Response of high density apple orchards on coarse-textured soil to form of potassium applied by fertigation

G. H. Neilsen and D. Neilsen

Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland, British Columbia, Canada V0H 1Z0 (e-mail: neilseng@agr.gc.ca). *Received 6 December 2005, accepted 10 April 2006.*

Neilsen, G. H. and Neilsen, D. 2006. **Response of high density apple orchards on coarse-textured soil to form of potassium applied by fertigation**. Can. J. Soil Sci. **86**: 749–755. This study tested the effects of fertigated potassium sources on orchard cation status. A randomized, complete block experimental design was maintained from 2000 to 2003, in a high density 'Jonagold'/M.9 apple (*Malus* × *domestica* Borkh.) orchard planted in 1993 on a loamy sand. Seven K-fertigation treatments included annual application of either no K (control), 15 g K/tree as either potassium chloride or potassium magnesium sulphate (KMag) or 30 g K/tree as potassium chloride, KMag, potassium sulphate or potassium thiosulphate, applied daily during 6 wk midsummer to six replicate, four-tree plots. Fertigated K-forms did not affect yield, but increased soil K after 3 yr to 30-cm depth beneath the drip emitters. This increased leaf and fruit K concentrations. Fruit K/Ca ratio was also increased by K-fertigation. A high incidence of bitter pit at harvest was unaffected by fertigating K, but rather was associated with low harvest fruit Ca concentration and large fruit size. KMag increased soil Mg availability, but leaf and fruit Mg concentrations were slightly affected, indicating the difficulties of improving apple Mg status when co-applying K. Leaf and fruit Ca concentrations were minimally affected by treatments. Soil Ca declined slightly after 3 yr of K fertigation.

Key words: Bitter pit, calcium, chloride, magnesium, *Malus* × *domestica*, sulphate, thiosulphate

Neilsen, G. H. et Neilsen, D. 2006. **Réaction des vergers à haute densité de pommiers plantés sur un sol à texture grossière aux applications de potassium par irrigation**. Can. J. Soil Sci. **86**: 749–755. Les auteurs ont vérifié l'incidence du potassium appliqué par irrigations fertilisantes sur le bilan cationique d'un verger. À cette fin, de 2000 à 2003, ils ont procédé à une expérience en blocs aléatoires complets dans un verger densément peuplé de pommiers Jonagold/M.9 (*Malus* × *domestica* Borkh.) plantés en 1993 sur un sable loameux. L'étude portait sur sept types d'irrigation fertilisante avec potassium : aucune application annuelle de K (témoin); application de 15 g de K par arbre sous forme de chlorure de potassium ou de sulfate double de potassium et de magnésium (KMag); application de 30 g de K par arbre sous forme de chlorure de potassium, de KMag, de sulfate de potassium ou de thiosulfate de potassium. Les auteurs ont fertilisé quotidiennement par irrigation six parcelles identiques de quatre arbres durant six semaines, au milieu de l'été. L'application de K par irrigation fertilisante ne modifie pas le rendement. Cependant, au bout de trois ans, elle accroît la concentration de K dans le sol à 30 cm de profondeur sous les buses goutte-à-goutte. Il s'ensuit une hausse de la teneur en K dans les feuilles et les fruits. L'application de K par irrigation fertilisante augmente aussi le ratio K/Ca dans le fruit. L'application de K par irrigation fertilisante n'a eu aucun effet sur une incidence élevée de point-amer, que l'on a plutôt attribuée à la faible teneur en Ca dans les fruits et aux fruits de plus gros calibre. Le KMag accroît la disponibilité de Mg dans le sol, mais la concentration de Mg dans les feuilles et les fruits n'est que légèrement touchée, signe qu'il est difficile d'améliorer le bilan de Mg dans les fruits quand on applique simultanément du K. Les traitements n'agissent que faiblement sur la concentration de Ca dans les feuilles et les fruits. La teneur en Ca du sol diminue légèrement après trois ans d'irrigations fertilisantes de K.

Mots clés: Point-amer, calcium, chlorure, magnésium, *Malus* × *domestica*, sulfate, thiosulfate

High-density apple orchards on dwarfing rootstocks offer economic advantages as a result of earlier and greater fruit yield per unit of land area (Quamme et al. 1997). In the major fruit-growing area of southern interior British Columbia, about two-thirds of orchards are located on coarse-textured sandy loams, loamy sands or sand soils composed of more than 50% sand sized particles. Such soils offer advantages to orchard production including rapid drainage, but are sensitive to management problems associated with their generally poor nutrient and water retention capacities (Ross et al. 1985). Problems can be exacerbated by the shallow and concentrated rooting of trees on dwarfing rootstocks when drip-fertigated (Neilsen et al. 1997), resulting in the development of nutrient deficiencies such as K, not normally observed for traditional, sprinkler-irrigated orchards with widely spaced trees.

Fertigation of KCl is effective for ameliorating K-deficiency and improving tree and soil K status (Uriu et al. 1980; Klein 1992; Neilsen et al. 1998), but there has been little assessment of the effectiveness of other soluble K fertilizers, which may contain additional plant nutrients. For example, soil Mg availability can become relatively low in leached soils after K-fertigation (Neilsen et al. 2000). Magnesium deficiency has an occasional and long established occurrence in British Columbia (Woodbridge 1955). Thus, the relative effectiveness of Mg-containing potassium magnesium sulphate (KMag) would be of interest to orchardists.

Abbreviations: **KMag**, potassium magnesium sulphate; **KTS**, potassium thiosulphate; **SSC**, soluble solids concentration; **TA**, titratable acidity

In most fruit production regions of the world, adequate Ca is considered the most important nutritional factor for optimizing the harvest quality and minimizing post-harvest storage disorders of apple (Vang-Peterson 1980; Himelrick and McDuffie 1983). Emphasis has often been placed on achieving balanced Ca, Mg and K nutrition of fruits (Bramlage et al. 1980) and concern expressed that excessive K may increase the incidence of Ca-related disorders such as bitter pit (Ferguson and Watkins 1989). This implies that K-fertigation may be detrimental to fruit quality, although few studies have assessed the direct effect of K-fertilization upon fruit Ca concentration and fruit quality (Cummings 1985).

Thus a 3-yr field experiment was designed to test the effects of various fertigated K-fertilizers, including KMag, on soil, leaf and fruit Ca, Mg and K content and fruit yield and quality in a high density Jonagold/M.9 apple orchard.

MATERIALS AND METHODS

An experimental block of Jonagold/M.9 apple (*Malus* × *domestica* Borkh.) was planted in 1993 at 1-m spacing within rows, 3 m apart. Trees were trained as slender spindles, each tree supported by a post. The block was maintained in a 2-m-wide herbicide strip according to standard commercial production practices with respect to insect and disease control, pruning, drip-irrigation and fertilization (annual N and Zn only) (British Columbia Ministry of Agriculture and Food 1998). Annual leaf K concentration ranged from 1.5 to 1.7% for the block prior to the experiment, suggesting K sufficiency (Shear and Faust 1980). Nevertheless a K experiment was initiated since Jonagold and other apple cultivars are frequently fertilized commercially with K, despite limited knowledge of critical leaf K concentrations or consequences to fruit quality. Commencing in 2000, when trees were in their 8th leaf, seven fertigation treatments were established in a randomized and replicated complete block design with six replicates (four-tree plots) each plot separated by a guard tree at each end. Treatments were (1) a control not receiving K, (2) 15 g and (3) 30 g K/tree/yr as KCl (0-0-60), (4) 15 g and (5) 30 g K/tree/yr as potassium magnesium sulphate (0-0-22-11% Mg-22%S, henceforth referred to as KMag), (6) 30 g K/tree/yr as potassium sulphate (0-0-50-17%S) and (7) 30 g K/tree/yr as liquid potassium thiosulphate, henceforth referred to as KTS (0-0-25-17%S). All fertilizers were available commercially except for potassium sulphate, which was purchased as an ultra fine grind suitable for fertigation from Diamond K (Richfield, UT). All treatments were also fertigated with a total of 15 g N/tree each year as ammonium nitrate (34-0-0) with daily applications made post-bloom for approximately 6 wk until early summer (2000 Jun. 05–Jul 10; 2001 May 14–Jun. 26; 2002 May 16–Jun. 28). K applications were made over approximately 6 wk during the summer when fruit size began to increase rapidly (2000 Jun. 26–Aug. 04; 2001 Jun. 26–Aug. 14; 2002 Jul. 02–Aug. 19). All trees received daily irrigation, as is essential for adequate fruit production in the semi-arid region, from about May 01 to Oct. 01 each year via 4 $L \cdot h^{-1}$ pressure compensating emitters located midway between trees (0.5 m) within the tree row. Irrigation ran 2 h daily delivering 8 L of irrigation water/tree. No overhead cooling occurred in the orchard.

The experimental site was located on a Skaha loamy sand soil series belonging to the Chernozem Order, Brown Great Group and Orthic Subgroup (Wittneben 1986), extensively planted to fruit crops in southern British Columbia. These soils have limited nutrient- and water-holding capacities as a result of low organic matter and exchange capacity. In March 2003, after three complete growing seasons, soil samples were collected from every treatment and replicate as composites, comprised of three samples collected directly beneath the drip emitters located in the middle of each plot at 0- to 10-, 10- to 20- and 20- to 30-cm depths. Thus, samples represented conditions under drip-irrigation where soil chemical changes are most rapid and roots are concentrated (Neilsen et al. 1997). Samples were oven dried at 55°C prior to determination of Ca, Mg and K via atomic absorption spectroscopy after extraction in 1M NH_4OAc. Soil pH was also measured on a 1:2 (wt:vol), soil:water slurry (Kalra and Maynard 1991).

Composite samples of 30 leaves from the mid-portion of the 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. One-gram samples were dry-ashed at 475°C and dissolved in 0.5 M HCl for determination of Ca, Mg and K by atomic absorption spectrophotometry.

Each year at commercial harvest, the number and weight of fruit (allowing the calculation of average fruit size) were recorded for each experimental plot. A randomly selected 10-apple subsample from each plot was evaluated for solid skin red colour (to the nearest 5%), flesh firmness, titratable acidity (TA), and soluble solids concentration (SSC) each year. Percent red skin colour was estimated visually. Flesh firmness was determined with a Baullaf penetrometer (11.1-mm-diameter tip). SSC 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. An additional 10-fruit sample was collected annually from the outside of the middle third of the canopy from all trees in each plot and was used to evaluate the incidence and severity of disorders at harvest. Bitter pit was classified as slight (one or two areas up to 2 cm wide), moderate (less that one-third of the cortex) or severe (more than one-third of the cortex affected). Watercore was also observed and assessed as slight (small areas around the seed cavity and vascular bundles), moderate (< 25% of cortex) or severe (> 25% of cortex).

Another random sample of fruit (n = 10) was selected at harvest from each treatment and replicate and rinsed under running, distilled water and then air-dried. Stem tissues 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

Table 1. Effect of K-fertigation treatment on exchangeable K, Mg and Ca concentration and pH of soil at 0–10, 10–20 and 20–30 cm directly beneath the emitter in March 2003

	Exchangeable K			Exchangeable Mg			Exchangeable Ca			pH		
Depth (cm)	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
Treatment[z]	cmol(+)kg^{-1}									(1/2:soil/water)		
Control (no K)	0.22*b*[w]	0.13*c*	0.12*c*	0.88*b*	0.73*b*	0.64*bc*	3.44*a*	2.64*a*	2.16*a*	7.1*a*	6.9*a*	7.0*a*
KCl	0.38*a*	0.41*ab*	0.47*b*	0.76*b*	0.68*bc*	0.57*c*	2.90*b*	2.46*ab*	1.92*b*	6.9*ab*	6.9*a*	6.9*a*
KMag[y]	0.36*a*	0.29*b*	0.38*b*	1.24*a*	1.38*a*	1.33*a*	2.91*b*	2.10*bc*	1.28c	7.1*a*	6.9*a*	6.8*a*
K_2SO_4	0.28*b*	0.34*b*	0.54*b*	0.85*b*	0.80*b*	0.69*b*	3.20*ab*	2.57*a*	2.07*ab*	7.1*a*	6.9*a*	6.9*a*
KTS[x]	0.37*a*	0.54*a*	0.76*a*	0.80*b*	0.61*c*	0.42*d*	2.85*b*	1.43*c*	1.38*c*	6.8*b*	6.3*b*	6.2*b*
Significance[v]	***	***	***	****	****	****	*	**	****	*	***	****

[z]All K treatments applied at 30 g K/tree annually.
[y]Potassium,magnesium sulphate.
[x]Potassium thiosulphate.
[w]Values within a column followed by different letters are significantly different at $P \leq 0.05$ level of probability using Duncan's multiple range test.
[v]Indicates the level of significance of the F-test as a whole, $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.001$ (***), or $P \leq 0.0001$ (****).

H_2SO_4 containing Na_2SO_4 (1.8 g), Cu (0.36 mL 25% $CuSO_4$ solution), and Se (0.67 g L^{-1}) at 350°C for 1 h. Calcium, Mg and K were determined in these extracts via atomic absorption spectrophotometry.

Analysis of variance (ANOVA) was performed on all leaf and fruit data as a randomized complete block design with six replicates (SAS Institute, Inc. 1989). Fruit data when expressed as a proportion were arcsine transformed prior to ANOVA. Data were analyzed separately by year due to the annual variation in yield over the experimental period. For leaf and fruit data, single degree of freedom contrasts were used to determine the effects of fertigating K (control vs. all other treatments), comparisons of KCl vs. KMag at two K-rates (K-form), comparisons of 15 g vs. 30 g K/tree for KCl and KMag (K-rate), the interaction of K-form × K-rate, and comparisons of individual K-fertilizers at the 30 g K/tree rate including K_2SO_4 vs. KTS and KMag vs. K_2SO_4. For soil data, ANOVA was performed on sampled treatments with mean separation by Duncan's multiple range test.

RESULTS AND DISCUSSION

Soil Cation Status

Soil cation status was altered throughout the surface 30-cm depth directly beneath the drip emitters after 3 yr of different K-fertigation treatments, as indicated by analysis of samples collected in spring 2003 from the high rate (30 g K/tree) and control treatments (Table 1). Potassium concentration was increased by fertigation of all K-forms with no consistent differences among forms over the three sampled depths. KMag also increased exchangeable soil Mg throughout the sampled soil profile, relative to all other treatments. The KTS treatment significantly reduced soil Mg relative to the control treatment at 10-to 20-cm and 20- to 30-cm depth. This treatment had the lowest pH in 2003 at these two depths (Table 1). In general, exchangeable soil Ca was highest at all soil depths for control and K_2SO_4 treatments. Calcium values were significantly less than control treatments at all three depths for the KMag and KTS treatments, a likely consequence of their greater ability to displace Ca, whether through the addition of both K and Mg (KMag) or K under acidifying conditions (KTS).

In previous studies on root distribution of apple trees on dwarfing rootstocks that were drip-irrigated daily and grown in coarse-textured soils, the average location of roots directly beneath the emitters was within 30 cm of the soil surface and roots were laterally concentrated near the tree row (Neilsen et al. 1997). This K study indicated that it is relatively easy to alter the cation status of this important rooting zone within 3 yr by annual fertigation of various soluble cation-containing fertilizers. For example, availability of soil K was particularly increased below 10 cm depth, where K values were otherwise low for control treatments, after application of 90 (3 × 30) g K/tree, regardless of chemical form of the applied K. Similarly, application of 55 (3 × 18.3) g Mg in association with the 90 g of K (contained in KMag) was sufficient to alter soil Mg status throughout the sampled soil depth. Thus, use of KMag as a fertigant would suffice to prevent the absolute and relative decline in soil Mg previously associated with K-fertigation (Neilsen et al. 2000). However, soil Ca decreased as soil Mg increased. The rapidity with which these soil nutrient changes occurred in these relatively unbuffered soils indicates a need for regular soil sampling to monitor soil cation changes when repeated, annual applications are made of fertilizers containing single cation nutrients.

Leaf K, Mg and Ca

Leaf K was increased by the various K-fertigation treatments relative to the control trees, receiving N-only, throughout the 3 yr of the experiment (Table 2). Increasing the rate of fertigated K from 15 to 30 g K/tree as KCl or KMag also increased leaf K in the last 2 yr of the study. There were few differences in leaf K performance among K forms throughout the study, with the exception of first year when single degree of freedom contrasts indicated a higher leaf K concentration for trees fertigated with 30 g K as KTS rather than K_2SO_4. Fertigating K decreased leaf Mg as indicated by highest leaf Mg concentrations consistently observed for control trees not fertigated with K during the study (Table 2). Increasing the rate of K applied as KCl and KMag further decreased leaf Mg concentration in the first year, although this effect was not observed for Mg-contain-

Table 2. Effect of K-fertigation treatment on mid-July leaf K, Mg and Ca concentration of Jonagold on M.9 rootstock 2000–2002

Fertigation treatments	Leaf K			Leaf Mg			Leaf Ca		
	2000	2001	2002	2000	2001	2002	2000	2001	2002
	% DW								
Control (no K)	1.38	1.58	1.46	0.30	0.34	0.37	1.23	1.35	1.15
KCl (15 g K/tree)	1.60	1.81	1.73	0.29	0.30	0.34	1.21	1.29	1.25
KCl (30 g K/tree)	1.67	1.96	1.83	0.27	0.27	0.32	1.18	1.18	1.19
KMag[z] (15 g K/tree)	1.66	1.89	1.74	0.28	0.29	0.35	1.21	1.22	1.15
KMag (30 g K/tree)	1.72	1.98	1.85	0.26	0.29	0.35	1.24	1.18	1.10
K_2SO_4 (30 g K/tree)	1.66	2.00	1.91	0.24	0.24	0.30	1.24	1.22	1.15
KTS[y] (30 g K/tree)	1.76	2.01	1.94	0.25	0.26	0.30	1.24	1.20	1.18
Contrasts[x]									
Control vs. all	****	****	****	***	****	****	NS	**	NS
K-form	NS	NS	NS	NS	NS	NS	NS	NS	*
K-rate	NS	*	*	**	*	NS	NS	NS	NS
Rate × Form	NS	NS	NS	NS	*	NS	NS	NS	NS
K_2SO_4 vs. KTS	*	NS	NS	NS	*	NS	NS	NS	NS
KMag vs. K_2SO_4	NS	NS	NS	NS	***	***	NS	NS	NS

[z]Potassium,magnesium sulphate.
[y]Potassium thiosulphate.
[x]Specified single degree of freedom contrasts not significantly different (NS) or significant at the probability level indicated as $P \le 0.05$ (*), $P \le 0.01$ (**), $P \le 0.001$ (***), $P \le 0.0001$ (****).

ing KMag in the second year or either form in the third year. Some differences in leaf Mg concentration were observed among forms of K fertigant with leaf Mg concentration higher for trees receiving KMag rather than K_2SO_4 from 2001 to 2002 and for trees receiving K_2SO_4 rather than KTS in 2001. It is also noteworthy that in 2002, after 3 continuous years of fertigated K application, leaf Mg concentrations were less than control trees for all treatments except for trees to which KMag was applied. Leaf Ca concentration was less affected by fertigation than Mg or K. Effects commenced only in the second year when fertigated K-treatments reduced leaf Ca concentration. This effect was not generally observed in the third year over all forms, although application of KMag, which contained both K and Mg reduced leaf Ca relative to KCl.

Previous research has indicated that the application of 15–30 g K per tree as KCl directly with irrigation water is sufficient to increase leaf K concentration from deficient values (Neilsen et al. 1998). Although trees in our more recent study had leaf K concentrations well above the 1% deficiency threshold (Shear and Faust 1980), the cumulative evidence indicates that fertigation of any sufficiently soluble K-form will augment apple tree K-nutrition. Leaf K concentration can be increased rapidly within a single growing season, increases as rate of applied K increases, but may be associated with decreased concentrations of especially Mg and to a lesser extent Ca.

Reduction of leaf Mg concentration after fertigation of K is a documented consequence of fertigating K to overcome deficiency (Neilsen et al. 2004). It was also observed in this latest experiment when K and Mg concentration were both at adequate values. Magnesium-containing KMag fertilizer had a moderating effect on leaf Mg decline although leaf Mg concentration was not increased by its application, indicating a preferential uptake of K by apple from a fertilizer containing 18% K and 11% Mg. This also implies that if leaf Mg concentrations are in the deficiency range (< 0.20% for apple) and K concentrations are already adequate, a soluble fertilizer containing Mg alone could be more effective. The application of both K and Mg (as with KMag) has the potential of reducing leaf Ca uptake in the long term, although significant decreases in leaf Ca concentration were observed for this treatment only in the third year. Leaf Ca greatly exceeded the 0.70% deficiency concentration, indicating an adequate supply of Ca for leaves in this experiment (Shear and Faust 1980).

Fruit K, Mg and Ca

The effects of K-fertigation on fruit K concentration were not observed until the second and third year of the study (Table 3). Increases in fruit K concentration associated with increasing the application rate of both KCl and KMag from 15 to 30 g K/tree, occurred in the third year of the study. Fruit Mg concentration changes were much less than those observed for leaves, being restricted to consistently higher fruit Mg concentrations after fertigation with KMag rather than K_2SO_4. Fruit Ca concentrations were not differentially affected by K-fertigation during the first 2 yr of the study. In the last year of the study fruit Ca concentration was decreased at the high (30 g K/tree) rate of KCl and KMag relative to the control and 15 g K/tree rate of KCl and KMag. K-fertigation significantly increased the fruit K/Ca ratio for all K-fertigated trees commencing in the second year (2001).

Increased concentration of K in fruit, especially relative to Ca concentration has been a commonly reported consequence of broadcast (Erani et al. 2002) and fertigated (Klein 1992) applications of K. Decreases in fruit Ca concentration were slight, and minimal effects on fruit Mg have also been observed after high rates of K-fertigation in Brazil (Erani et al. 2002). Whole fruit Mg and K concentrations measured for Jonagold at harvest (Table 3) were within the normal

Table 3. Effect of K-fertigation treatment on harvest fruit K, Mg and Ca concentration and fruit K/Ca ratio of Jonagold on M.9 rootstock, 2000–2002

	Fruit K			Fruit Mg			Fruit Ca			Fruit K/Ca		
Fertigation treatment	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
	mg/100g FW											
Control (no K)	106	105	101	4.93	4.98	4.98	3.26	2.47	2.60	33.0	42.5	39.4
KCl (15 g K/tree)	110	124	115	4.84	5.23	5.19	3.48	2.38	2.63	31.9	52.9	44.9
KCl (30 g K/tree)	112	124	123	4.98	5.07	5.17	3.63	2.37	2.42	31.6	53.6	50.8
KMag[z] (15 g K/tree)	112	124	116	5.02	5.20	5.00	3.56	2.32	2.62	32.2	54.9	44.3
KMag (30 g K/tree)	119	129	123	5.17	5.25	5.27	3.48	2.20	2.25	34.5	60.8	54.5
K_2SO_4 (30 g K/tree)	116	118	123	4.75	4.72	4.91	3.28	2.35	2.46	35.9	50.7	50.5
KTS[y] (30 g K/tree)	112	124	122	4.87	5.13	5.00	3.32	2.36	2.46	34.5	53.5	49.6
Contrasts												
Control vs.all	NS	**	****	NS	NS	NS	NS	NS	NS	NS	*	***
K-form	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
K-rate	NS	NS	*	NS	NS	NS	NS	NS	**	NS	NS	***
Rate × Form	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
K_2SO_4 vs.KTS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
KMag vs.K_2SO_4	NS	NS	NS	*	*	**	NS	NS	NS	NS	NS	NS

[z]Potassium, magnesium sulphate.
[y]Potassium thiosulphate.
Specified single degree of freedom contrasts, not significantly different (NS) or significant at the probability indicated as $P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.001$ (***) or $P \leq 0.0001$ (****).

range for standard cultivars grown commercially in southern British Columbia (Wolk et al. 1998) with fruit K exceeding the 100 mg K/100 g FW concentration associated with K-deficiency (Neilsen et al. 2004). In contrast, fruit Ca concentrations were very low for all treatments, including the controls not receiving K, much below the 4.0 mg Ca/100 g FW harvest concentrations which has been suggested as a critical threshold, below which Ca-related fruit quality problems might be expected (Neilsen and Neilsen 2003). The simultaneous existence of inadequate fruit Ca with adequate leaf Ca concentrations for these Jonagold trees supports the general belief that fruit Ca disorders reflect low Ca transport to phloem-dependent organs rather than inadequate supply from the soil (Himelrick and McDuffie 1983).

Fruit Yield and Quality

Treatments had no effects on tree vigour (data not shown), yield and size of fruit or many fruit quality parameters including fruit firmness, percent red colour and titratable acidity (Table 4). Thus, despite relatively low soil organic matter (and S) contents at the experimental site, there was no evidence to indicate significant confounding growth responses to other nutrients, such as S, co-applied with the K contained in the different treatments. Typical of Jonagold grown in this region, fruit size was very large, exceeding 300 g over all treatments in 2001. As a result of the large fruit size, fruit firmness was generally low. Red colour and titratable acidity showed typical values and year-to-year ranges for this cultivar.

Fruit SSC was most affected by treatments during the study with control fruit not receiving K having greater SSC at harvest relative to the K-fertigation treatments in 2 of 3 yr (Table 5). In first year, SSC increased as rate of fertigated KCl increased from 15 to 30 g K/tree but decreased with increased rate of KMag, reflecting the significant interaction between rate and form of K. The major physiological disorders of fruit observed during the study were bitter pit and water core, which were only affected by treatments in a minor way (Table 5). For example, incidence of bitter pit was unaffected by treatment throughout the study, while severity of bitter pit was greater in the last year of the study for fruit receiving KMag- relative to fruit receiving KCl. Occasionally, incidence or severity of water core was associated with treatments, as indicated by a higher incidence of water core for KMag- rather than K_2SO_4-treated fruit in 2001 and a greater severity of water core in all K-fertigated fruit in 2001 and for KMag (relative to K_2SO_4) fruit in 2002.

Table 4. Annual average ± standard error over all treatments for fruit characteristics unaffected by treatments for Jonagold on M.9 rootstock, 2000–2002

	Year		
Fruit characteristic (unit)	2000	2001	2002
Yield (kg/tree)	15.0 ± 1.0	9.6 ± 1.7	10.1 ± 1.0
Size (g fresh wt)	246 ± 9	335 ± 8	297 ± 9
Firmness (N)	64.1 ± 0.9	69.5 ± 1.3	69.0 ± 0.8
Red (% solid red)	57.0 ± 5.0	55.0 ± 5.0	60.0 ± 5.0
Titratable acidity (mg malic acid/100 mL juice)	790 ± 20	980 ± 40	610 ± 15

The lack of response of fruit production (size and yield) and the fruit quality parameters red colour and titratable acidity to K-fertigation treatments are consistent with adequate leaf and fruit K concentrations observed during the study, regardless of treatment. Thus, K-fertigation treatments were made in an experimental block sufficient in K. Increased yield, higher percent red colour and greater fruit acidity (TA) have been previously reported consequences of increasing K supply to K-deficient trees (Cummings 1985). A decrease in fruit SSC after application of K as K_2SO_4 when K nutrition was sufficient has previously been mea-

Table 5. Effect of K-fertigation treatment on fruit soluble solids and incidence and severity of bitter pit and water core at commercial harvest for Jonagold on M.9 rootstock, 2000–2002

	Soluble solids (%)			Bitter pit incidence[w]			Bitter pit severity[x]			Water Core incidence[w]			Water Core severity[x]		
Fertigation treatment	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
Control (no K)	14.2	15.2	15.6	0.08	0.15	0.17	0.61	1.06	0.67	0.17	0.22	0.15	1.06	0.67	0.92
KCl (15 g K/tree)	13.8	15.6	15.2	0.02	0.13	0.18	0.17	1.04	1.27	0.03	0.42	0.35	0.33	1.08	1.09
KCl (30 g K/tree)	14.0	15.5	15.0	0.05	0.05	0.18	0.50	0.42	0.50	0.03	0.40	0.22	0.33	1.22	1.03
KMag[z] (15 g K/tree)	14.0	15.4	15.2	0.08	0.10	0.27	0.38	1.22	1.62	0.12	0.37	0.30	0.83	1.11	0.83
KMag (30 g K/tree)	13.5	15.3	15.0	0.07	0.08	0.20	0.33	0.5	1.86	0.05	0.43	0.28	0.67	1.29	1.28
K_2SO_4 (30 g K/tree)	13.9	15.3	15.2	0.02	0.05	0.10	0.20	0.5	1.50	0.16	0.18	0.23	0.60	1.33	0.83
KTS[y] (30 g K/tree)	13.5	14.9	15.0	0.08	0.04	0.13	0.70	0.30	1.42	0.18	0.32	0.23	1.05	1.12	1.17
Selected contrasts															
Control vs. all	*	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
K-form	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Rate × Form	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
KMag vs. K_2SO_4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	*

[z]Potassium, magnesium sulphate.
[y]Potassium thiosulphate.
[w]Incidence ranges from none (0.00) to all sampled fruit (1.00) affected.
[x]Severity ranges from none (0) to slight (1), moderate (2) or severe (3).
Specified single degree of freedom contrasts, not significantly different (NS) or significant at the probability indicated as $P \leq 0.05$ (*).

sured for Conference and Doyenne du Comice pears in England (Johnson et al. 1998). Decreases in SSC as high as 0.6% were however not detectable in taste-panel assessments of those fruit. The decreased SSC observed in our apple study implied that K-application delayed maturity, but average starch values at harvest were unaffected (data not shown).

Bitter pit was economically the most important harvest disorder observed in this cultivar. It has been well established that bitter pit is a Ca-related disorder, which is effectively ameliorated by foliar Ca applications (Ferguson and Watkins 1989). The overriding nutritional characteristic of the Jonagold apples in the experiment was the low harvest fruit Ca concentrations regardless of treatment. Thus, large fruit size rather than fertigation of various K forms, was the most important factor in the commercially unacceptable high incidence and severity of bitter pit observed at harvest in this study. Nevertheless K application, regardless of form, increased the ratio of whole fruit K/Ca. Although no fruit storage studies were conducted on this fruit, this ratio has previously been positively correlated with an increased susceptibility of British Columbia fruit to subsequent development of storage disorders (Wolk et al. 1998). A high fruit K/Ca ratio has been identified as problematic in other fruit-growing regions with K/Ca ratios less than 28/1 recommended for Jonagold growing in Poland (Piestrzeniewicz and Tomala 2001) and less than 30–35/1 for Golden Delicious in northern Italy (Drahorad and Aichra 2001). The high K/Ca ratios of Jonagold fruit in our study, especially in 2001–2002, indicate that foliar application of Ca, regardless of treatment, would have been desirable. Furthermore, despite the unproved link between K application and bitter pit in this study, it would be prudent when fertigating K to also consider implementing a foliar Ca spray regime. This would be particularly relevant when K application rates exceed 30 g/tree, where Mg is also being applied, harvest fruit size is anticipated to be large and cultivars or sites are known to be susceptible to the development of bitter pit disorders at harvest. Since the development of water core shows little relationship with fruit Ca nutrition (Ferguson and Watkins 1989) and furthermore tends to decrease after fruit storage, Ca application is less important for this disorder.

CONCLUSIONS

The K status of this apple orchard on coarse-textured soil responded rapidly to K-fertigation, with increased leaf K concentration in the first year, increased fruit K concentrations by the second year, and increased soil K availability through the surface 30 cm depth after 3 yr. There were few differences among K-forms indicating a range of materials would be suitable fertigants for improving inadequate K-nutrition. Use of KMag was effective at increasing extractable soil Mg content, but relative effects on leaf Mg concentrations were slight, indicating the difficulties of ameliorating inadequate Mg via fertigation when co-applying K. Differential effects of treatments on leaf and fruit Ca concentrations were minimal. The sensitivity of the orchard production system to long-term disruption in Ca nutrition was indicated by a general decrease in soil Ca availability after fertigation of K, especially in association with Mg additions and low pH, and by increased whole fruit K/Ca ratios at harvest.

During the experimental period, leaf K and Mg concentrations were adequate, but fruit size was very large and fruit Ca concentrations inadequate for prevention of bitter pit over all treatments. Thus, for these Jonagold, the most effective production strategy would have been to make foliar applications of Ca and investigate fruit thinning strategies, such as king bloom removal and retention of more doubles, that might reduce fruit size without compromising regular, annual cropping. It was also apparent that fertigation of K, when Jonagold leaf K concentrations averaged 1.4 to 1.6%, as in this block, was not essential to optimum performance of these trees. Although K-fertigation had minimal effect on fruit Ca concentration relative to large fruit size, it nevertheless increased fruit K/Ca ratio, which has been associated with reduced fruit storage quality. Thus, application of significant amounts of K to coarse-textured soils, via irrigation water, when the K nutritional status of apple trees is unknown, should be accompanied by vigilance to ensure Ca concentration of harvested fruit is optimum.

Bramlage, W. J., Drake, M. and Lord, W. J. 1980. The influence of mineral nutrition and storage performance of pome fruits grown in North America, Pages 29–39 *in* D. Atkinson et al., eds. Mineral nutrition of fruit trees. Butterworths, London, UK.

British Columbia Ministry of Agriculture and Food. 1998. Tree fruit production guide for commercial growers. Interior districts 1998–99 edition. BC Ministry of Agriculture and Food, Victoria, BC. 170 pp.

Cummings, G. A. 1985. Potassium nutrition of deciduous and small fruits. Pages 1087–1104 *in* R. D. Munsen, ed. Potassium in agriculture. ASHS and SSSA, Madison, WI.

Drahorad, W. and Aichner, M. 2001. Development and evaluation of a bitter pit prognosis model in apple orchards in the south Tyrol (Northern Italy) Acta Hortic. **564**: 91–96.

Erani, P. R., Dias, J. and Flore, J. A. 2002. Annual additions of potassium to the soil increased apple yield in Brazil. Commun. Soil Sci. Plant Anal. **33**: 1291–1304.

Ferguson, I. B. and Watkins, C. B. 1989. Bitter pit in apple fruit. Hortic. Rev. **11**: 289–355.

Himelrick, D. G. and McDuffie, R. F. 1983. The calcium cycle: uptake and distribution in apple trees. HortScience **18**: 147–150.

Johnson , D. S., Samuelson, T. J., Pearson, K. and Taylor, J. 1998. Effects of soil applications of potassium sulphate on the mineral composition and eating quality of stored 'Conference' and 'Doyenne du Comice' pears. J. Hortic. Sci. **73**: 151–157.

Kalra, Y. P. and Maynard, D. G. 1991. Methods manual for forest soil and plant analysis. Information report Nor-x-319, Northern Forestry Centre, Edmonton, AB.

Klein, I. 1992. The effect of potassium applied by drip irrigation on the growth, fruit quality and storage of apples on a soil with marginal Mg content. Pot. Rev. Subject 19 No.1: 1–7.

Neilsen, G. H. and Neilsen, D. 2003. Nutritional requirements of apple. Pages 267–302 *in* D. C. Ferree and I. J. Warrington, eds. Apples: Botany, production and uses. CABI Publ., Oxford, UK.

Neilsen, G. H., Neilsen, D., Herbert, L. C. and Hogue, E. J. 2004. Response of apple to fertigation of N and K under conditions susceptible to the development of K deficiency. J. Am. Soc. Hortic. Sci. **129**: 26–31.

Neilsen, G. H., Parchomchuk, P., Berard, R. and Neilsen, D. 1997. Irrigation frequency and quantity affect root and top growth of fertigated 'McIntosh' apple on M.9, M.26 and M.7 rootstock. Can. J. Plant Sci. **77**: 133–139.

Neilsen, G. H., Parchomchuck, P., Meheriuk, M. and Neilsen, D. 1998. Development and correction of K deficiency in drip-irrigated apple. HortScience **33**: 258–261.

Neilsen, G. H., Parchomchuck, P., Neilsen, D. and Zebarth, B. J. 2000. Drip-fertigation of apple trees affects root distribution and development of K deficiency. Can. J. Soil Sci. **80**: 353–361.

Piestrzeniewicz, C. and Tomala, K. 2001. Some factors affecting the storage ability of 'Jonagold' apples. Acta Hortic. **564**: 435–442.

Quamme, H., Brownlee, R. T., Kappel, F., Geldhart, G., Sanders, M., Arndt, H., Watson, T. and Waterman, P. 1997. Evaluation of five apple training systems in the Okanagan Valley of British Columbia. Acta Hortic. **451**: 495–504.

Ross, G. J., Hoyt, P. B. and Neilsen, G. H. 1985. Soil chemical and mineralogic changes due to acidification in Okanagan apple orchards. Can. J. Soil Sci. **65**: 347–355.

SAS Institute, Inc. 1989. SAS/STAT user's guide. Version 6. Vol. 2. SAS Institute, Inc., Cary, NC.

Shear, C. B. and Faust, M. 1980. Nutritional ranges in deciduous tree fruits and nuts. Hortic. Rev. **2**: 142–163.

Uriu, K., Carlson, R. M., Henderson, D. W., Shulbach, H. and Aldrich, T. M. 1980. Potassium fertilization of prune trees under drip irrigation. J. Am. Soc. Hortic. Sci. **105**: 508–510.

Vang-Peterson, O. 1980. Calcium nutrition of apple trees: a review. Sci. Hortic. **12**: 1–9.

Wittneben, U. 1986. Soils of the Okanagan and Similkameen Valleys. Min. of Environment Technical Report 18. Report No. 52. British Columbia Survey, Victoria, BC.

Wolk, W. D., Lau, O. L., Neilsen, G. H. and Drought, B. G. 1998. Factors and time of sample collection for correlating storage potential of 'McIntosh', 'Spartan', and 'Golden Delicious' apple. J. Am. Soc. Hortic. Sci. **123**: 104–109.

Woodbridge, C. G. 1955. Magnesium deficiency in apple in British Columbia. Can. J. Agric. Sci. **35**: 350–357.