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Response of Apple to Fertigation of N and K under Conditions Susceptible to the Development of K Deficiency

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Abstract. A split-plot experimental design was imposed in the year of planting and maintained for the first five growing seasons in a high density apple orchard on M.9 rootstock planted at 1.5 m (within row) × 4 m (between row) in a loamy sand soil susceptible to K deficiency when drip-irrigated. Four N–K fertigation treatments involving low (N1) and high (N2) rates of N combined with 0 (K0) or 15 g K/tree per year (K1) were applied in five replicated and randomized main plot units. Subplots consisted of three-tree plots of each of the apple cultivars Gala, Fuji, Fiesta and Spartan. Soil solution monitoring indicated the maintenance of distinctly different soil solution N and K concentrations in the respective N–K treatments during the study. The most important plant response was prevention of the development of K deficiency by the K1-fertigation treatment. Fertigation of 15 g K/tree generally increased leaf K, fruit K and Mg concentrations, fruit size and yield and fruit titratable acidity and red coloration at harvest for all cultivars. K fertigation also decreased leaf Mg and B concentrations, fruit N, P and Ca concentration and fruit firmness. In addition to leaf K concentrations <1%, K deficiency was associated with fruit K concentrations <100 mg/100 g fresh weight and soil solution K concentration <5 mg·L^{-1}. Increasing the rate of fertigated N when growth was constrained by K deficiency increased leaf N and Mn and decreased leaf P and B, but had no effect on tree vigor or fruit production and quality.

The advantage of application of N–P–K directly with irrigation water (fertigation) in high density apple orchards in the Pacific Northwest has recently been evaluated (Neilsen et al., 1999) in light of the ability of fertigation to allow a more exact synchronization of nutrient application with plant demand (Bar-Yosef, 1999; Haynes, 1985). Potential limitations to effective fertigation include soil acidification (Edwards et al., 1982) and nutrient depletion (Haynes and Swift, 1986), especially within the restricted rooting volume known to develop in trickle-irrigated apple orchards (Levin et al., 1979). NP-fertigated and drip-irrigated orchards in the Pacific Northwest appear to be susceptible to the development of K deficiency on the coarse-textured soils commonly used for fruit growing in the region (Neilsen et al., 2000). Short term correction of K deficiency can be achieved by broadcast applications of K fertilizer directly beneath the drip emitters or via fertigation of K (Neilsen et al., 1998a; Uriu et al., 1980). Much less is known concerning the long term consequences of fertigation with K to correct K deficiency since most reported K fertigation studies have been of short duration (Callan et al., 1996; Neilsen et al., 1998a).

Soil solution monitoring has been useful for assessment of the effectiveness of N fertigation (Neilsen et al., 1998b). Much less is known concerning the variation of soil solution K concentrations in response to K fertigation to overcome K deficiency.

The development of K deficiency in a long term, multicultivar N × K fertigation trial (Neilsen et al., 2000) provided an opportunity to investigate the long term consequences of K fertigation to correct K deficiency of apple. In this study, emphasis was placed upon monitoring the effects of K fertigation on soil solution K, leaf and fruit nutrition, yield, and harvest fruit quality.

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Materials and Methods

An experimental block was planted in May 1992 at a 1.5 m (within row) × 4 m (between row) spacing. A randomized complete block, split-plot experimental design was imposed commencing the year of establishment. Pertinent to this paper were four annual N–K fertigation treatments (low and high rates of N both with or without K). Subplots consisted of four apple [*Malus sylvestris* (L) Mill var. *domestica* (Borkh.) Mansf.] cultivars (Gala, Fuji, Fiesta, and Spartan) on M.9 rootstock randomly planted in three-tree plots in each of the five replications for each fertigation treatment. 'Elstar' apple trees on M.9 separated each main plot fertigation treatment and were also planted as a border completely surrounding the experimental block.

Trees were trained to a slender spindle system supported by posts and grown in a 1.5-m-wide herbicide strip maintained by applications of 1 kg·ha^{-1} glyphosate each year in early May, midsummer and early fall. All trees received daily irrigation from about 1 May to 1 Oct. in each year via a single 4 L·h^{-1} 'Hardie' pressure compensating drip emitter located 0.5 m from the tree trunk within the row (Hardie Irrigation, El Cajon, Calif.), delivering 8 L of irrigation water/tree. Average budbreak of apples in this region is mid-April. All fertigation treatments received 18 g P/tree in the establishment year, applied in three weekly applications, commencing 19 May in the form of phosphoric acid (0N–30P–0K). Cumulative annual N treatments were applications of either 5 g N/tree (N1) or 35 g N/tree (N2) in 1992 and 1993, in the form of Ca $(NO_3)_2$ daily (except on the days of P-fertigation) over 9 weeks commencing mid-May. Nitrogen application rates were increased to 15 g N/tree for N1 and 45 g N/tree for N2 in 1994–96, although form and timing of N application remained the same each year. The fertigated K treatment (K1) received 15 g K/tree each year, applied daily as KCl (0N–0P–50K), over 8 weeks annually in July–August from 1992-1996. Micronutrient applications of B and Zn were made to all plots by conventional commercial foliar sprays in 1994 and via fertigation in 1995-1996. Insect and disease control procedures also followed stan-

dard commercial recommendations (British Columbia Ministry of Agriculture and Food, 1998).

The experimental site was located on a Skaha loamy sand (Wittneben, 1986), an Aridic Haploxeroll, extensively planted to orchards or vineyards in southern British Columbia. These soils have limited nutrient and water holding capacities and were previously shown to be susceptible to development of K deficiency in drip-irrigated apple orchards (Neilsen et al., 1998a). Soil solution lysimeters with 2.5-cm-diameter × 5-cm-long porous cups attached to plastic tubes (Irrometer Co. Riverside, Calif.) were used to monitor soil solution concentrations. Before use, lysimeters were equilibrated three times in 0.5 M HCl for 30 min and then flushed with distilled H_2O. The lysimeters were installed around the middle tree of each 'Gala' subplot at a 30-cm depth and at a 45° angle to minimize preferential flow of irrigation water and fertigation solutions down the side of the lysimeter. The hole into which a 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 on a regular basis throughout the irrigation seasons, 1992–96, by applying a 70-kPa vacuum to the lysimeters for one hour after irrigation shut off. Nitrate N and K concentrations were measured using their respective portable ion-specific meters (Horiba/Spectrum Technologies Inc., Plainfield, Ill.). Nitrate-N measurements were initiated in 1992 and K measurements in 1993.

Composite samples of 30 leaves from the mid-portion of extension shoots of the current year's growth were collected in mid-July of each growing season from each treatment and replicate. All samples were oven-dried at 65 °C and ground in a stainless steel mill. A 250-mg subsample was digested for 0.75 h on a block digester at 350 °C in 5mL concentrated H_2SO_4 solution containing 1.9 g K_2SO_4 and 40 mg 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. 334-74 A/A; Technicon, Elmsford, N.Y.). One-gram samples were also dry-ashed at 475 °C and dissolved in 0.5 M HCl for determination of Ca, Mg, K, Mn, Zn, Fe, and Cu by atomic absorption spectrophotometry. A 0.5 g sample was dry ashed at 525 °C in a porcelain crucible and dissolved in 10 mL of 1.2 M HCl before determination of B by inductively coupled argon plasma spectrophotometry.

Trunk cross-sectional areas were calculated from trunk diameters measured at 0.3 m height above the graft union each spring commencing in 1992. Blossoms were removed at the beginning of the first two growing seasons (1992–93) to avoid over-cropping of the trees and to encourage vegetative growth. Number and weight of harvested fruit were measured each year at commercial maturity for each experimental plot commencing in 1994, the first year of fruiting. Each year a randomly selected 10-apple subsample from each plot was evaluated for skin color, flesh firmness, titratable acidity (TA), and soluble solids concentration. Percent red skin color was estimated visually. Flesh firmness was determined with a Baullaf penetrometer (11.1-mm-diameter tip). Soluble solids concentration in the juice was measured with a refractometer and TA was determined by titration of juice with 0.1 M NaOH to an 8.1 pH end point. Juice was obtained from sectors taken from each apple in the 10-fruit subsample.

A random sample of 25 fruit was selected at harvest from each treatment and replicate and rinsed under running, distilled water and then air-dried. Stem tissue and seeds were removed and opposite, unpeeled quarters were blended with 1.5 times their weight of distilled water. A 150-mL subsample was further homogenized with a high-speed tissue homogenizer. A weighed 9-mL subsample of homogenized slurry was digested in 5.4 mL of concentrated H_2SO_4 containing Na_2SO_4 (1.8 g), Cu (0.36 mL 25% $CuSO_4$ solution), and Se (0.67 $g \cdot L^{-1}$) at 380 °C for 1 h. Calcium, Mg and K were determined in these extracts via atomic absorption spectrophotometry. Nitrogen and P were determined via colorimetric methods as described for the leaf samples.

Analysis of variance (ANOVA) was performed on all leaf, fruit, yield and growth data according to the experimental design (SAS Institute Inc., 1989). Data were analyzed as a split-plot design, with a factorial arrangement of all combinations of two fertigated N levels (N1 and N2) and two fertigated K levels (K0 and K1) replicated each in five randomized main plot rows. Subplots within each row were random three-tree plots of each of four different cultivars. Data were analyzed separately by year due to the transition of the plot from vegetative to fruiting growth over the 5-year experimental period.

Results and Discussion

Soil solution K and N concentrations. Soil solution K concentrations were clearly distinct between K treatments throughout the study, fluctuating around 10 $mg \cdot L^{-1}$ and averaging 8.9 $mg \cdot L^{-1}$ over 4 years in soil fertigated with K and below 5 $mg \cdot L^{-1}$ (four year average 3.1 $mg \cdot L^{-1}$) in the zero-K treatment (Fig. 1). Minimum values for soil K concentration in the K0 treatment were recorded in 1996. There was no consistent within-season trend in soil solution K concentration for the treatments. In the K1 treatment, it was not possible to clearly distinguish the initiation and cessation of fertigation based upon changes in soil solution K concentrations. This implies buffering of soil solution K concentration. There have been few reports of soil solution K concentrations in orchard soils (Neilsen and Hogue, 1985). However, an increase in soil solution K concentration from 40 to 60 ppm at a 30-cm depth in response to K fertigation of apple has previously been demonstrated on a fine textured sandy clay soil in Israel (Klein and Spieler, 1987).

Soil solution NO_3-N concentrations generally reflected N fertigation treatments with higher values usually observed for N2 when N was being fertigated throughout the growing season (Fig. 2). Differences between Ntreatments were less obvious during 1992, the year the suction lysimeters were installed. Within-season soil solution NO_3-N concentrations increased in response to fertigation, regardless of N rate. Concentrations were very low and not different between N treatments before initiation and after cessation of fertigation. It was not possible to distinguish the change in N fertigation rate which commenced in the 1994 growing season, since highest soil solution NO_3-N concentrations throughout the study were measured in 1993 for both N treatments. Quantities of applied irrigation water have been reported to directly affect soil solution NO_3-N concentrations when fixed rates of N per tree were applied (Neilsen and Neilsen, 1997). Application of more water dilutes NO_3-N decreasing soil solution concentrations. Frequent monitoring of soil solution NO_3-N concentrations has been shown to be a useful method of determining N availability to apple trees when measured at a depth likely to contain a high proportion of a tree's roots (Neilsen et al., 1998b). Collectively, the soil solution data (Figs. 1 and 2) indicate the establishment and maintenance of

distinctly different soil and root N and K regimes in the various treatments for the apple trees in this experiment.

Leaf K and N. K fertigation consistently increased leaf K concentration for the 5 years of the study in all cultivars (Table 1). By the second year of the study (1993) average leaf K concentration in trees not receiving K (K0) was <1%, a value commonly identified as a K deficiency threshold (Shear and Faust, 1980). Leaf K concentrations in K0-trees remained below 1% for the remainder of the study with the exception of 1994 when a significant K treatment by cultivar interaction was measured and leaf K was <1% only for 'Fuji' in the K0-treatment. K deficiency symptoms, characterized by interveinal browning and leaf scorch, particularly on fruiting spur leaves were observed on some K0-trees by 1993. This implies that soil solution K concentrations ≤5 mg·L^{-1} are inadequate to prevent the development of K deficiency in apple trees.

Despite the development of K deficiency in K0-trees, N fertigation generally increased leaf N concentration for all cultivars (Table 1). In 2 of these years (1993 and 1996), a significant N × K interaction resulted in an increase in leaf N being measured only for trees not receiving K. Nitrogen was relatively decreased in the leaves of trees receiving K. Growth of these trees was therefore not constrained by the development of K deficiency. Their higher fruit yields (see Tree Yield) likely contributed to decreased leaf N concentrations. Cultivar differences were few. However, there were exceptions, for example in 1994 leaf N concentration was decreased only for 'Fuji' apple when K was fertigated. Leaf K concentration was little affected by N fertigation rate being decreased by high N fertigation only in the first year. Thus, leaf K was diluted at high N only when growth was not limited by K deficiency.

Other leaf nutrients. Important effects (two or more years) of K and N fertigation on other leaf nutrients were limited and there was only a single difference in response among cultivars (leaf B, 1996) (Table 2). The most striking consequence of K fertigation was a reduction in leaf Mg, 1993-1996. Thus K0-trees, which had developed K deficiency, compensated by taking up more Mg so that leaf Mg concentrations as high as 0.50% were measured. Compensatory uptake of Mg after development of K deficiency has previously been observed for the cultivar McIntosh (Neilsen et al., 1998a) but appears to be more general for apples, as it was observed in this study for all cultivars tested (data not shown). Amelioration of K deficiency in the K1-treatment tended to decrease leaf B concentration, as indicated for all cultivars in 1994 and 1995, and for 'Fuji' and 'Spartan' in 1996 (significant K × cultivar interaction).

Fertigation of N at N2 rather than N1 increased leaf Mn in 3 years and generally decreased leaf P (4 years, although only at K0 in 1992). Leaf B was sometimes (2 years) decreased in the N2 treatment. Changes in leaf Mn and P status were of little practical significance since altered values were usually within the normal adequacy range for apple in the region (British Columbia Ministry of Agriculture and Food, 1998). An exception to this was a temporarily high leaf Mn in 1992, the first year in the orchard, after growing in a high N nursery environment. The sensitivity of apple to increased leaf Mn concentrations, as a result of fertilization with NH_4-based N fertilizers which acidify the soil, has previously been reported (Atkinson and White, 1983). The more modest but statistically significant increases in Mn reported here occurred despite fertigation with calcium nitrate, a nonacidifying fertilizer. Leaf B concentrations were near deficiency in 1993 (Shear and Faust, 1980) requiring foliar applications in 1994 (hence high leaf B values) and regular B applications each year afterwards. The subsequent decreases in leaf B measured at higher rates of N (and K) fertilization were not limiting to growth but could be an indication of dilution, as a result of fertilizer-induced growth stimulation.

Fruit nutrition. K fertilization (K1), which prevented the development of K deficiency had a major effect on fruit nutrition. Whole-fruit K concentration was consistently increased for all cultivars at K1 each year after the initiation of cropping in 1994 (Table 3). In 1995 and 1996 all cultivars had increased whole fruit K concentrations resulting from K fertigation despite a significant K × cultivar interaction. There were differences in fruit K concentrations between K treatments. For example, 'Gala' and 'Fuji' had

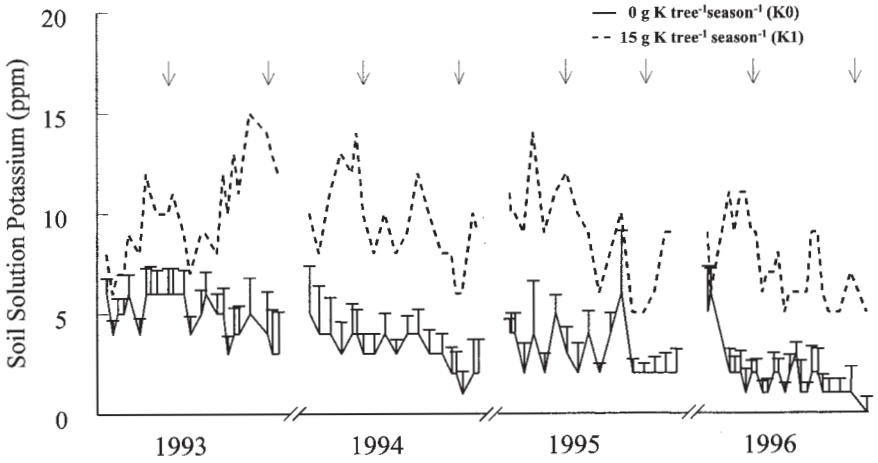

Fig. 1. Effect of K-fertigation treatments on average soil solution K concentrations at 30 cm depth below drip emitters, 1993-1996 growing seasons. Arrows indicate start and end of fertigation for each growing season (mid-June and mid-August). (Standard error for each sampling date for both treatments indicated on K0 treatment).

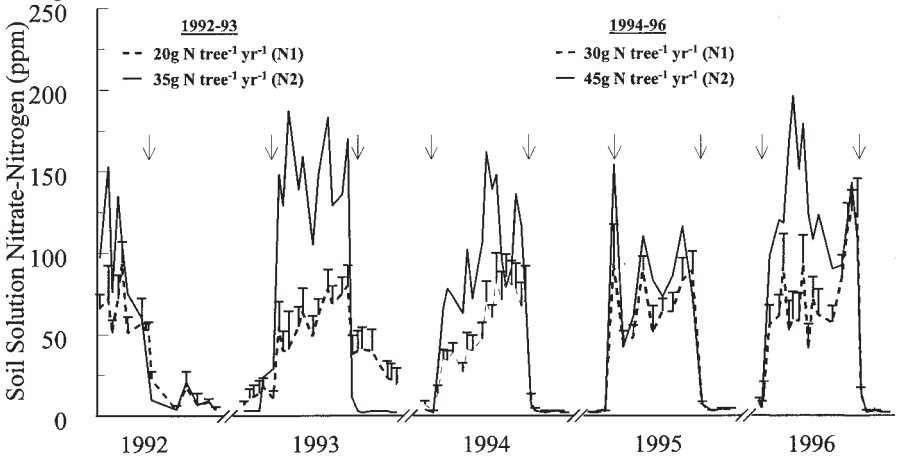

Fig. 2. Effect of N-fertigation treatments on average soil solution NO_3-N concentrations at 30 cm depth below drip emitters, 1992-1996 growing seasons. Arrows indicate start and end of fertigation for each growing season (mid-May and Mid-July). Sample collection did not start until Mid-June in 1992. (Standard error for each sampling date for both treatments indicated on N1 treatment).

Table 1. Effect of N and K fertigation treatment on leaf N and K concentration of 'Gala' (G), 'Fuji' (Fu), 'Fiesta' (F), and 'Spartan' (S) apple cultivars (C), 1992–96.

	Leaf K (% dw)								Leaf N (% dry wt)						
			1994								1994				
Treatment	1992	1993	G	Fu	F	S	1995	1996	1992	1993	F	1995	1996		
K rate (K)															
K0	1.53	0.99	1.15	1.11	0.96	1.03	0.85	0.75	2.52		2.47	2.48			
K1	1.73	1.38	1.84	1.59	1.60	1.79	1.36	1.28	2.55		2.35	2.51			
Significance/interaction	***	****		K × C (*)			****	****	NS		K × C (*)	NS			
SE				SE = 0.05							SE = 0.03				
N rate (N)										K0	K1			K0	Kl
N1	1.70	1.18		1.41			1.11	0.99	2.46	2.17	2.26	2.53	2.46	2.49	2.61
N2	1.55	1.20		1.36			1.09	1.04	2.61	2.28	2.26	2.61	2.54	2.55	2.55
Significance/interaction	**	NS		NS			NS	NS	***	N × K (*)		*	**	N × K (*)	
SE										SE = 0.02				SE = 0.02	

NS,*,**,***,****Paired means nonsignificant or significant at $P = 0.05$, 0.01, 0.001, or 0.0001, respectively. Standard errors indicated when interactions significant. With significant interaction, only significantly different cultivar means tabulated.

Table 2. Major effects on other leaf nutrients of N and K fertigation for 'Gala' (G), 'Fuji' (Fu), 'Fiesta' (F,) and 'Spartan' (S) apple cultivars (C), 1992–96.

											1996	
Treatment	1992	1993	1994	1995	1996		1992	1993	1994	1995	Fu	S
K rate (K)	Leaf Mg (% dry wt)						Leaf B (mg kg^{-1})					
K0	0.30	0.31	0.50	0.43	0.50		31	20	136	45	52	56
K1	0.29	0.26	0.36	0.31	0.37		31	18	74	42	50	49
Significance/interaction	NS	****	****	****	****		NS	NS	**	*	K × C (*)	
SE											SE = 0.9	

	Leaf P (% dry wt)						Leaf B (mg·kg^{-1})					Leaf Mn (mg·kg^{-1})				
	K0	K1														
N fertigation	1992		1993	1994	1995	1996	1992	1993	1994	1995	1996	1992	1993	1994	1995	1996
N1	0.27	0.25	0.18	0.20	0.18	0.171	32	20	110	46	48	82	40	46	44	41
N2	0.24	0.26	0.15	0.19	0.17	0.168	29	18	100	42	48	120	45	46	44	43
Significance/interaction	N × K (**)		****	**	NS	*	**	NS	NS	**	NS	**	*	NS	NS	*
SE	SE = 0.004															

NS,*,**,****Paired means nonsignificant or significant at $P = 0.05$, 0.01, or 0.0001, respectively. Standard errors indicated when interactions significant. With significant interaction, only significantly different cultivar means tabulated.

Table 3. Effect of N and K fertigation treatment on fruit mineral concentration of 'Gala' (G), 'Fuji' (Fu), 'Fiesta' (F), and 'Spartan' (S) apple cultivars (C), 1994–96.

			1996											
	1994	1995	G	F	S	1994	1995	1996		1994	1995	1996		
Treatment	Fruit N (mg/100 g fresh wt)					Fruit P (mg/100 g fresh wt)				Fruit Ca (mg/100 g fresh wt)				
K rate (K)														
K0	48.5	46.3	44.8	55.0	46.7	12.0	10.4	9.9		4.98	6.44	5.62		
K1	48.3	43.5	37.6	44.4	42.2	12.2	9.7	8.6		4.48	5.98	5.48		
Significance/interaction	NS	**		K × C (*)		NS	*	**		**	*	NS		
SE				SE = 1.1										
N rate (N)										G	Fu			
N1	48.0	45.4		44.9		12.1	10.2	9.5		6.07	4.96	6.18	5.47	
N2	48.7	44.5		43.9		12.1	9.8	9.1		7.25	4.11	6.24	5.62	
Significance/interaction	NS	NS		NS		NS	NS	NS		N × C (*)		NS	NS	
SE										SE = 0.36				

	Fruit Mg (mg/100 g fresh wt)						Fruit K (mg/100 g fresh wt)								
		1995			1996			1995				1996			
Treatment	1994	Fu	F	S	F	S	1994	G	Fu	F	S	G	Fu	F	S
K rate (K)															
K0	5.90	5.88	5.49	5.61	5.36	5.49	110	95	97	87	85	83	87	85	88
K1	6.18	5.61	6.01	5.91	5.84	5.86	132	126	113	114	117	109	107	111	124
Significance/interaction	*	K × C (****)			K × C (*)		***		K × C (*)			K × C (*)			
SE		SE = 0.08			SE = 0.07				SE = 4.1			SE = 2.7			
N rate (N)		G	Fu	S					Fu						
N1	6.04	6.28	6.01	5.85	5.52		117		112			99			
N2	6.04	6.07	5.48	5.67	5.34		115		98			97			
Significance/interaction	NS	N × C (*)			*		NS		N × C (*)			NS			
SE		SE = 0.08							SE = 2.4						

NS,*,**,***,****Paired means nonsignificant or significant at $P = 0.05$, 0.01, 0.001, or 0.0001, respectively. Standard errors indicated when interactions significant. With significant interaction, only significantly different cultivar means tabulated.

higher fruit K than other cultivars in the K0-treatment in 1995. 'Gala' (1995) and 'Spartan' (1996) had higher K than other fruits in the K1 treatment. Potassium concentrations measured in fruit not receiving K were usually <100 mg/100 fresh weight. Such concentrations may indicate K deficiency and are much lower than typical whole fruit K concentrations ranging from 100 to 150 mg/100 g fresh weight at harvest for commercial orchards in the growing region (Wolk et al., 1998).

In contrast to the results for leaf Mg, K fertilization increased fruit Mg concentration in 1994 but only for 'Fiesta' and 'Spartan' in 1995 and1996 (cultivar × K interaction, Table 3). Only 'Fuji' in 1995 showed the increase in Mg concentration under K deficiency conditions (K0), which was universally characteristic of leaf Mg. These results imply that K deficiency does not induce a compensatory uptake of Mg by fruit.

In 2 of 3 years, K fertigation decreased fruit Ca concentration by about 0.5 mg/100 g fresh weight. Concern has long been expressed that an antagonism between K and Ca means K fertilization will adversely affect Ca nutrition (Vang-Petersen, 1980). Under conditions of K deficiency, as in this experiment, it is clearly necessary to supply K to the tree. The decrease in fruit Ca concentrations in this study coincided with increased fruit size in both years (Table 4) with the consequence there was little difference in absolute Ca uptake between K treatments. Thus K fertigation which prevented K deficiency did not directly affect fruit Ca supply.

K fertigation decreased fruit N and P in two of three years although decreased fruit N was only observed for three cultivars (Gala, Fiesta, and Spartan) in 1996 as a result of a significant K × cultivar interaction that year. These results are consistent with a dilution of these nutrients in the fruit because of improved growth resulting from K fertigation.

The effects of fertigating two rates of N on fruit mineral nutrition under conditions of inadequate K nutrition (K0-trees) were minor and generally not consistent across all cultivars (Table 3). Fruit N and P were unaffected by N level. Fruit Ca was reduced at a high N rate (N2) in a single year for 'Fuji' apple but increased at N2 for 'Gala' in the same year. Fruit Mg was decreased at N2 for all cultivars in a single year but only for 'Fuji' in another year. Decreased fruit K at N2 was observed in a single year but only for 'Fuji'.

Tree vigor and yield. Tree vigor, as indicated by trunk cross-sectional area, was unaffected by fertigation of K or N throughout the experiment (data not shown). After the commencement of fruiting in the 1994 growing season, fertigation of K but not N influenced fruit production. Fruit size was usually larger in trees fertigated with K, although the effect was only measured for 'Fiesta' and 'Spartan' in 1996 (Table 4). Fruit yield was also significantly increased for K fertigated trees for all cultivars in 1995-1996. These results imply that fruit growth is improved more by the amelioration of K deficiency than vegetative growth.

Fruit quality. Quality of harvested fruit was unaffected by N fertigation rate (data not shown). Many fruit quality parameters were affected by K fertigation (Table 5). Fruit titratable acidity was consistently increased at K1 in all cultivars in all years. Red coloration of fruit was often increased on trees receiving K fertigation, as measured for 'Gala' and 'Fuji' in 1994 and in all cultivars in 1995. Fruit firmness could be decreased as a result of fertigating K as indicated for 'Fuji' apples in 1995 and in all cultivars in 1996. Fruit soluble solids content was the only parameter unaffected by K fertigation (data not shown). Increased TA and red color of harvested fruit has been a previously observed consequence of increasing the K status of apple trees, particularly those of low K status (Neilsen et al., 1998a). The negative result of decreased fruit firmness as a consequence of fertilizing apple with K has not been frequently documented (Cummings, 1985). However, in our study, decreased fruit firmness was associated with a desirable increase in fruit size after fertigation of K.

In summary, the concentrations of N and K in soil solution in the main rooting zone of dwarf apple trees were increased by fertigating with their respective nutrient. Soil solution NO_3-N concentrations increased in proportion to the rate of applied N

Table 4. Effect of K fertigation treatment on fruit size and yield of 'Gala'(G), 'Fuji'(Fu), 'Fiesta(F), and 'Spartan'(S) cultivars (C), 1994–96.

	Fruit size (g fresh wt)				Fruit yield (kg/tree)		
			1996				
Treatment	1994	1995	F	S	1994	1995	1996
K rate (K)							
K0	207	171	166	135	3.44	4.53	5.62
K1	222	189	193	167	3.71	5.34	7.47
Significance/interaction	*	***	K × C (*)		NS	*	**
SE			SE = 5				

NS,*,**,***Paired means nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively. Standard errors indicated when interactions significant. With significant interaction, only significantly different cultivar means tabulated.

Table 5. Effect of K-fertigation treatment on fruit quality of 'Gala'(G), 'Fuji'(Fu), 'Fiesta'(F), and 'Spartan'(S) cultivars (C), 1994–96.

	Titratable acidity (mg malic acid/100 mL)			Red color (% solid red)				Firmness (N)		
				1994					1995	
Treatment	1994	1995	1996	G	Fu	1995	1996	1994	F	1996
K rate (K)										
K0	569	520	581	73.3	73.0	79.8	67.9	85.4	92.3	84.0
K1	652	586	641	76.9	75.6	84.3	72.2	85.3	85.4	81.4
Significance/interaction	***	***	*	K × C (*)		**	NS	NS	K × C (**)	**
SE				SE = 1.1					SE = 0.9	

NS,*,**,***Paired means nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively. Standard errors indicated when interactions significant. With significant interaction, only significantly different cultivar means tabulated.

and increases were restricted to the duration of actual fertigation. Changes in soil solution K concentration were more buffered, with differences between treatment apparent year-round. There was no long term increase in soil solution concentration of either nutrient. This implies a need for annual fertigation of both nutrients and, for K, that there was no long term improvement in soil K status.

The prevention of K deficiency by the K fertigation treatment was the most significant effect observed in the experiment. Annual fertigation of a relatively modest 15 g K per tree was effective for five growing seasons at preventing the development of K deficiency on all tested cultivars in drip-irrigated, high density orchards, when grown on sandy soils known to be susceptible to the development of K deficiency. Amelioration of K deficiency generally increased leaf K, fruit K and Mg concentration, fruit size and yield and fruit titratable acidity and red coloration at harvest. At the same time, K fertigation often decreased leaf Mg and B concentration, fruit N, P and Ca concentrations and fruit firmness. The negative changes in B and Ca nutrition and the decreases in fruit firmness were potentially of most concern. However, the benefits of K fertigation on tree performance by preventing K deficiency indicate the necessity of K fertigation. Also, decreased fruit firmness and fruit Ca concentration were associated with increased fruit size rather than a decline in Ca-uptake by the fruit. Foliar sprays of Ca can always be applied to augment inadequate fruit Ca concentrations. Boron is a common micronutrient deficiency in the region and macronutrient fertigation that stimulates growth or yield will require maintenance B applications to prevent the development of B deficiency. In addition to leaf K concentrations <1%, a traditional indicator of K deficiency for apples, K deficiency in this study was also associated with fruit K concentrations <100 mg/100 g fresh weight and soil solution concentrations <5 $mg \cdot L^{-1}$.

Despite the increased availability of N in the soil for the high N treatment, there were few effects of rate of fertigated N on tree performance. Effects were limited to increased leaf N and Mn and decreased P and B at high N. Thus, under conditions of K limited growth, leaf nutrient accumulation could be altered but tree vigor, fruit nutrition, yield and quality performance were generally unaffected by increasing rate of fertigated N.

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