Development and Correction of K-deficiency in Drip-irrigated Apple

Gerry Neilsen, Peter Parchomchuk, Michael Meheriuk, and Denise Neilsen

Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland, BC V0H 1Z0, Canada

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Abstract. Various schedules of 40 g N and 17.5 g P/tree per year were applied with irrigation water (fertigation) to 'Summerland McIntosh' apple (*Malus ×domestica* Borkh.) trees on M.9 rootstock commencing the year of planting. Leaf K concentrations averaged 0.82% dry mass, indicating deficiency, by the third growing season. This coincided with extractable soil K concentrations of 50–60 $\mu\text{g}\cdot\text{g}^{-1}$ soil in a narrow volume of the coarse-textured soil located within 0.3 m of the emitters. The decline in leaf K concentration was reversed and fruit K concentration increased by additions of K at 15–30 g/tree applied either as granular KCl directly beneath the emitters in spring or as KCl applied as a fertigant in the irrigation water. K-fertigation increased fruit red color, size, and titratable acidity only when leaf K concentration was <1%. Fruit Ca concentration and incidence of bitter pit or coreflush were unaffected by K application. NPK-fertigation commencing upon tree establishment is recommended for high-density apple orchards planted on similar coarse-textured soils.

Adding fertilizers directly with irrigation water (fertigation) increases the potential for synchronizing fertilizer additions with plant nutrient demand (Haynes, 1985), and has received much attention as Pacific Northwest fruit growers have increased orchard planting density. Fertigation has supplied both N and P effectively to apple trees (Neilsen et al., 1993), whether applied via drip- or microjet-irrigation systems (Neilsen et al., 1995). Potential problems resulting from fertigation were also identified, including soil acidification due to $\text{NH}_4\text{-N}$ application (Edwards et al., 1982), which causes various nutrient imbalances, including K-deficiency (Neilsen et al., 1994).

The consequences of K-deficiency have long been identified in apple orchards (Cummings, 1985), although only rarely observed in the Pacific Northwest in traditional, widely spaced, nonintensive orchard systems (Neilsen et al., 1989). The reduction in mass, length, volume, and surface area of root systems associated with increased planting density (Atkinson, 1978) necessitates a reevaluation of traditional fertilizer strategies for high-density plantings, especially for sites with infertile soils. This includes approaches to the amelioration of K-deficiency, which may develop rapidly in drip-fertigated apple orchards (Neilsen et al., 1995), and may involve adoption of methods that have been effective for drip-irrigated prune trees (Uriu et al., 1980).

The present study assessed the development of K-deficiency in a high-density, NP-

fertigated and drip-irrigated apple orchard. A further objective was to assess various strategies to correct the K-deficiency.

Materials and Methods

N and P treatments. A block of 'Summerland McIntosh' on M.9 rootstock was planted in Mar. 1989 at a 1.5-m (within row) $\times$ 4.0-m (between row) spacing. Throughout the experiment, the trees were drip-irrigated (10 L/tree) daily from about 1 May to 1 Oct. through a single 4 L·h⁻¹ emitter located 0.5 m from each tree. The planting was originally designed to test five different schedules for fertigating N at 40 g and P at 17.5 g/tree as mixtures of ammonium nitrate (34N–0P–0K) and ammonium polyphosphate (10N–15P–0K), and was arranged in a randomized complete-block design with four blocks and six trees per treatment per block, each treatment separated by pollinizer trees (24 trees per treatment). The NP-fertilizer was applied annually for the first five growing seasons (1989–93) according to the schedules, which ranged from application as a single dose in early May to 12 weekly applications from early May to mid-July. There were few growth or nutritional responses to these different fertigation schedules, so additional detail will not be provided concerning them. Upon initiation of K-fertigation treatments in 1994, NP-fertigation treatments were terminated and all trees were fertigated with N at 40 g/tree per year applied as 12 equal weekly applications of NH_4NO_3 from May to July.

K treatments. In 1992, three-tree subplots were randomly selected within each of the 20 main plots (five NP-schedule treatments $\times$ four replications). The 40 subplots received K at either 0 (K1) or 15 g (K2) applied as granular KCl (0N–0P–50K) deposited on the soil sur-

face directly beneath each emitter in early May. In 1993, due to increasing severity of K-deficiency symptoms in K1-plots in 1992, K-application rates were increased in these plots to K at 15 g applied as KCl beneath the emitters in May. Trees in K2-plots received K at 15 g, as previously, in each of May, July, and August (45 g total). In 1994, five K-fertigation treatments were randomly applied to the previous NP-schedule plots as 1) no K, 2) K at 15 g, or 3) K at 30 g/tree as KCl split into eight weekly applications in May and June (early K), 4) K at 15 g, or 5) K at 30 g/tree as KCl split into eight weekly applications in July and August (late K). The K-fertigation treatments were applied to assess the effectiveness of this method of improving K-nutrition.

Soil analysis. The soil at the experimental location was a Skaha loamy sand (Wittenben, 1986). During the first 3 years (1989–91), soil samples were collected from each of the N-fertigation treatments every 2–3 weeks from mid-May through August for a total of 27 sampling times. Treatment samples were composites from all replicates and collected at 20- to 40-cm depth immediately below and 15, 30, and 60 cm away from the emitter, perpendicular to the tree row. Samples were oven-dried at 55 °C and subsequently analyzed for K by inductively coupled plasma (ICP) spectrophotometry after extraction with 0.25 M HOAc + 0.015 M NH_4F (Van Lierop, 1986).

Leaf analysis. Cultural management of the block followed commercial recommendations (British Columbia Ministry of Agriculture, Fisheries and Food, 1996). During the course of the experiment, several trees throughout the block were affected by herbicide toxicity, frost, or severe pruning to remove suspected fireblight, and were excluded from subsequent sampling and analyses. Composite leaf samples were collected in mid-July of each growing season from each treatment and replicate. Each composite contained 30 leaves sampled from the midportion of extension shoots of the current year's growth. 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 a H_2SO_4 solution containing K_2SO_4 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 475 °C and dissolved in 0.5 M HCl for determination of Ca, Mg, K, Mn, Zn, Fe, and Cu by atomic absorption spectrophotometry.

Tree growth, yield, and fruit characteristics. Trunk cross-sectional areas were calculated from trunk diameters measured at 0.3-m height each spring, including the year of planting. Fruit yield was measured each year, starting in 1990. Commencing in 1992, the 1st year of K-treatments, a box of apples (about 70 fruit) was harvested from each of the plots at commercial maturity (determined by industry personnel) and stored in air at 0 °C. A 15-apple subsample chosen at random from each box at

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harvest was evaluated for red skin color, average fruit mass, flesh firmness, titratable acidity (TA), and soluble solids concentration. An additional 15-apple sample was taken from each box after 90 d in storage and evaluated for flesh firmness, TA, and soluble solids concentration. The remaining fruit in each box were ripened at 20 °C for 7 d immediately after the 90-d storage period and assessed for bitter pit and coreflush (diffuse browning of the tissue around the core area). Both disorders were rated as none, slight, moderate, or severe.

Red skin color was estimated visually. Flesh firmness was determined with a Baullaf penetrometer (11.1-mm tip). Soluble solids concentration in the juice was measured with a refractometer and TA was determined by titration of juice to an 8.1 pH endpoint. Juice was obtained from sectors taken from each apple in each 15-apple sample.

A random sample of 25 fruit at harvest from each treatment and replicate was also rinsed under running, distilled water and air-dried. Stems and seeds were removed and opposite, unpeeled quarters were blended with 1.5 times their mass of distilled water. A 150-mL subsample was further homogenized with a high-speed tissue homogenizer. A weighed 9-mL aliquot 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 of 25% $CuSO_4$ solution), and Se (0.67 g·L⁻¹) at 380 °C for 1 h. Calcium, Mg, and K were determined on the extracts via atomic absorption spectrophotometry. Nitrogen and P were determined via colorimetric methods as described above.

Statistical analyses. Analysis of variance

(ANOVA) was performed on all leaf, fruit, yield, and growth data according to the experimental design. Average plot rather than individual fruit values were used in subsequent ANOVA. Data from 1989 to 1991 were analyzed as a randomized complete-block design with five NP-schedule treatments and four replicates. Commencing in 1992, a split-plot design (40 plots sampled) was utilized with mainplot units representing N-schedules (1992–93) or K-fertilization treatments (1994). Subplot treatments were K-fertilizer application rates in 1992–93. Leaf and fruit samples were collected and growth measurements made in 1994 in order to test the residual effects of 1992–93 K-treatments. Data were analyzed separately by year due to the modification of treatments each year. For the soil data collected 1989–91, composite samples from each N-treatment were treated as replicates for soil-K values because N-treatments had no apparent effect on tree K-nutrition. Analysis of variance was then undertaken to test for the effects of sampling time, year, and their interaction separately at each of the four locations. All statistical analyses were undertaken using the general linear model procedure (SAS, 1989). Main effects were separated using Duncan's multiple range test.

Results and Discussion

Tree response, 1989–91. Variation in NP-fertilization schedule had no consistent effect on orchard nutrition, yield, or growth in the first three growing seasons. Only leaf N (1990) and annual trunk cross-sectional area incre-

ment (1989–90) were significantly affected by scheduling of the NP-additions (data not shown). However, for neither variable were the effects of practical significance. For example, leaf N concentration increased from already adequate levels (2.5%) to higher values (2.8%) in 1990 in the two treatments involving application of N weekly for 12 weeks (data not shown). Tree vigor, as indicated by annual cross-sectional area increment, was lowest after 1989 for the single-time N-application, but trees in this treatment had greatest growth in 1990 with no differences among treatments after 3 years. During this period, leaf concentrations were adequate, averaging 2.11%, 2.62%, and 2.81% leaf N, and 0.25%, 0.26%, and 0.26% leaf P, in 1989–91, respectively.

The most noteworthy nutritional effect of the first phase of this experimentation was development of leaf K deficiency, as indicated by a decline in average annual leaf K concentration from 1.34% to 1.3%, to 0.82% during the first 3 years. Simultaneously, average annual leaf Mg concentration increased from 0.26% to 0.31%, to 0.37%. Thus low leaf K concentration was associated with high leaf Mg. Increased leaf Mg concentration under conditions of K-deficiency was previously observed for 'McIntosh' (Neilsen et al., 1989). Potassium deficiency symptoms were apparent in numerous trees by the 3rd year and were characterized by development of an irregular chlorotic leaf surface by midsummer that developed into interveinal browning and marginal leaf scorch, especially in spur leaves subtending fruit. Fruit adjacent to spurs with

Fig. 1. Extractable soil K at 20- to 40-cm depth directly beneath the emitter (0 cm) and at 15-cm, 30-cm, or 60-cm lateral distance from the emitter, perpendicular to the crop row, from May–August over a 3-year period of NP-fertilization in a sandy soil. Vertical bars indicate $\pm$ pooled SE from analysis of variance ($n = 135$).

severe symptoms appeared to be smaller and susceptible to sunburn and development of a yellow-orange coloration prior to harvest. Similar leaf symptoms were observed on basal leaves of new years' growth but were less common.

Levels of K in soil, 1989–91. During the first 3 years, extractable soil-K concentration at 20- to 40-cm depth was significantly affected by a year $\times$ sampling time interaction at all distances from the emitter (Fig. 1a–d). Minimum values were observed in the 3rd year at each location with minima reaching 50, 60, 70, and 90 mg·kg⁻¹ at 0-, 15-, 30-, and 60-cm horizontal distance from the emitter, respectively. This pattern is consistent with K-leaching and pH decline beneath and near emitters accelerated by fertigation with ammonium polyphosphate (Parchomchuk et al., 1993). Soil acidification is a historical problem in local orchards resulting from fertilization, irrigation, and herbicide use (Ross et al., 1985). The rate of decline of soil pH and cation levels is much more rapid where fertilizers are added to irrigation water. This may reflect the addition of some dissolved cations with irrigation water. Irrigation water applied at this site contained Ca, Mg, K, and Na at 28.4, 8.5, 2.2, and 8.7 mg·L⁻¹, respectively. Decline in soil K concentration was greater directly beneath the emitter (Fig. 1a) than at 60-cm distance (Fig. 1d). This indicates a narrow zone with substantial downward flow of water under drip irrigation in coarse-textured soils. However, the association of lower leaf K with declining soil K is an indication of the importance of this narrow wetted zone to nutrient uptake. Use of two emitters per tree might have delayed the effects of K-leaching by increasing the volume of the root zone, provided the amount of fertilizer applied was not increased. Drip-fertigation of apple trees on dwarfing rootstocks, including M.9, results in a concentration of apple roots near the emitter and the soil surface in coarse-textured soils (Neilsen et al., 1997). Extractable soil-K concentrations averaging $\approx$ 40 mg·kg⁻¹ in the surface 30 cm of an orchard soil have been associated with K-deficiency on 'McIntosh' on M.4 rootstock (Neilsen et al., 1989). In this study, decreases in extractable-soil K from apparently adequate values (130–140 mg·kg⁻¹) to values averaging 50–60 mg·kg⁻¹ in a major portion of the rooting zone resulted in the development of K-deficiency on 'McIntosh' on M.9 rootstock.

Levels of K in leaves, 1992–94. Unless specifically stated, only main effects of treatments in 1992–94 are discussed due to a general lack of significant interaction between soil-applied K subplot treatments and either NP-fertigation treatments in 1992–93 or K-fertigation treatments in 1994.

Leaf N and P concentrations remained adequate for all trees during the 1992–94 period of differential K-treatments, with plot averages ranging from 2.39% to 2.74% for leaf N and 0.19% to 0.26% for leaf P. The placement of K at 15 g as KCl (K2) directly beneath the single emitter per tree in May 1992 significantly increased leaf K concentration relative to trees receiving no K (0.85% vs. 0.68%;

Table 1). However, addition of this amount of K was insufficient to prevent leaf K deficiency in 1992 (<1%). For this reason, 1993 K rates were increased, with K1-trees receiving K at 15 g/tree and K2-trees receiving K at 45 g/tree for the whole year (but K at only 30 g/tree prior to mid-July leaf sampling). K2-trees had significantly increased leaf K concentration relative to K1-trees in 1993, although both averages were >1%. Increases in leaf K concentration in 1993 may have been partially associated with a low cropping level (45% of 1992) due to spring frost damage. An inverse relationship between leaf K concentration and crop load was previously reported for apple (Hanson, 1980). The effect of the different amounts of K applied directly beneath the emitters [60 g (K2) vs. 15 g (K1)/tree, 1992–93] was measurable in 1994 despite the imposition of K-fertigation treatments to main plot units in that year, indicating carryover effects from previous soil-K applications. Nevertheless, fertigation with K at 15 or 30 g/tree in May–June 1994 significantly increased mid-summer leaf K concentrations, despite half of all plot trees being treated with soil-applied K at 15 g and the remainder with 60 g in 1992–93. Clearly, fertigation with K can increase leaf K concentrations rapidly. Fertigating with either rate of K in July–August, however, had not increased leaf K concentration by mid-July in 1994. Application of late-season KCl apparently delayed the increase in leaf K, and therefore is not desirable when trees are already under K-stress.

The cumulative evidence indicates that midsummer leaf K concentrations could be increased significantly by rather low rates (15–30 g/tree) of K, either applied in a concentrated band directly beneath the emitter, or in the irrigation water early in the growing season. Similar results were observed by Uriu et al. (1980) when correcting K-deficiency of prune trees in California, although K application rates were much higher, approaching 2 kg/tree. In part, the higher K-rates in the California study reflect experimental conditions involving large, mature fruit trees grown on a

fine-textured "K-fixing" soil. Nevertheless, in our study, rates of applied K may have been too low when applied directly beneath the emitter, as indicated by the modest increase in leaf K during the first 2 years. Even after fertigation, maximum leaf K concentration had not yet exceeded 1.4%. Because 31 g of K per tree can be removed with a single, 45 t·ha⁻¹ harvest of 'McIntosh' fruit (Neilsen and Neilsen, 1996), higher fertigated-K rates may be desirable. Application of a single heavy rate of K followed by lighter applications as dictated by leaf K concentrations might also have been appropriate.

With the exception of leaf Mg concentration (Table 1), no other leaf nutrient concentration was consistently affected by the K-treatments. Leaf Mg concentration decreased as K concentration increased, although values were always adequate, >0.26%. Excess K in the drip zone can suppress both leaf Mg and Ca in sour cherry (*Prunus cerasus* L.) (Callan and Westcott, 1996). These studies, which compared sources of fertigated-K, also cautioned against the use of high rates of Cl-sources of K, >1 kg K per tree, due to the potential for chloride toxicity and eventual suppression of leaf P and K concentration. These rates greatly exceeded rates used in our study with apple.

Effects on fruit, 1992–94. In 1992, the first year of differential K-treatments, fruit K concentration, TA, red color, and mean fruit mass were increased by the addition of K (K2-treatment; Table 2), but the increase in fruit size was insufficient to increase yield per tree. As in 1989–91, there were few responses to N-schedule in 1992 and 1993, although the TA increase with K application did not occur for all N schedules in 1992 due to a significant interaction between N-schedules and K-treatments (data not shown). Potassium application increased both fruit K and TA in 1993. Residual effects from differential K-additions in 1992–93 were measurable in 1994 only as increased fruit K concentration. The various K-fertigation treatments in 1994 did not affect any of the previously affected fruit variables (Table 2) although firmer fruit was observed

Table 1. Main effects of K-treatments on leaf K and Mg concentrations of 'Summerland McIntosh' apple, 1992–94.

K-treatment	Leaf K (% dry mass)			Leaf Mg (% dry mass)		
	1992	1993	1994	1992	1993	1994
K-soil applied ²						
K1	0.68	1.07	1.03	0.48	0.30	0.47
K2	0.85	1.20	1.18	0.40	0.26	0.42
Significance	****	****	**	****	*	**
K (g/tree)-fertigated ³						
S1 K (0)			1.01 b			0.45 a–c
S2 (15 May–June)			1.27 a			0.40 bc
S3 (30 May–June)			1.34 a			0.38 c
S4 (15 July–August)			0.96 b			0.49 a
S5 (30 July–August)			0.93 b			0.51 a
Significance			**			**

²K1 = single application of K as KCl at 0 and 15 g/tree in May directly beneath the drip emitter in 1992 and 1993, respectively; K2 = application of K as KCl at 15 g/tree directly beneath the drip emitter in May in 1992 and 3 $\times$ 15 g/tree in May, July, and Aug. 1993.

³Treatments applied in 1994 only. K fertigated as KCl, weekly for 8 weeks during time period indicated. Means in 1994 are main effect means. Interaction between K-fertigation main plot treatments and K-soil applied subplot treatments was nonsignificant.

*, **, **** Significant at $P = 0.05, 0.01, \text{ or } 0.0001$, respectively.

Table 2. Main effects of K-treatments on fruit K concentration, titratable acidity, red color, fruit mass, and yield, of 'Summerland McIntosh' apple, 1992–94.

K-treatment	Fruit K (mg·100 g ⁻¹ fm)			Titratable acidity ^a			Red color(%)			Fruit mass (g)			Fruit yield (kg/tree)		
	1992	1993	1994	1992	1993	1994	1992	1993	1994	1992	1993	1994	1992	1993	1994
K-application treatments^y															
K1	72	94	96		1137	841	70	63	63	163	200	145	9.2	4.4	11.8
K2	87	105	103		1288	879	75	62	65	173	204	148	10.1	4.3	13.6
Significance	****	****	*		*	NS	*	NS	NS	**	NS	NS	NS	NS	NS
K (g/tree)-fertilized^x															
S1 (0)			98			886			61			151			11.6
S2 (15 May–June)			102			830			65			147			14.1
S3 (30 May–June)			111			915			66			143			12.3
S4 (15 July–August)			90			833			61			143			13.2
S5 (30 July–August)			96			836			66			151			12.3
Significance			NS			NS			NS			NS			NS

^aExpressed as mg malic acid per 100 mL of juice.

^yK1- single application of 0 and 15 g/tree K as KCl in May directly beneath the drip emitter in 1992 and 1993, respectively; K2-application of 15 g/tree K as KCl directly beneath the drip emitter in May in 1992 and 3 × 15 g/tree in May, July, and Aug. 1993.

^xTreatments applied in 1994 only. K fertilized as KCl, weekly for 8 weeks during time period indicated. Means in 1994 are main effect means. Interaction between K-fertilization main plot treatments and K-soil applied subplot treatments was nonsignificant.

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

after early season K-fertilization in 1994 only (data not shown). Fruit N, P, Ca, and soluble solids were not affected by K-treatment over the 3-year K-application period. Application of K did not affect the incidence of bitter pit or coreflush after storage. Neither disorder was of commercial significance, not >5% in any treatment.

Higher average fruit mass, red coloration, and fruit TA associated with increased fruit K concentration were previously reported as consequences of increasing the K-supply to trees of low K status (Cummings, 1985). Fruit K concentration and TA seemed to be the variables most consistently affected by differential K-treatments in our study. Considerable seasonal variation in TA values of apple, as observed in this study, was reported by Eaves and Leefe (1955). K-fertilization was previously shown to have a small effect on fruit color development, especially under conditions of K-deficiency (Fisher and Kwong, 1961). Fruit Ca concentration, critical to fruit storage quality, and physiological disorders were unaffected by K-treatments. Malquori and Parri (1978) also found that K-application had little effect on fruit storage quality.

Conclusions

A desirable strategy for this planting would have been to fertigate NPK commencing at plot establishment, thus avoiding the development of K-deficiency, which, although correctable, can reduce fruit quality. A strategy of NPK-fertilization would thus be recommended for drip-irrigated, high-density apple orchards on coarse-textured soils when acidifying $\text{NH}_4\text{-N}$ fertilizers are applied, even when initial soil-K concentrations appear adequate. Relatively low per tree K-application rates maintained K-nutrition, as indicated by leaf K concentrations. Although little evi-

dence of a fruit Ca-K antagonism was observed in this study, fruit Ca concentrations should be monitored when continuously K-fertilizing to maintain leaf K at higher levels. Monitoring changes in leaf Mg concentration and extractable soil-K concentrations in the critical near-emitter zone would also be useful for avoiding excessive K-application.

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