# Consequences of potassium, magnesium sulphate fertilization of high density Fuji apple orchards

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Neilsen, G. H. and Neilsen, D. 2011. **Consequences of potassium, magnesium sulphate fertilization of high density Fuji apple orchards**. Can. J. Soil Sci. **91**: 1013–1027. Three annual broadcast fertilizer treatments of 0, 100 or 200 kg K $ha^{-1}$ as K, Mg sulphate (KMag) were applied in a randomized complete block design with six replicate multi-tree plots. The study was undertaken for three successive growing seasons in eight commercial apple orchards of fruiting 'Fuji'/M.9 (*Malus* × *domestica* Borkh.) located on coarse-textured soils typical of the Okanagan valley fruit production region of southern British Columbia. After 3 yr, KMag fertilization increased the amount and proportion of exchangeable K and Mg at the 0–10 and 10–20 cm depth. Soil exchangeable Ca was generally decreased in the surface 0–10 cm layer although the Ca/Σ[Ca + Mg + K] ratio decreased over the surface 20 cm. During the study, application of KMag fertilizer often increased leaf and fruit K concentrations, minimally affected leaf Mg and sometimes decreased fruit Ca concentration by years 2 and 3 and had little effect on fruit K/Ca or Mg/Ca ratio. KMag fertilization was effective in an orchard of marginal K nutritional status, increasing cumulative yield, fruit size and red colouration, implying an economic response to the K contained in the fertilizer. KMag fertilization was effective for maintaining leaf Mg concentration, but could not be relied upon to increase deficient leaf Mg. There were no widespread declines in fruit Ca concentration, nor increases in Ca-related harvest disorders after 3 yr of KMag fertilization, despite declines in exchangeable Ca and Ca/Σ[Ca + Mg + K] in surface soil layers.

**Key words:** Potassium, magnesium sulphate, fruit quality, leaf and soil Ca, Mg and K, yield

Neilsen, G. H. et Neilsen, D. 2011. **Conséquences de la bonification des vergers de pommes Fuji à forte densité avec du sulfate de potassium et de magnésium**. Can. J. Soil Sci. **91**: 1013–1027. Les auteurs ont épandu à la volée 0, 100 ou 200 kg de K par hectare sous forme de sulfate de potassium et de magnésium (KMag) sur six parcelles comptant de nombreux arbres dans le cadre d'une expérience en blocs aléatoires complets. L'étude s'est poursuivie pendant trois périodes végétatives successives, dans huit vergers commerciaux de pommiers Fuji/M.9 (*Malus* × *domestica* Borkh.) poussant sur un sol à texture grossière typique de la vallée de l'Okanagan, région de fruiticulture du sud de la Colombie-Britannique. Après trois ans, l'amendement KMag avait augmenté la quantité et la proportion d'ions K et Mg échangeables dans le sol, aux profondeurs de 0 à 10 et de 10 à 20 cm. En général, la concentration d'ions Ca échangeables était plus faible dans la couche superficielle de 0 à 10 cm de profondeur, bien que le rapport Ca/Σ[Ca + Mg + K] ait diminué dans les 20 premiers centimètres de profondeur. Durant l'étude, l'application de KMag a souvent accru la concentration de K dans les feuilles et le fruit, n'a eu qu'une incidence minime sur la concentration foliaire de Mg, a parfois diminué la concentration de Ca dans le fruit au bout de deux ou trois ans et n'a pas vraiment modifié les rapports K/Ca ou Mg/Ca dans le fruit. L'amendement KMag a donné de bons résultats dans un verger dont le bilan K était marginal, ce qui a permis d'accroître le rendement fruitier cumulatif, le calibre des fruits et la coloration rouge, signes que la culture a réagi au K que renfermait l'engrais. La bonification du sol avec du KMag a permis de maintenir la concentration foliaire de Mg, mais on n'a pu se fier sur ce traitement pour remédier à la carence de Mg dans les feuilles. Aucune diminution générale de la concentration de Ca dans le fruit ni de hausse des problèmes associés au Ca à la récolte n'ont été relevées après les trois années de fertilisation au KMag, et ce malgré la concentration plus faible d'ions Ca échangeables et la diminution du rapport Ca/Σ[Ca + Mg + K] dans les couches superficielles du sol.

**Mots clés:** Potassium, sulfate de magnésium, qualité des fruits, concentration de Ca dans les feuilles et le sol, Mg et K, rendement

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Nutritional issues concerning more than a single nutrient can be of concern in orchard nutrition, even though much research focuses on tree fruit nutrition from the viewpoint of individual nutrients (Faust 1979). The balance of Ca, Mg and K is of particular concern in apple tree nutrition because of the long-established and critical importance of Ca in optimizing fruit quality (Faust 1989) and its close association with fruit disorders, such as bitter pit, which have been identified as expressions of Ca deficiency (Ferguson and Watkins 1989). Potentially adverse effects of excessive Mg and especially K availability relative to Ca have been identified as threats to the accumulation of sufficient Ca to optimize fruit quality (Vang-Petersen 1980).

Distinguishing the nature of such excesses is of particular importance in many fruit-growing regions due to the recognition that cation imbalances can

**Abbreviations:** **KMag**, potassium magnesium sulphate; **TA**, titratable acidity

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adversely impact Ca cycling in the orchard (Himelrick and McDuffie 1983). In regions such as the Okanagan, both Mg-deficiency on susceptible cultivars (Woodbridge 1955) and K-deficiency on NP-fertigated high-density apple orchards undergoing drip-irrigation have been reported (Neilsen et al. 2004). Furthermore, worldwide, many orchard soils are sandy loams, loamy sands or sands of inherently low nutrient and water-holding capacity with susceptibility to leaching of the base nutrients Ca, Mg and K, especially when drip-fertigating with $NH_4$-N fertilizers (Haynes and Swift 1987). Drip fertigation of most soluble forms of K can increase tree K uptake, but effects on Ca and Mg nutrition were ambiguous (Neilsen and Neilsen 2006). In Brazil, 12 yr of broadcast application of K in an apple orchard decreased Mehlich-I extractable Ca but not Mg in the 0–30 cm soil layer but tree response was not measured (Nachtigall et al. 2007).

There has been limited research on the use of potassium, magnesium sulphate (KMag) as a nutrient source for horticultural crops, despite its potential to supply both K and Mg (Davenport and Bentley 2001). Fertigating KMag can increase soil Mg in a narrow soil volume directly beneath drip emitters, but has minimal effects on leaf and fruit Mg concentrations in a 'Jonagold'/M.9 orchard (Neilsen and Neilsen 2006). There are no comparable data for broadcast application of KMag where a more extensive proportion of the root zone would be expected to be influenced when fertilizer delivery does not depend upon water application from a point source.

For these reasons, broadcast KMag fertilizer trials were established to determine the effects of KMag application on Ca, Mg and K availability in orchard soils, leaves and fruit while monitoring yield and fruit quality performance. Eight, high density, sprinkler-irrigated 'Fuji' apple orchards on dwarfing rootstocks with historically low Mg and K contents were used as experimental sites over a 3 yr period.

## MATERIALS AND METHODS

In 2000, the fertilization treatments were initiated in the 'Fuji' apple (*Malus* × *domestica* Borkh.) orchards (Table 1). The orchards chosen were selected from an initial list of 44 orchards provided by local district packing house personnel based on historical composite leaf samples with low leaf K and Mg and poor yield performance. Selection of the orchards based on these criteria precluded the use of techniques such as the diagnosis and recommendation integrated system (Walworth and Sumner 1987) or compositional nutrient diagnosis (Parent and Dafir 1992), which are based upon the establishment of reference norms of a representative range of high-yielding individuals.

The eight 'Fuji' orchards in the fertilizer study were located throughout the apple-growing region of the Okanagan Valley from Osoyoos to Vernon (Fig. 1). Orchard soils were representative of the two-thirds of

**Table 1. Characteristics of 'Fuji' apple orchards involved in potassium, magnesium sulphate (KMag) fertilization trial between the 2000 and 2002 growing seasons across the Okanagan Valley**

| Site/orchard/region | Soil series | Rootstock | Tree spacing (m) | Planting density (trees $ha^{-1}$) | Measurement trees per rep. | Irrigation system | Commercial harvest date | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 2000 | 2001 | 2002 |
| 1. Gill/Osoyoos | Osoyoos loamy sand | M.9 | 1.8 × 4.3 | 1292 | 3 | Under tree sprinkler | 17 Oct. | 19 Oct. | 21 Oct. |
| 2. Klatt/Oliver | Skaha gravelly sandy loam | M.9 | 1.1 × 3.5 | 2597 | 5 | Mini-sprinkler | 17 Oct. | NS[z] | 18 Oct. |
| 3. Marshall/Vernon | Nahun gravelly sandy loam | M.9 & O.3 | 1.0 × 4.0 | 2500 | 5 | Mini-sprinkler | 20 Oct. | 26 Oct. | 24 Oct. |
| 4. Kopje/Kelowna | Osoyoos loamy sand | M.9 | 1.5 × 3.6 | 1852 | 6 | Microjet sprinkler | 18 Oct. | 24 Oct. | 17 Oct. |
| 5. Sunrise/Penticton | Osoyoos sandy loam | M.9 | 1.3 × 3.0 | 2564 | 3 | Overhead sprinkler | 13 Oct. | NS | NS |
| 6. Kiran/Kelowna | Osoyoos sandy loam | M.9 | 1.5 × 3.7 | 1802 | 3 | Microjet sprinkler | 18 Oct. | 25 Oct. | 16 Oct. |
| 7. Stearns/Kelowna | Osoyoos sandy loam | M.9 | 1.2 × 3.6 | 2315 | 3 | Overhead sprinkler | 19 Oct. | NS | 17 Oct. |
| 8. Golf Club/Kelowna | Osoyoos sandy loam | M.9 | 1.5 × 3.4 | 1961 | 3 | Under tree sprinkler | 24 Oct. | 24 Oct. | 24 Oct. |

[z]No samples collected due to early harvest by grower.

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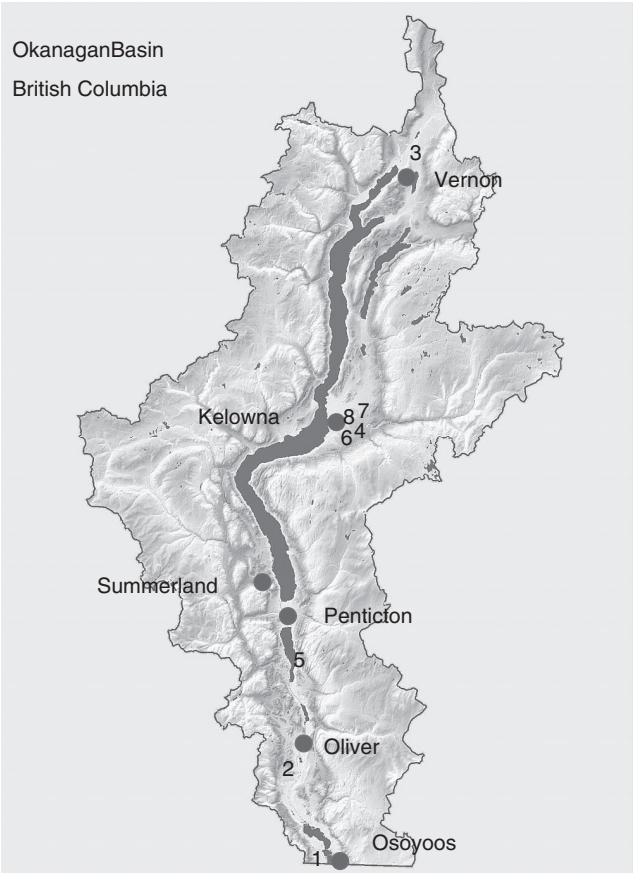


**Fig. 1.** Location of experimental orchards (1–8) within the Okanagan valley fruit growing region.

orchards in the fruit-growing area of southern interior British Columbia that are located on soils composed of more than 50% sand sized particles. The experimental sites were located on soil series that have been extensively planted to orchard or vineyards throughout the Okanagan valley. Osoyoos and Skaha soils are Orthic Brown Chernozems (Wittneben 1986) and the Nahun soil near Vernon, an Orthic Black Chernozem (Kelley and Spilsbury 1949) (Table 1). All locations had low to moderate water-holding capacity and generally low natural fertility coinciding with their coarse texture. Orchards were planted at high density (about 1300–2600 trees $ha^{-1}$) on the dwarfing M.9 rootstock. Orchard 3 also contained some similar dwarfing O.3 rootstock. All monitored orchards received some form of sprinkler irrigation, which wets a higher proportion of the orchard floor than drip-irrigation, and is currently practiced on 54% of apple orchards in the region.

Fertilizers were applied annually, in 2000, 2001 and 2002, in a randomized complete block design with six replicate, multi-tree plots, containing three to six measurement trees. Experimental plot layout was adapted to the shape of the available orchard block, but was always rectangular, occupying from two (three reps per row) to six (one rep per row) orchard rows. Every plot contained a guard tree at each end, resulting in plot separation by two trees within the tree row since adjacent plots within each row bordered on each other. Trees were between 5 and 10 yr of age and were producing fruit. Potassium, magnesium sulphate fertilizer (0N-0P-22K-11Mg-22S) treatments included application of 0, 100 and 200 kg K treated $ha^{-1}$ $yr^{-1}$. KMag fertilizers supplied by IMC Kalium (Bannocburn, IL) were uniformly applied to the soil surface in a 2-m-wide strip (approximately the herbicide application zone) centred on the tree row. Annual applications were made in June 2000 and subsequently in 2001 and 2002 in April prior to bloom. All plots were assumed to receive the same rate of N, as applied throughout the block by the co-operating orchardist, following commercial recommendations of approximately 100 kg N $ha^{-1}$ $yr^{-1}$ as urea (46N 0P 0K) or ammonium nitrate (34N 0P 0K) [British Columbia Ministry of Agriculture and Land (BCMAL) 2007].

Trees were trained and pruned to slender spindle, supported by posts (and sometimes wire). Micronutrient applications and insect and disease control treatments were made by the co-operating orchardist and followed standard commercial recommendations (BCMAL 2007). Recommended micronutrient applications included bloom-time foliar B sprays or late summer soil B applications and Zn sulphate sprays during late dormancy to maintain leaf B and Zn concentrations. Occasional general micronutrient sprays containing small quantities of Fe, Mn and Zn were made with insect and disease control sprays in May–June in some orchards. Irrigation, required in the region, was applied by sprinkler systems located to optimize soil water content within the 2-m herbicide strips centered on the tree rows (Table 1).

Composite samples of 30 leaves from the mid portion of extension shoots of the current year's growth from the three to six trees in every plot from all orchards were collected in early August 2000, and the last 2 wk of July in 2001 and 2002. All samples were oven-dried at 65°C and dissolved in 0.5 M HCl for determination of Ca, Mg and K by atomic absorption spectrophotometry. Leaf cation ratios (e.g., Ca:Mg) were subsequently calculated as the dimensionless ratio of concentrations expressed on a dry weight basis. Leaf nutrients other than Ca, Mg and K including N, P, S, Zn, Fe, Mn, and Cu, analyzed as previously described (Neilsen et al. 1997), were within or above the adequate range for all sites, but showed large differences from site to site for all nutrients except S and Cu (data not shown). In midsummer of the concluding year of the study (2002), composite soil samples were collected from each treatment and replicate at 0–10, 10–20 and 20–30 cm depth for each orchard. Each composite was composed of three samples collected from the tree row midway between the central measurement trees of each plot. Compacted, gravel subsoils

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prevented the collection of sample at 20–30 cm depth for orchards 2 and 4. Soil samples were oven dried at 50°C prior to determination of Ca, Mg and K via atomic absorption spectrophotometry after extraction with 1 M. $NH_4OAc$ [5 g:25 mL; soil:solution ratio (Hendershot et al. (1993)]. Cation values were calculated as cmol (+) $kg^{-1}$ soil dry weight or as their respective ratio of total Ca + Mg + K (eg. Ca/Σ[Ca + Mg + K].

Each year, immediately prior to grower fruit harvest in each commercial orchard, a randomly selected 30-apple sample from each plot was collected for fruit quality and mineral analyses. The remaining fruit not harvested in each plot were counted and using the average fruit weight calculated from the 30-fruit sample, yield was calculated for each plot as the product of average fruit weight and the number of remaining fruit plus total weight of the 30-fruit sample, expressed on a per-tree basis. Earlier than expected grower harvests precluded fruit sampling in orchard 2 and 7 in 2001 and orchard 5 in 2001–2002.

A randomly selected 10-apple sub-sample from the original 30-fruit sample was assessed for fruit quality characteristics. Percent solid red skin colour was estimated visually to the nearest 5%. Flesh firmness was determined with a Baullof penetrometer (11.1-mm-diameter tip). Juice was obtained from sectors taken from each subsample apple prior to measurement of soluble solids concentration and titratable acidity (TA) by titration of juice with 0.1 M NaOH to an 8.1 pH end point. The incidence and severity of the fruit disorders bitter pit and watercore were also determined on each sub-sample fruit. Bitter pit was classified as slight (one or two areas up to 2 cm width), moderate (less than one-third of the cortex) or severe (more than one-third of the cortex affected). Watercore was also assessed as slight (small areas around the seed cavity and vascular bundles), moderate (<25% of cortex) or severe (>25% of cortex).

The remaining fruit ($n = 20$) from each treatment and replicate were washed under running distilled water and air-dried in preparation for mineral analyses. Stem tissues and seeds were removed and opposite unpeeled quarters were blended with 1.5 times their weight of distilled water. A 150-mL sub-sample was homogenized with a high-speed tissue homogenizer. A weighed 9-mL sub-sample of this slurry was digested in 5.4 mL of concentrated $H_2SO_4$ containing 1.8 g $Na_2SO_4$, 0.36 mL 25% $CuSO_4$ solution and 0.67 g $L^{-1}$ of Se at 350 C for 1 h. Calcium, Mg and K were determined in these extracts via atomic absorption spectrophotometry. Fruit cation ratios (e.g., Ca:Mg) were subsequently calculated as the dimensionless ratio of concentrations expressed on a fresh weight basis.

Analysis of variance (ANOVA) was conducted on all leaf and fruit data by repeated measures over time (3 yr) using a randomized, complete block design at each site with six replicates (SAS Institute, Inc. 1989). Fixed effects included sites and soil depth and random effects replicates and years. Soil measurements, which were made only once in 2002, were not analyzed over years. Date (year) was highly significant ($P < 0.0001$) for 58 of the 60 variables analyzed by year, dominating any significant effects of treatment or interaction between treatment and date ($P < 0.05$, 7 of 60 occurrences). Thus the data are presented separately by year in order to illustrate the annual variation in variables from year to year. The implications of seasonal variation are subsequently discussed in detail for the key fruit quality variable Ca concentration. Data were also analyzed and presented separately by site due to site × treatment interactions, a consequence of the range of geographic location and different soils among orchards. Site crop load variation also occurred due to inconsistent fruit thinning and variable cropping among orchards from year to year so that orchards deviated from ideal 5 to 7 fruit $cm^{-2}$ per trunk cross sectional area ratios with the average of annual means ranging from 1.9 to 8.2 fruit $cm^{-2}$. The study period was generally much warmer than the long-term normal (Table 2) but not in all months. However, there was a consistent pattern of colder temperatures in the north (Vernon). Such differences in seasonal degree day accumulation spatially contributed to large variation in production among orchards. Fruit data, when expressed as a proportion, were arcsine transformed prior to ANOVA. Linear (L) and quadratic (Q) effects of KMag rate were determined using contrast statements.

**Table 2. Mean monthly temperature of most northern (orchard 3, Vernon) and southern (orchard 1, Osoyoos) orchards during the study period, 2000–2002 compared with the 30-yr normal (1971–2000)**

| | | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Year | *Mean temperature (°C)* | | | | | | | | | | | |
| Vernon | 2000 | −3.6 | 1.1 | 4.2 | 9.2 | 9.8 | 14.2 | 19.0 | 21.6 | 14.5 | 7.8 | 0.6 | −4.5 |
| | 2001 | −2.7 | −2.4 | 4.1 | 8.1 | 13.6 | 14.9 | 19.7 | 20.1 | 15.5 | 6.5 | 5.9 | −2.1 |
| | 2002 | −2.0 | −0.5 | 0.1 | 8.4 | 11.6 | 18.1 | 20.8 | 19.0 | 14.8 | 6.9 | 2.9 | 0.8 |
| | 1971–2000 | −5 | −2 | 3.3 | 8.4 | 12.8 | 16.4 | 19.1 | 18.7 | 13.7 | 7.3 | 0.6 | −4.1 |
| Osoyoos | 2000 | −1.4 | 1.5 | 6.9 | 12.0 | 14.5 | 19.2 | 22.5 | 22.0 | 16.0 | 9.8 | 2.0 | −2.6 |
| | 2001 | −0.2 | 0.4 | 6.0 | 10.0 | 16.5 | 17.8 | 23.0 | 23.4 | 18.4 | 9.0 | 6.1 | 0.9 |
| | 2002 | 0.6 | 2.3 | 3.0 | 10.8 | 14.3 | 20.6 | 24.0 | 21.9 | 17.1 | 8.8 | 4.9 | 3.5 |
| | 1971–2000 | −2.5 | 0.2 | 4.7 | 9 | 13.6 | 17.4 | 20.5 | 20.2 | 15 | 8.8 | 2.4 | −1.9 |

## RESULTS

### Potassium

After 3 yr of annual differential KMag fertilization, soil-exchangeable K was linearly increased in response to application rate at both the 0–10 and 10–20 cm depths in all eight orchards (Fig. 2). The results were the same whether expressed as concentrations or $K/\Sigma[Ca+Mg+K]$ (data not shown). Maximum soil exchangeable K values were measured in the surface (0–10 cm) soil layer for the control plots for all sites except orchard 7. Significantly increased soil exchangeable K after KMag fertilization was measured regardless of the initial K-status of the soil, which ranged in the surface of the control treatment from $<0.20$ cmol (+) $kg^{-1}$ ($K/\Sigma[Ca+Mg+K]$ averaging 0.05) in orchards 1 and 5 to highest values exceeding 0.50 cmol (+) $kg^{-1}$ in orchards 6, 7 and 8 in the Kelowna region where $K/\Sigma[Ca+Mg+K]$ averaged 0.13. There was a limited effect of KMag fertilization below 20 cm depth as only orchard 5 had increased soil exchangeable K and soil $K/\Sigma[Ca+Mg+K]$ with fertilization. Two orchards (2 and 4) had extremely rocky subsoils, which precluded soil

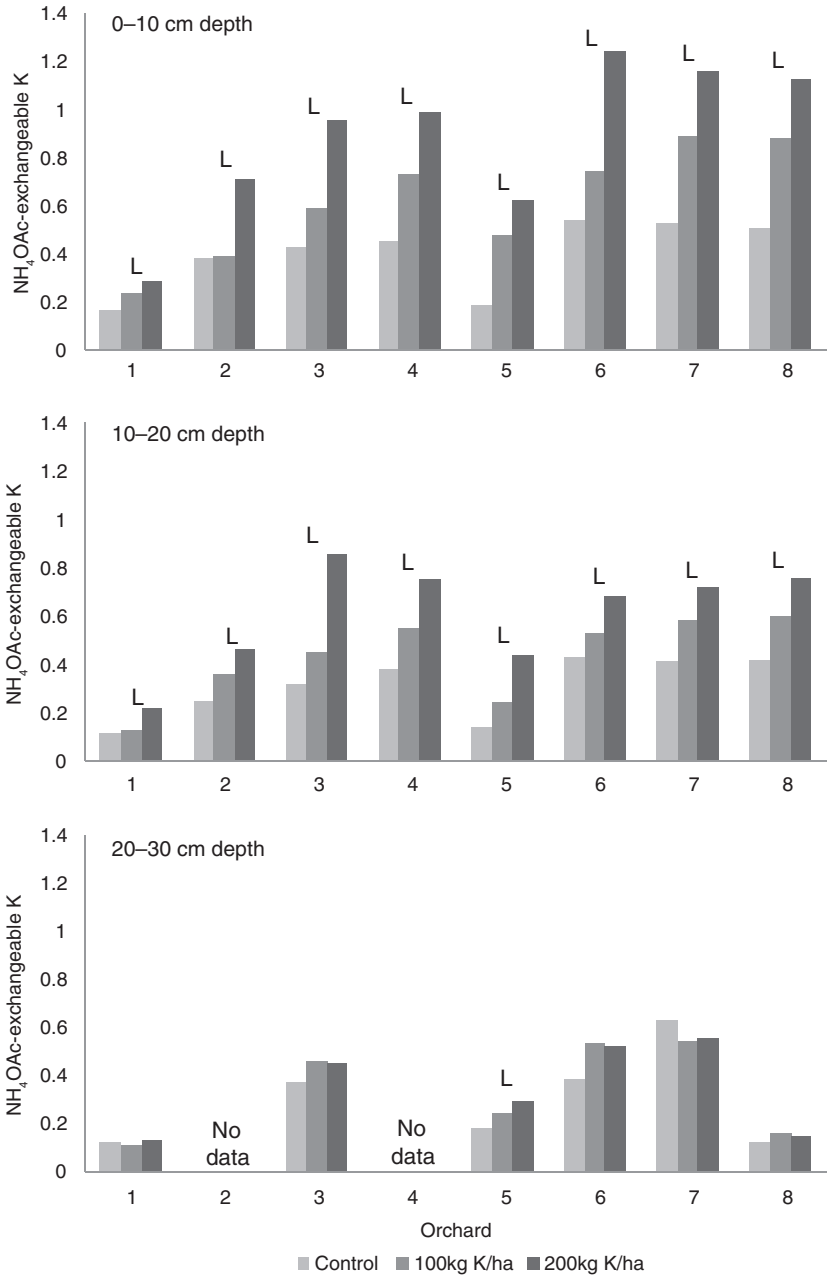


**Fig. 2a.**

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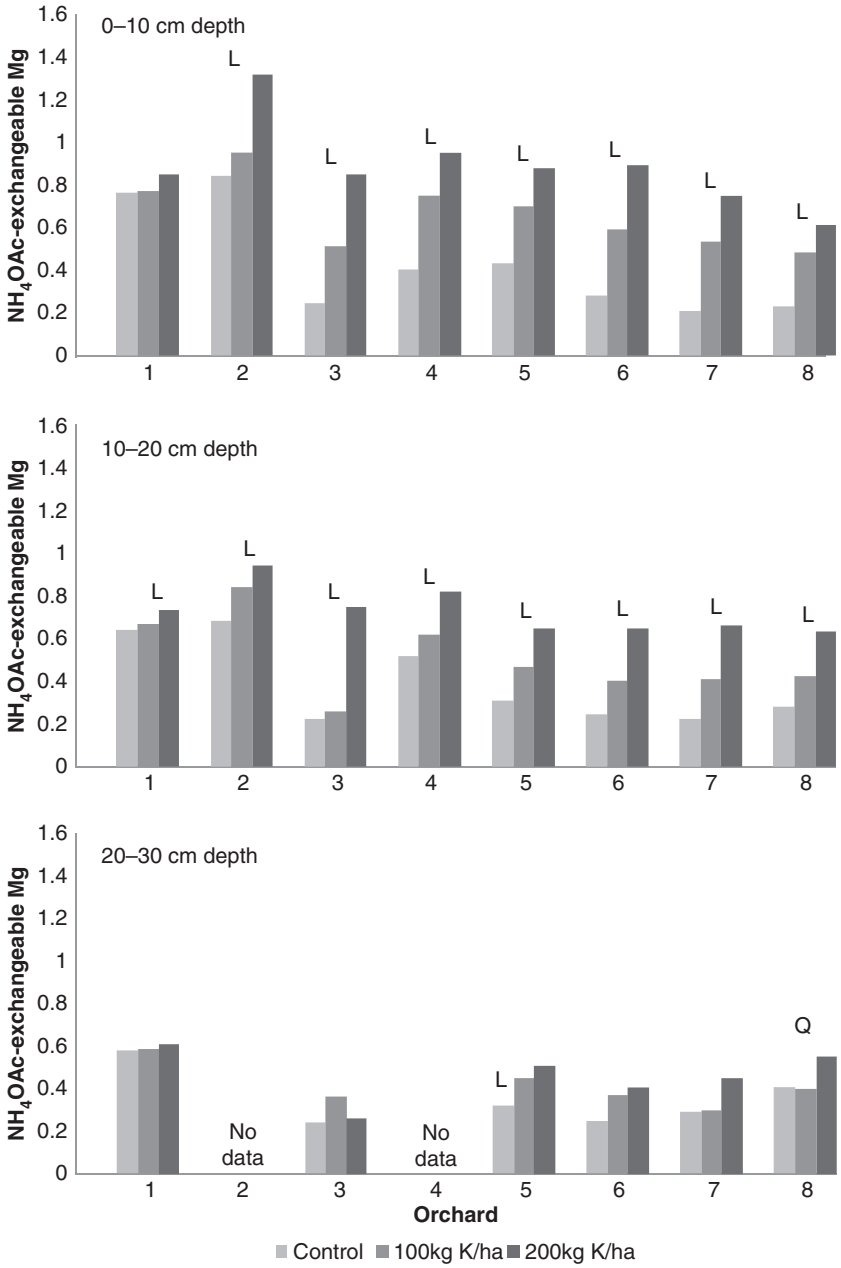


**Fig. 2.** Soil $NH_4OAc$-exchangeable K (cmol (+) $kg^{-1}$) as measured at 0–10, 10–20 and 20–30 cm depth for 'Fuji' apple orchards after application of 0, 100 and 200 kg K/treated ha as potassium, magnesium sulphate (KMag), applied annually 2000 to 2002. Significant linear (L) responses to fertilizer application rate are at $P < 0.05$.

sampling at this depth and appeared to severely limit root penetration.

Leaf and fruit K concentrations exhibited a range of values which varied across orchards, years and treatments (Table 3). Near deficient (<13 mg $kg^{-1}$ DW; Shear and Faust 1980) leaf K concentrations were observed in trees not receiving KMag applications (control treatments) in orchard 1 (2001–2002), 5 (2000), 6 (2000, 2002) and 7 (2000). These orchards were also characterized by very low fruit K concentrations near or below 1 g K $kg^{-1}$ FW. Leaf and fruit K was affected by KMag fertilization, with linear or quadratic increase ($P < 0.10$) in response to application rate in 11 of 24 orchard-years and in 7 of 20 orchard-years, respectively (Table 4). Some significant increases were measured in year 1, although increases were more frequent in years 2 and 3.

## Magnesium

Cumulative application of KMag for 3 yr also generally increased the availability of soil exchangeable Mg

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**Table 3. Mid-terminal leaf K and harvest fruit K concentrations as affected by annual application of 0, 100 and 200 kg K ha$^{-1}$ as potassium, magnesium sulphate (KMag) between 2000 and 2002**

| | | Leaf K (g kg$^{-1}$) | | | | Fruit K (g kg$^{-1}$ FW) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Orchard | Year | 0 | 100 | 200 | Signif.[z] | 0 | 100 | 200 | Signif.[z] |
| 1 | 2000 | 13.5 | 13.1 | 14.0 | 0.50 | 1.03 | 1.02 | 1.05 | 0.52 |
| | 2001 | 11.9 | 13.0 | 13.5 | 0.01 | 1.05 | 1.11 | 1.11 | 0.25 |
| | 2002 | 12.0 | 13.6 | 15.2 | 0.0001 | 1.18 | 1.17 | 1.21 | 0.47 |
| 2 | 2000 | 15.1 | 16.3 | 16.0 | 0.18 | 1.05 | 1.07 | 1.06 | 0.84 |
| | 2001 | 16.2 | 17.3 | 17.8 | 0.005 | ND[y] | ND | ND | |
| | 2002 | 17.1 | 18.3 | 18.9 | 0.02 | 1.15 | 1.21 | 1.18 | 0.34 |
| 3 | 2000 | 15.3 | 14.7 | 14.8 | 0.28 | 1.16 | 1.12 | 1.14 | 0.58 |
| | 2001 | 13.4 | 14.0 | 13.9 | 0.11 | 1.24 | 1.21 | 1.31 | 0.25 |
| | 2002 | 16.0 | 16.6 | 16.2 | 0.73 | 1.10 | 1.18 | 1.23 | 0.01 |
| 4 | 2000 | 13.4 | 14.9 | 14.4 | Q 0.03 | 1.16 | 1.26 | 1.22 | 0.24 |
| | 2001 | 13.6 | 15.4 | 16.9 | 0.0001 | 1.23 | 1.33 | 1.43 | 0.0001 |
| | 2002 | 15.4 | 16.8 | 17.5 | 0.0006 | 1.11 | 1.17 | 1.21 | 0.01 |
| 5 | 2000 | 11.5 | 12.6 | 13.0 | 0.12 | 1.03 | 1.07 | 1.17 | 0.03 |
| | 2001 | 13.8 | 16.9 | 17.1 | 0.001 | ND | ND | ND | |
| | 2002 | 15.4 | 14.6 | 13.8 | 0.31 | ND | ND | ND | |
| 6 | 2000 | 12.1 | 11.8 | 12.0 | 0.82 | 1.06 | 1.07 | 1.09 | 0.33 |
| | 2001 | 13.7 | 13.6 | 14.4 | 0.19 | 1.08 | 1.09 | 1.15 | 0.20 |
| | 2002 | 12.9 | 14.2 | 14.3 | 0.02 | 1.01 | 0.98 | 1.12 | Q 0.04 |
| 7 | 2000 | 11.3 | 11.3 | 11.5 | 0.69 | 0.90 | 0.93 | 0.92 | 0.34 |
| | 2001 | 14.2 | 15.1 | 15.2 | 0.004 | ND | ND | ND | |
| | 2002 | 13.5 | 14.5 | 14.2 | 0.13 | 0.92 | 1.02 | 1.03 | 0.01 |
| 8 | 2000 | 13.0 | 14.1 | 14.5 | 0.11 | 1.04 | 1.06 | 1.03 | 0.73 |
| | 2001 | 17.2 | 18.8 | 17.6 | 0.76 | 1.56 | 1.71 | 1.71 | 0.09 |
| | 2002 | 14.4 | 15.7 | 16.2 | 0.06 | 1.16 | 1.20 | 1.26 | 0.11 |

[z]Linear response otherwise quadratic (Q) response with K rate at probability level indicated.
[y]Not determined (ND) due to no fruit sample.

**Table 4. Annual and cumulative number of total sampled sites where leaf and fruit Ca, Mg and K concentrations were increased (+) or decreased (−) by KMag fertilization at $P < 0.1$**

| Nutrient parameter | Year 1 | Year 2 | Year 3 | Cumulatively |
|---|---|---|---|---|
| Leaf Ca | 2/8 | 6/8 (−) | 6/8 (−) | 14/24 (−) |
| Leaf Mg | 1/8 (−) | 1/8 (−) | 1/8 (−) | 3/24 (−) |
| Leaf K | 1/8 (+) | 5/8 (+) | 5/8 (+) | 11/24 (+) |
| Fruit Ca | 0/8 | 0/5 | 3/7 (−) | 3/20 (−) |
| Fruit Mg | 2/8 | 0/5 | 3/7 (+) | 5/20 (+) |
| Fruit K | 1/8 (+) | 2/5 (+) | 4/7 (+) | 7/20 (+) |

(Fig. 3) or the Mg/Σ[Ca + Mg + K] (data not shown) over both the 0–10 and 10–20 cm depths. In the surface 0–10 cm depth, only orchard 1 failed to exhibit increased soil exchangeable Mg with increasing KMag fertilization rate (Fig. 3). However, a significant increase in orchard 1 was observed when values were expressed as Mg ratio (increasing from 0.21 to 0.25 Mg/Σ[Ca + Mg + K]). Maximum profile soil exchangeable Mg values were usually (five of eight orchards) observed in the surface layer with higher soil exchangeable Mg at the greater depth in orchards 4, 7 and 8. There was a range in soil exchangeable Mg status in the surface soils of the controls with relatively low values (<0.25 cmol (+) kg$^{-1}$; Mg/Σ[Ca + Mg + K] <0.06) for orchards 3, 7 and 8 and much higher values (>0.75 cmol (+) kg$^{-1}$; Mg/Σ[Ca + Mg + K] >0.10) for orchards 1 and 2. There was little effect of KMag fertilization on the Mg status of the 20–30 cm depth, but soil exchangeable Mg was highest at the maximum rate of KMag fertilization in orchards 5 and 8. The soil Mg/Σ[Ca + Mg + K] ratio was highest at the highest KMag application rate in both these orchards.

Leaf Mg concentrations were minimally affected by KMag fertilization and on the rare occasion (3 of 24 orchard-years) when statistical differences ($P < 0.05$) were measured, they were associated with decreases in Mg as application rate of KMag increased (Tables 4 and 5). Inadequate leaf Mg concentrations (below 2.0 g kg$^{-1}$; Shear and Faust 1980) were measured at one point in orchards 2, 3 and 7 in control treatments but KMag fertilization failed to improve leaf Mg concentration in these orchards. Fruit Mg concentrations were infrequently affected by KMag fertilization in the first 2 yr, but by the third year (2002) significant linear or quadratic increases in fruit Mg concentrations occurred in three of seven orchards (Table 5). None of these final year increases was associated with inadequate leaf Mg concentrations in control trees.

## Calcium

Soil exchangeable Ca tended to decline at increased rate of KMag fertilization (Fig. 4). Decreases in soil Ca concentration occurred in six orchards at 0–10 cm,

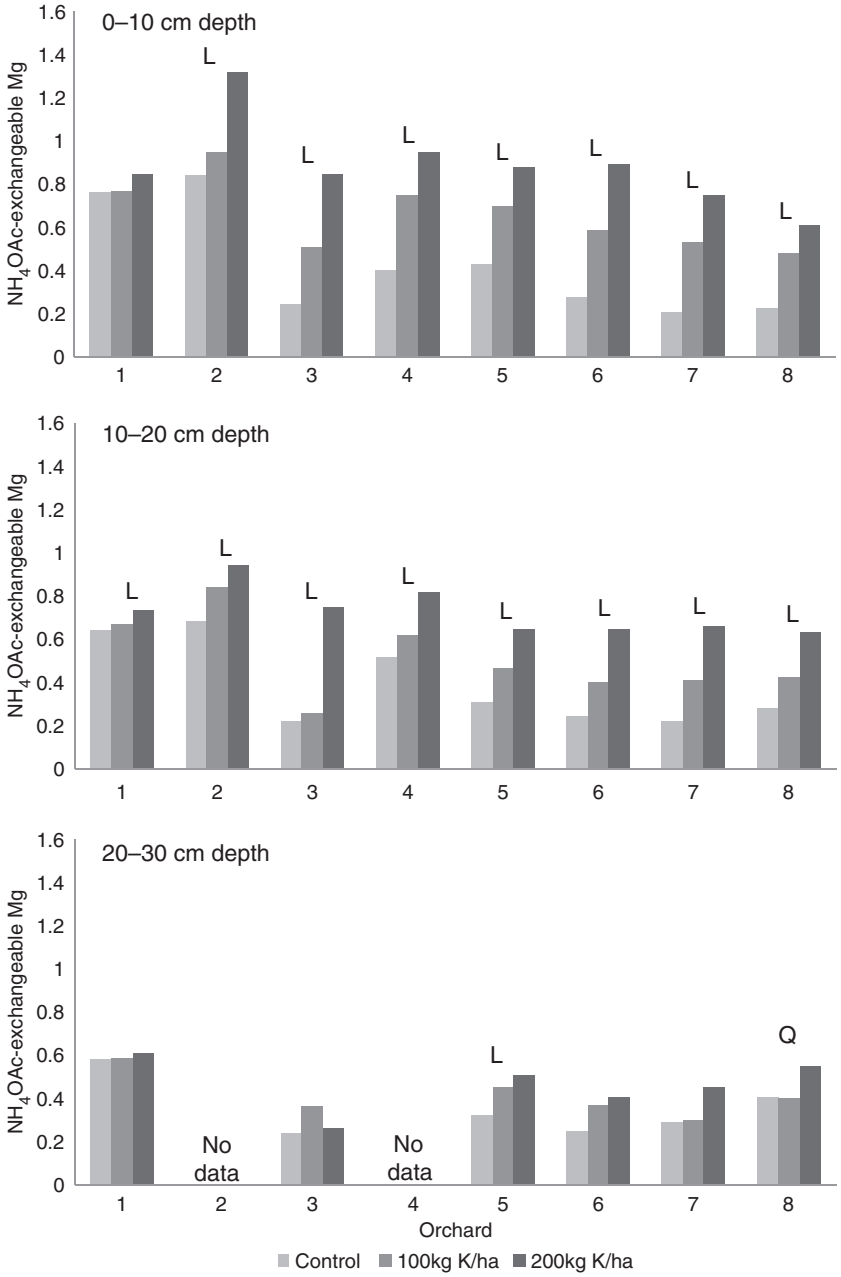


**Fig. 3.** Soil $NH_4OAc$-exchangeable Mg (cmol (+) $kg^{-1}$) as measured at 0–10, 10–20 and 20–30 cm depth for 'Fuji' apple orchards after application of 0, 100 and 200 kg K/treated ha as potassium, magnesium sulphate (KMag), applied annually 2000–2002. Significant linear (L) or quadratic (Q) responses to fertilizer application rate are at $P < 0.05$.

three orchards at 10–20 cm and none of the orchards at 20–30 cm. Decreased soil exchangeable Ca in response to KMag application was more apparent when expressed as $Ca/\Sigma[Ca + Mg + K]$ which decreased for all orchards at the 0–10 and 10–20 cm depths and for orchard 5 at the 20–30 cm depth (Fig. 5). Decreases in soil exchangeable Ca at the 0–10 cm depth were observed over a wide range of Ca content including orchards with highest (orchard 2) or lowest values (orchard 8).

Leaf and fruit Ca concentrations, if significantly affected by KMag fertilization (in 17 of 44 orchard-years), decreased as application rate increased (Table 6). The year-to-year variation in Ca concentrations exceeded differences among treatments within years. Decreased leaf Ca was frequent after year 2 and decreased fruit Ca (three orchards) was more common in year 3 (Table 6). Fruit Ca concentrations were generally adequate with low values ($< 0.040$ g Ca $kg^{-1}$

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**Table 5. Mid-terminal leaf Mg and harvest fruit Mg concentrations as affected by annual application of 0, 100 and 200 kg K ha$^{-1}$ as potassium, magnesium sulphate (KMag) between 2000 and 2002**

| | | Leaf Mg (g kg$^{-1}$) | | | | Fruit Mg (g kg$^{-1}$ FW) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Orchard | Year | 0 | 100 | 200 | Signif.[z] | 0 | 100 | 200 | Signif.[z] |
| 1 | 2000 | 3.2 | 3.2 | 3.2 | 0.77 | 0.044 | 0.043 | 0.044 | 0.67 |
| | 2001 | 3.5 | 3.4 | 3.3 | 0.21 | 0.045 | 0.045 | 0.046 | 0.77 |
| | 2002 | 3.5 | 3.2 | 3.2 | 0.002 | 0.041 | 0.040 | 0.041 | 0.62 |
| 2 | 2000 | 1.6 | 1.6 | 1.6 | 0.69 | 0.041 | 0.042 | 0.040 | 0.60 |
| | 2001 | 1.8 | 1.7 | 1.6 | 0.30 | ND[y] | ND | ND | |
| | 2002 | 2.4 | 2.4 | 2.3 | 0.47 | 0.039 | 0.040 | 0.039 | 0.61 |
| 3 | 2000 | 2.3 | 2.3 | 2.2 | 0.78 | 0.046 | 0.046 | 0.047 | 0.44 |
| | 2001 | 1.9 | 1.9 | 1.9 | 1.00 | 0.046 | 0.045 | 0.046 | 1.00 |
| | 2002 | 2.9 | 3.0 | 2.9 | 0.85 | 0.040 | 0.040 | 0.041 | 0.66 |
| 4 | 2000 | 2.7 | 2.5 | 2.5 | 0.10 | 0.051 | 0.051 | 0.050 | 0.72 |
| | 2001 | 2.5 | 2.3 | 2.2 | 0.02 | 0.048 | 0.049 | 0.050 | 0.13 |
| | 2002 | 2.8 | 2.8 | 3.0 | 0.17 | 0.047 | 0.049 | 0.052 | 0.01 |
| 5 | 2000 | 3.5 | 3.4 | 3.4 | 0.38 | 0.051 | 0.053 | 0.054 | 0.09 |
| | 2001 | 3.2 | 2.9 | 3.1 | 0.72 | ND | ND | ND | |
| | 2002 | 4.0 | 4.0 | 4.1 | 0.66 | ND | ND | ND | |
| 6 | 2000 | 2.9 | 3.0 | 3.0 | 0.34 | 0.045 | 0.046 | 0.044 | 0.44 |
| | 2001 | 2.3 | 2.4 | 2.3 | 0.88 | 0.042 | 0.042 | 0.043 | 0.61 |
| | 2002 | 2.9 | 2.9 | 3.1 | 0.23 | 0.039 | 0.038 | 0.042 | Q 0.02 |
| 7 | 2000 | 2.3 | 2.4 | 2.4 | 0.62 | 0.038 | 0.040 | 0.039 | Q 0.09 |
| | 2001 | 1.9 | 1.9 | 2.0 | 0.16 | ND | ND | ND | |
| | 2002 | 2.4 | 2.5 | 2.6 | 0.16 | 0.036 | 0.038 | 0.040 | 0.04 |
| 8 | 2000 | 3.2 | 3.1 | 3.1 | 0.42 | 0.047 | 0.046 | 0.048 | 0.69 |
| | 2001 | 2.3 | 2.2 | 2.2 | 0.29 | 0.058 | 0.059 | 0.060 | 0.22 |
| | 2002 | 3.7 | 3.5 | 3.4 | 0.13 | 0.044 | 0.044 | 0.044 | 0.96 |

[z]Linear response otherwise quadratic (Q) response with K rate at probability level indicated.
[y]Not determined (ND) due to no fruit sample.

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FW; Neilsen and Neilsen 2003) measured only in orchard 8 in 2002. These low values were associated with application of KMag fertilizer. Fruit K:Ca ratio was little affected by KMag fertilization so that by the third year of the study only orchard 6 had increased fruit K:Ca (data not shown). Four orchards had increased fruit Mg:Ca ratio this year.

### Yield and Fruit Quality

Over all orchards, fruit size and cumulative yield were minimally affected by KMag fertilization although cumulative yield increased as rate of KMag application increased in orchard 1 ($P = 0.06$). Orchard 1 also had an increase in fruit size in 2002 (Table 7) and the lowest soil exchangeable K concentration (Fig. 2) of all orchards. Cumulative yield peaked at the 100 kg K ha$^{-1}$ application rate in orchard 7 (quadratic response to fertilization, Table 7). Fruit size was negatively affected by KMag fertilization in orchard 3 in 2000. This orchard was also characterized by low soil exchangeable Mg (Fig. 3).

Fruit quality was infrequently affected by KMag fertilization with no effect consistently observed in all years in any orchard (Table 7) and with fruit soluble solids and titratable acidity unaffected by fertilizer treatment (data not shown). Percentage red colour was most often affected by KMag application with an increase in red colour observed after KMag application in orchards 1, 3 and 8 (1 yr) and a decrease in orchard 4 (Table 7). Orchard 4 had a shallow root zone and low soil exchangeable Ca (Fig. 4) and soil Ca/Σ[Ca + Mg + K] (Fig. 5). Decreased fruit firmness after KMag fertilization was also observed in the first year of the study for orchard 4. There was no major occurrences of fruit disorders observed throughout the study that were associated with KMag fertilization. Bitter pit was of minor occurrence (<1%) and unaffected by KMag fertilization (data not shown). This included a low bitter pit incidence (4 of 240 sample apples) in orchard 8 where fruit Ca concentration was decreased below the 0.040g kg$^{-1}$ FW threshold at the highest KMag application rate. Water core was the only disorder whose incidence but not severity was associated with KMag fertilization, but results were inconsistent, increasing in orchard 5 in 2000 and decreasing in orchard 8 in 2001 and orchard 7 in 2002 (Table 7).

## DISCUSSION

### Benefits of K and Mg Additions

#### *Soil Response*

During the 3 yr experiment, KMag fertilizer treatments resulted in the cumulative application of 300 (3 × 100) or 600 (3 × 200) kg K and 180 (3 × 60) or 360 (3 × 120) kg Mg ha$^{-1}$. These unit area application rates were sufficient to increase exchangeable soil K

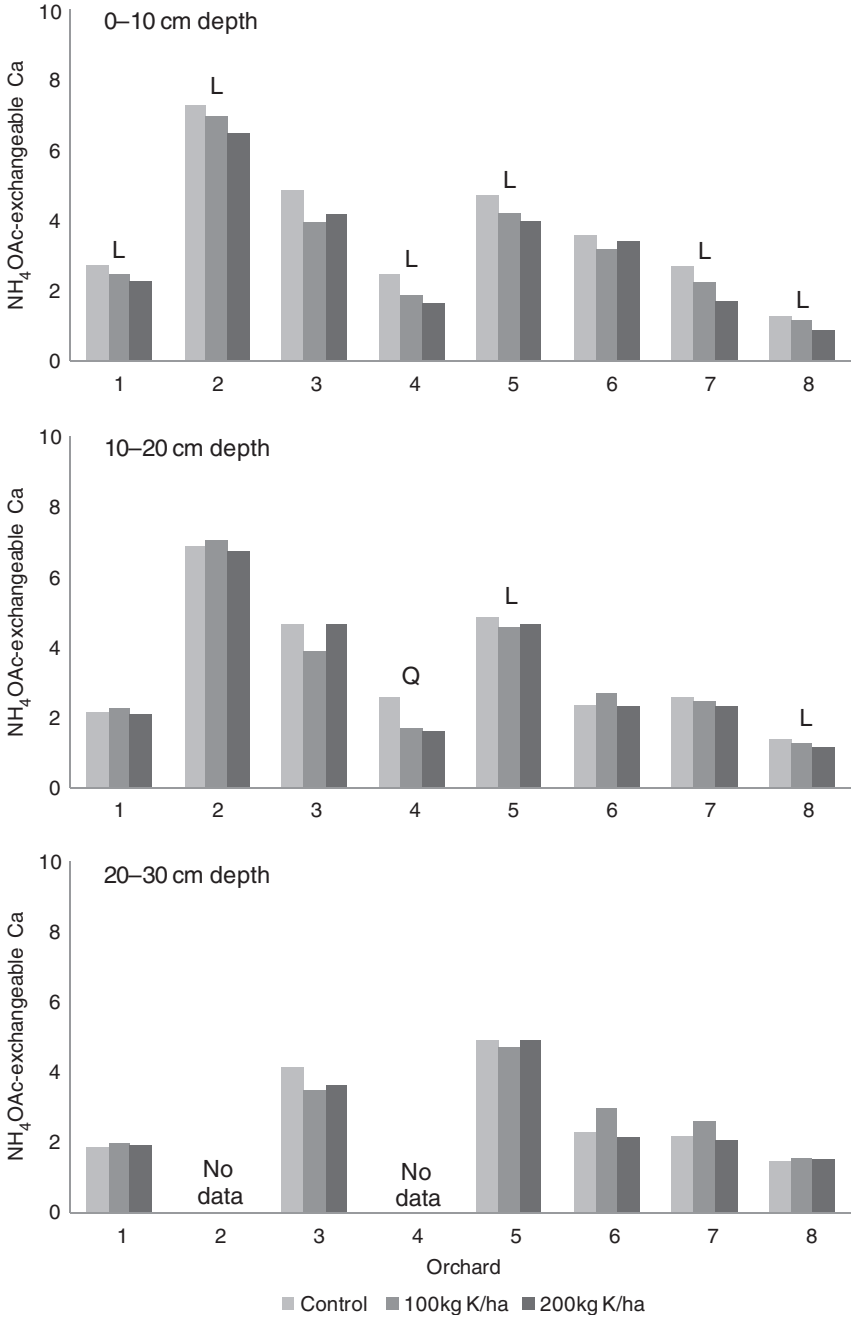


**Fig. 4.** Soil $NH_4OAc$-exchangeable Ca (cmol (+) $kg^{-1}$) as measured at 0–10, 10–20 and 20–30 cm depth for 'Fuji' apple orchards after application of 0, 100 and 200 kg K/treated ha as potassium, magnesium sulphate (KMag), applied annually 2000 to 2002. Significant linear (L) or quadratic (Q) responses to fertilizer application rate are at $P < 0.05$.

and Mg and K/Σ[Ca + Mg + K] and Mg/Σ[Ca + Mg + K] throughout the profile of these sprinkler-irrigated, coarse-textured orchard soils (Figs. 2 and 3). These changes in soil K and Mg were much more rapid than changes observed in a Brazilian orchard oxisol (increased Mehlich 1 extractable K, 0–20 cm depth) after 12 yr of annual broadcast application of 50–150 kg $ha^{-1}$ of $K_2O$ (Nachtigall et al. 2007). This is an indication of the relative ease of altering the exchangeable K status of local soils compared with the Brazilian oxisol, which had high clay (59%) and cation exchange capacity ( pH 7; 170 mmol $dm^{-3}$) values.

The increase in soil exchangeable K and Mg from the control to the highest rate of KMag ranged from 62 to 350 kg K $ha^{-1}$ and from 17 to 160 kg Mg $ha^{-1}$ when normalized over a 0.3 m depth for all orchards

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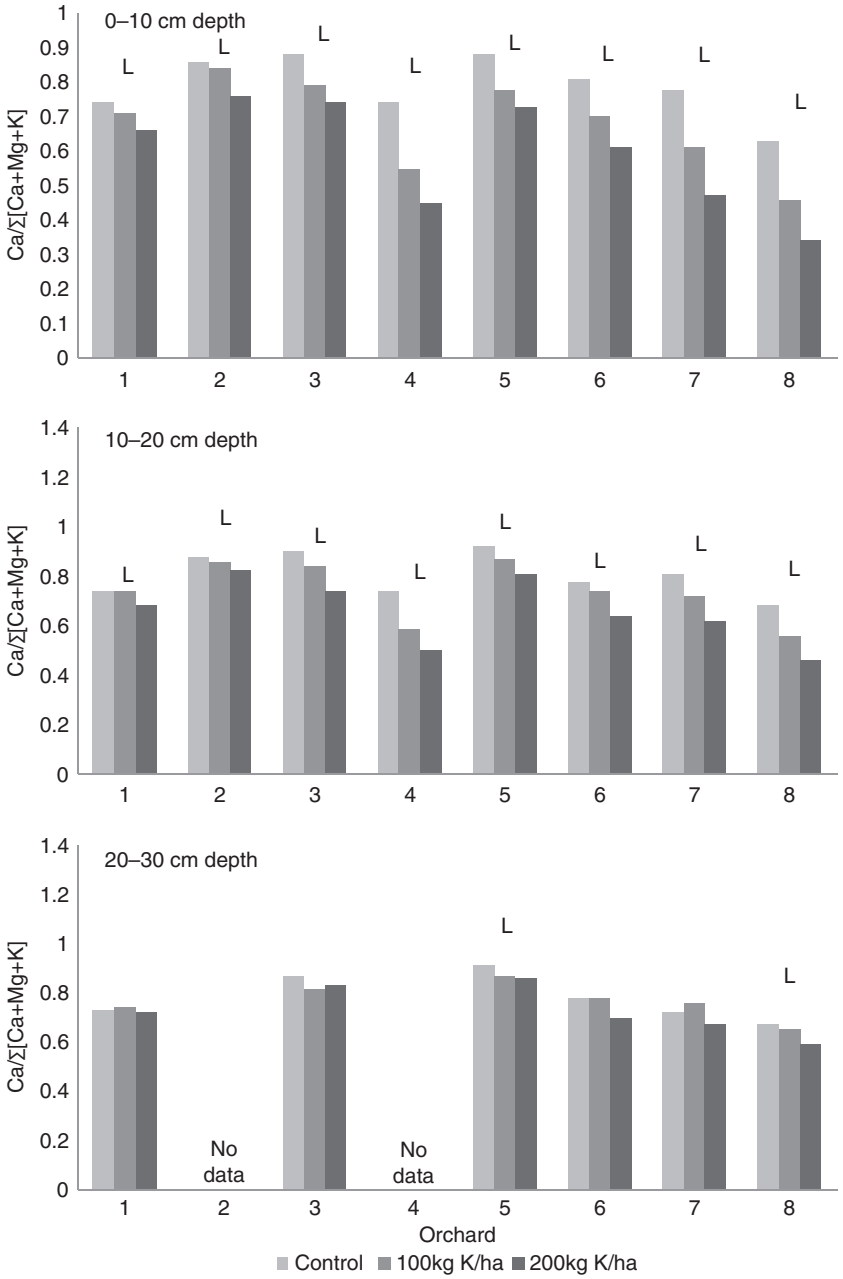


**Fig. 5.** Soil Ca/Σ[Ca + Mg + K] calculated for 0–10, 10–20 and 20–30 cm depths for 'Fuji' apple orchards after application of 0, 100 and 200 kg K/treated ha as potassium, magnesium sulphate (KMag), applied annually 2000 to 2002. Significant linear (L) responses to fertilizer application rate are at $P < 0.05$.

(Table 8). On average, over all orchards the proportion of K retained in the surface 0.3 m after KMag fertilization exceeded that of Mg. Percent retention showed considerable variation among orchards, ranging from 10 to 58% for K and from 5 to 44% for Mg with no consistent relationship between the nutrients and planting density (Table 1) or fertilized area per tree (Table 8). Leaching was not measured at these sites but it is known to be greater for Mg than K in local sandy loam soils, averaging 48 kg K $ha^{-1}$ and 320 kg Mg $ha^{-1}$over 4 yr from soils with a range of irrigation regimes (Neilsen and Stevenson 1983). This may have contributed to greater soil K retention. Also, K is efficiently recycled to the soil surface within the orchard from additions from annual leaf shedding and recycled grass cuttings (Haynes and Goh 1980). The pattern of retention of leaves and orchard floor cuttings would vary from orchard to orchard, which might

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**Table 6. Mid terminal leaf Ca and harvest fruit Ca concentrations as affected by annual application of 0, 100 and 200 kg K ha$^{-1}$ as potassium, magnesium sulphate (KMag) between 2000 and 2002**

| | | Leaf Ca (g kg$^{-1}$) | | | | Fruit Ca (g kg$^{-1}$ FW) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Treatment | Year | 0 | 100 | 200 | Significance[z] | 0 | 100 | 200 | Significance[z] |
| Orchard | | | | | | | | | |
| 1 | 2000 | 11.8 | 11.8 | 11.7 | 0.64 | 0.045 | 0.045 | 0.045 | 0.86 |
| | 2001 | 10.9 | 10.9 | 10.2 | Q 0.03 | 0.045 | 0.047 | 0.045 | 0.96 |
| | 2002 | 12.2 | 11.5 | 11.3 | Q 0.002 | 0.046 | 0.046 | 0.045 | 0.69 |
| 2 | 2000 | 14.5 | 13.7 | 14.4 | Q 0.10 | 0.054 | 0.055 | 0.054 | 0.97 |
| | 2001 | 11.8 | 11.4 | 11.7 | 0.71 | ND[y] | ND | ND | |
| | 2002 | 14.0 | 13.2 | 13.3 | 0.08 | 0.045 | 0.044 | 0.045 | 0.95 |
| 3 | 2000 | 11.5 | 11.2 | 11.5 | 0.87 | 0.057 | 0.058 | 0.062 | 0.19 |
| | 2001 | 8.9 | 8.9 | 8.1 | 0.06 | 0.053 | 0.050 | 0.049 | 0.22 |
| | 2002 | 13.7 | 13.6 | 13.5 | 0.70 | 0.049 | 0.045 | 0.044 | 0.009 |
| 4 | 2000 | 12.2 | 11.6 | 12.2 | Q 0.03 | 0.061 | 0.056 | 0.060 | Q 0.06 |
| | 2001 | 11.0 | 10.3 | 9.8 | 0.01 | 0.053 | 0.055 | 0.047 | 0.15 |
| | 2002 | 14.4 | 13.3 | 12.9 | 0.001 | 0.050 | 0.053 | 0.048 | 0.51 |
| 5 | 2000 | 16.8 | 16.0 | 16.3 | 0.34 | 0.084 | 0.084 | 0.088 | 0.29 |
| | 2001 | 13.0 | 12.2 | 11.5 | 0.05 | ND | ND | ND | |
| | 2002 | 14.9 | 14.9 | 16.8 | 0.11 | ND | ND | ND | |
| 6 | 2000 | 16.3 | 16.5 | 16.2 | 0.82 | 0.079 | 0.077 | 0.074 | 0.14 |
| | 2001 | 13.4 | 13.1 | 12.9 | 0.17 | 0.068 | 0.065 | 0.068 | 0.47 |
| | 2002 | 13.8 | 13.3 | 13.0 | 0.08 | 0.070 | 0.062 | 0.065 | Q 0.04 |
| 7 | 2000 | 18.7 | 17.3 | 18.5 | 0.79 | 0.069 | 0.072 | 0.068 | 0.90 |
| | 2001 | 12.2 | 11.3 | 11.0 | 0.003 | ND | ND | ND | |
| | 2002 | 14.5 | 13.0 | 12.6 | 0.0009 | 0.060 | 0.060 | 0.058 | 0.54 |
| 8 | 2000 | 11.8 | 11.8 | 11.3 | 0.27 | 0.053 | 0.053 | 0.055 | 0.48 |
| | 2001 | 7.6 | 7.3 | 6.8 | 0.01 | 0.055 | 0.048 | 0.054 | 0.95 |
| | 2002 | 11.5 | 10.9 | 10.6 | 0.09 | 0.040 | 0.038 | 0.035 | 0.06 |

[z]Linear response otherwise quadratic (Q) response with K rate at probability level indicated.
[y]Not determined (ND) due to no fruit sample.

account for some of the site variation in apparent soil K recovery. Furthermore, it has been well documented that rate of annual uptake of K exceeds that of Mg by as much as 20-fold in fruit (Palmer and Dryden 2006) and 3.7-fold in shoots and leaves (Cheng and Raba 2009) of high density orchards.

Similar rapid changes in soil Mg and K were measured directly beneath drip emitters throughout the first 30 cm of a local Skaha loamy sand soil series after 3 yr of fertigation of KMag, which applied 90 g K and 55 g Mg per tree (Neilsen and Neilsen 2006). In the current study involving broadcast application of the fertilizer within the herbicide strip centred on the tree row with season long sprinkler-irrigation, per tree cumulative application exceeded these rates for all treatments and orchards, averaging 490 g K per tree and 294 g Mg per tree for the highest KMag fertilizer rate and half these values for the lower KMag fertilizer rate. These applications exceeded amounts applied via fertigation regardless of application rate. Thus, although trends of increased soil K and Mg were the same under the two KMag fertilization rates, changes were less pronounced for soil K and Mg below the 20 cm depth when fertilizers were broadcast rather than fertigated as a point source. Nevertheless, it is likely that changes in soil Mg and K resulting from broadcast application of

**Table 7. Orchards and years when significant effects of potassium, magnesium sulphate (KMag) fertilization on fruit size, cumulative yield, harvest fruit red colour, firmness and incidence of water core were measured between 2000 and 2002**

| Characteristic | Fruit size (g) | | Cumulative Yield (kg tree$^{-1}$) | | Red colour (% red) | | | | | Firmness (N) | Water core incidence (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Orchard | 1 | 3 | 1 | 7 | 1 | 1 | 3 | 4 | 8 | 4 | 5 | 7 | 8 |
| Year | 2002 | 2000 | 2000–2002 | | 2000 | 2002 | 2001 | 2000 | 2002 | 2000 | 2000 | 2002 | 2001 |
| Treatment (KMag) | | | | | | | | | | | | | |
| 1. 0 kg K ha$^{-1}$ | 261 | 163 | 98.2 | 52.1 | 75 | 81 | 76 | 78 | 80 | 85.0 | 30 | 72 | 63 |
| 2. 100 kg K ha$^{-1}$ | 263 | 151 | 105.7 | 65.2 | 80 | 89 | 87 | 75 | 80 | 84.0 | 42 | 68 | 38 |
| 3. 200 kg K ha$^{-1}$ | 282 | 150 | 110.7 | 40.4 | 81 | 88 | 85 | 72 | 87 | 81.8 | 53 | 47 | 42 |
| Significance[z] | 0.06 | 0.01 | 0.06 | Q 0.05 | 0.07 | 0.01 | 0.05 | 0.04 | Q 0.05 | 0.04 | 0.06 | 0.009 | 0.03 |

[z]Linear response otherwise quadratic (Q) response with K rate at probability level indicated.

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**Table 8. Total plot area, soil (0–0.3 m) bulk density, absolute K and Mg recovery (kg ha$^{-1}$) and as a percent of cumulative K (600 kg ha$^{-1}$) and Mg (360 kg ha$^{-1}$) applied over 3 yr for eight experimental orchards**

| | | | Recovered | | Percent of applied | |
|---|---|---|---|---|---|---|
| | | | K | Mg | K | Mg |
| Orchard | Plot area (m$^2$) | Bulk density (kg m$^{-3}$) | (kg ha$^{-1}$) | | (%) | |
| 1 | 14.4 | 1.58 | 62 | 17 | 10 | 5 |
| 2 | 13.2 | 1.58 | 264 | 160 | 44 | 44 |
| 3 | 12.0 | 1.53 | 296 | 94 | 49 | 26 |
| 4 | 21.0 | 1.58 | 350 | 103 | 58 | 29 |
| 5 | 10.4 | 1.58 | 218 | 50 | 36 | 14 |
| 6 | 12.0 | 1.58 | 280 | 94 | 47 | 24 |
| 7 | 9.6 | 1.58 | 113 | 91 | 18 | 25 |
| 8 | 12.0 | 1.58 | 129 | 79 | 22 | 22 |

KMag were sufficient to influence an important portion of the rooting zone within 3 yr since previous research has indicated the depth of the roots of apple trees on M.9 rootstocks was shallower than 30 cm after 7 yr of irrigation at weekly intervals more typical of sprinkler irrigation systems (Neilsen et al. 1997).

### *Foliar and Fruit Response*

In the 3 yr of the study, across the range of orchards, broadcast application of KMag was effective at augmenting leaf and fruit K concentration. Potassium deficiency in apple has traditionally been associated with leaf K concentrations $<10$ g kg$^{-1}$ (Cummings 1985), fruit K concentrations $<1.0$ g K kg$^{-1}$ FW (Neilsen et al. 2004) or $NH_4OAc$-exchangeable soil K of about 0.13 cmol (+) kg$^{-1}$ (Neilsen et al. 1998). Current BC production practices recommend K-application when leaf K concentrations are less than 13 g kg$^{-1}$ (BCMAL 2007). Application of KMag fertilizer would be most effective in augmenting K nutrition of apple trees at sites where trees already exhibit marginal K uptake as illustrated for leaf and fruit K concentrations for some, but not all, of the study sites. Thus, KMag fertilization would be an effective K source consistent with the positive response of apple to soil-applied K previously reported by Cummings (1985).

In contrast, despite the co-application of Mg contained in KMag fertilizer and increased soil exchangeable Mg (0–20 cm depth) after KMag fertilization, no increase in leaf Mg was measured despite the occurrence of deficient leaf Mg concentrations ($<2.0$ g kg$^{-1}$, BCMAL 2007) in several orchards. Fertigation of KMag has previously moderated leaf Mg decline, but did not increase its concentration in an orchard with adequate K and Mg nutrition (Neilsen and Neilsen 2006). The results of this study across orchards with a range of K and Mg availability suggest it will not be easy to increase apple leaf Mg nutrition when co-applying larger amounts of K as a surface broadcast application. This would be better achieved by foliar Mg applications (Ford 1964). Long-term KMag fertilization is, however, effective at maintaining soil Mg status and may increase fruit Mg concentration after 3 yr.

Broadcast application of KMag fertilizer has been advocated as a method of simultaneously increasing both soil Mg and K availability, since both these cations can be depleted in local coarse-textured soils as a consequence of irrigation and fertilization practices (Neilsen et al. 1995). This has been achieved via broadcast applications to the soil surface, within an important portion of the root zone within 3 yr, as in this study. Meaningful consequences to fruit yield and quality, however, were limited. Larger fruit size, increased red colour and TA are previously reported consequences of K fertilization of trees of low K status (Cummings 1985). As increased leaf and fruit K concentrations were frequent plant nutritional outcomes of KMag fertilization in this study, benefits would most likely be observed for trees of low K status. Increased cumulative yield, fruit size and percent red colour in orchard 1, which had low leaf and soil K concentrations, suggested this site was deficient in K and benefited from KMag fertilization. Similar responses were observed for early season 'Summerland McIntosh' after K-fertilization of low K-status trees (Neilsen et al.1998) However, unlike 'Summerland McIntosh', TA of late season 'Fuji' apples was unaffected by K-fertilization for any 'Fuji' orchard. The dominant effect of seasonal factors on fruit TA has been recognized (Eaves and Leefe 1955). Positive production and quality responses to KMag fertilization were not always observed when leaf K concentrations were inadequate ($<13$ g kg$^{-1}$). Such values were measured in at least 1 yr in orchard 5, 6 and 7, which exhibited limited benefits from KMag fertilization. Orchards 5 and 6 did not benefit from KMag application while incidence of water core increased in 2000 in orchard 5 (Table 7). There was a quadratic response of cumulative yield to KMag fertilization, with yields peaking at 100 kg K ha$^{-1}$ and declining at 200 kg K ha$^{-1}$ for orchard 7. This orchard also had low soil, leaf and fruit Mg concentrations, implying high KMag applications could be detrimental to tree performance. Although water core incidence declined at high rates of KMag fertilization in this orchard, the decline was insufficient to overcome the undesirable effects of high rates of KMag application. Decreased red colour and fruit firmness at harvest in 2000 were measured in orchard 4, which had adequate levels of K and Mg, suggesting KMag fertilizer should not be applied when Mg and K nutrition is sufficient.

## Impacts on Ca Availability and Nutrition

Decreases in soil Ca availability were more apparent when expressed relative to availability of K and Mg (as $Ca/\Sigma[Ca+Mg+K]$) than as absolute amounts. Unlike Mg and K, Ca is not a constituent of the applied fertilizer. Calcium was the dominant cation in the soil with $Ca/\Sigma[Ca+Mg+K]$ of control plots ranging from 0.63 (orchard 8) to 0.90 (orchard 5) with a minimum Ca/

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$\Sigma$[Ca + Mg + K] ratio at the highest KMag application rate of 0.34 in orchard 8 (Fig. 5). Decreases in exchangeable Ca and Ca/$\Sigma$[Ca + Mg + K] have also been reported in limed Brazilian soils in response to annual applications of 50 to 150 kg ha$^{-1}$ of $K_2O$ and represented a serious future problem in tropical soils susceptible to acidification (Nachtigall et al. 2007). In BC, there was no consistent relationship between decline in exchangeable soil Ca and initial soil Ca status, indicating a similar trend across all sites.

In the long term, the combined application of K and Mg via KMag fertilization tends to diminish plant Ca availability, as illustrated by frequent declines in leaf Ca concentration and decreases at the end of the 3 yr study in fruit Ca concentration in some orchards. Leaf Ca can be diluted in vigorous trees but KMag fertilization did not affect trunk cross sectional area during the study (data not shown). Adequate fruit Ca concentration is considered critical for optimizing harvest and post-harvest quality of apples (Vang-Petersen 1980). A concentration at harvest exceeding 0.040 g Ca kg$^{-1}$ FW is recommended for apples (Neilsen and Neilsen 2003). Extensive industry research in BC over 270 orchard-years for 'McIntosh', 'Spartan' and 'Golden Delicious' apples found large fruit size, low fruit Ca concentration and a high fruit K:Ca ratio at harvest were factors most often correlated with storage disorders (Wolk et al. 1998). Since KMag fertilization minimally affected fruit size and these size increases were not associated with declines in fruit Ca concentration (Tables 6 and 7) increased fruit growth rate (dilution) induced by fertilization was not an important factor in declining fruit Ca concentration. Few criteria exist to indicate desirable fruit cation ratios for local orchards with the exception of recommended optima of $<15$ for K:Ca and $<0.8$ Mg:Ca for 'Ambrosia' apples collected 6 wk prior to anticipated harvest (BCMAL 2007). Only orchards 5, 6 and 7 during 1 yr had K:Ca ratios exceeding the standard while Mg:Ca ratios were exceeded in the last year of the study in orchard 6. Given the lack of Ca-related disorders observed in our study, it would appear that ratio standards developed for 'Ambrosia' are not appropriate for 'Fuji'. Fruit Ca concentration was generally adequate in the present KMag fertilization study with values exceeding the critical Ca concentration, excepting orchard 8 in 2002. Nevertheless, continued long-term application of KMag fertilizer, with its possibility of decreasing fruit Ca while increasing fruit K and Mg concentrations, requires vigilance to ensure adequate fruit Ca concentration is not compromised. Otherwise the grower may have to resort to increased foliar Ca applications which have been successfully developed to increase harvest apple fruit Ca concentration (Ferguson and Watkins 1989) but increase production costs.

The minimal short-term impact of KMag fertilization on harvest fruit disorders in this study is consistent with the low incidence of bitter pit ($<1\%$ of sampled apples over all orchards and years) and the high Ca concentration of harvested fruit, frequently well above the 0.040 g Ca kg$^{-1}$ threshold. Over the 3 yr study, KMag fertilization did not amplify the occurrence of the Ca-related disorder bitter pit in these orchards. Continued long-term application of KMag should be accompanied by monitoring of fruit Ca concentration due to the continued displacement of exchangeable soil Ca by K and Mg originating from fertilizer. 'Fuji' apples are susceptible to the development of water core, which is not considered a serious problem in Japan (Marlow and Loescher 1984). In BC, its marked decrease after low oxygen cold storage further lessens the practical significance of its decline. Recent research has shown an association between fruit P concentration and membrane stability, including reduced incidence of water core at harvest with high fruit phosphorus (Neilsen et al. 2008). The inconsistent effects of KMag fertilization on water core incidence of 'Fuji' apples indicate its application does not play a predictable role in the disorder.

## CONCLUSIONS

After 3 yr, annual broadcast application of KMag fertilizers at rates of 100 or 200 kg K ha$^{-1}$ yr$^{-1}$ consistently increased soil exchangeable K and Mg and decreased Ca supply when expressed as Ca/$\Sigma$[Ca + Mg + K] to 20 cm depth in typical coarse-textured orchard soils situated throughout the main Okanagan fruit-growing region. Broadcast application of KMag fertilizer in sprinkler-irrigated orchards is effective for augmenting soil levels of Mg and K at the cost of relative Ca availability. Decreased soil exchangeable Ca was also measured but changes were more muted, being observed in a majority of orchards but only to a 10 cm depth. Leaf and fruit K concentrations of 'Fuji' apple trees increased within the first year in some orchards and occurred in a majority of orchards during second and third years, consistent with increasing soil K. Despite increased soil Mg, leaf Mg did not increase during the study with improvements in plant Mg status limited to increased fruit Mg concentration in some but not all orchards by the third year. Since leaf Mg concentration is important for diagnosing orchard Mg status, KMag fertilization would be considered less effective than foliar application for increasing short-term tree Mg status. Choosing to apply KMag fertilizers to maintain long-term soil Mg and K fertility status in general did not improve economic performance in these orchards, which exhibited the typical wide range of relative soil Ca, Mg and K availability observed locally. An exception was an orchard of marginal K status (low soil, leaf and fruit K concentrations) which had higher cumulative yield and improved fruit quality, including larger fruit size and increased red colour as KMag application increased. As these are responses related to improved K nutrition, broadcast application of KMag fertilizer can be an effective source of K. Percentage red colour was increased in a single year in two other orchards but was

unrelated to their K nutritional status. Despite indications of widespread declines in relative soil Ca status after 3 yr of KMag application, no serious decline in fruit Ca concentration or increase in Ca-related harvest disorders was measured. Seasonal differences in fruit Ca concentration much exceeded any changes associated with annual fertilizer treatments, suggesting a deserving future research subject would be to improve our understanding of seasonal effects, including annual crop load variation, on fruit Ca accumulation. Nevertheless, annual monitoring of fruit Ca concentration would be a useful strategy to assess the need to make foliar Ca applications when applying KMag fertilizer.

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