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Fertigation Frequency Affects Growth and Water and Nitrogen Use Efficiencies of Swingle Citrumelo Citrus Rootstock Seedlings

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***Abstract*. We determined if frequency of application of irrigation water plus fertilizer in solution (fertigation) could modify root and shoot growth along with growth per unit nitrogen (N) and water uptake of seedlings of the citrus rootstock Swingle citrumelo growing in a greenhouse. In the first experiment, all plants received the same amount of water with sufficient fertilizer N but in three irrigation frequencies applied in 10 1.5-mL pulses per day, one 15-mL application per day, or 45 mL applied every 3 days. Plants irrigated at the highest frequency grew the least total dry weight and had the highest specific root length. Plants with lowest irrigation frequency grew the most and used the least water so had the highest water use efficiency. There were no irrigation frequency effects on relative growth allocation between shoot and roots, net gas exchange of leaves, or on leaf N. A second experiment used identical biweekly irrigation volumes and fertilizer rates, but water and fertilizer were applied using four frequency combinations: 1) daily fertigation; 2) daily irrigation with fertilizer solution applied every 15 days; 3) fertigation every 3 days; or 4) irrigation every 3 days and fertilizer solution applied every 14 days. Total plant growth was unaffected by treatments, but the highest frequency using the lowest fertilizer concentration grew the greatest root dry weight in the uppermost soil depths. Roots grew less and leaf N was highest when N was applied every 15 days, implying that root N uptake efficiency was increased when fertigated with the highest fertilizer concentration. All plants had similar water use efficiencies. A third experiment was conducted with irrigation every 3 days and with four different N application frequencies: every 3, 6, 12, or 24 days using four fertilizer concentrations but resulting in similar total N amounts every 24 days. There were no differences in growth, gas exchange, or water use efficiency. Given the fact that all treatments received adequate and equal amounts of water and fertilizer, fertigation frequency had only small effects on plant growth, although very high frequency fertigation decreased N uptake efficiency.**

High citrus production and good fruit quality usually depend on irrigation and fertilization, especially in semiarid areas, but also in subtropical humid areas like Florida, where rainfall is seasonal and sandy soils have low water- and nutrient-holding capacities (Koo, 1980). Water-saving irrigation techniques and fertilizer strategies can be used to improve efficiency of water uptake in grapevines (*Vitis vinifera* L.) and peach trees [*Prunus persica* (L.) Batsch] (Chalmers et al., 1981; Dry et al., 1996) and also fertilizer use efficiency (Quiñones et al., 2003; Russelle et al., 1981). Because tree growth and yield can be limited by low nitrogen (N) supply (Syvertsen and Sax, 1999), historical emphasis has been on applying sufficient N to maximize yield (Dasberg, 1987; Tucker et al., 1995).

Nitrogen fertilization exceeding the recommendation rates {maximum rates of 225 kg N/ha for young orange trees [*Citrus sinensis* (L.) Osbeck] and 280 kg N/ha for mature trees; Obreza et al., 2008} can result in low N use efficiency, reduced fruit quality, and groundwater contamination (Legaz and Primo-Millo, 1988).

Nitrate concentrations above the drinking water quality standards (maximum contamination limit of 10 ppm NO_3-N; U.S. Department of Health, Education, and Welfare, 1962) have been found in groundwater of citrus-producing regions like Florida and Spain (Lamb et al., 1999; Riotte, 1994; WHO, 2004) as a result of the excessive or inefficient use of inorganic fertilizers in citrus production (Bacchus and Barile, 2005). In Florida, coarse-textured soils with low organic matter, shallow root systems of citrus, and intense rainfall increase the probability that fertilizer N will leach beyond the root zone. However, citrus can be grown in the sandy soils with only minimum contamination of groundwater if best management practices are followed using reduced N application rates (Paramasivam et al., 2000; Schumann et al., 2003). Schumann et al. (2003) estimated an optimal N rate of 145 kg N/ha for young orange trees [*Citrus sinensis* (L.) Osbeck] and 260 kg N/ha for mature trees, although optimal rates depend on factors such as soil type, land history, and yield potential. Low N fertilizer rates and increased frequency of applications of fertilizer in solution (fertigation) may enhance nutrient use efficiency and tree productivity while minimizing NO_3 leaching losses (Alva and Paramasivam, 1998; Syvertsen and Smith, 1996). Good N management has been reported to decrease leaf Cl^- concentration in lemon trees [*Citrus* × *limon* (L.) Burm. f.] under salt strees (Gimeno et al., 2009). Fertigation management might also be beneficial to limit excessive root and vegetative flush growth (Yuan et al., 2005) because fertilizer rates can change root density of grapefruit trees (*Citrus paradisi* Macfad.) (Zhang et al., 1998). Intensively managed irrigation systems may reduce summer growth flush in citrus (Schumann et al., 2009), which could reduce the growth rate of pests like Asian citrus psyllid that feed on new leaves. Psyllids are the vector of Huanglongbing, one of the most devastating diseases in citrus all over the world (Bové, 1986; da Graça, 1991).

Frequent applications of low N concentrations can minimize residual soil N that is susceptible to leaching (Willis and Davies, 1990). Intensively managed fertigation systems, in which trees are fertigated as frequently as daily or hourly, have been proposed as a tool to increase water and N uptake efficiency (Schumann et al., 2009). Our objectives were to precisely measure daily evapotranspiration (ET) and to make frequent applications of water and fertilizer to determine if different fertigation frequencies with identical rates of N and water application could alter both daily ET and root and shoot growth of potted Swingle citrumelo [*Citrus paradisi* Macfad. × *Poncirus trifoliata* (L.) Raf.] rootstock seedlings under controlled conditions in a greenhouse. We tested the hypothesis that fertigation frequency determines growth per unit water and N uptake and, thus, water and N use efficiency.

Materials and Methods

Plant material and growth conditions. Three separate experiments were conducted in a greenhouse at the University of Florida/IFAS, Citrus Research and Education Center, Lake Alfred, FL (long. 28.09° N, lat. 81.73° W; elevation 51 m). For all three experiments, uniform 5- to 6-month-old Swingle citrumelo seedlings were purchased from a commercial nursery and transplanted into 30-cm tall, 2.4-L pots filled with previously autoclaved Candler fine sand soil, a hyperthermic, coated Typic Quartzipsamment containing ≈98% sand and less than 1% organic matter (Li et al., 2006). The bottom 15 cm of each pot was filled with air-dried sand, whereas the top 15 cm, which included the entire initial root zone of ≈10 cm, was filled with thoroughly wet sand near field capacity. Thus, roots were not subjected to dry soil

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conditions at transplanting. All plants were grown in an unshaded translucent greenhouse for 12 weeks with maximum photosynthetically active radiation (*PAR;* LI-170; LICOR, Inc., Lincoln, NE) measured above the plants of 1300 $\mu mol \cdot m^{-2} \cdot s^{-1}$, natural photoperiods of ≈11 h, average day/night temperature of 36 °C day/21 °C night, and relative humidity varied between 40% to 100%. All plants were fertigated with varying volumes corresponding to daily ET calculated gravimetrically by weighing plants daily and estimating ET by difference. Irrigation solution was prepared from a complete 8N–0.9P–6.6K–0.1Mg liquid fertilizer (Growers Fertilizer, Lake Alfred, FL) diluted to the appropriate concentration with deionized water. No leaching from the bottom of the pots was observed.

Expt. 1: Irrigation frequency. Thirty 5-month-old seedlings were arranged randomly in three groups of 10 plants each and one of three irrigation frequencies was applied to each group: 1) 15 mL per day applied in 10 1.5-mL pulses applied each hour for 10 h beginning at 0900 HR; 2) 15 mL per day applied in only one 30-s pulse per day at 0900 HR; or 3) 45 mL applied every 3 d at 0900 HR. Two different N rates were applied in this experiment. Seedlings from the first two treatments (those with daily applications) were initially fertigated with 15 mL of 300 mg N/L per plant per day (378 mg N during the whole experiment; Table 1), whereas those irrigated with 45 mL every 3 d received 100 mg N/L per plant per day (126 mg N during the experiment). Rates from 200 to 400 mg N/L are commonly used for fertigation of containerized citrus grown in a potting medium (Scholberg et al., 2002) and similar concentrations have been successfully used in similar experiments (Lea-Cox and Syvertsen, 1993; Syvertsen et al., 2010). Because daily ET increased slightly as plants grew, fertigation volumes increased to as high as 22 mL per day so weekly fertigation rates increased to as high as 46.2 mg N per week in the first two treatments and up to 15.3 mg N per week in the third treatment. These ranges of weekly N applied should have been sufficient for actively growing seedlings while avoiding any nutrient salt accumulation without leaching (Lea-Cox and Syvertsen, 1996).

Precise irrigation treatments were applied using a custom-built irrigation control system consisting of a programmable microcontroller (BasicX24; NetMedia Inc., Tucson, AZ). The irrigation schedules were set and controlled using a MaxStream 9XStream radio (Digi International, Minnetonka, MN) to connect with a file server in the laboratory. A standard 120-V electric solenoid valve was used to open and close the irrigation line. Fertigations were automatically applied using a Flojet injector pump (ITT Corp., White Plains, NY). Volumetric soil water content was measured periodically using time-domain reflectometry (TDR; Fieldscout 135; Spectrum Tech. Inc., Plainfield, IL) probes that were 20 cm long. Probes were inserted in the top soil layers and through the bottom of the pots to measure water content in the bottom 20 cm.

Table 1. Nitrogen (N) concentration, total N applied during the 12 weeks, electrical conductivity (EC), and pH of the fertigation solutions for all the treatments in Expts. 1, 2, and 3.

Treatment	N ($mg \cdot L^{-1}$)	Total N (mg)	EC ($dS \cdot m^{-1}$)	pH
Expt. 1				
1.5 mL 10 pulses/day	300	378–554.4	2.97	6.21
15 mL 1 pulse/day	300	378–554.4	2.97	6.21
45 mL 1 pulse/3 d	100	126–183.6	1.26	7.08
Expt. 2				
Fertigation daily	20	25.2–54	0.59	8.10
Water daily; fertigation every 15 d	300	25.2–54	2.97	6.21
Fertigation every 3 d	20	25.2–54	0.59	8.10
Water every 3 d; fertigation every 15 d	100	25.2–54	1.26	7.08
Expt. 3				
N every 3 d	30	42–63.6	0.68	7.89
N every 6 d	60	42–63.6	0.92	7.47
N every 12 d	120	42–63.6	1.38	6.99
N every 24 d	240	42–63.6	1.70	6.85

Table 2. Expt. 1: Effects of three different irrigation frequencies on mean (n = 10) root, stem and leaf dry weight (DW, g), shoot DW, total plant DW (TPDW, g), root length (m), specific root length (SRL, $m \cdot g^{-1}$), leaf dry weight per area (LDW/A, $g \cdot m^{-2}$), shoot/root (S/R, dimensionless), accumulated evapotranspiration (ET_{total}, mL), and WUE_{WP} ($g \cdot kg^{-1}$).[z]

Irrigation frequency	Root DW	Stem DW	Leaf DW	Shoot DW	TPDW	Root length	SRL	LDW/A	S/R	ET_{total}	WUE_{WP}
10 pulses/day	5.8 b[y]	3.4 c	1.6	5.1 b	10.8 b	31.8	5.5 a	88.9	0.9	1538 a	7.8 b
1 pulse/day	6.2 ab	3.7 b	1.7	5.4 a	11.6 a	33.0	5.3 a	88.7	0.9	1360 b	8.5 a
1 pulse/3days	6.7 a	4.0 a	1.7	5.7 a	12.3 a	31.0	4.7 b	88.1	0.9	1270 c	9.0 a
CV (%)	8.9	6.3	7.1	5.2	5.9	12.9	10.0	4.1	8.5	2.4	6.0

[z]Measurements were made after 80 d of treatment.
[y]Within each column, different letters indicate significant differences at $P \leq 0.05$.

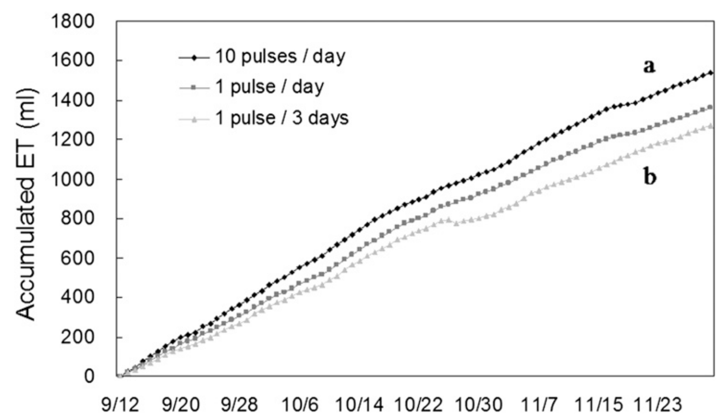

Fig. 1. Expt. 1. Effects of irrigation frequency on mean (n = 10) accumulated plant evapotranspiration (ET). Significant differences ($P = 0.0112$) were observed between the linear regression corresponding to the 10 pulses/day treatment ($y = 19.62x + 45.95$; $R^2 = 0.99$) and one pulse/3 d treatment ($y = 16.21x + 13.75$; $R^2 = 0.99$).

Expt. 2: Irrigation and fertigation frequency. Forty 6-month-old seedlings were transplanted into pots as described for Expt. 1 in four groups of 10 replicate plants and one of four treatments were applied: 1) daily fertigation of 20 mg N/L; 2) daily irrigation and fertigation every 15 d with 300 mg N/L; 3) fertigation every 3 d with 20 mg N/L; or 4) irrigation every 3 d and fertigation every 15 d with 100 mg N/L (Table 1). Volumes of irrigation or fertigation water varied from 15 to 32 mL per plant per day depending on ET so all seedlings from all treatments received identical total amounts of water and N that varied from 25.2 to 54.0 mg N. These rates of N were considerably lower than those applied

Table 3. Expt. 1: Effects of three different irrigation frequencies on mean (n = 10) leaf nitrogen (N_g basis: %, g N/g leaf DW; and N_a basis: $g \cdot m^{-2}$) and N use efficiency (NUE; $g \cdot g^{-1}$).[z]

Irrigation frequency	N_g (%)	N_a ($g \cdot m^{-2}$)	NUE
10 pulses/day	2.8 b[y]	5.0	26.1 b
1 pulse/day	2.9 ab	5.2	28.2 b
1 pulse/3 days	3.0 a	5.3	90.0 a
CV (%)	3.9	6.1	7.9

[z]Measurements were made after 80 d of treatment.
[y]Within each column, different letters indicate significant differences at $P \leq 0.05$.

in the previous experiment because in this second experiment, there were two treatments with N applications every 15 d and we were concerned about potential salt accumulation when using high fertilizer concentrations without leaching. Thus, to supply the total amount of N without exceeding 300 mg·L^{-1}, we reduced the rate of N. Fertigation treatments were applied using a manual pipette.

Expt. 3: Uniform irrigation but varied fertigation frequency. Thirty-six 6-month-old seedlings were established as described previously in four groups of nine replicate plants. All plants received similar amounts of water every 3 d but with one of four fertigation treatments: 1) fertigation every 3 d with 30 mg N/L; 2) irrigation alternating with fertigation every 3 d with 60 mg N/L; 3) irrigation every 3 d and fertigation every 12 d with 120 mg N/L; or 4) irrigation every 3 d and fertigation every 24 d with 240 mg N/L (Table 1). Volumes of irrigation water varied from 16.7 to 25 mL per plant per day depending on ET, but all seedlings received identical total amounts on N that varied from ≈42.0 to 63.6 mg N during the experiment. Fertigation treatments were applied like in Expt. 2 using a manual pipette.

Stem water potential. Midday (near 1200 HR) stem water potential (SWP; McCutchan and Shackel, 1992) was measured in six mature leaves per treatment in the first experiment. Leaves to be measured were placed in aluminum foil-covered plastic bags for at least 1 h before measurement. Stem water potential was measured at the middle (6 weeks) and at the end (11 weeks) of treatments in Expt. 1 using a Scholander-type pressure chamber (PMS Instrument, Corvallis, OR; Scholander et al., 1965).

Gas exchange and leaf water relations. In Expts. 2 and 3, net gas exchange of leaves was measured 11 weeks after the initiation of the treatments using fully expanded single leaves from the middle of the shoot of five replicate plants per treatment. Net assimilation of CO_2 (A_{CO2}), stomatal conductance, leaf transpiration (E_{lf}), and instantaneous water use efficiency ($WUE_{lf} = A_{CO2}/E_{lf}$) were determined with a portable photosynthesis system (LI-6200; LICOR, Inc.) using a 250-cm^3 cuvette. Measurements were made in the morning (0900 HR TO 1100 HR) to avoid high afternoon temperatures and low humidity, which can cause midday depression of net gas exchange (Hu et al., 2009; Jifon and Syvertsen, 2003). During all gas exchange measurements, conditions within the cuvette were: *PAR* greater than 800 μmol·m^{-2}·s^{-1}, leaf temperature 27 ± 5 °C, and leaf to air water vapor pressure difference 1.8 ± 0.5 kPa.

Growth and nutrient concentration. In all three experiments, plants were harvested after 12 weeks of treatment. Leaves, stems, and roots were separated and fresh weights measured. Total leaf area was measured with a leaf area meter (LI-3000; LICOR, Inc.) in combination with a transparent belt conveyor accessory (LI-3050A; LICOR, Inc.). Roots from the second and third experiments were divided in three groups by depths of: 0 to 10 cm, 10 to 20 cm, and 20 to 30 cm. Root length at each depth was estimated using a line-intercept method (Tennant, 1975) and the amount of root length per unit root biomass or specific root length (SRL, m/g) was calculated. All leaves were briefly rinsed with deionized water, oven-dried at 60 °C for at least 48 h, weighed, and ground to a powder. Total dry weights of leaves, stems, and roots were summed as total plant dry weight (TPDW); leaf dry weight/leaf area (LDW/A) and shoot/root dry weight ratio (S/R) were calculated. Because all seedlings were similar in size at the beginning of each experiment, an estimate of whole plant water use efficiency (WUE_{WP}) was calculated as TPDW/total water consumed during the 12 weeks and expressed in units of g·kg^{-1}. Leaf N concentrations were determined by a commercial analytical laboratory (Waters Agricultural Laboratory, Camilla, GA) and expressed as mg/g dry weight (DW) and also as mmol·m^{-2}. Whole plant N use efficiency (NUE) was estimated as TPDW/total N applied (g·g^{-1}) during the 12 weeks (Sorgona et al., 2006).

Experimental design and data analysis. Data from each experiment were analyzed separately using analysis of variance (SAS Institute Inc., Cary, NC) as completely randomized designs with nine or 10 replicate plants per treatment. When a significant F-test was observed, Duncan's multiple range test ($P \leq 0.05$) was used to separate means. The slopes of the fitted linear regression lines to accumulated ET data within each experiment were compared using a *t* test (Sigmaplot 10.0; Systat Software Inc., Chicago, IL).

Results

Expt. 1. Midday SWP varied between –0.6 and –0.9 MPa and there were no SWP differences attributable to treatment after 6 or

Table 4. Expt. 2: Effects of four combinations of irrigation frequencies and nitrogen (N) application on mean (n = 10) root, stem and leaf DW (g), shoot DW, total plant DW (TPDW, g), root length (m), specific root length (SRL, m·g^{-1}), leaf dry weight per area (LDW/A, g·m^{-2}), shoot/root (S/R, dimensionless), accumulated evapotranspiration (ET_{total}, mL), and WUE_{WP} (g·kg^{-1}).[z]

Irrigation and N application	Root DW	Stem DW	Leaf DW	Shoot DW	TPDW	Root length	SRL	LDW/A	S/R	ET_{total}	WUE_{WP}
Water daily N daily	3.7 a[y]	2.4	1.5	3.8	7.6	22.3 a	6.1	71.3	1.1	2066 a	4.0
Water daily N every 2 weeks	2.7 b	2.0	1.4	3.5	6.2	18.0 ab	6.6	72.7	1.3	1983 ab	3.2
Water every 3 d N every 3 d	3.1 ab	2.1	1.4	3.5	6.6	20.5 a	6.7	73.3	1.2	1901 bc	3.5
Water every 3 d N every 2 weeks	2.6 b	1.9	1.4	3.2	5.8	14.6 b	6.0	77.2	1.3	1840 c	3.1
CV (%)	24.7	23.6	20.8	22.0	20.9	22.5	19.6	15.3	24.3	3.9	20.9

[z]Measurements were made after 80 d of treatment.
[y]Within each column, different letters indicate significant differences at $P \leq 0.05$.

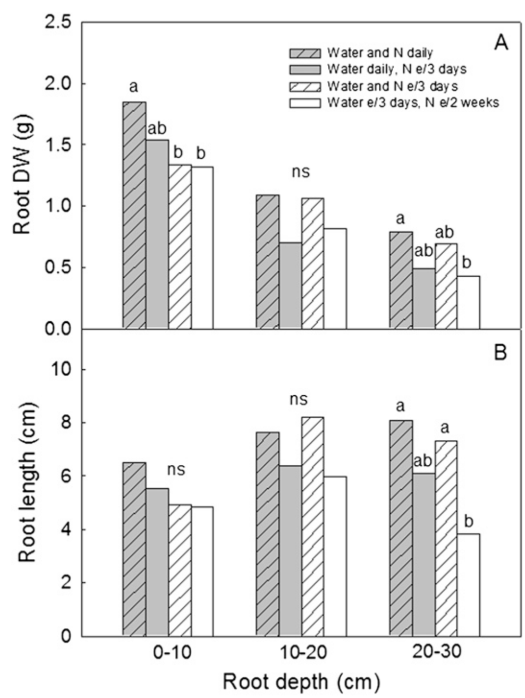

Fig. 2. Expt. 2. Effects of fertigation frequency on mean (n = 10) root dry weight (**A**) and root length (**B**) at three soil depth intervals: 0 to 10, 10 to 20, 20 to 30 cm. Within each depth interval, different letters indicate significant differences at $P \leq 0.05$; NS = nonsignificantly different.

11 weeks of treatments (data not shown). The highest irrigation frequency (10 hourly pulses per day) significantly decreased root and shoot growth because these seedlings grew the least TPDW (Table 2). Plants with lowest irrigation frequency not only grew more, but also had the lowest accumulated ET (Fig. 1) and consequently, a WUE_{WP} greater than in the treatment with 10 pulses per day (Table 2). There were no treatment effects on total leaf DW, leaf area (data not shown), or LDW/A. Plants with the lowest irrigation frequency had the lowest SRL, or the thickest roots, but there were no irrigation frequency effects on relative growth allocation to shoot and roots because S/R was unaffected by treatment. Periodic measurements of soil water content using TDR confirmed that water content at the bottom of the pots was higher in plants receiving less frequent applications of higher volume of water than in the other plants (data not shown).

Although all leaf N concentrations were above levels considered to be sufficient (greater than 26 mg N/g DW), leaf N concentration increased with decreasing fertigation frequency (Table 3), but this difference disappeared when leaf N was expressed on a leaf area basis. The lowest fertigation frequency that received the lowest N rate resulted in the highest NUE. Leaf gas exchange parameters, including WUE_{lf}, were unaffected by treatment (data not shown).

Expt. 2. Leaf, stem and total plant growth (TPDW) were unaffected by treatments (Table 4). Although the total accumulated ET was highest with the daily fertigation and lowest with the least frequent fertigation of every 2 weeks, there were no treatment effects on WUE_{WP}. Total root DW was greatest with daily fertigation, whereas total root length was greatest for the frequent fertigations. Averaging overall soil depths, however, there were no changes in SRL as a result of the fertigation treatments. Root DW tended to be greatest at soil depths above 10 cm and below 20 cm when seedlings were fertigated daily, although there was overall less root DW at the deepest soil depth interval (Fig. 2A). Root length also was greatest below 20 cm in the daily fertigation treatment (Fig. 2B). When N was applied only every 2 weeks, there was less root DW and less root length below 20 cm.

Seedlings with the highest fertigation frequency, the daily fertigation treatment with the lowest concentration of N, took up the least N because they had lower values of leaf N, regardless of unit of expression, than other treatments (Table 5). However, there was no treatment effect on NUE.

Expt. 3. When all treatments were irrigated every 3 d, there were no fertigation frequency effects on total ET or WUE_{WP} (Table 6). In addition, the different fertigation frequencies did not affect any of the measured growth parameters even when roots were separated in three 10-cm depth intervals (data not shown). Different N frequencies did not have any effect on leaf N concentration, NUE (Table 6), or any gas exchange parameter, including WUE_{lf} (data not shown).

Table 5. Expt. 2: Effects of four combinations of irrigation frequencies and nitrogen (N) application on mean (n = 10) leaf N (N_g basis: %, g N/g leaf DW; and N_a basis: $g \cdot m^{-2}$) and N use efficiency (NUE; $g \cdot g^{-1}$).[z]

Irrigation and N application	N_g	N_a	NUE
Water daily N daily	2.4 b[y]	3.5 b	199.6
Water daily N every 2 weeks	2.9 a	4.3 ab	160.7
Water every 3 d N every 3 d	2.9 a	4.3 ab	176.1
Water every 3 d N every 2 weeks	2.9 a	4.5 a	158.3
CV (%)	6.4	18.6	20.9

[z]Measurements were made after 80 d of treatment.
[y]Within each column, different letters indicate significant differences at $P \leq 0.05$.

Discussion

The first experiment showed that low irrigation frequencies in citrus seedlings increased WUE_{WP} and root DW and decreased SRL. Thicker roots tend to decrease water and mineral nutrient transport and can result in lower rates of photosynthesis (Syvertsen and Graham, 1985; Syvertsen et al., 2000). Shoot/root allocation was not altered, however, and total root length was unchanged. As a consequence, the lower SRL was the result of an increased root DW. The lowest SRL observed at the lowest irrigation frequency could have decreased water uptake and, thus, increased WUE_{WP}. Also, the lowest WUE_{WP} in plants with high irrigation frequency could have been the result of a presumably higher evaporation rate from the soil surface after every pulse than after the less frequent applications of higher volumes. Water from the treatment of hourly 1.5-mL pulses probably would have remained mostly in the shallow soil layers, especially during the first pulses every day, after irrigation water redistributed overnight.

The plants with the lowest fertigation frequency (where the lowest N rates were applied) had the highest NUE, as also reported in apple trees (*Malus domestica* Borkh.) by Neilsen and Neilsen (2002). The high leaf N concentration, greater plant growth, and higher WUE_{WP} observed at the lowest irrigation frequency in the first experiment were the basis for developing the second experiment with daily or every 3-d irrigation frequencies as well as different frequencies of fertilizer application. In earlier field studies, there was a decrease in root density when N was applied at excess levels (Ford et al., 1957), but there was an increase in root density if N was applied within optimum levels (Zhang et al., 1998). In the second experiment, we did not observe changes in shoot growth, total plant growth, or water and N use efficiency, but root growth was increased in plants with the highest fertigation frequencies. Root development response to fertilizer nutrients is more sensitive than leaves (Zhang et al., 1998) and we observed that differences in root growth among treatments were mostly the result of roots at the 20- to 30-cm depth. Increases in citrus root growth and decreases in S/R ratio under low irrigation frequency has been reported to be an adaptive mechanism to exploit more soil volume (Syvertsen and Hanlon, 2008). However, the differences in root growth found in our seedlings were a consequence of the N fertilization more than the irrigation frequency because roots can adapt to non-uniform distributions of soil resources (Sultan, 2000). Plants fertigated daily had higher root DW and consequently a larger percentage of roots near the surface than plants irrigated every 3 d (Cahoon et al., 1961; Castle, 1974). This has also been observed in other fruit tree species like apple (*Malus domestica* Borkh.) (Beukes, 1984) and peach [*Prunus persica* (L.) Batsch] (Layne et al., 1986).

In the third experiment, when irrigation was applied every 3 d with a similar amount of total N applied in all the treatments, N application frequency had no effect on growth, water use, or leaf N. Thus, fertigation frequency was of no consequence (Ferguson et al., 1990; Koo, 1980; Weinert et al., 2002) when application rates were similar. In all the three experiments, leaf N concentration was always within the optimal range supporting

Table 6. Expt. 3: Effects of four fertilization frequencies on mean (n = 9) root, stem and leaf dry weight (DW; g), shoot DW, total plant DW (TPDW, g), root length (m), specific root length (SRL, $m \cdot g^{-1}$), leaf dry weight per area (LDW/A, $g \cdot m^{-2}$), shoot/root (S/R, dimensionless), accumulated evapotranspiration (ET_{total}, mL), WUE_{WP} ($g \cdot kg^{-1}$), leaf N ($mg \cdot g^{-1}$ DW), and N use efficiency (NUE; $g \cdot g^{-1}$).[z]

Fertigation frequency	Root DW	Stem DW	Leaf DW	Shoot DW	TPDW	Root length	SRL	LDW/A	S/R	ET_{total}	WUE_{WP}	Leaf N	NUE
N every 3 d	4.2	2.8	1.5	4.4	8.6	26.6	6.4	87.4	1.1	1631	5.2	29.5	164.7
N every 6 d	4.0	2.9	1.6	4.5	8.5	29.8	7.5	87.7	1.2	1573	5.1	30.2	151.3
N every 12 d	3.6	2.9	1.5	4.3	7.9	25.6	7.1	89.8	1.3	1575	4.7	30.7	135.2
N every 24 d	4.2	2.9	1.3	4.2	8.4	27.4	6.5	96.5	1.0	1667	5.1	30.0	163.2
CV (%)	32.0	23.7	26.8	22.9	25.6	35.5	17.8	8.5	19.5	7.0	25.0	8.9	25.9

[z]Measurements were made after 80 d of treatment. No letters within each column indicates no significant differences.

the concept that increased N rates in well-nourished trees are not reflected in changes in leaf N concentrations (Du Sautoy, 1992; Smith, 1954).

In conclusion, water was a better growth regulator than fertilizer because less frequent fertigations increased water use efficiency, decreasing root growth but without altering shoot growth. In addition, infrequent fertigation did not affect N use efficiency, growth, or WUE_{WP}. These results are thought to be beneficial for citrus nurseries but will have to be carefully considered in field-grown citrus trees whose susceptibility to significant nutrient leaching losses from rainfall would increase with decreasing fertigation frequency, thus reducing NUE.

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