i> value ^z	0.001	0.06	0.64	0.28	0.99	0.61	0.1	0.17
FR	Flotation	11.6	79.9	167.3	53.9	3.8	26.7	0.51	2.6
	Overhead	2.1	81.6	169.9	54.6	4.0	26.9	0.52	2.5
	<i>P</i> value	0.01	0.48	0.29	0.32	0.31	0.52	0.92	0.92
IR	Linear	14.1 a	73.7 b	162.3 b	53.3 b	3.6 b	26.8 ab	0.50	3.1 a
	Surface	3.2 b	85.0 a	176.2 a	54.1 ab	3.9 ab	27.6 a	0.53	2.5 b
	Subsurface	3.2 b	83.6 a	167.3 b	55.2 a	4.1 a	26.0 b	0.52	2.1 c
	<i>P</i> value	0.02	0.001	0.0002	0.09	0.09	0.004	0.79	<0.0001

^zExcept for P_n ($N \times FR \times IR$), all $N \times FR \times IR$, $N \times FR$, and $N \times IR$ interactions were not significant ($P = 0.05$).

FR = fertigation; IR = irrigation; LAI = leaf area index; N = nitrogen; SPAD = chlorophyll content.

Table 6. Yield and head quality of artichoke fertigated using 75 and 150 mg-L^{-1} N and with flotation and overhead systems at transplant stage, and field irrigated using overhead (linear), surface and subsurface drip irrigation systems.

Treatment		Marketable (t-ha ⁻¹)	Unmarketable (t-ha ⁻¹)	Total yield (t-ha ⁻¹)	Head wt (g)	Heart wt (g)
N	75	19.47	4.91	24.38	251.7	41.5
	150	18.63	5.51	24.14	245.0	40.0
	<i>P</i> value ^z	0.264	0.31	0.690	0.49	0.45
FR	Flotation	18.25	5.05	23.30	255.9	42.7
	Overhead	19.85	5.37	25.55	240.9	38.8
	<i>P</i> value	0.036	0.58	0.002	0.128	0.045
IR	Linear	19.36	2.80 c	22.16 c	256.6	41.5
	Surface	19.14	5.24 b	24.38 b	247.3	40.9
	Subsurface	18.65	7.60 a	26.25 a	241.2	39.8
	<i>P</i> value	0.721	<0.0001	<0.0001	0.43	0.75

^z $N \times FR \times IR$, $N \times FR$, and $N \times IR$ interactions were not significant ($P = 0.05$).

FR = fertigation; IR = irrigation; N = nitrogen.

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