Leaf Nutrition and Soil Nutrients Are Affected by Irrigation Frequency and Method for NP-Fertigated 'Gala' Apple

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Abstract. 'Gala' apple (*Malus domestica* Borkh) on M.26 rootstock was subjected, in the first five growing seasons, to NP-fertigation and a factorial combination of treatments involving method and frequency of irrigation. Two types of emitters (drip or microjet) were used to apply the same quantity of water at high (daily), intermediate (about weekly) and low (about bi-weekly) irrigation frequencies. Although initial tree vigor and yield were higher for drip-fertigated trees, by the end of the study microjet fertigation produced larger trees of similar yield. These microjet fertigated trees had higher leaf P, K and Cu but lower leaf N, Mg, and Mn than drip-fertigated trees. Soil pH and extractable Mg and K concentrations were higher and extractable-P concentrations lower directly beneath microjet-emitters as a result of the larger fertigated soil volume relative to drip-emitters. High frequency irrigation improved tree growth but had less effect on leaf nutrient concentrations or soil chemical changes than lower frequency irrigation. Leaf N concentration was most affected by irrigation frequency, tending to decrease with daily irrigation.

The delivery of fertilizers to deciduous fruit trees through microirrigation systems has been advocated because of the potential to synchronize fertilizer application with plant nutrient demand (Haynes, 1985). A more efficient use of fertilizers and water should also be realized. Nitrogen and P fertigation of young, high density apple orchards are increasing in semiarid regions of the Pacific Northwest where irrigation is required for production and where water conservation is gaining momentum (Neilsen et al., 1993b). More research is required to understand factors affecting the performance of this novel method of controlled nutrient and water application.

Previous research indicated several factors that are likely to influence tree response to fertigation. For example, growth and nutrition of apple trees was related to soil moisture conditions (Goode and Hyrycz, 1964), which can be influenced by variations in irrigation frequency and differences in a soil's conductivity and moisture holding characteristics (Levin et al., 1980). Variations in irrigation frequency and quantity of applied water are also likely to differentially affect nutrients, which vary in their solubility and reactivity with the soil (Rolston et al., 1981). Top growth and nutrition of 'Delicious' apple trees responded differently to trickle and sprinkler methods of irrigation (Middleton et al., 1981). Restriction in root volume has been measured beneath trickle emitters in semiarid regions (Levin et al., 1979), and it has been speculated that such reductions-in root volume make trees more dependent on external fertilizer supply (Levin et al., 1980). Limited research reported on this topic has mostly studied the effects of root volume on uptake of N (Bar-Yosef et al., 1988). Acidification of sandy soil as a consequence of $\text{NH}_4\text{-N}$ application is a potential limitation of trickle fertigation (Haynes and Swift, 1987). Little information is available on how this process might be mitigated by other factors, such as a larger root volume.

No studies have investigated the effects of these major variables

on apple tree performance when trees are being fertigated. This study investigates the effects of irrigation frequency and method during the first five growing seasons on growth and nutrition of 'Gala' apple trees fertigated annually with N and P.

Materials and Methods

A block of 'Gala' apple on M.26 rootstock was planted in April 1989 at a spacing of 2 m (within row) $\times$ 4 m (between row). Trees were trained to a vertical axe system supported by posts and wire. Vegetation in the tree row was controlled over a 1.5 m width with glyphosate at 1 kg-ha⁻¹ in early May, midsummer, and early fall of each year. A factorial arrangement of treatments, involving all combinations of two methods of applying water and three irrigation frequencies, was applied in a randomized complete block design with six trees per treatment, replicated in four blocks (two blocks each of 'Royal Gala' and 'Regal Gala'). Irrigation was applied, as required for fruit production in this area, from 1 May-1 Oct. Treatments were maintained for the first five growing seasons (1989-1993). Irrigation water was applied either via 4 liter-h⁻¹ drip emitters located 50 cm from the trunk of both sides of the tree or via a single 24-liter-h⁻¹ emitter located halfway between trees (Microjet Irrigation Systems, Inc., Orlando, Fla., hereafter referred to as microjet emitters). It was estimated that the drippers wet a 1-m wide strip, while the microjet-emitters wetted a 2-m wide strip. Maintenance of a 1.5-m-wide herbicide strip resulted in covercrop growth on the edges of the wetted area for microjet-but not drip-irrigated plots. Irrigation frequencies were high (F1), medium (F2), and low (F3). With high frequency irrigation (F1), water was applied daily for 2 h (drippers, 16 liters/tree) or 1.5 h (microjet, 36 liters/tree) during the five growing seasons. Irrigation for the intermediate frequency (F2), was applied once every 10-15 days in the first 2 years and once every 7-10 days in the next 3 years. Irrigation for the F3-treatment was applied once every 15-21 days in the first 2 years and biweekly over the last 3 years. The same total amount of water was applied for all irrigation frequencies, but subsequent drying between irrigations for the F2 and F3 treatments resulted in reduced overall soil moisture conditions.

Fertilizer (40 g N/tree, 17.5 g P/tree) was applied through the irrigation systems as mixtures of ammonium nitrate (34-0-0) and

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anionium polyphosphate (10-34-0) in four equal weekly doses during May of each year. On the days when fertilizer was applied, it was necessary to operate the nonscheduled F2 and F3 treatments for the same duration as the daily irrigation treatment in order to apply the fertilizer on a weekly schedule.

The soil at the experimental location was a Skaha loamy sand (Wittneben, 1986). In each of the first 3 years, soil samples were obtained within the week following the cessation of fertigation (6-7 June 1989, 4-6 June 1990, 10 June 1991) at four locations and four depths beneath and around the irrigation emitters. Soil nutrient analyses are reported for samples from the 10-20 cm depth immediately beneath the emitters where previous research (Parchomchuk et al., 1993) indicated that chemical changes were most rapid. Samples were obtained from different trees within the same experimental unit each year avoid sampling from previously disturbed sites. The approximate 300-g samples were air-dried and sieved through a 2-mm screen before analysis. Soil pH was measured on a 10:20-ml soil : 0.01 M CaCl₂ slurry. Analysis for available P, Mg, and K were carried out at Griffin Laboratories (Kelowna, B.C.) by inductively coupled argon plasma (ICAP) spectrophotometry after extraction with 0.25 M HOAC + 0.015 M NH₄F (Van Lierop, 1988).

Cultural management of the block followed commercial recommendations (British Columbia Ministry of Agriculture and Fisheries, 1991). Composite leaf samples were collected in mid-July of each growing season. Each composite contained 30 leaves (five from each tree within the plot) sampled from the mid-third portion of extension shoots of the current year's growth. All samples were oven dried at 65C and ground in a stainless steel mill. A 250 mg subsample was digested for 0.75 h on a block digester at 350C in a H₂SO₄ solution containing K₂SO₄ and HgO. Nitrogen in the digest was determined through the formation of an ammonium-salicylate complex, and P was determined through the formation of a phosphomolybdenum blue complex (Technicon Autoanalyzer II Industrial Method No. 334-74A/A; Technicon, Elmsford, N.Y.). One-gram samples were also dry ashed at 475C and dissolved in 0.5 M HCl for determination of Ca, Mg, K, Mn, Zn, Fe, and Cu by atomic absorption spectrophotometry.

Trunk cross-sectional area was calculated each spring, including the year of planting, from trunk-diameter measurements taken at 0.3 m above the graft union. Yield commenced in the second year and was measured each year at commercial harvest.

All nutrition, growth, yield, and soil data for each year were

subjected to an analysis of variance (factorial design consisting of two types of emitters x three irrigation frequencies x four blocks). Analysis of variance was performed using SAS procedures (SAS, Cary, N.C.). Since block effects were generally not significant for the variables, no differential response between the two 'Gala' strains was indicated. Subsequent discussion focuses on pooled means for both strains. Means were separated according to Duncan's multiple range test.

Results and Discussion

Tree growth and yield. Method and frequency of irrigation affected growth and yield of 'Gala' apple in the first five seasons as illustrated by average trunk cross-sectional area measured each spring and by annual yield measured at the end of each growing season (Table 1). After the first growing season (Spring 1990), greater tree growth was measured for drip relative to microjet-irrigated trees and these growth differences persisted into the second year but not for infrequently irrigated (F3) trees. However, commencing in 1991 and each year afterwards, the relative growth rate of microjet-irrigated trees was significantly greater than that of drip-irrigated trees (data not shown). Significantly greater yield was also measured in the first two fruiting seasons (1990 and 1991) for drip-irrigated trees. By 1994, larger trees were observed with microjet irrigation, rather than drip irrigation. During 1992 and 1993, the type of irrigation emitter did not significantly affect yield. Daily (F1) irrigation resulted in increased tree growth beginning in 1991, with significantly larger trees observed for this treatment. Initial growth differences between F2 and F3 irrigation frequencies were observed in 1991 (for drippers only) and 1992, but were not measurable in the final two years of the study. Frequent daily irrigation decreased yield in the first fruiting year but this trend was reversed in 1991 and 1992 when highest yield was measured for frequently irrigated trees. No yield differences related to irrigation frequency occurred in 1993 after a cool, wet summer.

The improvements in initial tree growth and yield measured for the drip-irrigated trees were consistent with results observed by Proebsting et al. (1977) for trickle- relative to sprinkler-irrigated trees. In our study, as trees aged, tree size increased more with microjet irrigation. It is known that use of drip irrigation in semiarid regions results in the development of a restricted root volume with a denser root network (Bielorai, 1977). This is

Table 1. Average-spring trunk cross-sectional area and annual yield of 'Gala' apple on M.26 as influenced by type of irrigation emitter and frequency of irrigation, 1989-94.

Factor	Average trunk cross-sectional area at 0.3 m (cm ²)						Average yield (kg/tree)			
	1989	1990	1991	1992	1993	1994	1990	1991	1992	1993
Irrigation emitter (E)										
Drip (E1)	1.3	2.4		11.0	16.6	23.0	0.6	8.7	9.1	15.7
Microjet (E2)	1.3	2.2		11.6	18.5	27.4	0.1	3.5	7.5	15.1
Significance	NS	*		NS	NS	*	****	****	NS	NS
Irrigation frequency (F)^a										
			E1	E2						
High (F1)	1.4	2.5	8.3	7.2	13.8 a	21.1 a	29.7 a	0.1b	8.6 a	11.1 a 17.3
Intermediate (F2)	1.3	2.3	6.9	5.2	10.8 b	16.9 b	24.2 b	0.6 a	5.8 b	7.4 ab 15.3
Low (F3)	1.2	2.1	4.7	5.2	9.3 c	14.7 b	21.8 b	0.5 a	3.9 c	5.7 b 13.5
Significance	NS	NS	SE ^b = 0.3		****	**	*	*	****	* NS
E x F interaction	NS	NS	*		NS	NS	NS	NS	NS	NS ;

^aF1 irrigated daily 1989-93, F2 irrigated about once every 10-15 days 1989-90 and every 7 days 1991-93, F3 irrigated about once every 15-21 days 1989-90 and once every 14 days in 1991-93.

^bStandard error of the mean when interaction significant.

NS, *, **, **** Nonsignificant or significant at *P* = 0.05, 0.01, or 0.0001, respectively.

Table 2. Average leaf N and P concentration of 'Gala' on M.26 as influenced by type of irrigation emitter and frequency of irrigation, 1989-93.

Factor	Leaf N (% dw)					Leaf P (% dw)				
	1989	1990	1991	1992	1993	1989	1990	1991	1992	1993
Irrigation emitter (E)										
Drip (E1)	2.17	2.32	2.75	2.43	2.19	0.30	0.31		0.23	0.21
Microjet (E2)	2.11	2.34	2.44	2.40	1.77	0.36	0.41		0.37	0.28
Significance	NS	NS	****	NS	****	*	****		****	****
Irrigation frequency (F)^z										
								E1	E2	
High (F1)	1.88 b	2.19 b	2.47 b	2.44	1.97	0.40 a	0.37	0.29	0.38	0.30
Intermediate (F2)	2.23 a	2.30 b	2.65 a	2.35	1.93	0.31 b	0.36	0.27	0.48	0.27
Low (F3)	2.32 a	2.51 a	2.66 a	2.45	2.05	0.29 b	0.34	0.28	0.58	0.32
Significance	****	**	*	NS	NS	**	NS	SE ^y = 0.02		NS
E × F interaction	NS	NS	NS	NS	NS	NS	NS	***	NS	NS

^{F1} irrigated daily 1989-93, F1 irrigated about once every 10-15 days 1989-90 and every 7 days 1991-93, F3 irrigated about once every 15-21 days, 1989-90 and once every 14 days in 1991-93.

^yStandard error of the mean when interaction significant.

NS, *, **, ****Nonsignificant or significant at $P = 0.05$, 0.01 , or 0.0001 , respectively.

desirable for supplying water and nutrients to establishing trees but, as these results imply, the larger root volume of microjet-irrigated trees may eventually be an advantage as canopy volume increases. Significant yield increases for microjet-irrigated trees had not been observed by the final year of our study. Water stress associated with less frequent irrigation increased blossom numbers (data not shown) and yield in the first fruiting year. This effect was subsequently reversed with high frequency, daily irrigation which caused increased yield in 1990 and 1991, and increased tree size commencing in 1991.

Leaf N and P. Both experimental factors affected leaf N, with a lower concentration being measured for trees fertigated via microjets in the third and fifth years of the study, and lower leaf N observed for FI-irrigated trees in the first three years (Table 2).

Leaf N concentrations were generally adequate and unlikely to have adversely affected growth during the study (British Columbia Ministry of Agriculture and Food, 1991). This was documented by observation of greater growth of FI-irrigated trees despite significantly lower leaf N concentrations in the first three growing seasons. The lowest leaf N concentration of 1.77% observed for microjet-irrigated trees in the last year of the study was sufficiently low that we anticipate next year's growth would be affected. Therefore, increasing the rate of N applied per tree may be required to maintain tree growth in maturing microjet-irrigated orchards due to the application of N over a larger soil volume relative to drip-irrigated trees. Weed competition for N was a greater problem with microjet irrigation because of increased weed growth at the edges of the herbicide strip associated with improved moisture conditions in this zone. The inverse relationship between leaf N concentration and frequency of irrigation for establishing trees implies a need to balance the growth advantages of frequent irrigation with its adverse effects on the leaching of N. The ready leachability of fertigated N has previously been observed as a depletion of NO₃-N from near the emitter (Rolston et al., 1981).

Leaf P was affected more by method of irrigation than by irrigation frequency. Higher leaf P was consistently measured for microjet-fertigated trees, including 1991 when a significant interaction between emitter type and irrigation frequency was observed (Table 2). The interaction in that year occurred because frequent irrigation (F1) reduced the difference between microjet- and drip-irrigated trees. Generally, irrigation frequency affected leaf P only in the first year, when daily irrigation increased leaf P concentration.

The higher leaf P concentration of microjet-irrigated trees was unexpected, since it was anticipated that available soil P would be

lower under microjet irrigation due to the larger volume of soil into which a similar quantity of P was added. Lower average extractable soil P concentrations were indeed measured at the 10-20 cm depth directly below the microjet emitters, compared to the drip emitters (Table 3). Such differences were observed in each of the first three years of the study including the second year when there was a significant emitter × frequency interaction. This was a result of high frequency irrigation having decreased the difference between soil P concentration beneath drip and microjet emitters. Previous research on P fertigation of peach trees (Nielsen et al., 1993a) indicated that response to P was more closely related to soil solution P concentrations than to the soil's extractable P or P adsorption capacity. This was attributed to localized saturation of P sorption sites in the restricted root zones typical of micro-fertigated crops. It is apparent in this apple experiment that extractable soil P values were not a good indicator of leaf P. Rather, the larger root volume and possibly greater root length associated with microjet-irrigation were more important. Furthermore, increased leaf P concentration of microjet-irrigated trees may reflect greater cover crop growth in the irrigated portion of the rooting zone (Nielsen and Hogue, 1985). Other factors which increase the diffusion of P to plant roots, such as high soil moisture content, which might result from high frequency irrigation, have been considered critical for plant P uptake (Nielsen et al., 1990). Irrigation frequency appears to have been important for these P-fertigated apples trees only in the first year when trees' root systems were establishing, and root length most limited. Although differences in leaf P were observed between treatments, leaf P concentration did not approach values which might have limited growth (British Columbia Ministry Agriculture and Food, 1991).

Leaf Ca, K, and Mg. Experimental treatments affected both leaf K and Mg (Table 4), but had little effect on leaf Ca (data not shown). Both experimental factors affected leaf K, although the strongest effect was from emitter type. Higher leaf K was measured for microjet-rather than for drip-irrigated trees in the last four years of the experiment. Significantly higher leaf K was also measured with high frequency, rather than with low frequency irrigation, but only during the first two years.

It is well known that leaf K concentration is inversely related to crop load (Cummings, 1985). This factor may have contributed to the decrease in leaf K for drip-irrigated trees in the first 2 years, due to their greater precocity. This is not an explanation for trees with high frequency irrigation in 1991 and 1992 or, in subsequent years, when microjet- and drip-irrigated trees had similar yields (Table

Table 3. Average extractable P, Mg and K concentration and pH at 10-20 cm depth immediately below the emitter as determined the week following cessation of fertigation, 1989-91 and as influenced by type of irrigation emitter and frequency of irrigation.

Factor	Extractable nutrient concn (mg·kg ⁻¹) ^z									pH (0.01 M CaCl ₂)			
	P			K			Mg						
	1989	1990	1991	1989	1990	1991	1989	1990	1991	1989	1990	1991	
Irrigation emitter (E)													
Drip (E1)	100		128	132	100	70	150	110	99	6.24	5.66	5.16	
Microjet (E2)	51		43	132	116	101	148	138	140	6.70	6.29	6.31	
Significance	*		****	NS	NS	*	NS	NS	**	**	**	****	
Irrigation Frequency (F) ^y		E1	E2										
High (F1)	66	64	42	63	143	106	86	150	142	126	6.37	6.12	5.71
Intermediate (F2)	71	105	36	77	137	120	95	158	126	112	6.55	6.22	5.84
Low (F3)	90	198	59	116	114	97	76	138	104	122	6.47	5.60	5.65
Significance	NS	SE ^x = 19		NS	NS	NS	NS	NS	NS	NS	NS	NS	
E × F interaction	NS	*		NS	NS	NS	NS	NS	NS	NS	NS	NS	

¹As extracted in 0.25 M acetic acid and 0.015 M NH₄F.

^yF1 irrigated daily 1989-93, F2 irrigated about every 10-15 days 1989-90 and every 7 days 1991-93, F3 irrigated once every 15-21 days 1989-90 and once every 14 days in 1991-93.

²Standard error of the mean when interaction significant.

NS, *, **, **** Nonsignificant or significant at *P* = 0.05, 0.01, or 0.0001, respectively.

1). The restricted soil volume of the drip-irrigated trees was apparently detrimental to tree K nutrition with leaf K concentrations near deficiency (1%) in 1992 (Shear and Faust, 1980). Greater cover crop growth as occurred over the whole of the larger wetted area under microjet-irrigation is known to contribute to increased leaf K concentration (Neilsen and Hogue, 1985). Also the smaller soil volume into which fertigated nutrients are applied for drip relative to microjet irrigation results in a potential acceleration of adverse chemical changes. Leaching of the major soil bases including Ca, Mg, and K is a known consequence of the pH decline, which has been associated with drip-fertigation of NH₄-N and P in coarse-textured soils (Parchomchuk et al., 1993). A significant decline in extractable soil K was measurable beneath drip relative to microjet emitters by 1991 at 10-20 cm depth (Table 3), which likely contributed to the poorer K nutrition of drip-fertigated trees. Reducing the fertigated volume of soil had a greater effect on K leaching than increasing the frequency of irrigation, since a significant decrease in soil K was not measured with high frequency, daily irrigation. Increasing irrigation frequency did increase leaf K concentration, but only in the first two years. Only in these years was the advantage of a high soil moisture content on plant K-uptake measurable (Grimme, 1979).

Leaf Mg concentration consistently varied in the opposite direction to changes in leaf K concentration (Table 4). Extractable

soil Mg showed the same pattern as soil K, i.e., a significant decrease beneath drip- relative to microjet-irrigation emitters by the third year and no measurable effects of variation in irrigation frequency (Table 3). Increased leaf Mg for drip-irrigated trees despite decreased soil Mg implies that the status of apple tree K nutrition had a stronger influence on Mg nutrition than the availability of soil Mg. The decreases in leaf Mg concentration were insufficient to adversely affect tree growth. A similar relationship between leaf Mg and K concentration in fertigated apple trees has been reported by Cassagnes et al., (1984).

Soil pH, leaf Mn and Cu. Soil pH at 10-20 cm depth beneath drip emitters was significantly lower than similar values beneath microjet emitters in each of the first three years with the differences exceeding one pH unit in 1991 (Table 3). The rapid decline in soil pH beneath drip emitters caused by NP-fertigation has previously been reported (Neilsen et al., 1994) with the availability of the micronutrients Mn and Cu most affected.

Consistent with this previous study, leaf Mn concentration increased as soil pH declined (Table 5). Thus leaf Mn concentration for trees irrigated via drip emitters was consistently higher than those irrigated via microjet, even though a significant emitter × irrigation frequency interaction was observed, in the three years from 1990-1992. This interaction occurred because leaf Mn increased as irrigation frequency decreased under drip-, but not

Table 4. Average leaf K and Mg concentration as influenced by type of irrigation emitter and frequency of irrigation, 1989-93.

Factor	Leaf K (% dw)					Leaf Mg (% dw)				
	1989	1990	1991	1992	1993	1989	1990	1991	1992	1993
Irrigation emitter (E)										
Drip (E1)	1.73	1.76	1.37	1.14	1.43	0.33	0.28	0.33	0.40	0.37
Microjet (E2)	1.84	2.17	1.89	1.92	2.09	0.34	0.24	0.24	0.28	0.26
Significance	NS	****	****	****	****	NS	****	****	****	****
Irrigation frequency (F) ²										
High (F1)	1.98 a	2.01 a	1.59	1.57	1.86	0.29 b	0.24 b	0.28	0.34	0.30
Intermediate (F2)	1.68 b	1.90 b	1.65	1.48	1.63	0.36 a	0.27 a	0.29	0.34	0.31
Low (F3)	1.68 b	1.98 ab	1.65	1.54	1.79	0.36 a	0.28 a	0.29	0.34	0.34
Significance	***	*	NS	NS	NS	**	***	NS	NS	NS

¹F1 irrigated daily 1989-93, F2 irrigated about every 10-15 days 1989-90 and every 7 days 1991-93, F3 irrigated once every 15-21 days 1989-90 and once 14 days in 1991-93.

NS, *, **, **** Nonsignificant or significant at *P* = 0.05, 0.01, or 0.0001, respectively

Table 5. Average leaf Mn and Cu concentration as influenced by type of irrigation emitter and frequency of irrigation, 1989-93.

Factor	Leaf Mn (mg·g ⁻¹ dw)					Leaf Cu (mg·g ⁻¹ dw)				
	1989	1990	1991	1992	1993	1989	1990	1991	1992	1993
Irrigation emitter (E)										
Drip (E1)	104				69	6.0	5.7		5.7	5.7
Microjet (E2)	85				50	6.5	7.6		6.8	5.9
Significance	**				****	*	****		***	NS
Irrigation frequency (F) ^z		E1 E2	E1 E2	E1 E2				E1 E2		
High (F1)	76 a	87 55	74 46	88 55	58	5.7 c	6.6	6.1 6.3	6.5	5.9
Intermediate (F2)	104 b	142 65	110 55	119 50	55	6.2b	6.5	5.6 7.3	6.1	5.7
Low (F3)	102b	173 64	150 54	157 55	65	6.8 a	6.9	5.9 7.3	6.3	5.7
Significance	**	SE ^y = 8	SE = 7	SE = 10	NS	***	NS	SE = 0.3	NS	
E × F interaction	NS	***	**	*	NS	NS	NS	*	NS	NS

^zF1 irrigated daily 1989-93, F2 irrigated about every 10-15 days 1989-90 and every 7 days 1991-93, F3 irrigated once every 15-21 days 1989-90 and once every 14 days 1991-93.

^yStandard error of the mean when interaction significant.

NS,*,**,****Nonsignificant or significant at $P = 0.05$, 0.01 , or 0.0001 , respectively.

under microjet irrigation. High frequency irrigation resulted in a decrease in leaf Mn when the root zone was restricted (under drippers). Similarly, in the first year, leaf Mn was lowest under high frequency irrigation, regardless of type of emitter. This implies that high frequency irrigation did not result in waterlogging, which is known to increase Mn solubility and availability to plants (Moraghan and Mascagni, 1991). A similar decrease in leaf Mn concentration with frequent irrigation has been measured for pears (Brun et al., 1985). Despite differences in leaf Mn concentration observed throughout the study, no deficiency and few toxic concentrations were measured. Leaf Mn concentration exceeding $1.50 \mu\text{g}\cdot\text{g}^{-1}$, which has been associated with Mn toxicity for 'Delicious' and 'Jonathan' apple cultivars (Shear and Faust, 1980), was measured only for these infrequently drip-irrigated 'Gala' trees from 1990-1992.

Leaf Cu concentration was greater for microjet- than for drip-irrigated trees in the first four years (1989-1992) although in 1991 a significant irrigation emitter × irrigation frequency interaction was observed. This occurred because increased leaf Cu concentration was observed for microjet-irrigated trees at F2- and F3-, but not F1-irrigation frequencies (Table 5). The lower soil pH beneath drip emitters would increase the extractability and plant availability of Cu, as has been demonstrated for Fe, Mn, Zn, and Cu by Haynes and Swift (1987). Since leaf Cu concentration decreased, this suggests that the restricted root volume under drip may have affected plant Cu uptake. This is consistent with other research suggesting that Cu movement into plants is strongly affected by the exploitation of soil by roots (Moraghan and Mascagni, 1991). As with Mn, high frequency irrigation reduced leaf Cu concentration in the first year. However, there were no deficient leaf Cu concentrations during the study.

Conclusions

Emitter type had a major effect on response of apple trees to NP-fertigation on a coarse-textured soil. The previously reported advantages of drip-irrigation for accelerating establishment and precocity of apple (Middleton et al., 1981; Proebsting et al., 1977) were confirmed in this study; the growth advantages of a larger root volume under microjet-fertigation were more apparent as the trees matured. The larger soil volume in which fertigated nutrients were applied for microjet-irrigated trees was apparently an advantage for P uptake but a disadvantage for N uptake, as indicated by frequent increased leaf P and decreased leaf N concentration.

Restricting the soil volume into which fertilizer nutrients are applied would potentially intensify the effect of beneficial or detrimental soil chemical changes. This was supported by observations that lower pH by first year, and lower extractable Mg and K by third year was observed directly beneath drip-emitters. These changes translated into lower leaf K and higher leaf Mn concentrations under drip irrigation. Potassium-deficiency may have contributed to the slower growth of drip-irrigated trees in later years (Nielsen et al., 1995). The availability of a smaller volume of soil for nutrient absorption could adversely affect the acquisition of immobile, non-fertigated nutrients whose uptake is dependent upon root length. The decrease in leaf Cu observed for drip-irrigated trees was attributed to this phenomenon. Use of microjet-irrigation appeared to have delayed the negative consequences of soil acidification, and leaching of bases attributed to the nitrification of $\text{NH}_4\text{-N}$ in poorly buffered soils over the five-year period of this study. However, that such changes would occur in the larger microjet-irrigated soil volume indicates a need for investigating the consequences of fertigating less acidifying N sources, including $\text{NO}_3\text{-N}$. Fertigation of nutrients such as K and Cu, which have not traditionally been applied as fertilizers in the Pacific Northwest, should also be investigated.

Daily irrigation was generally advantageous to tree growth and yield in this study, but had much less effect on leaf nutrient concentration than emitter type. Minor increases (K-2 years, P-1 year) or decreases (Mg-2 years, Mn, and Cu-1 year) were observed with daily irrigation, but the observed values would not have been sufficient to affect growth. Nitrogen was the nutrient most affected by irrigation frequency, with decreases in leaf N observed in three of five years with daily irrigation. Such results imply that timing and quantity of applied irrigation water will be important considerations in maximizing uptake and minimizing leaching of fertigated-N.

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