Using Soil Solution Monitoring to Determine the Effects of Irrigation Management and Fertigation on Nitrogen Availability in High-density Apple Orchards

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ABSTRACT. Direct application of fertilizers in irrigation water (fertigation) is an efficient method of supplying nutrients to fruit trees. Information is needed on the relationship between irrigation and N inputs on N availability in order to target nutrient applications to meet plant demands. Soil solution was collected from permanently installed suction lysimeters and NO₃-N concentration was measured over the growing season in three experiments: 1) comparison of sprinkler irrigation + broadcast fertilizer with weekly fertigation + daily drip irrigation; 2) comparison of (NH₄)₂SO₄ or Ca(NO₃)₂ as N sources under daily fertigation; and 3) comparisons of combinations of irrigation applied at either fixed rates or to meet evaporative demand and fertilizer (Ca(NO₃)₂) applied daily either at fixed rates or to maintain a given concentration in the fertigation solution in two soil types—loamy sand and silt loam. Trials are located in high density apple plantings of either ‘Gala’ or ‘Empire’ apple (*Malus × domestica* Borkh.) on M.9 rootstock. Nitrate-N concentration in the soil solution measured at 30 cm deep remained higher, over more of the growing season, for weekly fertigation + daily drip irrigation than for a single broadcast fertilizer application + sprinkler irrigation. With daily Ca(NO₃)₂ fertigation, soil solution NO₃-N concentrations increased and decreased rapidly with the onset and end of fertigation respectively, remained relatively constant during the intervening period and were directly proportional to either the amount of N or the amount of irrigation water added. Daily fertigation with (NH₄)₂SO₄ resulted in less control of NO₃-N availability in the root-zone than with Ca(NO₃)₂, which may be problematic for precise timing of N nutrition. Except for the fixed irrigation rate applied to the loamy sand soil, soil solution NO₃-N concentrations at 30 cm beneath the emitter were similar to average concentrations in the fertigating solution, for all methods of irrigation management in both soil types. Elevated NO₃-N concentrations in soil solution below the root zone (75 cm deep) were detected in the loamy sand regardless of methods of N application and irrigation although there was some evidence of less leaching to this depth, under scheduled irrigation. In the silt loam soil, considerably lower concentrations of NO₃-N were found beneath the root zone than at 30 cm deep for all of irrigation procedures and frequently there was insufficient water moving to 75 cm to provide sample. Tree growth in the loamy sand was less than in the silt loam soil; was limited by low application of irrigation water in 1992 and 1993; was unaffected by NO₃-N concentration in the root zone, indicating that N inputs could be minimized by adding N to maintain concentrations of 75 µg·mL⁻¹ or possibly less. Nitrogen inputs may also be reduced if fertilizer N and irrigation water could be retained within the root zone. For coarse-textured soils this will require precise additions of water and possibly soil amendments to improve water holding capacity.

Production methods for apple orchards have become increasingly more intensive over the past 20 years. Currently, in British Columbia and throughout the Pacific Northwest, apple plantings have changed from traditional, low densities (125 to 250 trees/ha) to densities which can be as high as 2000 to 5000 trees/ha. Irrigation is essential for fruit production in these semiarid areas and concomitant with changes in planting systems there has been a change in irrigation practice from overhead or under-tree sprinklers to microirrigation systems such as drip or microjet. This allows not only conservation of water, but also a means to control, more readily than before, nutrient inputs by delivery through the irrigation system (fertigation) (Haynes, 1985), and nutrient losses through leaching, provided that water and nutrient applications can be more closely timed to plant needs with inputs retained in the root zone.

Previous research has indicated some of the potential and limitations of fertigating high-density orchards through drip irri-

gation systems. In addition to the ability to control nutrient inputs, advantages include increased growth and yield in the early production years (Proebsting et al., 1977) and reduction in water usage (Haynes, 1985) when compared with other types of irrigation systems. Disadvantages include accelerated nutrient leaching and depletion within the root zone (Neilsen et al., 1995) and soil acidification particularly if NH₄-based N fertilizers are used (Haynes and Swift, 1986; Parchomchuk et al., 1993).

Root growth is also affected by irrigation method. Root volume can be restricted under drip irrigation in semiarid regions (Levin et al., 1979) and root distribution determined by the size of the wetted soil zone (Bravdo and Proebsting, 1993). Under drip irrigation, roots tend to be shallow (Neilsen et al., 1997) and clustered around the emitter (Goldberg et al., 1971). Root distribution also depends on rootstock, with more dwarfing rootstocks having shallower, more restricted root zones than less dwarfing rootstocks (Neilsen et al., 1997). Thus the combination of drip-irrigation and trees with dwarfing rootstocks is likely to result in a root system which is highly dependent on external nutrient sources (Levin et al., 1980). The drawback of such a limited root system is that the trees are more susceptible to nutrient and water deficits. The small soil volume does, however, allow for more careful monitoring of soil nutrient status and more precise control of nutrient additions.

To take advantage of the flexibility offered by fertigation and to provide adequate nutrition for intensive orchard systems, it is

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Table 1. Summary of irrigation and N treatments for Expt. 3 during 1993–96.

Treatment	1993–94		1995		1996			
	Both soils		Both soils		Silt loam		Loamy sand	
	N	Irrigation (L·d ⁻¹)	N	Irrigation (L·d ⁻¹)	N	Irrigation (L·d ⁻¹)	N	Irrigation (L·d ⁻¹)
1	50 g/tree/yr	4	75 g/tree/yr	8	75 g/tree/yr	11.5 ^z	75 g/tree/yr	9.5 ^z
2	50 g/tree/yr	8	75 g/tree/yr	Variable ^y	75 g/tree/yr	Variable	75 g/tree/yr	Variable
3	75 µg·mL ^{-1x}	8	90 µg·mL ⁻¹	Variable	90 µg·mL ⁻¹	Variable	90 µg·mL ⁻¹	Variable
4	150 µg·mL ⁻¹	8	150 µg·mL ⁻¹	Variable	150 µg·mL ⁻¹	Variable	150 µg·mL ⁻¹	Variable

^zAverage daily application over the season.^yWater was applied according to evaporation measured by an atmometer.^xIn treatments 3 and 4, N concentration is the average concentration in the fertigating solution.

necessary to determine how nutrient availability varies in the soil in response to fertigation and irrigation practices. Nitrogen concentration in saturation paste extracts from soil samples has been used to determine nutrient status in drip irrigated soils (Bar-Yosef et al., 1980; Klein et al., 1989), but is not feasible if soils are to be sampled frequently. Djurhuus and Jacobsen (1995) compared KCl extracts of soil cores and solutions from suction lysimeters and found little difference in NO₃-N concentrations. Suction lysimeters have the advantage that, once installed, there is little further disruption of the root zone.

In the present study, using permanently installed soil suction lysimeters, a series of experiments was initiated to examine NO₃-N concentration in the soil solution of fertigated, high density apple orchards. The aim of this work was to determine the effect of differing fertilizer and irrigation practices on N concentration and availability in the root zone of drip-irrigated dwarf apple trees. It was considered that the information generated from these studies could be used to design nutrition programs which can target fertilizer applications to optimize growth, yield and fruit quality, while minimizing nutrient loss from the root zone.

Materials and Methods

INSTALLATION OF SOIL SUCTION LYSIMETERS. Monitoring of soil solutions was undertaken in a number of experimental orchards using soil suction lysimeters with 2.5 cm diameter × 5-cm-long porous cups attached to tubes of various lengths (Irrometer Co. Riverside, Calif.). Before use, lysimeters were equilibrated three times with 0.5 M HCl for 30 min and then flushed with distilled H₂O. The lysimeters were installed either 30 or 75 cm deep and at an angle (45 or 60°) to minimize preferential flow of irrigation water and fertigation solutions down the side of the lysimeter. The hole into which the lysimeter was inserted was formed by pounding a 2.5-cm-diameter rod into the soil at the desired angle. To ensure that the soil remained in contact with the ceramic cup, a slurry of local fine-textured soil (Penticton silt loam) was poured

into the prepared hole just before the lysimeter was inserted. Samples were collected by applying a 70 kPa vacuum to the lysimeters for one hour after irrigation shut off.

EXPERIMENT 1: EFFECT OF BROADCAST FERTILIZER VS FERTIGATION. Monitoring of soil solutions was undertaken in an existing experiment designed to test the effects of either broadcast N fertilizer + microsprinkler irrigation or N fertigation through drip emitters on the performance of 'Gala' (*Malus × domestica*) on M.9 apple trees. Trees were planted at 1.5 × 4 m spacing on a Skaha loamy sand soil (Wittneben, 1986). Each tree had either one microsprinkler or one drip emitter (4-L·h⁻¹ pressure compensating, Hardie Irrigation, El Cajon, Calif.) located 75 or 50 cm from the tree, respectively. Nitrogen was applied at 25 g/tree in the drip-irrigated plots as liquid NH₄NO₃/urea mixture (28–0–0) through the irrigation water (fertigation) in eight doses at 5-d intervals during May and June and in the microsprinkler irrigated plots as granular NH₄NO₃ (34–0–0) broadcast in the herbicide strip over a 1 m² area around each tree on May 25. Fertigated trees received 10 L of H₂O/day and sprinkler irrigated trees received 240 L in a single weekly irrigation. The experiment was laid out as a randomized complete block experiment with five replications. Suction lysimeters were located 30 cm deep, centered within the tree row at 50 cm lateral distance from the tree (within the fertilizer band in the microsprinkler plots and beneath the emitter in drip irrigated plots). Soil solution samples were collected from plots under both irrigation systems on a regular basis, three times per week from May until August. In the drip-irrigated plots, sampling occurred immediately before and twice in between fertigations. Nitrate-N was measured using a portable ion-specific NO₃ meter (Horiba/Spectrum Technologies Inc., Plainfield, Ill.).

EXPERIMENT 2: EFFECT OF FORM OF N FERTILIZER. In 1992, buried concrete pots, 0.9 m in diameter and 0.6 m deep, with a 7.6-cm drainhole were filled with Skaha loamy sand (Wittneben, 1986) and planted with 'Empire' on M.9 apple trees. Spacings between pot centres were 2.7 × 3.0 m. Irrigation was applied to each pot once daily through a small orifice to give 4 L/tree per day. Trees

Table 2. Amount of N and irrigation water applied during the fertigation period (63 d) in 1993–96 in a silt loam or loamy sand soil in response to different irrigation and fertigation practices for Expt. 3.

Treatment	1993–94		1995		1996			
	Both soils		Both soils		Silt loam		Loamy sand	
	N (g/tree)	Irrigation (L/tree)	N (g/tree)	Irrigation (L/tree)	N (g/tree)	Irrigation (L/tree)	N (g/tree)	Irrigation (L/tree)
1	50	252	75	504	75	728	75	596
2	50	504	75	360	75	579	75	546
3	37.5	504	32.5	360	52	579	49	546
4	75	504	54	360	87	579	82	546

were supplied with either $\text{Ca}(\text{NO}_3)_2$ or $(\text{NH}_4)_2\text{SO}_4$ at the rate of 30 g N/tree per year in daily fertigations from 31 May to 9 Aug. Soil suction lysimeters were installed 30 cm deep in each pot at 0.25 m from the tree and samples collected three times each week. Nitrate-N was measured using a portable ion-specific NO_3^- meter, as noted above. Ammonium-N was measured colorimetrically using standard AutoAnalyser procedures (Technicon Industrial Method No. 329-74W/A; Technicon Instruments Corp., Tarrytown, N.Y.).

EXPERIMENT 3: EFFECT OF FERTIGATION AND IRRIGATION PRACTICE IN DIFFERENT SOIL TYPES. From 1993 to 1996, experiments were conducted in drip-irrigated 'Gala' on M.9 apple trees. The trees were planted in 1993 at 1.25 m (in-row) $\times$ 3 m (between rows) spacing in two soil types, Skaha loamy sand and Penticton silt loam (Wittneben, 1986), which represented the textural range of soils commonly used for tree fruit production in the interior of British Columbia. In each soil type, various rates and concentrations of N solution were applied in conjunction with two levels of irrigation (Table 1). The treatments were arranged in a randomized complete block design with four replicates in the loamy sand and six replicates in the silt loam. Fertigated N solution in the form of $\text{Ca}(\text{NO}_3)_2$ was applied daily for 9 weeks each year (1993–96) starting in late May to early June through venturi injectors (model 283, Mazzei Injector Corp., Bakersfield, Calif.). Irrigation water was supplied to each tree by two 4-L·h⁻¹ pressure compensating, drip emitters (Hardie Irrigation, El Cajon, Calif.) located 50 cm from the trunk on each side of the tree.

In 1993–94, treatments (1 to 4) were applied to supply either 50 g N/tree per year in combination with 4 or 8 L of H_2O /tree per day or to supply 75 or 150 mg N/L in the fertigating solution which, under constant irrigation rate of 8 L/tree per day (Table 1), resulting in fertilizer application rates of 37.5 and 75 g N/tree per year, respectively (Table 2).

In 1995, the irrigation and fertilizer regime was changed (Table 1). Treatment 1 was irrigated at a constant rate of 8 L of H_2O /day and received N at the rate of 75 g/tree per year applied in equal daily doses over 9 weeks. In the other treatments, irrigation was scheduled according to evaporation measured by an atmometer (ET Gage Co., Loveland, Colo.) with irrigation rates manually adjusted to account for the previous week's estimated water use. However, to allow sufficient water for regular application and distribution of the N solutions, which were injected as a pulse at the beginning of each irrigation cycle, a minimum amount of water (4 L/tree per day) was applied in the scheduled irrigation treatments (2 to 4). In

treatment 2, N was added at the rate of 75 g/tree per year which, because of the variable water application, resulted in a variable concentration of N in the fertigating solution. In treatments 3 and 4, the rate of N addition was adjusted weekly according to the variable irrigation rate to maintain N concentrations of 90 and 150 $\mu\text{g}\cdot\text{mL}^{-1}$ respectively.

In 1996, the irrigation rate for treatment 1 was increased to 11.5 L/tree per day for the silt loam and 9.5 L/tree per day for the loamy sand. In the other treatments, irrigation was scheduled according to atmometer evaporation as before except that data loggers (Campbell Scientific, Logan, Utah) were used to electronically monitor evaporation and automatically adjust irrigation according to the previous day's estimated water use. Nitrogen was applied to all treatments on the same basis as 1995 (Table 1). As a result different amounts of water and N were applied to the two soil types (Table 2).

Soil suction lysimeters (Irrometer Co. Inc., Riverside, Calif.) were permanently installed in 1994, at 30 and 75 cm beneath one of the drip emitters in all experimental plots receiving 50 g N/tree per day and 4 or 8 L of H_2O /tree per day and 30 cm deep in the plots receiving 37.5 and 75 g N/tree per year. In 1995, soil suction lysimeters were also installed 75 cm deep in plots receiving 90 and 150 $\mu\text{g}\cdot\text{mL}^{-1}$ irrigation solutions. Soil solution samples were collected on a regular basis (weekly), usually one hour after the morning irrigation had ceased. Nitrate-N was measured using a portable ion-specific NO_3^- meter, as noted before.

Analysis of variance was carried out using the GLM procedure of SAS (1989).

Results and Discussion

EXPERIMENT 1: EFFECT OF BROADCAST FERTILIZER VS. FERTIGATION. Soil solution NO_3^- -N concentrations were dependent on the methods of N application and irrigation (Fig. 1). When 25 g N was broadcast onto the herbicide strip and watered in by microsprinkler, soil solution NO_3^- -N concentration 30 cm deep rose immediately and remained relatively constant until the next irrigation seven days later, after which it decreased substantially and with each successive irrigation until it reached pre-application background levels. Thus fertilizer N was available in the root zone at elevated concentrations for ≈ 1 to 2 weeks after application. A similar pattern of increased NO_3^- -N concentration was observed in response to fertigation every 5 d followed by decreased concentrations due to either dilution or leaching by subsequent daily drip

Fig. 1. Soil solution NO_3^- -N concentration during a growing season in response to N at 25 g/tree applied as either a single application of broadcast fertilizer with microsprinkler irrigation or periodic fertigation and drip irrigation. Vertical bars represent mean $\pm$ SE.

Fig. 2. Soil solution NO_3^- -N concentration during a growing season in response to N at 30 g/tree applied as either $(\text{NH}_4)_2\text{SO}_4$ or $\text{Ca}(\text{NO}_3)_2$. Vertical bars represent mean $\pm$ SE.

irrigation. However, concentrations peaked two days after application and remained higher than at any time under the broadcast-sprinkler application method for at least three to four days after each fertigation (Fig. 1). Thus, overall, fertilizer N remained in the root zone longer and at higher concentrations from weekly fertigation than from a single broadcast application. Given that in the broadcast/sprinkler application treatment 25 g N was added in 240 L of H₂O ($\approx 104 \mu\text{g}\cdot\text{mL}^{-1}$) and that soil solution NO₃-N concentrations peaked at $30 \mu\text{g}\cdot\text{mL}^{-1}$, it is likely that much of the broadcast N was leached below the root zone during the first irrigation period.

EXPERIMENT 2: EFFECT OF FORM OF N FERTILIZER. Soil solution NO₃-N varied with fertilizer N source (Fig. 2). When Ca(NO₃)₂ was used, the concentration of NO₃-N in the soil solution at 30 cm beneath the drip emitter increased rapidly at the onset of fertigation and decreased rapidly after fertigation ended. Background NO₃-N levels measured before and after the fertigation season were much lower ($\approx 5 \mu\text{g}\cdot\text{mL}^{-1}$). A similar rapid decline in soil solution NO₃-N after the end of fertigation was observed by Dasberg et al. (1983) in samples taken from the root zones of fertigated orange trees. When (NH₄)₂SO₄ was the N source, NO₃-N concentration in the soil solution did not increase until ≈ 30 d after the start of fertigation. By the end of the fertigation period the concentration of NO₃-N derived from the NH₄ source was as high as that from the NO₃ source but it persisted in the soil solution for a further 40 d. Nitrification of NH₄-N added at the beginning of the fertigation period was slow. This may be attributed either to lower soil

temperatures earlier in the season or to an initial low level of microbial activity in the soil which has an organic matter content of <1%.

These results indicate that there is far less predictable control of N availability over time if an NH₄ source of N is used instead of a NO₃ source. This should be taken into account when designing N fertilizer programs which target different developmental stages of the plant, or if late season availability of N might extend the period of vegetative growth and thus inhibit the development of dormancy (Faust, 1989). As previously observed by Klein and Spieler (1987), measured NH₄-N concentrations in the soil solution were always low ($<2 \mu\text{g}\cdot\text{mL}^{-1}$).

EXPERIMENT 3: EFFECTS OF FERTIGATION AND IRRIGATION PRACTICES IN DIFFERENT SOIL TYPES. In 1994, the concentration of NO₃-N in the soil solution at 30 cm beneath the drip emitter increased rapidly at the onset and decreased rapidly at the termination of fertigation in both a silt loam and loamy sand soil in response to daily fertigation of Ca(NO₃)₂ (Fig. 3). During fertigation, NO₃-N concentration was relatively stable for both soil types, and varied in proportion to the amount of fertilizer added, 37.5 or 75 g N/tree per year, (Fig. 3 a and b) and the volume of irrigation water, 4 or 8 L/tree per day, (Fig. 3 c and d).

For the silt loam soil (Fig. 3 a and c), soil solution NO₃-N concentration at 30 cm was quite close to the expected average concentration in the fertigation solution (calculated from the Ca(NO₃)₂ input per irrigation and the amount of water added). This supports the findings of Dasberg et al. (1983) who reported that soil

Fig. 3. Measured soil solution NO₃-N concentration in response to (a) rate of fertilizer in a silt loam soil, (b) rate of fertilizer in a loamy sand soil, (c) rate of irrigation in a silt loam soil, and (d) rate of irrigation in a loamy sand soil during the 1994 growing season. Vertical bars represent mean $\pm$ SE.

solution $\text{NO}_3\text{-N}$ concentration was proportional to the rate of added fertilizer in the trickling solution and of Bar-Yosef and Sheikholeslami (1976) who showed that within a 12 cm radius of the drip emitter, soil solution concentrations were relatively constant over time and were similar to the concentration of N in the trickling solution.

In the present study, in 1994, N was not continuously injected into the irrigation line as in other studies (Dasberg et al., 1983; Klein et al., 1989) but was pulsed for a short period (1 to 3 min) at the beginning of each irrigation event. Thus the concentration measured in the soil solution sample reflects mixing within the irrigation system plus mixing within the soil of the current input of water and N with the existing soil solution. In addition, there was little effect of the timing of fertilizer injection during irrigation events on soil solution $\text{NO}_3\text{-N}$ concentration as there was little difference between soils receiving one pulse of fertilizer and either one or two irrigation cycles per day—4 and 8 $\text{L}\cdot\text{d}^{-1}$ irrigation treatments respectively (Fig. 3 c and d) or pulses of fertilizer at each irrigation cycle (Fig. 3 a and b). Despite other factors, which may affect soil solution $\text{NO}_3\text{-N}$ concentration, including plant and microbial uptake of N, denitrification and leaching through either drainage or displacement, these findings suggest that in medium textured soils, it may be possible to control $\text{NO}_3\text{-N}$ concentrations in the soil solution 30 cm deep based on the amounts of fertilizer N and irrigation water being added at a given time.

In the loamy sand soil however, soil solution $\text{NO}_3\text{-N}$, although

proportional to fertilizer and irrigation volume, did not reach expected concentrations (Fig. 3 b and d). Bar-Yosef and Sheikholeslami (1976) also found effects of soil texture on soil solution $\text{NO}_3\text{-N}$ concentration beneath drip emitters, however, in contrast with the present findings, concentrations in a fine textured soil were less than those of the trickling solution and in a coarse textured (sandy soil) were equal to them. The relatively low concentration in the clay soil they attributed to denitrification. In the present study, the observed effects of soil type on the relationship of trickling solution to soil solution $\text{NO}_3\text{-N}$ concentration may reflect a shorter residence time of the initial pulse of added N in the loamy sand soil than in the silt loam soil.

Since the results were essentially similar and to avoid repetition, results from 1995 and 1996 are presented only for plots where the irrigation treatments differed from 1994—that is, those receiving variable irrigation and either a constant rate of N (75 g N/tree per year) or a variable rate of N to give 150 $\mu\text{g}\cdot\text{mL}^{-1}$ in the fertigating solution (Table 1).

Soil solution $\text{NO}_3\text{-N}$ concentrations were more consistent if N fertilizer was added to maintain a given concentration in the fertigating solution (variable N rate) rather than at a given rate per tree (constant N rate) when irrigation was applied to meet evaporative demand as measured by an electronic atmometer (Fig. 4). However, in 1995, soils receiving the variable rate of N (Fig. 4 a and b), had soil solution $\text{NO}_3\text{-N}$ concentrations that were less

Fig. 4. Soil solution $\text{NO}_3\text{-N}$ concentration in response to N applied according to a fixed daily rate (constant N) or to maintain a fixed concentration under irrigation scheduled to meet evaporative demand (variable N) (a) to a silt loam soil in 1995, (b) to a loamy sand soil in 1995, (c) to a silt loam soil in 1996, and (d) to a loamy sand soil in 1996. Vertical bars represent mean $\pm$ SE.

Table 3. Effect of irrigation and fertigation on fruit yield and tree growth in 2- to 4-year-old Gala on M.9 in Expt. 3.

Treatment ^y	Fruit yield (kg/tree)			TCSA ^z (cm ²)		
	1994	1995	1996	1994	1995	1996
1	2.2	6.4	14	3.75 a ^x	5.97 a	7.99 a
2	2.6	8.6	15	5.05 b	7.45 b	9.95 b
3	3.1	8.1	17	4.96 b	7.85 b	10.2 b
4	3.0	7.9	15	5.08 b	7.76 b	9.76 b
SE	0.39	0.85	1.7	0.33	0.56	0.69
Significance	NS	NS	NS	**	*	*

^zTCSA = trunk cross-sectional area.^yTreatments given in Table 1. Years analysed separately as treatments changed from year to year. Data averaged for both soil types since there was no soil by treatment interaction.^xMeans separation in columns by Duncan's multiple range test. Means followed by the same letter are not significant $P = 0.05$ NS, ** Nonsignificant or significant at $P = 0.05$, or 0.01 respectively.

and d). This likely reflects differences in fertilizer injection and irrigation practice. In 1994, constant fertigating solution concentrations were maintained by injecting a pulse of N at each irrigation event but because the irrigation rate did not vary, the amount of N added in each pulse also remained constant. In 1995, a variable rate of water was irrigated and N was added in a pulse at the beginning of the irrigation cycle. Constant concentrations in the fertigating solutions were maintained by adjusting the amount of added fertilizer manually on a weekly basis to correspond to weekly adjustments in watering. Thus, it is possible that there was some unevenness of N delivery throughout the irrigation system. In contrast, in 1996, N was injected throughout the irrigation cycle to maintain a constant concentration. Moreover, in 1996, irrigation was also adjusted on the basis of soil moisture measurements. If soil moisture content fell below 14% in the loamy sand and 26% in the silt loam, the crop coefficients used to estimate crop water use from atmometer readings were adjusted to increase water application rates. Additional water was also added to bring the soil moisture content back to the target levels. This occurred three times for the silt loam soil at day 186, 189, and 199 (Fig. 4c) and once for the loamy sand soil at day 199 (Fig. 4d). Thus soil moisture content was likely more uniform in 1996 than in 1995. There was an unanticipated and large irrigation event just after fertigation ended in the silt loam soil (Fig. 4c) consequently, the measured concentrations at that time may not relate to treatments.

PLANT GROWTH. There were few effects of either irrigation or fertigation treatments on plant growth or fruit yield in Expt. 3 (Table 3). The exception to this was a reduction in growth of trees receiving the low irrigation rate (4 L/tree per day) 1994. This effect persisted through 1996 even though the irrigation rate was increased in 1995 and 1996. Soil type had little effect on fruit production or growth until 1996, when trees grown on the silt loam soil were larger than those grown on the loamy sand (data not shown). These results imply that a soil solution N concentration of $75 \mu\text{g}\cdot\text{mL}^{-1}$ is adequate for young apple tree growth. It is possible that optimum growth could occur at lower soil solution $\text{NO}_3\text{-N}$ concentrations than those imposed in this experiment. It has been suggested that at high solution $\text{NO}_3\text{-N}$ concentrations N uptake is independent of concentration and that maximum uptake of $\text{NO}_3\text{-N}$ occurs at very low solution concentrations of $0.28 \mu\text{g}\cdot\text{mL}^{-1}$ for apple trees (Bhat, 1983). However, there have been many reports of increased plant growth in response to soil solution $\text{NO}_3\text{-N}$ concentrations far exceeding theoretical maxima (Robinson et al., 1991). Neilsen et al. (1993) found that for apple trees in pots, optimum growth occurred in plants receiving daily fertigation of 56 to 112 $\mu\text{g}\cdot\text{mL}^{-1}$ and lower growth in plants receiving both lower and higher N concentrations ($\leq 28 \mu\text{g}\cdot\text{mL}^{-1}$ $\text{NO}_3\text{-N}$ and $224 \mu\text{g}\cdot\text{mL}^{-1}$ $\text{NO}_3\text{-N}$).

Bhat (1983) suggested that under field conditions plant NO_3

uptake occurs either at near maximum rate or ceases rapidly and that low uptake is due to the difficulty of maintaining nutrient flux to the plant rather than to low soil solution concentration. In the current study, limitations to growth occurred when the irrigation was low (Table 2), which may have caused either a water or nutrient deficit if flux was the limiting factor. In addition, by comparison with the silt loam soil, growth was also limited in the loamy sand for all irrigation and fertigation treatments despite the application of large amounts of water and fertilizer in some treatments (Table 2). This could also be attributed to localized poor hydraulic conductivity in the rhizosphere limiting movement of water and N in the immediate vicinity of the root although the effect of other factors restricting growth cannot be discounted.

MOVEMENT OF FERTIGATED N BENEATH THE ROOT ZONE. In 1994, in the silt loam soil, $\text{NO}_3\text{-N}$ concentrations 75 cm deep, below the root zone, remained lower than the concentrations in the fertigating solution for both the 4 and 8 L of $\text{H}_2\text{O}/\text{day}$ treatments (Fig. 5a). This can be attributed to the movement of only small volumes of the fertigation solution to 75 cm to mix with the existing soil solution, which had a low $\text{NO}_3\text{-N}$ concentration. At most sampling times, soil solution could only be extracted from four or fewer of the six sites per treatment and after day 180 the soil was too dry to supply any solution confirming the lack of irrigation water movement down-profile. Similar results were found in 1995 and 1996 when irrigation was scheduled to meet evaporative demand (Fig. 5 c and e).

In the loamy sand, $\text{NO}_3\text{-N}$ concentrations in the soil solution 75 cm deep were less than but approximately proportional to the concentrations in the fertigating solution and the distribution over time was offset with respect to the start and end of fertigation (Fig. 5b). The presence of high $\text{NO}_3\text{-N}$ concentrations in the soil solution below the root zone suggests that a substantial portion of added N was being leached. It is not possible to determine the quantity of leached N because we have no measure of water flow and hence no means of determining N flux. Halving the amount of irrigation water did not prevent movement below the root zone, even though plant measurements indicated that the lower amount of irrigation had reduced tree growth (Table 3). Less irrigation water, when applied uniformly throughout the growing season, only had the effect of delaying leaching. Moreover, by day 250, the reduction of $\text{NO}_3\text{-N}$ concentrations to background levels indicated that leaching beyond 75 cm had likely occurred.

In the same soil, however, more control of $\text{NO}_3\text{-N}$ movement within the soil profile was achieved the following year (1995) when water application rates were determined by reference to evaporation from an electronic atmometer. Soil solution $\text{NO}_3\text{-N}$ concentrations differed depending on whether fertilizer was applied either at a fixed rate or at a fixed average concentration in the

However, in 1996, irrigation was scheduled to meet daily evaporative demand and because the trees were larger and the crop coefficient was higher, more water was added than in 1995. As a result, N movement down-profile started earlier in the fertigation season than in 1995 (Fig. 5f). Although concentrations decreased

Fig. 5. Soil solution $\text{NO}_3\text{-N}$ concentration below the root zone (75 cm deep) in response to: irrigation of 4 or 8 L/tree per day in a silt loam (a) and loamy sand soil (b) in 1994; scheduled irrigation and N applied at constant or variable rate in a silt loam (c) and loamy sand (d) in 1995; scheduled irrigation and N applied at constant or variable rate in a silt loam (e) and loamy sand (f) in 1996. Vertical bars represent mean $\pm$ SE.

rapidly after fertigation ended they did not decline to background levels, as in 1994, suggesting that later-season irrigation applications did not penetrate deeply enough to leach accumulated NO_3 further. These findings illustrate the difficulty of trying to irrigate a coarse-textured soil well enough to meet plant needs while minimizing nutrient leaching. Strategies to achieve better retention of N in the root zone may include more frequent, but smaller applications of water and amending soils to improve water holding capacity.

In summary, frequent monitoring using permanently installed soil suction lysimeters proved a useful tool for determining soil solution $\text{NO}_3\text{-N}$ concentrations in the root zone of fruit trees in response to various fertilizer and water application strategies. Under daily drip fertigation, it is possible to control the concentration of soil solution $\text{NO}_3\text{-N}$ derived from a NO_3 fertilizer in the soil zone most likely to contain a high proportion of tree roots in young, high density apple plantings. This information should be useful in targeting N supply to meet different physiological requirements of the tree at different stages in the growing season. Plant growth responses suggest that soil solution $\text{NO}_3\text{-N}$ concentrations of $\leq 75 \mu\text{g}\cdot\text{mL}^{-1}$ may be sufficient to meet plant requirements when available over an extended period. It is suggested that in coarse textured soils, water and nutrient movement to the root may limit growth. Decreasing the amount of applied N in the root zone can only be achieved by either denitrification, removal by plants or microorganisms or by leaching. The present results indicated that some control of leaching can be achieved by relatively simple irrigation management techniques in a medium textured soil and to some degree by irrigation scheduling in a coarse textured soil. Future research should emphasize more precise irrigation scheduling, which could result in higher nutrient use efficiency by the plant and thus lower N inputs. The control of the timing of N availability through the reduction of soil solution $\text{NO}_3\text{-N}$ concentrations could then possibly be achieved by plant uptake and dilution from subsequent irrigation water rather than by removal through leaching.

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