Optimising the posharvest qualities of Hass avocado through improved calcium nutrition

Peter Hofman
QLD Department of Primary Industries & Fisheries

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(HAL AV02009)

Final report

Peter Hofman et al.

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Final report of the project

" Optimising the postharvest quality of Hass avocado through improved calcium nutrition"

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Contents

1 Media summary

The Australian avocado industry has had a long focus on improving quality to the consumer by developing better production, harvesting, storage, ripening and retail practices.

The main avocado fruit quality problems are rots and flesh disorders which cause browning of the flesh. Most of the research in recent years has been to grow fruit which can better prevent rots and disorders development. This approach will also help reduce the use of chemicals during production and after harvest.

In many fruit crops, fruit with higher calcium (Ca) concentrations often have less rots and disorders. Previous research has confirmed that this relationship also exists in avocados. Therefore, the Australian avocado industry, along with Horticulture Australia Ltd and the Queensland Department of Primary Industries and Fisheries funded a four-year programme to develop Ca fertiliser recommendations with a view to improving fruit Ca and quality.

The research suggested that, contrary to commonly-held views, Ca is not held very well in most avocado growing soils, so that leaching of added Ca can easily occur. More frequent applications of smaller amounts of Ca will reduce this risk, however even with this strategy we had difficulty improving fruit Ca concentrations and quality.

It appeared that other factors are involved in fruit Ca nutrition, especially potassium (K) nutrition, the genetics of the tree, and tree yield. The results again confirmed that Ca is important in fruit quality, but that it is difficult to manipulate.

Further work is recommended to reduce K nutrition to minimise competition with Ca, and assisting growers to improve overall tree yield to improve fruit quality. Harvesting fruit specifically from higher yielding blocks or trees could provide fruit for more distant markets where longer transport and storage times are often required.

More information can be obtained from the 2007 summer edition of Talking Avocados.

2 Technical summary

Fruit calcium (Ca) can have a significant effect on avocado fruit quality. Strong correlations have been shown between more fruit Ca and less rots (Hofman *et al.* 2002b; Penter and Stassen 2000) and internal disorders (Eaks 1985; Penter and Stassen 2000; Thorp *et al.* 1997). Most of these results were obtained by comparing fruit from different production locations and relating fruit quality to fruit minerals concentrations, or by obtaining fruit from trees growing on different rootstocks. Attempts to increase Ca concentrations in fruit by soil applications have been inconsistent. However, the benefits of improved Ca nutrition justified further investigations at manipulating fruit Ca concentrations using soil applications.

In this project Ca nutrition trials were conducted on one typical avocado orchard in Bundaberg. An orchard on a sandy loam was chosen because of concerns that the kraznosem soils common in many avocado orchards would prevent rapid distribution of added Ca through the soil profile. Trials using a range of Ca (0-2.4 t/ha) and K (0-600 Kg/ha) treatments were conducted on the same orchard block over four seasons. Leaf, soil, xylem sap, fruitlet and mature fruit skin and flesh mineral concentrations were measured, as well as total tree yield and fruit quality. The results indicated that:

- Calcium was lost from the top 30 cm of the soil far more rapidly than expected. This is likely to occur in most avocado producing soils because of their low cation exchange capacity (CEC).
- Calcium application increased total exchangeable and soil solution Ca, and in one season increased concentrations in the xylem sap. However, in most years there was little increase in leaf or fruit Ca concentrations, and any increases (< 40 mg/Kg) were far less than those observed between adjacent trees (>250 mg/Kg).
- There were nil or minor effects on fruit quality, most likely because of insufficient treatment response.
- There were interactions between Ca and K, where K slightly reduced fruit Ca concentrations, and Ca reduced fruit K concentrations in one season.
- Higher yielding trees often had less fruit rots and higher fruit Ca concentrations. This was observed particularly in low yielding years. There was also less variation in fruit quality between the higher yielding trees compared with between low yielding trees.
- There are differences between avocado soil types with respect to Ca/K affinity, suggesting that WA gravelly loams have a higher affinity and selectivity for Ca than K compared with the Childers Ferrosol and the Mareeba Candasol. This suggests that the latter soil types would be more susceptible to Ca being displaced from the exchange complex by K, and leached.

The results confirm the challenges with increasing fruit Ca concentrations, but also confirmed the beneficial role of fruit nutrition in quality. We recommend that regular Ca applications during fruit growth are preferred to a single application. Potassium fertilisers should not be applied at the same time as Ca.

Further research is suggested to reduce K leaf recommendations to minimise competition with Ca, and applying K during the non-fruiting period. Further research into the relationship between yield and quality is also recommended, since this is likely to be an easier way of improving quality. Consideration could be given to selectively

harvesting fruit from higher yielding blocks and trees for more distant and discerning markets.

3 General introduction

Mineral nutrition of tree crops, including avocado, can have a significant affect on the postharvest quality of the fruit, in particular its size, shape, shelf life and susceptibility to rots and internal disorders (Hofman et al. 2002a).

Calcium (Ca) is the nutrient most frequently implicated in flesh disorders and diseases in many fruit crops. In avocado, strong correlations have been shown between more fruit Ca and less rots (Hofman et al. 2002b; Penter and Stassen 2000) and internal disorders such as diffuse discolouration, vascular browning and pulp spot (Eaks 1985; Penter and Stassen 2000; Thorp et al. 1997). Also, fruit from higher yielding trees often have less rots and more Ca because of their smaller size (Hofman et al. 2002b). Lower fruit potassium (K) and higher magnesium (Mg) concentrations have also been related to reduced fruit rots and internal disorders (Witney et al. 1990a), possibly because of their interaction with Ca uptake into the fruit (Hofman et al. 2002a). Therefore, it is likely that Ca is a dominant factor driving the relationship between fruit quality and tree nutrition.

In contrast, higher rates of nitrogen (N) application to avocado trees, especially as ammonium, have been associated with more rots and internal disorders (Arpaia et al. 1996; Penter and Stassen 2000). More recently, higher fruit flesh and skin N have been correlated with more rots and internal disorders in avocado (Kruger et al. 2004; Marques et al. 2003; Willingham 2003). However, large strategically timed applications of N can also increase yield and fruit size (Lahav and Whiley 2002). This highlights the importance of balancing N nutrition to optimise both fruit yield, size and quality.

The above studies confirm the significance of nutrition in avocado fruit quality, and highlight the advantages of developing systems to improve fruit nutrition, especially Ca and N. However, most of these results were obtained by comparing fruit from different production locations and relating fruit quality to fruit minerals concentrations, or by obtaining fruit from trees growing on different rootstocks. Hence, the "manipulation" of fruit minerals has been by indirect means, such as variations in soil type and rootstock genetics.

Attempts to increase Ca concentrations in fruit by soil applications have been inconsistent. This is thought to be partly due to the relative immobility of Ca in the soil and plant and its dependence on water for distribution in plant tissue (Lahav and Whiley 2002). Because Ca moves passively, it tends to concentrate in those tissues that lose more water, so that leaves accumulate more Ca at the expense of developing fruit. These mechanisms result in a number of factors affecting distribution of Ca into the fruit, such as:

- Soil solution concentrations.
- Leaf/fruit ratio. Generally trees with a higher crop load (with similar canopy volume) have better quality fruit. This is also reflected in whole-of-country observations (for example South Africa), so that fruit quality in an on-year is often better than fruit quality in an off-year (Nelson *et al.* 2000).
- Fruit position in the tree. For example, apple fruit that are adjacent to the bourse leaves generally have high Ca concentration because of subtending leaves "pulling" the transpiration flow (and Ca) towards these fruit (Volz *et al.* 1994).
- Water relations, since water stress will affect the movement of Ca to the roots, and the relative partitioning of the transpiration stream between the leaves and the fruit (Bower 1985; Witney *et al.* 1990b).

- Method of Ca application, for example soil compared with foliar application.
- The ratio with the other cations in the soil (Lahav and Whiley 2002).
- Genetics, particularly of the rootstock, since this affects root movement to locations of high soil Ca concentration, and also the number of root tips and degree of root branching, both of which are the major points of Ca uptake into the roots.

Thus, Ca absorption and regulation into fruit requires a holistic approach which should consider rootstock, soil type, water availability to the roots, and the potential for excess vegetative vigour (which can be promoted by N) to compete with Ca accumulation in the fruit. This may be partly the reason why the South African avocado industry has moved away from Ca to improve fruit quality and is now concentrating on N, which is easier to manipulate and control (Wolstenholme 2004). This may be the best approach in situations of excess residual soil N where both yield and quality could be suppressed because of excessive vegetative vigour. However, in Australia most avocado orchards are unlikely to have high residual soil N, and in most cases reducing N further could also reduce yield. Therefore, it is important to continue to focus on Ca in order to maintain and improve quality.

This project initially focused on Ca soil applications and their effects on fruit quality. Minerals concentrations were measured in the soil, xylem sap, leaves, fruit skin and fruit flesh. Yield per tree and its impact on fruit quality was also studied. The results from this and other work (The role of rootstocks and nutrition in the quality of Hass avocado; AV00013) indicated a possible interaction with K so this was included. It also became clear that there was little knowledge on the cation behaviour of the typical subtropical soils used for avocado production in Australia, so more detailed laboratory investigations of Ca and K behaviour of a number of typical avocado soils in Australia was conducted.

4 Effect of Ca and K soil applications on Ca movement from the soil to the fruit, and fruit quality

4.1 Introduction

It is well recognized that Ca nutrition plays a significant role in fruit quality in general, including avocado. Most of the evidence for this relationship has been gained by comparing fruit mineral concentrations and quality from trees growing under a range of conditions, or by comparing adjacent trees grown under the same conditions where the most likely variant was rootstock genetics (Hofman *et al.* 2002b; Vuthapanich 2001). Given the strength of these relationships, work in several crops (and again including avocado) attempted to consistently improve fruit Ca concentrations by soil and foliar applications. The results have often been inconsistent and frustrating. However, little work has been done on avocado in Australia, and the strength of the influence of Ca and fruit quality justified work in this area.

It is well recognised that developing fertiliser recommendations ideally requires work under a range of soil/climatic situations. However, to gain an initial appreciation of the potential for Ca applications to consistently improve avocado quality, the decision was made to conduct trials on only one typical avocado orchard in the major production district of Bundaberg. An orchard on a sandy loam was chosen because of concerns that the kraznosem soils common in many avocado orchards would prevent rapid distribution of added Ca through the soil profile. This would require at least 3-4 years of application before any fruit quality effects were possible.

In the first year, a single gypsum application was applied just before flowering because most orchards followed this practice. In addition, micro-fine gypsum (MicroGyp®) was used to maximise Ca movement through the soil profile to achieve a treatment response during the first 12 weeks of fruit growth. However, the first two years results indicated more rapid movement of Ca through the soil than expected, so two-weekly applications during early fruit growth were adopted, which is similar to the application regime obtained with fertigation. This treatment programme was more likely to maintain high soil solution Ca concentrations around the roots, which is essential for improving nutrient uptake. The results also indicated a potential interaction with K, so several K treatments were included.

Because the early results provided no consistent treatment effect on fruit quality or Ca concentrations, more detailed studies of nutrient movement from soil to fruit were included, such as analysis of soil solution and xylem sap concentrations.

Yield per tree and fruit number were also measured to investigate the interactions with crop load.

4.2 Materials and methods

4.2.1 Treatments (soil applications)

Visually uniform 10-year old ‘Hass’ avocado trees on seedling rootstocks of unknown origin were selected in a commercial orchard at Bundaberg (south east Queensland). The trees were at 10mx5m intervals (about 200 trees/ha), with rows running east-west. The soil type is classified as a kurasol, consisting of a light sandy loam over a heavier

soil. The experiments were conducted on the same orchard block over four years (starting in 2002/3) using a completely randomised block design. The treatments were randomly applied to plots of five trees, with the middle three trees being the experimental trees, and the two outer ones being guard trees between each treatment. Due to differences in flowering dates between the two sides of the row, only fruit samples from the northern side of the trees were taken to reduce sample variability.

All standard commercial Ca, K and Mg applications were excluded from the experimental site, but the standard N and micro-nutrient applications were applied as per normal farm practice.

2002/3

Calcium as microfine gypsum (MicroGyp, 21.6% of Ca) and K as potassium sulphate (K_2SO_4, 41.5% of K) were evenly spread under the drip zone of each tree (about 35 m2) on the 26th of August 2002 (about one week of full flowering) at the rates given in Table 1.

Table 1. Form and rates of Ca (as microfine gypsum; MicroGyp) and K (as potassium sulphate; K2SO4) applied to avocado trees before flowering in 2002.

Treatment	**Form**	**Rate of form per tree** (kg/35 m^2)	**Total rate of form** (kg/ha)
Control	Nil	Nil	Nil
1-Ca	MicroGyp	1.0	200
2-Ca	MicroGyp	2.0	400
3-Ca	MicroGyp	3.0	600
6-Ca	MicroGyp	6.0	1,200
12-Ca	MicroGyp	12.0	2,400
1-Ca+2-K	MicroGyp, K_2SO_4	1.0, 2.0	200, 400
2-Ca+2-K	MicroGyp, K_2SO_4	2.0, 2.0	400, 400

The treatments were replicated six times across six rows of trees, with one replicate (or block) per row (total of 144 experimental trees), as shown in Appendix 1.

Six soil samples per plot (replication) at each of 0-10, 10-20 and 20-30 cm depths, were taken 70 days after fertilizer application (four samples taken around the middle datum tree and the other two at the end of datum tree one and tree three; Appendix 2). The six samples per plot were combined for each depth (total of one sample per depth for each of the 6 plots or replications). At the same time, 10 leaves per tree were sampled from the mature spring flush and the leaves from the three trees in each plot combined to give one sample per plot. Ten fruit per tree were harvested in early July 2003 (commercial maturity), transported to the laboratory, ripened and individually assessed for quality as detailed in section 4.2.2. A further six fruit per tree were sampled for flesh and skin minerals (section 4.2.3), and the samples from the three trees in each plot combined before analysis.

The trees in the trial block were injected with potassium phosphonate to control phytophthora when the summer flush hardened (around March/April).

2003/4

Calcium as microfine gypsum (MicroGyp) and K as potassium sulphate (K2SO4) were applied as per the previous season within one week of full flowering (26th September

2003) at the rates given in Table 2. The 2 kg/tree Ca treatment from 2002/3 was removed and a K only treatment included.

Table 2. Form and rates of Ca (as microfine gypsum; MicroGyp) and K (as potassium sulphate; K_2SO_4) applied to avocado trees before flowering in 2003.

Treatment	**Form**	**Rate of form per tree** (kg/35 m^2)	**Total rate of form** (kg/ha)
Control	Nil	Nil	Nil
1-Ca	MicroGyp	1.0	200
3-Ca	MicroGyp	3.0	600
6-Ca	MicroGyp	6.0	1200
12-Ca	MicroGyp	12.0	2400
4-K	K_2SO_4	4:0	0;
1-Ca+2-K	MicroGyp, K_2SO_4	1.0, 2.0	200, 400
1-Ca+4-K	MicroGyp, K_2SO_4	1.0, 4.0	200, 800

The treatments were replicated six times across six rows of trees (running east west), with one replicate (or block) per row (total of 144 experimental trees), as shown in Appendix 1.

Soil and leaf samples were taken in the same way as in 2002/3. Fruit were harvested in early May 2004 (commercial maturity, 23.4% dry matter), counted and total yield per tree determined. The height, breath and width of the trees were measured to determine canopy volume. Thirteen average sized fruit per tree were selected, taken to the laboratory, ripened and individually assessed for quality (section 4.2.2). A further seven fruit per tree were sampled to determine percentage dry matter (% DM) and minerals concentration (section 4.2.3).

2004/5

The 2002/3 and 2003/4 results suggested that Ca moved rapidly below the 30 cm zone, so more frequent Ca applications were applied to consistently increase soil solution Ca. Also the number of treatments was reduced, but individual tree data were collected to reduce the impact of tree differences and improve statistical analysis.

Calcium as either microfine gypsum (MicroGyp) or normal gypsum (24% of Ca) was evenly applied under the drip zone of each tree (about 35 m2) as either a single application or split equally over seven fortnightly applications as shown in Table 3. Applications started on the 31st of August 2004 (about two weeks before full flowering).

Table 3. Form and rates of Ca as either microfine gypsum (MicroGyp) or normal gypsum applied to avocado trees in 2004.

Treatment	**Form**	**Rate of form per tree** (kg/35 m^2)	**Total rate of form** (kg/ha)	**No. of fortnightly applications**
Control	Nil	Nil	Nil	0
6-Ca	MicroGyp	6.0	1200	7
12-Ca	MicroGyp	12.0	2400	7

12-Ca(G)	Normal gypsum	12.0	2400	1

The treatments were replicated six times across six rows of trees (running east west), with one replicate (or block) per row (total of 72 experimental trees), as shown in Appendix 3. As much as possible, the treatments were applied to trees receiving similar treatments in the previous years.

Soil, sap, leaf and fruitlet sampling

Six soil samples per tree at each of 0-10, 10-20 and 20-30 cm depths were taken in early December (about 11 weeks after full flowering) and combined for each depth (total of 18 samples from the 18 trees per treatment per depth). About 1 mL of xylem sap was collected by removing four branches (about 10-12 mm of diameter) from around each tree and placing the base of each branch (after removal of bark) under vacuum (95 mm) using the apparatus shown in Plate 1. Small sections of the branch were continually cut from its tip to expose new tissue and increase sap flow. The samples from the four branches were combined to give one sap sample per tree. Ten recently mature leaves and 10 average sized fruitlets per tree were also sampled at the same time, with the leaves and fruit from the branches for sap extraction used where possible. The trees were irrigated for about six hours the day before to ensure consistent water relations across the trees. In addition, about 16 mm rain was received the night before.

Plate 1. Equipment used to extract xylem sap under vacuum from small Hass avocado branches.

Harvesting and fruit sampling

Fruit were harvested on the 24th and 25th of May 2005 (commercial maturity; 22.5% DM), counted and total yield per tree determined. Twenty fruit per tree were selected for quality assessments from fruit on the northern side of the canopy and packed directly into single layer trays. A further ten fruit per tree were sampled for % DM and minerals analysis (section 4.2.3). The trial was harvested over two days, but fruit harvested on the first day were held at 6-10°C on farm until all fruit were harvested. Fruit were then transferred to the laboratory within 36 hours of harvest, ripened and individually assessed for quality (section 4.2.2).

2005/6

The 2004/5 results indicated a potential Ca effect, and confirmed an interaction with K. Therefore, treatments were continued until fruit maturity, and K treatments were included.

MicroGyp and/or K2SO4 were evenly applied under the drip zone of each tree (about 35 m^2) as shown in Table 4. Applications started on the 25th of August (about two weeks before full flowering) and continued fortnightly over the first 12 weeks from flowering until late November (total of seven applications). Thereafter, three weekly applications were given from Mid-December until about two weeks before harvest (total of eight applications).

Table 4. Form and rates of Ca (as microfine gypsum; MicroGyp) and K (as potassium sulphate; K_2SO_4) applied to avocado trees in 2005-6.

Treatment	Form	Application details				Total Kg of form	
		To late Nov.		Late Nov. to harvest		Per tree	Per ha
		Kg/application	No	Kg/application	No		
Control	No Ca	Nil	0	Nil	0	Nil	Nil
Ca	MicroGyp	1.29	7	1.29	8	19.3	3860
K	K_2SO_4	0.43	7	0.43	8	6.4	1290
Ca+K	MicroGyp + K_2SO_4	1.29, 0.43	7	1.29, 0.43	8	19.3, 6.4	3860, 1290

The treatments were replicated six times across three rows of trees (running east west), with two replicates (or blocks) per row (total of 72 experimental trees), as shown in Appendix 4. The treatments were applied on different trees in the same orchard block.

Soil, sap, leaf and fruitlet sampling

Six soil samples per tree at 0-20 cm depth were taken in late November (about 10 weeks after full flowering) and combined for each tree (total of 18 samples per treatment). About 1 mL of xylem sap was collected from ten branches (as described for the previous season) and combined to give one sap sample per tree. Ten recently mature leaves and ten average sized fruitlets per tree were sampled from the branches used for sap extraction. The trees were irrigated for about six hours the day before to ensure consistent water relations across the trees.

Harvesting and fruit sampling

Fruit were harvested on June 1st and 2nd 2006 (commercial maturity; 25.4% DM), counted and total yield per tree determined. Twenty fruit per tree were selected for quality assessment and packed directly into single layer trays. An additional ten fruit per tree were sampled for % DM and minerals analysis (section 4.2.3). The trial was harvested over two days, but fruit harvested on the first day were held at 6-10°C on farm until all fruit were harvested. Fruit were then transferred to the laboratory within 36 hours of harvest, ripened and individually assessed for quality (section 4.2.2).

4.2.2 Postharvest operations

On arrival at the laboratory, the fruit from the first two seasons were dipped in 0.55 ml/ L Sportak® (a.i. 450g/L Prochloraz) for 30 sec for disease control, dried and placed in single layer trays. Fruit from all seasons were held at 10°C for 5-7 days, then 5°C for 3-

4 days, then ripened at 18°C with 10 ppm ethylene for 3-5 days until the fruit were well sprung (fruit deformed by 2-3 mm under extreme thumb pressure), then held at 2°C for 3-5 days before ripening at 20°C. This program simulated average commercial conditions from the packhouse to the retail store (Hofman and Ledger 2001). Fruit quality, including fruit softening, the stage of ripeness, and the severity of diseases and internal disorders was assessed as described in the International Avocado Quality Manual (White et al. 2005). Fruit firmness was determined daily by gently squeezing the fruit in the palm of the hand. Hand firmness was regularly calibrated against a digital Firmometer (Anderson Manufacturing and Toolmaking, New Zealand). Fruit was considered as eating soft at a hand firmness similar to a reading of 75-85 using a 0.2 kg weight on the Firmometer. This corresponded to a firmness of about 4 N when measured with an Instron Universal Testing Machine model 1122 (Instron Ltd, UK), fitted with an 8 mm hemispherical probe (probe penetration 2 mm). Ripening time was considered as the number of days taken from the removal of the fruit from ethylene until the eating soft stage. Fruit skin at ripe was visually rated based on a 1-6 scale (1 = green and 6 = black). Severity ratings for diseases and the internal disorders diffuse discolouration and vascular browning were based on the percentage of the flesh volume affected by lesions. Severity of tissue breakdown was based on the flesh area affected by the disorder. Diseases were classified as either body or stem-end rots based on the location of the lesion on the fruit, rather than detailed identification of the fungi causing each lesion. Fruit that had 10% or less of the flesh volume affected by diseases and internal disorders (except tissue breakdown) and 25% or less of the area of the outside of the fruit flesh affected by tissue breakdown were considered to be acceptable. Fruit acceptability was calculated as the percentage of acceptable fruit in relation to the total number of fruit per treatment.

4.2.3 Dry matter and minerals analyses

Fruit flesh samples (about 20 g) were dried at 60oC in a dehydrating oven until constant weight to determine % DM. Wood, leaf and fruit skin were also dried at 60°C, then ground to <1mm and combined to provide one composite sample for each tissue per plot or per tree. All samples were re-dried at 60°C for at least 3 h immediately before minerals analysis. About 0.2-0.3 g of fruit flesh was weighed for N analysis by a combustion analyser (model CNS 2000, LECO Corporation, USA) set at 1100^{o}C and calibrated with EDTA. A further 0.5 g was wet digested (nitric and perchloric acid, 5:1 v/v) (Baker and Smith 1974) for analysis of Ca, K and Mg by an inductively coupled plasma atomic emission spectrophotometer (ICPAES; Spectroflame P, Spectro Analytical Instruments, Germany). Two certified samples of known nutrient concentrations (avocado leaf and oat herbage) were included as references. The results were checked for contaminants against blanks which only had the digestion solution added to the flasks (three blanks for each digestion batch of 50 samples). All results are presented on a dry weight basis.

The sap samples were placed in a freezer overnight just before analysis, then thawed to remove any particulate matter. They were then diluted 2:1 with concentrated nitric acid and analysed by ICPAES. The results are expressed as mg/mL of sap.

All soil samples were re-wetted to near field capacity where necessary and stored at 3°C before extraction. About 250 g of wet soil was vacuum filtered through Whatman No 1 filter paper. The filtrate was then acidified with concentrated HCl and stored at 4°C prior to analysis by ICPAES. A sub-sample of the wet soil was then air dried, ground to pass a 2mm screen, and a 5 g sample weighed into a 50 mL centrifuge tube and extracted with 1M ammonium acetate on an end-over-end shaker for 30 minutes. The tubes were then centrifuged at 3000 rpm for 10 minutes and 5 mL of the supernatant

transferred to a plastic vial for analysis by ICPAES (Australian Standard Method 15D3). The results representing the cations on the soil solution are expressed in mg/L. Those cations held on the exchange complex plus those in the soil solution are referred to as total exchangeable cations, being expressed in cmol/Kg of soil.

4.2.4 Statistical analysis

Data were analysed with Genstat® for Windows™ 8th Edition (Release 8.1) (Lawes Agricultural Trust, The United Kingdom) using the 'General Analysis of Variance' model. The protected least significant difference (LSD) procedure at F=0.05 was used to test for differences between treatment means (Steel and Torrie 1980). Only significant differences are discussed, unless otherwise stated.

Do we need to comment on the fact that we combined the three trees together for one plot in the first two years, but then used individual tree applications in the final two years.

The relationships between tree characteristics, fruit quality attributes, and fruit minerals concentrations were established using correlation analysis (performed by Genstat® 8) to determine the strength (as expressed by the correlation coefficient, r) and direction of the relationships. The significance of the correlations were determined by linear regression analysis at P = 0.05.

4.3 Results and discussion

4.3.1 Season 2002-3

4.3.1.1 Soil minerals

The highest Ca treatment (12-Ca) resulted in more total exchangeable soil Ca than the control and the lowest Ca treatments (1-Ca, 2-Ca and 1-Ca+2-K) (Table 5). The 3-Ca and 6-Ca treatments also resulted in more exchangeable soil Ca than control and 1-Ca treatments. Compared with control, treatment 12-Ca reduced total exchangeable soil Mg, while treatment 3-Ca reduced soil K and treatment 2-Ca reduced soil N. Overall, these results suggest that soil treatments had only a small effect on soil Ca 70 days after treatment.

The higher Ca treatments (12-Ca and 6-Ca) also increased soil electrical conductivity (an indicator of soil properties affecting plant growth, including soil texture, retention and cation exchange capacity; CEC) compared to control, suggesting an improvement in one or more of those soil properties. There were slightly significant but inconsistent treatment effects on soil pH (data not shown).

There was more Ca, Mg, K and N in the top profile (0-10 cm), which generally decreased with depth (Table 5). The CEC of the top 10 cm layer was significantly higher (4.5) than the 10-30 cm layers (3.4-2.7), which could explain the reduction in mineral retention in the soil profile. This was likely due to more organic matter in the top layer, as evidenced from the darker colour of this layer compared to deeper layers. Organic matter typically accounts for at least half the CEC of soils (Brady 1974).

There was little effect of added Ca on K or Mg concentrations in the soil. This result , differs from two studies in South Africa (Barnard 1989; Du Plessis and Koen 1987), in which soil application of gypsum to avocado trees displaced K and Mg from the top soil and sub-soil zones. However, in both studies much higher rates of gypsum was used (10

ton/ha, compared with up to 2.4 ton/ha in the present study), resulting in K and Mg displacement because of mass action.

Table 5. Total exchangeable Ca, Mg, K and N concentrations (cmol/Kg) and electrical conductivity (EC; dS/M) in the soil 70 days after application of Ca (as microfine gypsum) and K (as potassium sulphate) to the soil under 'Hass' avocado trees just before flowering in 2002.

Treatment	Total exchangeable (cmol/Kg soil)				EC
	Ca	Mg	K	N	(dS/M)
Control	2.51 [a]	0.56 [c]	0.134 [ab]	12.1 [c]	0.054 [a]
1-Ca	2.47 [a]	0.56 [c]	0.152 [bc]	8.6 [abc]	0.054 [a]
2-Ca	2.58 [ab]	0.56 [c]	0.132 [ab]	5.9 [a]	0.052 [a]
3-Ca	2.85 [bc]	0.67 [c]	0.167 [c]	7.5 [ab]	0.059 [ab]
6-Ca	2.88 [bc]	0.54 [bc]	0.134 [ab]	10.7 [bc]	0.079 [b]
12-Ca	3.02 [c]	0.41 [b]	0.112 [a]	9.0 [abc]	0.133 [c]
1-Ca+2-K	2.62 [ab]	0.63 [c]	0.144 [bc]	9.9 [bc]	0.061 [ab]
2-Ca+2-K	2.77 [abc]	0.65 [c]	0.141 [bc]	11.1 [bc]	0.063 [ab]
LSD	0.33	0.15	0.03	3.8	0.020
Soil depth (cm)					
0-10	3.49 [c]	0.73 [c]	0.15 [c]	14.4 [c]	0.089 [c]
10-20	2.58 [b]	0.52 [b]	0.14 [bc]	8.5 [b]	0.067 [b]
20-30	2.07 [a]	0.46 [b]	0.12 [b]	5.2 [a]	0.053 [a]
LSD	0.20	0.09	0.02	2.3	0.012

Means of 18 samples per treatment or 48 samples per soil depth.

Means for treatment or depth within columns with different letters are significantly different ($P<0.05$).

4.3.1.2 Plant minerals

There were no treatment effects on leaf or fruit flesh Ca (Table 6). For leaf Ca, these results differ from previous studies conducted in Australia (Broadbent et al. 1989), in which soil application of gypsum significantly increased leaf Ca by 25% in 'Fuerte' avocado trees over a 6-year period. However, the rates of fertiliser applied in that study were much higher than in this trial (10 compared with up to 2.4 ton/ha, respectively). There were some slight but inconsistent treatment effects on fruit skin Ca. The K treatments (1-Ca+2-K and 2-Ca+2-K) increased leaf K, but none of the treatments affected fruit flesh K.

Table 6. Calcium and K concentrations (g/Kg) in the flesh of 'Hass' avocado fruit, as affected by Ca (as microfine gypsum) and K (as potassium sulphate) soil applications to the trees just before flowering in 2002.

Treatment	Leaf (g/kg)		Fruit flesh (g/kg)		Fruit skin (g/kg)	
	Ca	K	Ca	K	Ca	K
Control	13.5	9.4 [c]	0.31	11.0	0.47 [c]	10.5
1-Ca	14.0	9.7 [bc]	0.30	11.7	0.41 [ab]	13.3
2-Ca	14.2	10.5 [bc]	0.32	13.1	0.41 [a]	11.9
3-Ca	14.7	9.7 [bc]	0.32	11.0	0.45 [abc]	10.9
6-Ca	14.0	10.2 [bc]	0.33	12.4	0.47 [bc]	12.5
12-Ca	15.0	10.1 [bc]	0.34	11.8	0.47 [c]	13.0
1-Ca+2-K	13.5	12.2 [a]	0.33	12.5	0.40 [a]	12.4
2-Ca+2-K	13.5	10.9 [ab]	0.31	12.5	0.43 [abc]	13.9
LSD	ns	1.31	ns	ns	0.06	ns

Means of six leaves or fruit per treatment.

Means within columns with different letters are significantly different ($P<0.05$).

There was also no treatment effects on leaf, fruit skin, or fruit flesh Mg (means across all treatments of 5.67, 0.89, and 0.96 g/kg, respectively), or on fruit flesh N (mean of 10.1 g/kg). All treatments increased leaf S, but not leaf Al, B, Cu, Fe, Na, Mn, P, and Zn (data not shown). There were no treatment effects on fruit flesh and fruit skin B, Na, and P (data not shown).

4.3.1.3 Fruit quality

Treatments 2-Ca and 12-Ca slightly delayed ripening compared with control (Table 7). Treatments 1-Ca, 2-Ca, 12-C and 2-Ca+2-K resulted in fruit with darker skin colour at ripe than control fruit. Treatment effects on fruit rots were inconsistent; compared with control, a low Ca treatment (2-Ca) and a high Ca treatment (6-Ca) resulted in fruit with more body rots, but most treatments had no effect. Likewise, treatments 2-Ca and 12-Ca resulted in fruit with more stem end rots than control fruit, with no effects for the other treatments. Most fruit had little or no internal disorders, with no treatment effects on diffuse discolouration, vascular browning and seed cavity browning (means of 0.02%, 0.8% and 0.1% of the flesh volume affected, respectively). Fruit quality was generally very good, and the treatment differences in fruit quality were small.

The increase in the severity of rots with some of the Ca treatments is unusual, as fruit with more Ca often have less rots (Hofman et al. 2002a). This could have been partly due to the Ca effects on ripening time. Fruit from treatments 2-Ca and 12-Ca (but not treatment 6-Ca) took longer to ripen and had more rots, an effect that has been reported in other studies (Hofman et al. 2002a).

Table 7. Ripening time (days), skin colour and severity (as % of the flesh volume affected) of body rots and stem end rots in ripe 'Hass' avocado fruit, as affected by Ca (as microfine gypsum) and K (as potassium sulphate) soil applications to the trees just before flowering in 2002.

Treatment	Ripening time	Skin colour	Body rots	Stem end rots	Acceptable fruit
	(days)	(1-6)	(% of flesh volume)		(%)
Control	9.9 ^{ab}	5.1 ^{ab}	2.6 ^{a}	1.0 ^{a}	89
1-Ca	9.7 ^{a}	5.3 ^{c}	3.2 ^{a}	1.2 ^{a}	85
2-Ca	10.5 ^{d}	5.4 ^{c}	5.2 ^{c}	2.5 ^{b}	75
3-Ca	9.7 ^{a}	5.1 ^{a}	2.8 ^{a}	1.2 ^{a}	79
6-Ca	9.9 ^{ab}	5.3 ^{bc}	5.0 ^{bc}	1.7 ^{ab}	81
12-Ca	10.3 ^{cd}	5.4 ^{c}	3.6 ^{ab}	2.2 ^{b}	81
1-Ca+2-K	10.1 ^{bc}	5.3 ^{bc}	3.7 ^{ab}	1.2 ^{a}	75
2-Ca+2-K	10.0 ^{b}	5.4 ^{c}	3.9 ^{abc}	1.1 ^{a}	83
LSD	0.3	0.2	1.5	0.8	ns

Means of 180 fruit (from 18 trees) per treatment.

Means within columns with different letters are significantly different ($P<0.05$).

Overall, these results suggest that the effects of the treatments on soil exchangeable cations were not sufficient to affect either leaf or fruit minerals concentrations. There was also no significant treatment effect on fruit quality. However, a relatively small number of replicates per treatment (six) were used for minerals analysis. For the next season, 18 replicates (individual trees) were used. An increase in the number and the concentration of the K treatments was also applied to increase the possibility for cation imbalance and to determine its influence on fruit Ca and quality.

4.3.2 Season 2003-4

4.3.2.1 Soil minerals

The highest Ca treatment (12-Ca) resulted in more total exchangeable soil Ca than the lowest ones (1-Ca and 3-Ca) and the K alone treatment (4-K), but was not significantly different from the control (Table 8). Adding Ca to the K treatments (1-Ca+2-K and 1-Ca+4-K) increased total soil Ca compared with the K alone treatment (4-K). The higher Ca rates (treatments 6-Ca and 12-Ca) reduced total exchangeable soil Mg compared with the control, suggesting the treatments could potentially result in cation imbalances in the soil. Similar effects were observed in other studies with avocado trees in South Africa (Barnard 1989; Du Plessis and Koen 1987). As expected, total exchangeable soil K increased with added K (treatments 4-K, 1-Ca+2-K and 1-Ca+4-K), but was not affected by the addition of Ca alone (treatments 1-Ca, 2-Ca, 3-Ca and 6-Ca). Only the highest Ca treatment (12-Ca) increased the soil EC. These results suggest that the soil treatments had only a small effect on soil Ca 70 days after treatment.

There was more Ca, Mg and K in the top profile (0-10 cm), decreasing with greater depth (Table 8), likely because of the higher organic matter content in the top layer.

When comparing the total available cations in the top 30 cm (Table 9), especially in relation to the control (treatment-control), it is obvious that most of the Ca treatments, except for 12-Ca, did not increase the total available Ca, and the increase with the 12-Ca was considerably less than expected. This strongly indicates significant removal of cations from the top 30 cm, most likely due to leaching. This suggests that most of the added Ca was leached from the top 30 cm within 70 days of application, contrary to the popular belief that Ca moves slowly through the soil profile. In addition, the inconsistent results point to significant soil variability, which was not addressed by the soil sampling procedures. This made it impossible to develop a cation mass balance to estimate losses from the profile.

Table 8. Total exchangeable Ca, Mg and K concentrations (cmol/Kg) and electrical conductivity (EC; dS/M) in the soil 70 days after application of Ca (as microfine gypsum) and K (as potassium sulphate) to the soil under 'Hass' avocado trees before flowering in 2003.

Treatment	Total available soil (cmol/Kg)						**EC**	
	Ca		**Mg**		**K**		(dS/M)	
Control	2.26	abc	0.55	c	0.076	a	0.28	a
1-Ca	1.95	ab	0.47	abc	0.048	a	0.29	a
3-Ca	2.24	ab	0.54	bc	0.051	a	0.29	a
6-Ca	2.26	abc	0.43	ab	0.051	a	0.39	a
12-Ca	2.64	c	0.40	a	0.061	a	0.76	b
4-K	1.92	a	0.47	abc	0.145	b	0.32	a
1-Ca+2-K	2.33	bc	0.53	bc	0.225	c	0.39	a
1-Ca+4-K	2.35	bc	0.55	c	0.191	bc	0.32	a
LSD	0.40		0.11		0.05		0.16	
Soil depth (cm)								
0-10	3.26	c	0.82	c	0.15	b	0.56	b
10-20	1.98	b	0.40	b	0.10	a	0.32	a
20-30	1.49	a	0.26	a	0.07	a	0.25	a
LSD	0.25		0.07		0.03		0.10	

Means of 18 samples per soil treatment, and 48 samples per depth.

Means for either treatment or depth within columns with different letters are significantly different ($P<0.05$).

Table 9. Total exchangeable Ca, Mg and K (cmol/Kg) in the top 30 cm, and the difference in total exchangeable cations between the treatment and the control (Trt-control) in the soil 70 days after application of Ca (as microfine gypsum) and K (as potassium sulphate) to the soil under 'Hass' avocado trees before flowering in 2003.

Treatment	Ca		Mg		K	
	Total	Trt-Control	Total	Trt-Control	Total	Trt-Control
Control	6.77		1.66		0.23	
1-Ca	5.84	-0.93	1.41	-0.25	0.14	-0.08
3-Ca	6.71	-0.07	1.62	-0.04	0.15	-0.08
6-Ca	6.78	0.01	1.28	-0.39	0.15	-0.07
12-Ca	7.92	1.15	1.19	-0.47	0.18	-0.04
4-K	5.77	-1.00	1.40	-0.26	0.44	0.21
1-Ca+2-K	6.99	0.22	1.60	-0.06	0.67	0.45
1-Ca+4-K	7.04	0.27	1.64	-0.02	0.57	0.35

One way of identifying treatment effects when there is large site variability is to express the cations as a percentage of the effective cation exchange capacity (ECEC), which is the sum of exchangeable Ca,K, Mg, Na and Al ion equivalent concentration. Table 10 indicates that increasing gypsum applications did increase the Ca saturation with 6 and 12-Ca and higher.

The poor retention of Ca is most likely due to the low cation exchange capacity (CEC), with the top 10 cm having a CEC of 4.5, compared with 2-2.6 for the 10-30 cm layers. This CEC is fairly representative of many of the coastal Australian avocado soils and suggests that a single application of Ca at the start of flowering would have little effect on available Ca to the roots during early fruit growth (Moody, personal communication). More frequent, smaller applications are more likely to improve Ca availability. Increasing the organic matter and maintaining the pH above 6 to maximise the exchange capacity of the organic matter will also help retain more Ca in the soil (Brady 1974).

Table 10. The percentage of the total effective soil exchange capacity (ECEC) that is saturated with Ca and K at 0-10, 10-20 and 20-30 cm depth in the soil 70 days after application of Ca (as microfine gypsum) and K (as potassium sulphate) to the soil under 'Hass' avocado trees before flowering in 2003

Treatment	Ca saturation of ECEC (%)			K saturation of ECEC (%)		
	0-10	10-20	20-30	0-10	10-20	20-30
Control	72	76	75	2	2	4
1-Ca	72	75	75	2	2	3
3-Ca	74	77	76	2	2	2
6-Ca	80	80	77	2	2	2
12-Ca	84	79	81	2	2	2
4-K	70	71	74	6	6	4
1-Ca+2-K	70	73	75	7	7	7
1-Ca+4-K	69	74	77	6	6	6

4.3.2.2 Fruit minerals

The Ca concentration in the fruit flesh was significantly higher in the highest Ca treatment (12-Ca) compared with control, and most of the K treatments (4-K and 1-

Ca+4K; Table 11). The highest K treatment applied with Ca (1-Ca+4-K) resulted in significantly less flesh Ca than the same Ca treatment with no added K (1-Ca). This suggests an antagonistic effect of K on Ca fruit nutrition. In other fruit crops this antagonism has been attributed to K suppressing Ca absorption by roots (Himelrick and McDuffie 1983) or decreasing Ca status of fruit by reducing the ratio of xylem to phloem transport into fruit (Bangerth 1979). However, the treatment effects on fruit Ca were small when compared to the range of flesh Ca concentrations between adjacent trees observed in this site this season (216-508 mg/kg). Also, Vuthapanich (2001) observed fruit Ca concentrations of 180-450 mg/Kg across 6-8 farms in SE Queensland, or of 210-500 mg/Kg between adjacent trees on the same site.

Treatment 12-Ca resulted in less flesh Mg compared with the lowest Ca rate (1-Ca). The K treatments (4-K, 1-Ca+2-K and 1-Ca+4-K) also reduced flesh Mg compared with Ca alone (1-Ca). All K treatments resulted in more flesh K and consequently a lower (Ca+Mg)/K ratio compared with no additional K. There were no treatment effects on fruit flesh N.

Table 11. Calcium, Mg and K concentrations (mg/K or g/Kg), and (Ca+Mg)/K ratio in the flesh of 'Hass' avocado fruit, as affected by Ca (as microfine gypcsum) and K (as potassium sulphate) soil applications to the trees just before flowering in 2003.

Treatment	Fruit flesh concentration				(Ca+Mg)/K ratio
	Ca (mg/Kg)	**Mg** (mg/Kg)	**K** (g/Kg)	**N** (g/Kg)	
Control	335 ^{ab}	1039 ^{bc}	20.1 ^{ab}	11.6	0.070 ^{b}
1-Ca	354 ^{bc}	1059 ^{c}	21.4 ^{b}	12.4	0.067 ^{b}
3-Ca	361 ^{bc}	1039 ^{bc}	19.7 ^{a}	11.2	0.072 ^{b}
6-Ca	355 ^{bc}	1022 ^{abc}	20.5 ^{ab}	11.4	0.067 ^{b}
12-Ca	372 ^{c}	1003 ^{ab}	20.1 ^{ab}	10.5	0.069 ^{b}
4-K	336 ^{ab}	1017 ^{ab}	23.4 ^{c}	11.0	0.058 ^{a}
1-Ca+2-K	343 ^{bc}	1013 ^{ab}	23.5 ^{c}	11.3	0.059 ^{a}
1-Ca+4-K	309 ^{a}	995 ^{a}	22.9 ^{c}	11.2	0.058 ^{a}
LSD	33	40	1.45	ns	0.006

Means of 18 samples (from 7 fruit each) per treatment.

Means within columns with different letters are significantly different ($P<0.05$).

The Ca+K treatments reduced fruit flesh B compared to control and treatment 1-Ca, while higher Ca treaments increased fruit flesh Mn (data not shown). There were no treatment effects on the fruit flesh concentrations of Al, Cu, Fe, Na, P, S, and Zn (data not shown).

4.3.2.3 Fruit quality

Treatment 12-Ca delayed ripening slightly compared with control and most of the other treatments (Table 12). In contrast, the highest K treatments (4-K and 1-Ca+4-K) resulted in faster ripening than most of the other treatments. The Ca treatments had less diffuse discolouration than several of the K treatments, suggesting a positive effect of Ca compared with K. However, there was no significant difference in diffuse discolouration between the Ca treatments and control. In contrast, fruit from the K treatments had less stem end rots and vascular browning than most of the other treatments. There were no treatment effects on the percentage of acceptable fruit. There was also no treatment effects on body rots severity (mean across all treatments of 18%), purple-black skin at ripe (mean of 5.3), or fruit % DM (mean of 23.4%).

The effects of Ca and K on ripening time and of K on diffuse discoloration were small, but similar in direction as observed in other studies (Hofman et al. 2002a). However, as

in the 2002-3 season, the higher rots severity with higher Ca treatment (with no added K) was not expected, since fruit with higher Ca often have less rots (Hofman et al., 2002a). Again, it is possible that this unexpected treatment effect is partly due to Ca effect on ripening time since fruit that ripen more slowly generally have more rots (Hofman et al. 2002a), and fruit from two of the K treatments ripened more quickly and had less rots than all other treatments. The treatment effects of Ca or K on fruit Ca were most likely sufficient to have a small effect on ripening time, but not adequate to override the negative effect of longer ripening time on diseases.

Table 12. Ripening time (day) and severity (as % of the flesh volume affected) of stem end rots, diffuse discolouration and vascular browning in ripe 'Hass' avocado fruit, as affected by Ca (as microfine gypsum) and K (as potassium sulphate) soil applications to the trees just before flowering in 2003.

Treatment	Ripening time	Body rots	Stem end rots	Diffuse discolour.	Vascular browning	Acceptable fruit
	(day)	Flesh volume affected (%)				(%)
Control	14.1 ^{bc}	19.0	12.2 ^{c}	0.9 ^{abc}	1.8 ^{b}	18.0
1-Ca	14.0 ^{bc}	18.6	11.7 ^{bc}	0.8 ^{abc}	2.0 ^{b}	15.9
3-Ca	14.2 ^{cd}	16.4	15.3 ^{e}	0.5 ^{a}	3.1 ^{c}	18.0
6-Ca	14.0 ^{bc}	19.4	12.9 ^{cd}	0.6 ^{ab}	2.0 ^{b}	15.7
12-Ca	14.4 ^{d}	17.3	15.0 ^{de}	0.4 ^{a}	1.6 ^{ab}	21.1
4-K	13.6 ^{a}	17.1	9.1 ^{a}	0.5 ^{ab}	1.2 ^{a}	23.5
1-Ca+2-K	13.9 ^{b}	17.2	9.9 ^{ab}	1.1 ^{bc}	1.1 ^{a}	14.2
1-Ca+4-K	13.6 ^{a}	19.0	8.3 ^{a}	1.4 ^{c}	1.2 ^{a}	21.3
LSD	0.2	2.5	2.2	0.6	0.7	ns

Means of 180 fruit (from 18 trees) per treatment.

Means within columns with different letters are significantly different ($P<0.05$).

These results indicate that the Ca treatments increased fruit Ca concentrations sufficiently to reduce diffuse discolouration, but not enough to reduce rots. This may be related to the single Ca application before flowering not increasing soil solution Ca sufficiently and consistently enough to impact on fruit Ca concentrations. The low CEC of this soil was a contributing factor to the low retention of the added Ca 70 days after application.

The most effective way of consistently increasing soil solution Ca concentrations under these conditions is smaller, more frequent applications during the critical stages of early fruit growth. This approach was used in the final two years of the project.

4.3.2.4 Tree yield

There were no treatment effects on tree yield (mean of 49.6 Kg per tree), fruit number per tree (mean of 241 fruit per tree) or average fruit mass (mean of 208 g). By contrast, trials in northern New south Wales (Broadbent et al. 1989) and South Africa (Du Plessis and Koen 1987) resulted in increased yield, but both studies applied 9-10 ton/ha compared with the highest rate in this trial of 2.4 ton/ha.

4.3.2.5 Correlations

There were several significant correlations between fruit quality (including ripening time, and rots and diffuse discolouration severity) and flesh Ca, N and K, and between fruit quality and yield (Appendix 5). Generally, fruit with higher flesh Ca, and lower N

and K were associated with slower ripening, and less body rots and less diffuse discolouration, which increased the percentage of acceptable fruit (Table 13). Similar results were found in other studies (Eaks 1985; Hofman et al. 2002b; Thorp et al. 1997). Likewise, higher yielding trees often produced fruit which had less body rots and diffuse discolouration. However, the correlations with yield were generally not as strong as those with flesh minerals. In addition, longer ripening times were often associated with more stem end rots ($P<0.001$, $r = 0.56$), and less diffuse discolouration ($P<0.001$, $r = 0.28$).

Table 13. Correlations (linear correlation coefficient, r) between the percentage of acceptable fruit, ripening time, the severity of body rots, stem end rots and diffuse discolouration and yield per tree, flesh Ca, N and K concentrations in ripe 'Hass' avocado fruit harvested in 2004.

	Yield	Flesh Ca	Flesh N	Flesh K
Acceptable fruit	0.19*	0.30***	-0.32***	ns
Body rots	-0.15*	-0.35***	0.26***	0.15*
Stem end rots	ns	0.19*	-0.27***	-0.37***
Diffuse discolouration	-0.18*	-0.24**	0.22**	0.23**
Ripening time	0.23**	0.35***	-0.27***	-0.45***

(*, **, *** = significance at P<0.05, 0.01 or 0.001, respectively. ns = not significant).
Correlations are based on means from 144 trees (13 fruit per tree for fruit quality, and seven for flesh minerals).

4.3.3 Season 2004-5

4.3.3.1 Soil minerals

All Ca treatments increased total exchangeable Ca by 15-22% compared with the control (Table 14). In contrast, all Ca applications increased soil solution Ca concentrations by 4 to 8 times, with larger effects with increasing application rates. Frequent applications were more effective in increasing soil solution Ca 11 weeks after flowering compared with one application of normal gypsum at the start (12-Ca(G)).

Increasing soil solution Ca is a pre-requisite for increasing Ca uptake. It is likely that the single gypsum application just before flowering (12-Ca(G)) increased soil solution Ca significantly in the weeks following application, but that solution concentrations decreased to below that of the frequent applications of the same total amount (12-Ca) by 11 weeks after flowering. Therefore regular applications of the same total amount of Microgyp would be more effective at maintaining consistent soil solution Ca than a single application at flowering.

Table 14. Total exchangeable Ca, Mg and K concentrations in the soil (cmol/Kg), and Ca, K and Mg concentrations in the soil solution (mg/L), as affected by Ca applied to 'Hass' avocado trees. Fertilisers were either microfine gypsum at the rates of 6 kg/tree (6-Ca) or 12 kg/tree (12-Ca), or gypsum at the rate of 12 kg/tree (12-Ca(G)).

Treatment	Total exchangeable (cmol/Kg)			Soil solution (mg/L)		
	Ca	**Mg**	**K**	**Ca**	**Mg**	**K**
Control	2.25 [a]	0.71 [d]	0.055 [b]	37 [a]	16 [a]	9.6 [b]
6-Ca	2.60 [b]	0.58 [c]	0.048 [a]	186 [b]	55 [c]	5.9 [a]
12-Ca	2.75 [b]	0.46 [b]	0.046 [a]	317 [c]	75 [d]	10.3 [b]
12-Ca(G)	2.60 [b]	0.38 [a]	0.044 [a]	148 [b]	32 [b]	5.2 [a]
LSD	0.22	0.07	0.0042	38	13	3.1
Depth (cm)						
0-10	3.71 [c]	0.87 [c]	0.052 [b]	211 [b]	54 [b]	10.0 [b]

10-20	2.26 [b]	0.45 [b]	0.047 [a]	159 [a]	42 [a]	6.5 [a]
20-30	1.67 [a]	0.28 [a]	0.046 [a]	147 [a]	37 [a]	6.6 [a]
LSD	0.19	0.06	0.0036	33	12	2.7

Means for either treatment or depth within columns with different letters are significantly different (P<0.05).

Means of 108 samples from 18 trees per treatment (total of 432 samples from 72 trees).

The soil solution Mg concentration also increased with Ca application (Table 14). However, total exchangeable Mg was lower with Ca treatments, suggesting a displacement of Mg from the exchange complex into the soil solution. Total exchangeable K was lower with all Ca treatments, and soil solution K lower with 6-Ca and 12-Ca(G). This suggests added Ca may have removed K from the exchange complex making it more susceptible to leaching.

As in previous seasons, the total exchangeable and soil solution Ca, Mg and K were higher in the top 0-10 cm compared with 10-30 cm (Table 14).

Except for exchangeable Mg, there was no interaction between treatment and soil depth for the soil solution or exchangeable Ca, K, or Mg. The differences in soil solution Ca between treatments were significant at all soil depths. The differences in soil solution Ca between the highest Ca treatment and the control were higher with lower soil depths (6.5 times higher at 0-10 cm, 9.7 times higher at 10-20 cm, and 12.7 times higher at 20-30 cm). In contrast, the differences in exchangeable Ca between treatments were only significant at the 0-10 cm layer.

4.3.3.2 Plant minerals

Calcium concentrations in the xylem sap increased by almost 50% with the 6-Ca treatment (Table 15). Higher applications of MycroGyp had no additional effect on xylem sap Ca, while normal gypsum at flowering had no effect on xylem sap Ca compared with control. In addition, Ca treatments had no effect on the Ca concentration in the leaf, fruitlet skin or fruitlet flesh 11 weeks after flowering. There were indications of increased flesh and skin Ca in the mature fruit with Ca treatment compared with control, but this effect was not statistically significant.

Table 15. Calcium, Mg and K concentrations in the sap (mg/L), leaf, fruitlet flesh and fruit flesh (g/Kg) from 'Hass' avocado trees fertilised with Ca as either microfine gypsum at 6 kg/tree (6-Ca) and 12 kg/tree (12-Ca), or gypsum at 12 kg/tree (12-Ca(G)).

Treatment	Sap	Leaf (g/Kg)		Fruitlet[1] (g/Kg)		Fruit[2] (g/Kg)	
	(mg/L)	(Dec)	(May)	Skin	flesh	Skin	flesh
Ca							
Control	14.2 [a]	14.3	20.1	1.57	1.56	0.32	0.37
6-Ca	20.4 [b]	14.2	21.9	1.61	1.66	0.36	0.40
12-Ca	18.3 [ab]	15.2	21.5	1.64	1.59	0.35	0.39
12-Ca(G)	12.7 [a]	14.3	21.3	1.57	1.47	0.38	0.41
LSD	5.8	ns	ns	ns	ns	ns	ns
Mg							
Control	16.5 [b]	5.3	7.1	1.26	1.67 [c]	0.88	1.29
6-Ca	18.5 [b]	5.0	6.8	1.25	1.59 [bc]	0.87	1.25
12-Ca	16.1 [ab]	4.9	6.4	1.21	1.49 [ab]	0.81	1.22
12-Ca(G)	13.4 [a]	4.9	6.8	1.21	1.46 [a]	0.88	1.30
LSD	2.8	ns	ns	ns	0.11	ns	ns
K							
Control	124	8.7	5.3 [c]	19.4	15.5	14.0	23.6

6-Ca	134	9.1	5.9 [bc]	20.0	16.0	14.7	23.7
12-Ca	138	9.6	6.8 [a]	19.9	15.8	14.5	23.7
12-Ca(G)	121	8.9	6.5 [ab]	19.8	15.3	14.2	22.9
LSD	ns	ns	0.7	ns	ns	ns	ns

Means for each mineral within columns with different letters are significantly different (P<0.05).
Means of 18 trees per treatment (total of 72 trees).
1 = Harvested in Dec/2004.
2 = Harvested in May/2005.

Treatment 12-Ca(G) resulted in lower sap Mg and lower flesh Mg compared with control and treatment 6-Ca (Table 15). There were no treatment effects on leaf or fruitlet skin Mg. Treatments 12-Ca and 12-Ca(G) increased leaf K (sampled in May) compared with the control, but there were no treatment effects on K in the other plant tissues.

During the sampling procedure, the leaf and fruit samples were obtained from the branches used to extract the xylem sap, as well as from other locations around the tree. Only mature leaves were sampled. It is possible that the increased Ca in the xylem sap as a result of soil Ca applications did not increase the leaf or fruit Ca, but increased immature leaf, wood and bark Ca.

The Ca treatments increased leaf S, but not S concentrations in the other sampled plant tissues (data not shown). There were no treatment effects on leaf, fruitlet skin, or fruitlet flesh N (data not shown). There were also no treatment effects in the concentrations of Al, B, Cu, Fe, Mn, Na, P, and Zn in any of the sampled plant tissues (data not shown).

The results suggest that there may be inherent limitations to increasing Ca uptake into the avocado trees used in this experiment. Increasing Ca application rates from six to 12 kg per tree with frequent applications almost doubled the soil solution Ca concentration, but did not increase Ca sap concentrations. This could suggest a genetic limitation to Ca movement into the roots or translocation from the roots to the branches. This effect of genetics on minerals accumulation has been suggested in apple (Drake et al. 1988) and citrus (Fallahi and Rodney 1992) through rootstock effects on leaf or fruit mineral concentrations. Similar effects have been shown on leaf concentrations in avocado (Haas 1950), and a rootstock influence also suggested for the large differences in avocado fruit minerals concentrations between adjacent trees on random seedling rootstocks, and in glasshouse trials with seedlings (Hofman and Mullen 2005; Hofman et al. 2002b).

4.3.3.3 Fruit quality

Treatment 6-MG slightly delayed fruit ripening compared with all other treatments (including control) (Table 16). All Ca treatments resulted in fruit with slightly darker skin colour at ripe compared with control fruit. All Ca treatments slightly increased stem end rots severity, 6-MG and 12-MG increased tissue breakdown severity, and 6-MG increased body rots severity compared with control. There were no treatment effects on diffuse discolouration (average across all treatments of 3.7%) or vascular browning (average of 1.1%).

Table 16. Ripening time (days), skin colour (1-6) and severity (as % of the flesh volume or area affected) of body rots, stem end rots, and tissue breakdown in ripe 'Hass' avocado fruit, as affected by Ca soil applications. Fertilisers were either microfine gypsum at 6 (6-MG) or 12 kg/tree (12-MG), or gypsum at 12 kg/tree (12-Ca(G)).

Treatment	Ripening	Skin	Flesh volume[1] or area[2] affected (%)

	time (day)	colour (1-6)	Body rots[1]	Stem end rots[1]	Tissue breakdown[2]
Control	12.2 [a]	4.7 [a]	9.3 [a]	4.3 [a]	18.0 [a]
6-Ca	12.6 [b]	5.1 [c]	12.0 [b]	6.2 [b]	25.2 [b]
12-Ca	12.3 [a]	4.9 [b]	10.1 [a]	5.5 [b]	24.2 [b]
12-Ca(G)	12.4 [a]	5.0 [bc]	10.6 [ab]	6.0 [b]	18.1 [a]
LSD	0.26	0.14	1.75	1.06	3.9

Means within columns with different letters are significantly different ($P<0.05$).

Means of 360 fruit from 18 trees per treatment (total of 1440 samples from 72 trees).

In general, these results were similar to previous years, where Ca applications slightly increased ripening time, but also increased rots. In this season also, ripening time was significantly correlated to rots and disorders (Section 4.3.3.5), again suggesting that the treatment effects were sufficient to increase ripening time but not to reduce rots and disorders.

Therefore, despite the treatments increasing soil solution and xylem sap Ca concentrations, fruit minerals concentrations and quality was not improved. The suggestions of increased fruit Ca with Ca application may indicate a potential for increased sap Ca to increase fruit Ca. However, the fact that the highest K treatment increased soil solution Ca but did not further increase sap Ca, would suggest a genetic barrier within the rootstock to take up this additional solution Ca. Rootstock effects on Ca uptake in avocado has been suggested previously (Vuthapanich 2001; Willingham 2003), and has also been observed in other fruit crops (Granger and Looney 1983).

Given the above, it is unlikely that increasing Ca application rates will produce a significant fruit Ca concentration affect in this orchard. Therefore an alternative approach of applying Ca from flowering right through to harvest was used in the following season.

4.3.3.4 Tree yield

As in the previous seasons, there were also no treatment effects on tree yield (average across all treatments of 83.5 Kg), fruit number or average fruit mass (average of 208 g).

4.3.3.5 Correlations

Linear regression analyses of the data showed that soil Ca status did not correlate well with plant Ca status (Appendix 6). There were no significant linear correlations between soil solution Ca and sap, leaf, fruitlet flesh or fruit flesh Ca. Likewise, the correlations between total exchangeable Ca and sap, leaf, fruitlet flesh or fruit flesh Ca were not significant. These results suggest that soil Ca is not a good indicator of what happens in the tree, and that other factors such as limitations within the tree (genetics) affect the capacity of the tree to respond to increased soil solution Ca.

There were several significant correlations between fruit quality (including severity of rots and internal disorders) and yield, and between fruit quality and ripening time (Table 17). Generally, higher yielding trees produced better quality fruit (less body rots and internal disorders, resulting in a higher percentage of ripe acceptable fruit). Likewise, fruit that ripened more slowly had more rots and diffuse discolouration, and were less acceptable. The correlation between tree yield and ripening time was not significant. Overall, the correlations between fruit quality and yield per tree were generally stronger than the correlations between fruit quality and flesh Ca or flesh N, thus highlighting the importance of crop load on avocado fruit quality. This was different from the 2003-4 season, possibly due to differences in the treatments, biennial bearing effects, and

average yield per tree (83.5 kg in 2004-5 compared to 49.6 kg in 2003-4). The correlations between fruit quality attributes and flesh K were not significant.

Similar relationships between avocado tree yield and quality have been noted between adjacent trees is in the same orchard block (Hofman et al. 2002b) and more generally across several districts (Vuthapanich 2001). This mechanism may also be a factor in the higher yielding rootstocks also producing better quality Hass fruit (Willingham 2005). These results suggest that focusing on improving yield may be a productive approach in improving quality, and also improving grower returns through yield improvement.

Table 17. Correlations (linear correlation coefficient, r) between the percentage of acceptable fruit, the severity of body rots, stem end rots, tissue breakdown and diffuse discolouration in ripe 'Hass' avocado fruit harvested in 2005, and yield per tree, ripening time, Ca, K and N concentrations in the fruit flesh.

	Yield	Ripening time	Flesh Ca	Flesh K	Flesh N
Acceptable fruit	0.39***	-0.45***	0.25*	ns	-0.25*
Body rots	-0.32**	0.56***	ns	ns	ns
Stem end rots	ns	0.69***	ns	ns	ns
Tissue breakdown	-0.40***	ns	-0.23*	ns	0.37***
Diffuse discolouration	-0.47***	-0.27*	ns	ns	ns

(*, **, *** = significant at P<0.05, 0.01 or 0.001, respectively. ns = not significant).
Correlations are based on means of 20 (ripening time) or 10 (flesh Ca and N) fruit per tree from 72 trees.

4.3.4 Season 2005-6

4.3.4.1 Soil minerals

The Ca treatments (Ca and Ca+K) increased Ca concentrations in the soil solution 4-6 times compared with the control (Table 18). Solution Ca was higher with Ca+K, compared with Ca alone. A similar trend was noted with total exchangeable cations, but the effects were not significant. Treatment effects this season were of the same magnitude as in 2004/5, but were not statistically significant

Table 18. Total exchangeable Ca, Mg and K concentrations in the soil (cmol/Kg), and Ca, K and Mg concentrations in the soil solution (mg/L), as affected by Ca or K applied to the soil under 'Hass' avocado trees. Treatments were Ca only (19.3 kg MicroGyp/tree), K only (6.4 kg potassium sulphate/tree), or MicroGyp and potassium sulphate combined.

Treatment	Total exchangeable (cmol/Kg)			Soil solution (mg/L)		
	Ca	**Mg**	**K**	**Ca**	**Mg**	**K**
Control	2.02	0.67	0.08 [a]	17 [a]	7 [a]	7 [a]
Ca	2.76	0.74	0.07 [a]	77 [b]	24 [b]	10 [a]
K	2.37	0.71	0.30 [b]	36 [a]	14 [a]	65 [b]
Ca+K	2.70	0.60	0.27 [b]	106 [c]	31 [b]	78 [b]
LSD	ns	ns	0.05	27	7.0	17

Means within columns with different letters are significantly different (P<0.05).

Means of 108 samples from 18 trees per treatment (total of 432 samples from 72 trees).

As expected, K applied alone, or with Ca, increased total exchangeable and soil solution K by 4-10 times, with no differences between both K treatments (Table 18). As in the previous season, soil solution Mg increased with Ca application but not with added K, while total exchangeable Mg was not affected.

The increase in exchangeable and solution concentrations was greater for K than for Ca. The large increase in exchangeable K with K treatment suggests a strong exchange complex affinity for K, potentially at the expense of Ca as evidenced by the increased solution Ca concentration. As a result, added K could remove Ca from exchange sites to the soil solution. If Ca is not regularly applied then depletion of solution Ca is possible.

The behaviour of typical avocado soils to Ca and K is investigated further in Chapter 5.

4.3.4.2 Plant minerals

Calcium application had no effect on sap, leaf, fruitlet or fruit Ca (Table 19). There were indications of higher Ca concentrations in the sap and leaf and fruitlet, but these differences were not significant. The only significant treatment effect on Ca was reduced concentrations in the fruit skin with K alone, compared with all other treatments.

There were also no significant treatment effects on Mg, apart from lower concentrations in the fruit skin with all treatments (Table 19).

Table 19. Calcium, Mg and K concentrations in the sap (mg/L), leaf, fruitlet flesh and fruit flesh (g/Kg) from 'Hass' avocado trees following Ca and K soil applications. Treatments were Ca only (19.3 kg MicroGyp/tree), K only (6.4 kg potassium sulphate/tree), or MicroGyp and potassium sulphate combined.

Treatment	Sap (mg/L)	Leaf (g/Kg)		Fruitlet[1] (g/Kg)		Fruit[2] (g/Kg)	
		(Nov)	(Jun)	Skin	Flesh	Skin	Flesh
Ca							
Control	19.1	22.3	26.4	1.39	1.06	0.31 ^{b}	0.28
Ca	23.7	24.2	29.1	1.42	1.08	0.31 ^{b}	0.27
K	20.9	23.9	26.7	1.34	1.10	0.27 ^{a}	0.26
Ca+K	21.8	23.5	25.9	1.36	1.07	0.31 ^{b}	0.28
LSD	ns	ns	ns	ns	ns	0.033	ns
Mg							
Control	15.5	8.6	9.3	1.3	1.5	0.92 ^{c}	1.1
Ca	17.9	8.5	9.4	1.3	1.5	0.89 ^{b}	1.1
K	15.0	8.6	9.3	1.3	1.5	0.86 ^{b}	1.1
Ca+K	16.9	8.4	9.1	1.3	1.5	0.82 ^{a}	1.1
LSD	ns	ns	ns	ns	ns	0.032	ns
K							
Control	67.6 ^{a}	6.9 ^{a}	5.8 ^{a}	19.1 ^{a}	13.1 ^{a}	14.5 ^{a}	19.4 ^{a}
Ca	86.2 ^{b}	7.7 ^{ab}	6.1 ^{ab}	20.5 ^{b}	13.9 ^{b}	14.6 ^{a}	21.1 ^{ab}
K	77.5 ^{ab}	8.3 ^{b}	7.0 ^{bc}	21.2 ^{b}	14.2 ^{b}	16.5 ^{b}	22.9 ^{bc}
Ca+K	79.9 ^{b}	8.4 ^{b}	7.0 ^{bc}	20.3 ^{ab}	14.3 ^{b}	14.5 ^{a}	23.8 ^{c}
LSD	12.0	1.1	0.93	1.3	0.8	1.4	2.0

Means for each mineral within columns with different letters are significantly different (P<0.05).
Means of 180 samples per treatment (total of 720 samples).
1 = Harvested in Nov/2005.
2 = Harvested in Jun/2006.

Compared with control, K applied alone or with Ca, increased K concentrations in the sap (Table 19), most likely because of the increase in soil solution K caused by these treatments. This generally resulted in increased K in the leaves, fruitlet, and fruit flesh compared with control. In a previous study conducted in a heavy soil in Israel, K applications to the soil did not increase leaf K in 'Hass' trees, but did increase in Fuerte trees (Lahav et al. 1976). There is no known published data on the effects of K soil application on avocado fruit K. The combination of K and Ca negated the effects of K alone in the fruit skin by decreasing the K concentration compared to K alone. Apart from this, the combination treatment showed little difference from the individual treatments.

Calcium alone increased sap and fruitlet skin and flesh K concentration (Table 19). The mechanisms involved are not clear since Ca alone did not increase the total exchangeable or the soil solution K (Table 18).

The Ca treatments increased leaf and fruit flesh S, while the Ca and K treatments reduced fruitlet flesh and fruit flesh Mn, although there were no treatment effects on S and Mn concentrations in the other sampled plant tissues (data not shown). There were also no treatment effects on the concentrations of N, Al, B, Cu, Fe, Na, P, and Zn in any of the sampled plant tissues (data not shown).

4.3.4.3 Fruit quality

Potassium applications (treatments K and Ca+K) resulted in lower dry matter at harvest compared with control fruit (Table 20). Calcium alone reduced diffuse discolouration severity compared with the other treatments, and reduced body rots compared with K alone.

Potassium alone increased diffuse discolouration compared with control and Ca alone, but addition of Ca with K resulted in similar severity to control (Table 20).

There were no treatment effects on ripening time (average across all treatments of 7.8 days after removal from ethylene), skin colour (average rating of 4.3), or stem end rots severity (average of 0.1%) and tissue breakdown (average of 0.2%) (data not shown). The severity of all defects was generally very low, and the severity of vascular browning was nil.

Table 20. Dry matter (%) of 'Hass' avocado fruit at harvest, and severity (as % of the flesh volume affected) of body rots and diffuse discolouration in ripe 'Hass' avocado fruit, following Ca and K soil applications. Treatments were Ca only (19.3 kg MicroGyp/tree), K only (6.4 kg potassium sulphate/tree), or MicroGyp and potassium sulphate combined.

Treatment	Dry matter	Flesh volume affected (%) at ripe	
	At harvest (%)	Body Rots	Diffuse discolouration
Control	26.0 [b]	0.2 [ab]	1.7 [b]
Ca	25.6 [ab]	0.1 [a]	1.0 [a]
K	25.1 [a]	0.3 [b]	2.4 [c]
Ca+K	25.0 [a]	0.2 [ab]	2.0 [bc]
LSD	0.73	0.14	0.67

Means within columns with different letters are significantly different ($P<0.05$).

Means of 360 fruit from 18 trees per treatment (total of 1440 samples from 72 trees).

Overall, the Ca treatments increased soil solution Ca markedly (3-5 times), but this had little effect on sap, leaf or fruit Ca concentration. This again indicates the difficulties in getting Ca into the tree and may further confirm a genetic limitation of the rootstock to Ca uptake. However, the Ca treatment improved fruit quality despite the absence of a treatment effect on fruit Ca. The reasons for this effect are unclear but may be related to the reduced fruit K concentration since higher fruit K can be associated with more rots in some seasons (Vuthapanich 2001). In contrast, K treatments resulted in an increase in K concentrations in the sap, leaf and fruit (about 10-20% depending on the plant tissue).

The increase in body rots and diffuse discoloration severity with K treatment is in agreement with the general observation that higher fruit K concentrations are associated with reduced fruit quality. In addition, the lower skin Ca concentration observed with K treatment (with similar trends for mature flesh Ca) may also have contributed to the reduced fruit quality with K treatment. These results again confirm the potential for K applications to negatively affect Ca nutrition and avocado fruit quality.

4.3.4.4 Tree yield

As in the last two seasons, there were no treatment effects on tree yield (average across all treatments of 141.7 kg), fruit number (average of 713 fruit per tree), or mean fruit mass (average of 199.2 g).

The leaf K concentrations in the control treatment (5.8 g/kg) were below the minimum recommended of 7.5 g/kg (Newett et al. 2001). The K treatment alone increased leaf K concentrations only slightly, even though the total application during the trial (the equivalent of 600 kg/ha) is generally more than recommended. The K treatment resulted in leaf concentrations close to the minimum recommended, but there was no effect on tree yield. In this season the average tree yield was equivalent to about 28 tons/ha, perhaps suggesting that the below recommended leaf K concentrations had little effect on yield. Therefore, it is possible that K recommendations could be reduced, with benefit to Ca nutrition and fruit quality.

4.3.4.5 Correlations

Linear regression analyses indicated that flesh Ca was positively correlated with ripening time and negatively correlated with dry matter, but there was no positive correlation with severity of rots and diffuse discolouration (Table 21). The absence of a correlation between fruit Ca and fruit quality over the three years may reflect seasonal influences, since there were significant relationships between fruit minerals and quality in only two of the three years, or an overriding effect of yield on the interaction between fruit Ca and quality. In contrast, flesh K was negatively correlated with ripening time and positively correlated with dry matter, in addition to being positively correlated with severity of diffuse discolouration. The correlation between flesh K and rots was not significant.

Table 21. Correlations (linear correlation coefficient, r) between the severity of body rots, stem end rots, or diffuse discolouration, ripening time, or dry matter at harvest in 'Hass' avocado fruit from 2004 to 2006, and yield per tree, and Ca and N concentrations in the fruit flesh.

	Yield	Flesh Ca	Flesh K
Body rots severity	-0.68***	ns	ns
Stem end rots severity	-0.63***	ns	ns
Diffuse discolouration severity	ns	ns	0.24*
Ripening time	ns	0.59***	-0.34*
Dry matter (at harvest)	0.52***	-0.36*	0.33**

*, **, *** = significant at P<0.05, 0.01 or 0.001, respectively. ns = not significant.

Correlations are based on means of 20 (ripening time) or 10 (flesh Ca and N) fruit per tree from 72 trees.

As in the previous season, soil Ca status did not correlate well with plant Ca status (Appendix 4). There were no significant linear correlations between soil solution Ca and sap, leaf, or fruit flesh Ca. There was a significant negative correlation between flesh Ca and flesh K, although not very strong (r = 0.23). There were no significant correlations between flesh Ca and soil, leaf, or sap K, nor between flesh Ca and flesh N.

In contrast with last season, there were no significant correlations between yield and fruit quality (including severity of rots and internal disorders), or between yield and ripening time (Appendix 4). There were also no significant correlations between yield and leaf or flesh Ca, flesh K, or flesh N. This may be related to the significantly higher yield across most trees this year, with few trees showing the low yields noted in previous years. This may have masked any effect of tree yield on fruit quality. In

addition, the higher yield in 2005/6 this may also explain the very good fruit quality in 2005/6, compared with 2004/5 and 2003/4 (Table 22).

Table 22. Average yield (kg) of 'Hass' avocado trees, severity (as percentage of fruit flesh volume affected) of body rots, stem end rots and diffuse discolouration, and the percentage of acceptable fruit from 2003 to 2006.

Season	Yield per tree (kg)	Flesh volume affected (%)			Acceptable fruit (%)
		Body rots	Stem end rots	Diffuse discolour.	
2003-4	49.6	18.0	11.8	0.8	18
2004-5	83.5	10.5	5.5	3.7	34
2005-6	141.7	0.2	0.1	1.8	95

When only the control trees were considered over the last three seasons (yield per tree was not determined in 2002-3), there were highly significant ($P<0.001$) and relatively strong (negative) correlations between yield and severity of rots (Figure 1, Table 21). Trees with higher yield generally produced fruit with lower severity of both body rots and stem end rots. Similar results for body rots were found in a previous study (Hofman et al. 2002a). In addition, the variation in rots severity was less among these higher yielding trees. These results confirm the importance of crop load on avocado fruit quality, and in the years with a lower yield, this relationship may play a more significant role in fruit quality than fruit minerals concentrations.

There were also significant positive correlations between yield per tree and dry matter (Table 21), indicating that higher yielding trees could reach legal maturity more quickly. The correlations between yield and severity of diffuse discolouration ripening time or ripening time was not significant.

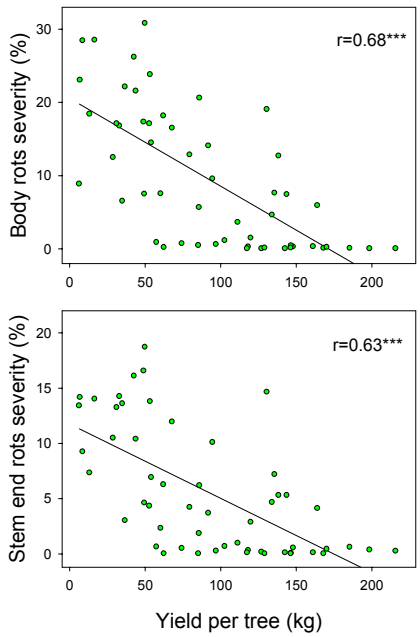

Figure 1. Relation between Hass avocado yield per tree and severity of either body rots or stem end rots (average per tree) for the control trees of the trial. Each point is the average for an individual tree in either the 2003-4, 2004-5, or 2005-6 season.

5 Selective adsorption of Ca and K in typical avocado soils under laboratory and glasshouse conditions

5.1 Introduction

The results of Chapter 4 indicated that gypsum applications to avocado orchards on sandy loam soil did not consistently improve fruit Ca concentrations or fruit quality. The results also demonstrated that:

- Contrary to generally accepted principles, soil-applied Ca moved rapidly through the top 30 cm of the sandy loam soil used in the field experiments. These results justified the use of more frequent Ca applications in the later field experiments.
- There are possible interactions between soil Ca and K which may interfere with tree and fruit Ca nutrition.
- It appears that the movement of Ca in our subtropical horticultural soils it is not the same as that in the Australian high cation exchange capacity broad acre agricultural soils on which the current understanding of Ca movement in Australian agricultural soils is based. Therefore, an examination of cation behaviour in typical sub-tropical horticultural soils is justified.

Plant nutritional status is a function of soil cation availability, governed by mass flow and diffusion through the soil solution, interactions between cations in solution, uptake capacity of plant roots and efficient nutrient transport within the plant (Jakobsen 1993). Plants take up cations from the soil solution phase, and thus cations in the soil solution are termed ‘available’.

Soil solution cations are in equilibrium with exchangeable cations on soil colloid (usually clay) exchange sites. The exchange capacity and the selectivity of exchange sites determine the proportion of cations in soil solution. Selective adsorption of one cation over another can lead to a decrease in availability of that nutrient and can cause plant nutritional deficiencies.

Current Ca fertiliser recommendations are based on requirements for effective leaf and tree functioning. Relatively little consideration has been given to Ca recommendations for fruit quality. This is partly because of a lack of information on dose-response curves for Ca and fruit quality. Avocado fruit Ca concentrations under Australian conditions range from about 250-500 mg kg-1 (Vuthapanich 2001), but there is no indication of negative effects of higher fruit concentrations. However, it is possible that increasing Ca soil applications to increase fruit concentrations can cause other mineral imbalances in the soil with negative effects on the overall tree nutrition.

Low Ca availability in soils is atypical (Himelrick and McDuffie 1983). Plant Ca deficiency is more often the result of antagonism between ions in soil solution, rather than poor soil availability. The results from Chapter 4, and from glasshouse studies on the interaction between rootstock variety and Ca/K nutrition suggest that K may be one cation involved in interactions with Ca. Rootstock genetic limitations may also be involved, as well as translocation from the roots to the top, and into the fruit (Hofman and Mullen 2005).

Obviously, the first "barrier" to Ca nutrition is adequate availability in the soil solution, which is determined by the exchange characteristics of the soil. The work in this chapter was conducted to determine the exchange selectivity of typical avocado producing soils to the major cations, as well as the impact of Ca/K fertiliser on avocado seedling Ca uptake. The results are applicable both to the understanding of exchange characteristics of our highly weathered avocado soils, as well as contributing to developing effective fertiliser regimes for improving avocado Ca nutrition.

Soil Ca and K may be present in mineral forms, inorganic compounds, organic matter, on the exchange complex and in soil solution. The amount in each component depends on the physical and chemical characteristics of the soil, degree of weathering, and the amount of organic matter (Himelrick and McDuffie 1983).

Calcium is the dominant exchangeable cation in most neutral to alkaline soils (Barber 1995). Exchangeable Ca is in the range of 30-40cmol$^{(+)}$/kg in most soil, however highly weathered acid soils have much lower amounts of less than 5cmol$^{(+)}$/kg (Bruce 1999; Menzies et al. 1994). Soil solution Ca exhibits a wide range of concentrations from at least 10 -15000µM. In the highly weathered acid soils typical of avocado orchards in Australia, values are usually less than 3000µM (Bruce 1999). In highly weathered soils K is more dominant in the soil solution than Ca, and the opposite is typical for young soils (Menzies and Bell 1988).

The dominant clay fraction in soil significantly influences soil Ca and K partitioning, as clay mineralogy largely determines ion exchange, release and fixation. Therefore it is important to understand the nature of clays and their predominance in different soils. Clay mineralogy can be used as a preliminary predictive tool to indicate ion exchange behaviour.

Clay minerals can be separated into three broad categories, layer silicates, Fe/Al oxides and hydroxides, and amorphous clays (Brady 1990). The crystal structure of layer silicates is that of silicon (Si) sheets in a tetrahedral coordination with oxygen (O), and aluminium (Al) sheets in octahedral coordination with hydroxides (OH) (White 2002). Crystal lattices or layers form with the sharing of O atoms between sheets in combinations of either 1:1 or 2:1 tetrahedral to octahedral sheets (Brady 1990). Surface charge is a result of the chemically active surfaces and edges of the crystal sheets (Taylor et al. 1983). Permanent negative charge resulting from isomorphous substitution is balanced by cations entering the interlayer space between sheets (Sposito 1989). Potassium ions are a ‘perfect fit’ and are the most common ion found in the interlayer space. Isomorphous substitution and interlayer expansion is more common in 2:1 layer silicates such as Smectite and Vermiculite, and results in a large negative charge (Goulding 1983), and greater affinity for K. The 1:1 layer silicates, such as Kaolinite, have a smaller negative charge as sheets are held together more strongly, thus restricting the effective exposed surface area (Brady 1990).

The size and chemical properties of K results in selective adsorption over other cations into the interlayer spaces and edge sites of micaceous minerals (Kirkman et al. 1994). The planar faces of Kaolinite and Smectite clays however have binding sites for other cations (Hisenger 2002). Potassium is much less strongly held in soils with a dominant clay fraction of Kaolinite and Smectite, than soils with a dominant clay fraction of Illite and Muscovite (Sparks and Huang 1985).

Fe/Al oxides and hydroxide clays are common in highly weathered, tropical soils. Their charge arises mainly from variable charge, and adsorption of nutrients is often specific or controlled by pH (Taylor et al. 1983). In strongly acid soils these clays contribute considerable anion exchange capacity (Taylor et al. 1983). Soils also comprise colloids with poor or no crystalline structure (amorphous clays). These clays are undetectable by

the X-ray diffraction techniques used in describing mineral compositions of soils (Brady 1990). This has implications because although undetected, it makes a considerable contribution to the soil exchange capacity (Taylor et al. 1983). The most common example is Allophane.

A Ferrosol is a highly weathered soil categorised as an Oxisol. In Queensland, Ferrosols are commonly used in avocado production. They are characteristically low in fertility, have low CEC, are often acidic, red in colour and are derived from basaltic material (Moody 1994). The clay fraction is predominantly the 1:1 layer silicate Kaolinite, so that permeability can be high especially in high rainfall areas (Gillman et al. 1989). They also contain a considerable portion of Fe/Al oxides and hydroxides.

Highly weathered soils are known to have very different physio-chemical properties than less weathered or temperate soils (Moody 1994). Exchange mechanisms and cation behaviour are less understood in these soils than those of the temperate soils. Soils with a low CEC in high rainfall areas are especially susceptible to loss of nutrients through leaching (Brady 1990). Due to the dominance of 1:1 layer silicates such as Kaolinite, it has been assumed in the past that highly weathered soils do not have the capacity to adsorb and exchange nutrients as well as 2:1 minerals (Poss et al. 1991). These factors have considerable implications for understanding nutrient mobility, exchange and fertiliser impacts on such soils. Considering the above, theoretically Ferrosols have a limited capacity to adsorb and exchange nutrients such as K. However, experimentally and practically results have shown otherwise.

Most of the current knowledge of K-Ca exchange has come for work on temperate soils and little is known about tropical soils, except for studies undertaken on Allophane rich soils (Alves and Lavorenti 2003). Theoretically, soils dominated by Kaolinite do not have selective binding sites for K (Malavolta 1985). Selectivity of kaolinitic soils for K could be attributable to impurities of 2:1 minerals, allowing for greater K selectivity capacity (Goulding 1983; Poss et al. 1997). One of the earliest studies focusing on K selectivity discovered that small amounts of Mica and Vermiculite impurities that are undetected by mineralogical analysis can account for the unexpectedly high selectivity of K (Carson and Dixon 1972). Therefore minor constituents in mineralogy can have a significant influence on nutrient dynamics, and nutrient exchanging capacity cannot be predicted solely by the dominant clay fraction (Goulding 1983).

Adding K to leaching columns results in no significant difference in the amount of K in the leachate between the control and treated column (added K) (White 2002). However, Ca, Mg and Na increased significantly in the leachate from the treated column (White 2002). The addition of K resulted in the adsorption of K at the surface, in turn displacing other cations such as Ca, Mg, and Na, that were lost from the profile via leaching, causing a significant decrease in exchangeable Ca relative to the control (White 2002). The Ferrosol showed a relative preference for K over Ca. This has important implications for the application and balance of Ca and K fertilisers on Ferrosols.

Liming has also been shown to increase the selectivity of Oxisols and Ultisols for K (Goedert et al. 1975). Liming created additional high affinity exchange sites for K possibly by increasing the pH, subsequently having an effect on variable charged clay surfaces (Goedert et al. 1975). Liming is a common practice on agricultural soils as an amendment for acidity and maintenance of soil structure.

Not all research on highly weathered soils has shown selectivity for K. Potassium added to a Queensland Oxisol (grass/legume pasture) showed rapid distribution up to 50cm deep; thus K was susceptible to losses through leaching (Gillman et al. 1989). The large applications of K also showed no effects on exchangeable Ca and Mg levels.

Soil solution is the most direct indicator of conditions around the root (Pearson 1971). Soil solution is the phase in which soil chemical reactions take place (Wolt 1994), and forms the pool of cations available for plant uptake (McLaughlin et al. 1999). Soil solution is in equilibrium with cations reversibly held by exchange sites on the solid phase (Lindsay 1979). Exchange sites release cations into soil solution via desorption when plants uptake cations, and thus the exchange phase replenishes and buffers the soil solution composition (Lindsay 1979). Thus due to the direct relationship between soil exchange and soil solution, the selectivity of exchange sites for cations directly affects the availability of those cations to plants.

For most soils Ca is the dominant exchangeable and soil solution cation. However, highly weathered soils tend to deviate from this norm (Wolt 1994). Surface soils of highly weathered acid soils have a typical soil solution cation ranking in the order of Na>K>Mg>Ca (Menzies and Bell 1988), in contrast to temperate soils with a typical ranking of Ca>K>Na>Mg (Edmeades et al. 1985).

Calcium deficiency has been reported in some pasture legumes on highly weathered soils of North Queensland, due to low values of soil solution Ca associated with highly weathered soils (Bruce et al. 1989). Recent findings of anomalously high selectivity of K on exchange sites of highly weathered soils (White 2002) contradicts past findings of elevated levels of K in soil solution as well as mineralogical characteristics. However, a combination of high relative selectivity of K and high levels of K in soil solution will only intensify any adverse interaction between K and Ca in affecting the Ca nutrition of avocadoes.

The aims of the experiments reported in this chapter were to:

1) Determine the exchange selectivity of typical avocado producing soils to Ca, K, Mg and Na.
2) Construct exchange isotherms and calculate selectivity coefficients for Ca-K, Ca-Mg and Ca-Na exchange on avocado producing soils.
3) Determine the effect of Ca:K fertiliser on the Ca availability in soil solution and uptake of avocado seedlings.

To achieve these aims the following work was completed;

1) Batch competitive adsorption experiments on ten representative avocado soils to determine solution and exchange phase cation concentrations.
2) The response of Velvick avocado seedlings grown in seven Ca:K ratios under glasshouse conditions was followed by measuring soil solution and tissue cation concentrations.

5.2 Materials and methods

5.2.1 Exchange selectivity

Ten soil samples were collected from commercial avocado orchards throughout Queensland and Western Australia. Bauxite residue was also included because of its known characteristics. The samples were taken from 15-30cm depth to minimise the influence of organic matter. The soils sampled are termed highly weathered soils, and their origin and classifications (Isbell 1996) listed in Table 23.

Table 23. The location and classification of the highly weathered surface soils of typical avocado orchards.

Location	Soil type
Gove	Anthroposol*
Bundaberg	Kurosol
Childers	Ferrosol
Mareeba	Kandosol
Tolga	Ferrosol
Toowoomba	Ferrosol
South Burnett	Ferrosol
St. Kolan	Kandosol
Western Australia	Kandosol/Lithosol**
Redland Bay	Ferrrosol

*Bauxite residue; a by-product of aluminium production (Kopittke *et al.* 2004). **Classification based on loamy texture and presence of lithic fragments (gravel).

Exchange selectivity of the sampled soils using Ca-K, Ca-Mg and Ca-K exchange reactions were determined by following the methods of Sumner and Miller (1996), with some modification. The solution ratios used are listed in Table 24 and Table 25, and were calculated at a constant ionic strength of 0.06M as this is a typical ionic strength of highly weathered soil solutions (Menzies et al. 1994). Soil samples were air dried (60º) and sieved to 2mm prior to analysis.

Table 24. Solution ratios and solution concentrations used to determine exchange selectivity between Ca-K and Ca-Na exchange reactions on 10 highly weathered soils. Ratios were calculated at a constant ionic strength of 0.06M.

Desired ratio	Equivalent ratio		Concentration required (mM)	
Ca/K and Ca/Na	Ca	K or Na	Ca	K or Na
0.01	0.0125	0.9875	0.4	60.0
0.03	0.025	0.875	0.7	57.7
0.05	0.05	0.95	1.5	56.1
0.11	0.1	0.9	2.9	52.2
0.25	0.2	0.8	5.5	44.0
0.67	0.4	0.6	10.0	30.0
1.50	0.6	0.4	14.0	18.7
4.00	0.8	0.2	17.3	8.6

Table 25. Solution ratios and solution concentrations used to determine exchange selectivity between Ca-Mg exchange on 10 highly weathered soils. Ratios were calculated at a constant ionic strength of 0.06M.

Desired ratio	Equivalent ratio		Concentration required (mM)	
Ca/Mg	Ca	Mg	Ca	Mg
0.25	0.2	0.8	4	16
0.43	0.3	0.7	6	14
0.57	0.4	0.6	8	12
1.00	0.5	0.5	10	10
1.50	0.6	0.4	12	8
2.33	0.7	0.3	14	6
4.00	0.8	0.2	16	4
9.00	0.9	0.1	18	2

The Ca-K, Ca-Na, Ca-Mg exchange experiments were carried out using a batch technique. Eight duplicate 2g soil samples of each soil were weighed into 50mL test tubes. Initially, to each of these test tubes was added 20mL of 0.1M $CaCl_2$ to equilibrate the samples. The samples were shaken end over end for 1h, centrifuged, supernatant discarded, and vortex mixed. Then to each of these test tubes was added 20mL of solution composed of various ratios of the two cations (Table 24 and Table 25). The samples were shaken end over end for 1h, centrifuged, supernatants extracted, and vortex mixed. This was repeated three more times. At the last wash the supernatants were collected after centrifuging for determination of cation concentrations in the solution phase. Each sample was then washed with 20mL, 0.1M $BaCl_2/NH_4Cl$ extracting solution, shaken end over end for 1hr, centrifuged, and supernatants collected to determine exchange phase cations. Solution and exchange phase supernatants were analysed for Ca, K, Na and Mg by inductively coupled plasma atomic emission spectroscopy (ICPAES).

Exchange isotherms were constructed for Ca-K and Ca-Mg and Ca-Na exchange reactions, from the cation concentrations in solution and on the exchange phase. Selectivity coefficients were calculated using the Vanselow selectivity equation as follows:

The monovalent-divalent exchange reaction at equilibrium can be written as

$$0.5X_2A_{(soil)} + B^{+}{}_{(solution)} \Leftrightarrow XB_{(soil)} + 0.5A^{2+}{}_{(solution)}$$

where A is the divalent cation, B is the monovalent cation and X-1 represents one unit of charge on the negative exchange complex (Evangelou and Marsi 2003). Based on the direction and stoichiometry of the above reaction, the Vanselow exchange selectivity coefficient (K_v) can be described as

$$K_v = \frac{X_A^{0.5} a_B}{X_B a_A^{0.5}} (L/mol^{0.5})$$

$$X_B = \frac{ExB}{ExB + Ex_2A}$$

$$X_A = \frac{Ex_2A}{ExB + Ex_2A}$$

where XB is the mole fraction of the exchangeable monovalent cation, XA denotes the mole fraction of the exchangeable divalent cation, aB represents the activity of solution phase monovalent cation and aA denotes the activity of solution phase divalent cation. ExB and Ex2A are exchangeable monovalent and divalent ion concentrations (expressed as moles/kg soil) (Kopittke 2005). Solution phase ion activities where calculated using the extended Debye-Huckel equation (McBride 1994). Under the Vanselow selectivity equation it is assumed that the activities of the ions on the exchange phase are equal to their mole fractions (Vanselow 1932). The Vanselow equation expresses a selectivity coefficient (Kv) that takes into account the valency effect in exchange reactions. When expressed as the above equation, Kv>1 indicates a selectivity for a divalent cation over a monovalent, Kv<1 represents selectivity for a monovalent ion.

The selectivity coefficients are dependent on solution ion activities, and thus are dependent on the ionic strength. If selectivity coefficients are determined in solutions of the same ionic strength, they can be used to compare the selectivity of the exchanger for

the cations of interest over a series of exchange reactions (Levy et al. 1988). Therefore the ionic strength of added ion solutions was kept constant at 0.06M.

These equations were modified appropriately when considering the Ca-Mg exchange (a divalent-divalent exchange).

5.2.2 Glasshouse trial

A plant growth pot trial was used to investigate the effect of increasing ratios of Ca:K in the soil on Ca and K availability to avocado seedlings. Six-month old Hass avocado seedlings were grown in seven treatments, with each treatment replicated 10 times (single seedling replications). Seventy avocado seedlings were used in total. Pots of 150mm diameter with a volume of approximately 1.2L were used. The experiment was carried out in a glasshouse over 81 days. Pots were arranged in a completely randomised design and were rearranged on days of watering to minimise position effects such as shading.

Redland Bay Ferrosol was used for the trial, sieved to 2mm. Each pot was lined with a plastic bag and filled with 1.3 kg of soil. Basal applications of nutrients (Appendix 8) were added as solutions and evenly distributed throughout the pot by tipping the soil out, mixing and re-potting. Potassium was added as solid K_2SO_4 and Ca as solid $CaSO_4.2H_2O$ at the rates shown in Table 26 and evenly distributed throughout the pot. These equated to about 4.5 t/ha of gypsum and 20-650 Kg/ha of K_2SO_4. One week prior to transplanting the seedlings were drenched with 3 mL/L phosphoric acid to prevent Phytophthora spp. root rot during the trial. On the day of transplanting, seedlings were removed from culture pots, the roots were rinsed to remove all potting mix and the cotyledons removed. The seedlings were then planted into the treatment pots and watered to field capacity.

Table 26. Treatment applications of Ca as $CaSO_4.2H_2O$ and as $CaCl_2.2H_2O$ (as a basal application) and K as K_2SO_4 for the glasshouse trial.

	Nutrient (g/Kg soil)			Element (g/Kg soil)		Ca:K per pot
Treatment	$CaSO_4.2H_20$	$CaCl_2.2H_2O$	K_2SO_4	Ca	K	
Ca+K	5.44	0	0.05	1.26	0.022	56.5:1
K	0	0.3	0.05	0.081	0.022	3.6:1
2K	0	0.3	0.1	0.081	0.045	1.8:1
4K	0	0.3	0.2	0.081	0.090	0.9:1
8K	0	0.3	0.4	0.081	0.179	0.45:1
16K	0	0.3	0.8	0.081	0.358	0.23:1
32K	0	0.3	1.6	0.081	0.717	0.11:1

During the first month the seedlings were watered to field capacity every 4-5d and increased to every 2-3d due to seedling growth and ambient temperatures. Any weeds and insects were removed as necessary.

At the end of the trial just prior to harvest, soil solution was extracted using polyacrylonitrile hollow fibre samplers (Menzies and Guppy 2000). The pots were watered to field capacity 12-18h prior to extraction; the fibres were then inserted into the pot through the surface of the soil. Soil solution was extracted and collected in 10mL evacuated blood collecting vials. The samples were refrigerated at 4°C before analysis by ICPAES for Ca, Mg, Na and K.

The youngest, fully expanded leaves were sampled for tissue analysis of Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S and Zn by ICPAES. Youngest expanded leaves where harvested as a direct indicator of Ca uptake as Ca is not remobilised within the plant (Marschner 1986). Potassium uptake could also be confidently attributed to leaf K concentrations as treatment K concentrations were not in the deficient range (Reuter and Robinson 1997) and hence remobilisation within the plant was expected to be minimal. Two to three leaves per pot were sampled providing new growth was available. The leaves were rinsed in de-ionised water to remove dust and insect matter. Samples were stored in paper bags and placed in a dehydrator at 60°C for 3d. Plant tissue was digested with nitric perchloric acid (Martinie and Schilt 1976) and analysed for cations as above.

Data from the pot trial was analysed using GenStat version 7.2. Regression using the exponential function and one-way analysis of variance (ANOVA) was used to test for the significance of treatment effects.

5.3 Results and discussion

5.3.1 Exchange Selectivity

Exchange isotherms are a graphical method of representing soil selectivity towards cations. An exchange isotherm can be constructed after determining activities of each exchangeable ion over a range of soil solution compositions (Sposito 1989). Exchange isotherms show the preference of a soil for one cation over another, relative to the non-preference isotherm (Figure 2). The position of the curve, above or below the non-preference line, indicates which cation is preferred (Sposito 1989).

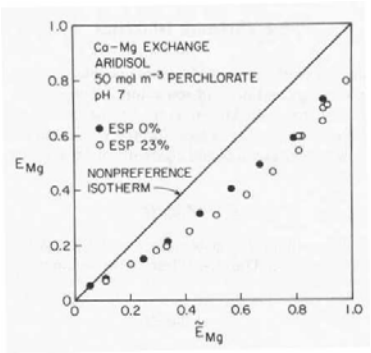

Figure 2. An exchange isotherm for divalent-divalent exchange (Sposito 1989), p.174).

Overall the highly weathered soils showed exchange preference for Ca over K, Mg and Na as illustrated by the exchange isotherms in Figure 4 (a), (b) and (c). Calculated Vanselow selectivity coefficients KV (which take into account valency effect on exchange) showed that the soils displayed an overall selectivity for K over Ca, Ca over Mg and variability in selectivity between Na and Ca as depicted in Figure 4 (e), (f) and (g).

The magnitude of K_V represents the affinity of the soil's exchange complex for Ca with respect to the other cation in the exchange reaction. When KV=1 the soil displays no preference between the cations. When K_V is greater than one at any given soil solution composition the soil's exchange surfaces display a preference for Ca, while when KV is less that one the exchange surfaces display preference for the other cation in the exchange reaction.

A mineralogical characteristic common in the Ferrosols and Kandosols sampled is a Kaolinite dominated clay fraction. A significant part of the charge on Kaolinite (a 1:1 mineral) is variable and exchange sites are primarily external (Taylor et al. 1983) (Brady 1990). Iron oxides and hydroxides in Ferrosols also posses external exchange surfaces and are variable charged colloids (Taylor et al. 1983). The exchange selectivity between Ca-K will be the focus of discussion as this was the primary objective of this research.

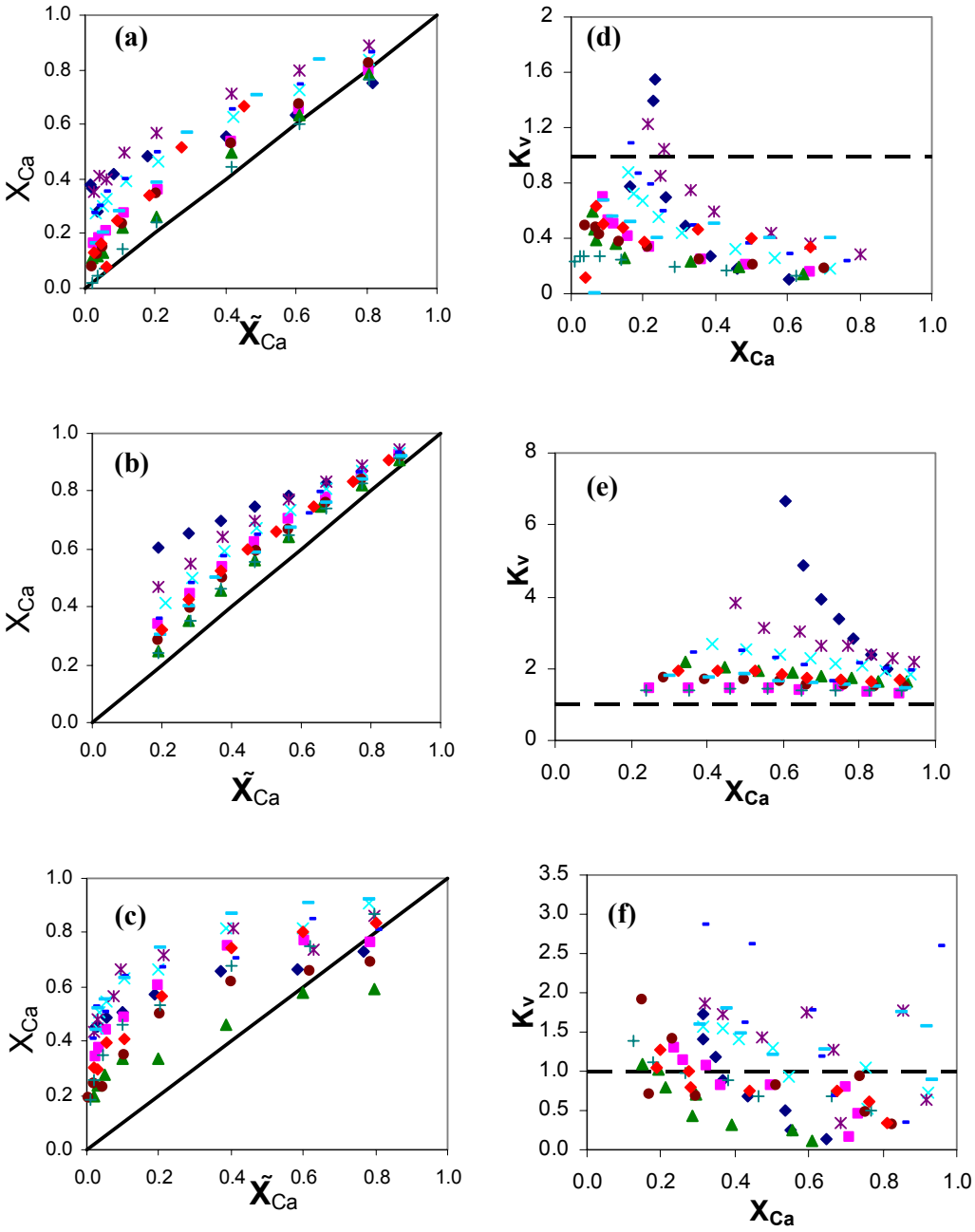

Figure 3. Measured cation exchange isotherms for Ca-K(a) Ca-Mg (b) and Ca-Na(c) exchange in some highly weathered soils. Isotherms were constructed by plotting the charge fraction of Ca in solution ($\tilde{X}_{Ca}$) versus charge fraction of Ca on exchange (X_{Ca}). The non-preference isotherm is represented by the solid black line. Isotherms lying above the non-preference line represent a preference for Ca over the other cation in the exchange reaction; isotherms below the non-preference line indicate selectivity for the other cation. Calculated Vanselow selectivity coefficients are presented in graphs (d) for Ca-K, (e) for Ca-Mg and (f) for Ca-Na. K_V=1 is represented by the dashed black line, with values <1 indicating a preference for K(d) Mg(e), or Na(f) and values >1 indicating a preference for Ca.

The general trend of exchange isotherms showing a preference for Ca over K, Na and Mg was expected. Soil colloidal particles will preferentially adsorb divalent ions (Ca^{2+}) over monovalent ions (K^+, Na^+), due to structural effects on selectivity, electrostatic affinities for exchange sites and hydrated ionic radii and hydration energy (Table 27) (Sposito 1989). Divalent ions compete more strongly for exchange sites over monovalent ions and are also more favourable in terms of stability and geometry (McBride 1994). The slight preference for Ca over Mg is well documented; selectivity trends between these ions are due to the nearly ideal exchange behaviour exhibited by a homovalent exchange reaction (McBride 1994).

Table 27. Ionic radii and hydration energy of some common ions (Tan 1993).

Ion	Valence (+)	Ionic radius (nm)	Hydrated ionic radius (nm)	Hydration energy (J/mol)
K	1	0.133	0.33	314
Na	1	0.098	0.36	397
Mg	2	0.066	0.42	1908
Ca	2	0.099	0.43	1577

When valence effects are taken into account by Vanselow selectivity coefficients the soils showed an anomalously high selectivity for K (Figure 3 (d)) and some selectivity for Na (Figure 3 (f)) over Ca. Selectivity between Ca-Mg exchange for some soils remained fairly constant and close to unity (K_V=1) most likely due to the nearly ideal exchange behaviour between cations of the same valence (McBride 1994). The other soils in Ca-Mg exchange were less constant and displayed much higher selectivity towards Ca at some solution compositions, especially bauxite. This can be attributed to other minerals within the clay fraction with exchange sites other than external sites which display different affinities for different cations (Edmeades 1980). However, the overall preference for Ca over Mg is consistent with other research findings (Edmeades 1980).

The shape of the Vanselow selectivity curves indicate a trend between exchange saturation of Ca and selectivity for Ca. Selectivity for Ca is highest at low exchange (XCa) saturation and decreases with increasing exchange saturation; concurrently the selectivity for K or Na increases (Figure 3 (d), (e) and (f)). This was also seen in the exchange isotherms for Ca-K (Figure 3 (a)) and Ca-Na (Figure 3 (c)) where curves for some soils were positioned just below the non-preference line at high charge fraction of Ca in solution indicating a shift in preference towards the monovalent ion. These trends in selectivity can be attributable to some common mechanisms.

Selectivity of ions can be understood by considering intrinsic ion properties and exchange phase characteristics (Alves and Lavorenti 2003). For example the K ion is smaller in size, polarisability and hydration energy, and therefore can be preferred over Ca in some circumstances (Alves and Lavorenti 2003; McBride 1994). The characteristics of an exchanger phase are more complex and therefore one single property cannot be identified as the characteristic responsible for the observed selectivity. However three main assumptions can be made.

The Diffuse Double Layer (DDL) theory describes the distribution of ions near charged colloids (Goldberg 2000), and is very useful in conceptualising exchange selectivity. The electrical potential of the DDL varies as the fraction of ions on the exchange and in the bulk solution change (van Olphen 1977). Variability in electrical potential changes the affinity and preference for cations (Levy et al. 1988). Kaolinite and iron oxides are dominated by external exchange surfaces creating a small electrical potential, therefore

a relative preference for a monovalent ion over a divalent ion is expected. The finding of increased preference for K over Ca are similar to other reports (Kopittke 2005; Levy et al. 1988). Increasing the fraction of Ca on the exchange acts to decrease the selectivity for Ca (Figure 3 (d) (e) and (f)). The preference for Ca increases with increasing negative potential of the DDL, and increasing Ca saturation of the DDL acts to decrease the negative potential and hence the affinity for the divalent ion. At decreased negative potentials (achieved by increased Ca fraction on the exchange) the affinity for monovalent ions such as K and Na is increased. Ion preference is again expected to change with ionic strength (Shainberg et al. 1980; van Olphen 1977). Increasing ionic strength will act to compress the DDL and increase the preference for Ca on external exchange surfaces (Kopittke 2005), however this research was carried out at constant ionic strength and thus do not alter the results of the current study.

In the past other researchers have also attributed the selectivity for K in kaolinite dominated clay fractions to trace amounts or impurities of 2:1 minerals with a higher selectivity towards K (Appel et al. 2003; Goulding 1983; Levy et al. 1988; Poss et al. 1991). Another similar explanation assumes there are various exchange sites with varying affinity for Ca. With increasing X_{Ca}, sites with the lowest affinity for Ca are occupied last and therefore the affinity for Ca decreases as X_{Ca} increases (Levy et al. 1988; Shainberg et al. 1987; Shainberg et al. 1980). The observed trend of selectivity coefficients for Ca, decreasing with increasing X_{Ca} (Figure 3 (d), (e) and (f)) support either of this explanations.

A less emphasised explanation involves both the exchange surface properties and the K^+ properties. The high affinity of kaolinite for K can be related to the effect of charge density and the hydration energy of K (Levy et al. 1988). Table 27 shows that K has much lower hydration energy than Ca and is termed a weakly hydrated ion. The high surface charge density of Kaolinite (Filep 1999) coupled with the low hydration energy of K will increase the dehydration of weakly hydrated ions compared to strongly hydrated ions such as Ca, and therefore results in an increased affinity for K over Ca (Appel et al. 2003; Levy et al. 1988).

Determining exchange selectivity of soils is useful when investigating plant nutritional deficiencies as it provides information about the partitioning of applied nutrients (fertilisers) between the exchange phase and solution phase. It can be used to predict possible cation interaction such as between Ca-K, thereby providing an indication of what is available to the plant. An understanding of the exchange selectivity of a soil can be used in conjunction with results obtained from plant growth pot trials, by examining how the availability of a nutrient affects plant uptake.

These results confirmed that all the soils tested had a stronger affinity for Ca over K. This was expected, since all soils have a higher preference for divalent and trivalent ions, than for monovalent ions such as K. This preference is largely the result of the charge on the ions. Removing the influence of the charge using the Vanselow selectivity coefficient, the results confirm a higher selectivity for K over Ca, especially with more Ca on the exchange. However, there were differences in soil behaviour in this respect. The WA gravelly loam had a higher affinity and selectivity for Ca, the Toowoomba Ferrosol was intermediate, while the Childers Ferrosol and the Mareeba Candasol had the lowest affinity and selectivity for Ca. This would suggest that soils such as those from Childers and Mareeba would be more susceptible to Ca being displaced from the exchange complex by K additions, suggesting more attention is required to Ca nutrition in these soils.

5.3.2 Glasshouse trial

Calcium treatment increased soil solution Ca and Mg concentrations compared with all other treatments (Table 28), which was also observed in the field trial (section 4.3.4.1). However, increasing K applications had no effect on Ca or Mg concentrations, while K applications increased solution Ca and Mg in the field trial. This may be because of the lower K application rates in the glasshouse trial. Calcium application alone had no effect on soil solution K, and only the high K application increased soil solution K concentrations compared with all other treatments. There were no significant treatment effects on the Ca:K ratio in the soil solution, although there was a very strong trend for a higher ratio in the Ca+K treatment.

The Ca+K treatment increased leaf Ca concentrations compared with most other treatments (Table 28). Potassium applications above 2K generally decreased leaf Ca concentration compared with lower K, and the Ca+K treatment. There was little effect of Ca or K on leaf K concentration, except where 32K increased K concentrations compared with all other treatments.

Table 28. Calcium, K and Mg concentrations in the soil solution, the soil solution Ca-K ratio, and the Ca and K concentrations in the leaves of Velvick avocado seedlings grown in red Ferrosol soil with varying Ca and K fertiliser regimes.

Treatment	Soil solution concentration (mg/L)			Soil solution Ca:K ratio	Leaf concentration (g/Kg)	
	Ca	K	Mg		Ca	K
Ca+K	288.2 ^{b}	76.3 ^{a}	131.8 ^{b}	6.80	4.3 ^{c}	12.0 ^{a}
K	55.5 ^{a}	28.2 ^{a}	57.0 ^{a}	1.94	3.5 ^{bc}	13.7 ^{a}
2K	54.3 ^{a}	28.2 ^{a}	62.4 ^{a}	1.73	4.2 ^{c}	12.0 ^{a}
4K	59.8 ^{a}	41.2 ^{a}	67.8 ^{a}	1.37	2.8 ^{ab}	12.4 ^{a}
8K	30.8 ^{a}	44.3 ^{a}	40.2 ^{a}	0.72	2.3 ^{a}	13.0 ^{a}
16K	28.0 ^{a}	56.6 ^{a}	35.4 ^{a}	0.52	2.4 ^{ab}	13.6 ^{a}
32K	63.3 ^{a}	187.1 ^{b}	74.7 ^{a}	0.35	2.0 ^{a}	15.9 ^{b}
LSD	98.2	60.5	53.5	ns	1.1	1.9

The means are the average of 3-4 (soil solution) or 6-10 (leaf) single seedling replications.

Means within each column with different letters are significantly different ($P<0.05$).

Presenting tissue Ca concentration as a function of absolute soil solution Ca concentration did not reveal a clear trend (Figure 4(a)). This lack of correlation is an artifact of two factors. The experimental design included only one treatment with additional Ca as the objective was to investigate Ca:K ratios, not total cation concentrations. Furthermore the ratio of Ca to total cations in solution is a better indicator of Ca availability than total Ca concentration alone (Barber 1995). The nil effect of increasing soil solution K on tissue K may result from the fact that K uptake is an active process (Leigh 2001), which may limit K uptake within the soil solution concentrations observed in this experiment.

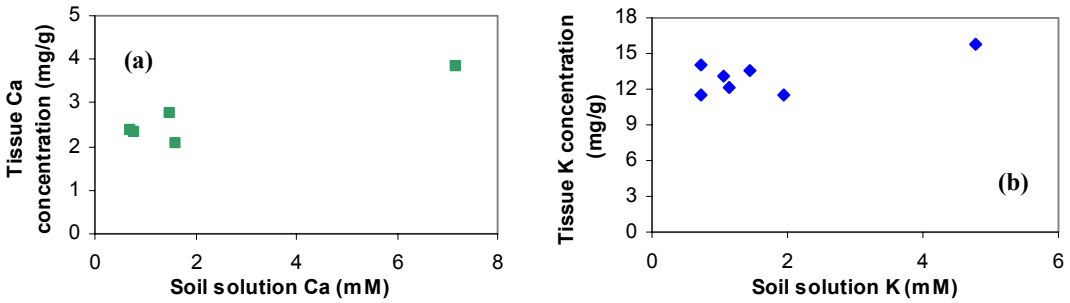

Figure 4. (a) Soil solution Ca concentration (mM) in relation to tissue Ca concentration (mg/g) and (b) soil solution K (mM) concentration in relation to tissue K concentrations (mg/g). Values are the arithmetic mean of leaf concentrations for the 10 trees per treatment (replications).

Presenting tissue concentration as a function of soil solution Ca:K provided a more meaningful relationship. Tissue Ca concentration increased significantly with higher Ca:K ratio (R2=0.84; Figure 5a), but there was little increase in leaf Ca at higher Ca:K ratios. The largest increases in leaf Ca was achieved by reducing K rather than adding additional Ca, which illustrates the potentially negative impact of excessive K fertilisation on tree and possibly fruit Ca nutrition. Increasing the soil solution Ca:K ratio reduced the leaf K concentration, but the decrease was proportionately less (25% decrease) than the increase in leaf Ca (100% increase) with increasing ratios (Figure 5b).

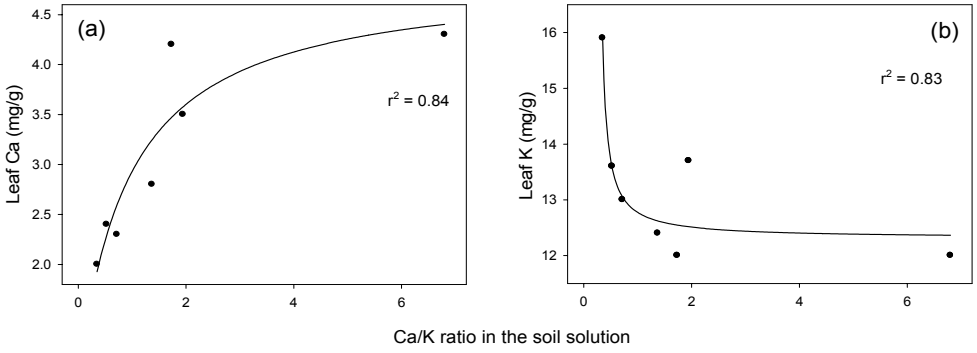

Figure 5. Effect of soil solution Ca:K on tissue Ca (a) and K (b) concentration in leaves (mg/g) as a function of Ca:K. Values plotted are the arithmetic mean of leaf concentrations for the 10 trees per treatment (replications).

The activity of an ion can be defined as the 'effective concentration' of that ion, since it takes into account the interaction of ions in a solution (Wolt 1994). Therefore, activity is often used as a more reliable measure of the ion's available for plant uptake. The activity of an ion decreases as the ionic strength increases. In the present experiment leaf Ca concentrations increased as Ca activity ratio (CAR) increased (p=0.025, R2=0.84) (Figure 6). The relationship between leaf Ca and CAR was similar to the relationship between Ca uptake and Ca:K (Figure 5a). Although activity is considered a more encompassing parameter for cation availability in some circumstances, ratios of cations such as Ca:K sometimes work equally well or better.

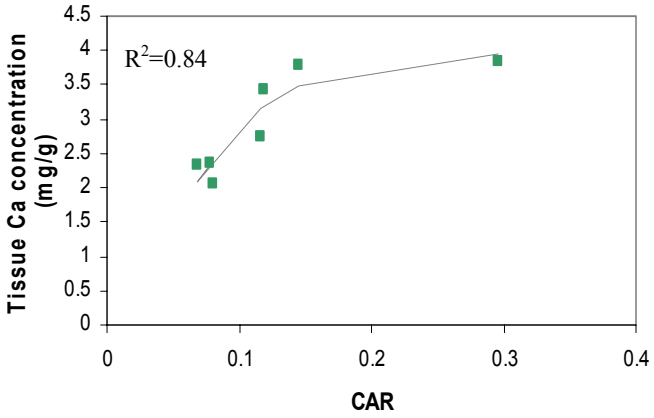

Figure 6. Relation between leaf Ca concentration (mg/g) and Ca activity ratio (CAR) as calculated from extracted soil solution. Activities were calculated using Phreeqcl version 2.12 (Parkhurst 2003). Values plotted are the arithmetic mean of leaf concentrations for the 10 trees per treatment (replications).

Therefore the soil solution Ca:K ratio and CAR identified that increasing K applications had a direct negative impact on Ca activity and hence leaf concentrations.

The above results suggest several factors can affect plant tissue Ca concentrations:

1) Soil solution Ca concentrations. This can be affected by:

   a) Ca applications. In order to increase the long term availability of Ca, the Ca fraction on the exchange must be increased;by doing so the soils buffering capacity for Ca will be improved. To conceptualise this idea a graph of tissue Ca concentration predicted exchangeable Ca levels is shown in Figure 7. Exchangeable Ca ($\mathbf{X_{Ca}}$) was calculated by finding the line of best fit to the Redland Bay Ferrosol Ca-K exchange isotherm (y=0.19ln(x) + 0.75) and substituting the measured soil solution Ca concentration (as a charge fraction in solution) for x. This shows that leaf Ca concentration increases with higher Ca fractions on the exchange complex. Improving the buffering capacity of soil is important as soil solution is dynamic and thus its composition is continually re-equilibrating.

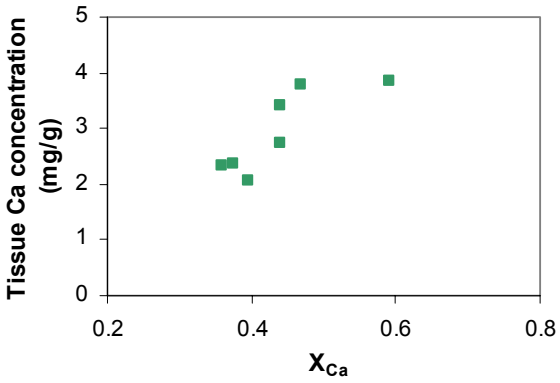

Figure 7. Tissue Ca concentration (mg/g) (values plotted are the arithmetic mean of samples taken) as a function of predicted exchangeable Ca levels as calculated from the Ca-K exchange isotherm for Redland Bay Ferrosol. This graph is a manipulation of data and is intended only to conceptualise an idea.

High CEC soils have greater buffering capacity, and greater ability to hold Ca in the soil on the exchange complex. Therefore, larger and less frequent applications will maintain adequate soil solution Ca concentrations over a longer period and reduce the risk of excess Ca being leached from the profile. Both normal (granular) gypsum or micro-fine gypsum would be appropriate in these soils.

In low CEC soils, the buffering capacity is less. Therefore, large applications would result in a larger proportion of the Ca remaining in the soil solution and possibly being leached. Under these conditions large applications of micro-fine gypsum would be inappropriate. Normal gypsum could be used, but ideally smaller and more frequent applications of micro-fine gypsum through fertigation is more appropriate.

b) Other cations. The results indicate differing preferences for Ca and K amongst the typical avocado soils in Australia, and this provides some guidelines in relation to cation fertilisation with respect to optimising Ca plant nutrition. There are some challenges here, since highly weathered soils have unique physiochemical properties; thus predictions about cation behaviour are inherently difficult. Indeed past and recent research has yielded variable findings, which only adds to the difficulty in understanding the mechanisms operating in these soils. In summarising, anomalously high selectivity of K in highly weathered soils has been reported (Goulding 1983; Poss *et al.* 1991) (White 2002). Deviation from Ca as the dominant cation in soil solutions of highly weathered soils has been reported and can cause disruption in plant nutrition (Bruce *et al.* 1989; Wolt 1994). Nevertheless, the following comments can be made. Soils such as the WA gravelly loam are less likely to have Ca displaced from the exchange complex by K fertilisers, compared with soils such as the Mareeba Kandasol and the Childers Ferrosol. Therefore, more care needs to be taken with the latter soils in relation to Ca/K interaction, since K fertilisers can more easily displace Ca from the exchange complex and decrease soil solution Ca if adequate Ca fertilisation is not maintained. Leaching of Ca is more likely. The Bundaberg Kurosol (from the field trial) is intermediate between these soils.

2) Ca uptake into the plant. The glasshouse trial illustrated that the main effect of increasing K application was increasing soil solution K rather than an affect on soil solution Ca. This increasing solution K was the main factor in reducing the Ca: K ratio with increasing K applications. The leaf analysis indicated that these treatment effects were not significant, although the regression relationship between soil solution Ca:K ratio and leaf Ca was. Therefore it is likely that the significant correlation between soil solution Ca: K and leaf Ca was primarily driven by the increased K in the soil solution rather than an affect on soil solution Ca. This indicates the potential for K to directly reduce the uptake of Ca from the soil solution independent of any effect of K on soil solution Ca concentration. This antagonism has been reported previously, and it can cause adverse interactions with uptake of other cations (Marschner 1995).

Therefore, the effect of K on Ca nutrition can be twofold; through affecting soil solution Ca and by affecting uptake and/or translocation mechanisms within the plant. Reports of

potassium induced Ca deficiency in other crops (Jakobsen 1993; Mengel 1985) are likely to involve these mechanisms.

6 Discussion/Conclusions

- The general principle that Ca is relatively immobile in soils was not the case in the sandy loam soil used in these trials. It is likely that this also applies to most avocado producing orchards in Australia because of their highly weathered nature and low CEC. To maintain adequate soil solution Ca concentrations under these conditions, regular applications of Ca are required during flowering and early fruit growth.
- The main reason for no treatment effects on fruit quality was likely the nil or relatively small increases in fruit Ca concentrations. The significant effect of trees on quality is associated with far greater differences in fruit Ca concentration than obtained by Ca applications. It is suggested that larger increases in fruit Ca concentration are required to see significant improvements in fruit quality.
- The Ca treatments increased soil solution Ca but had little effect on fruit Ca concentration, indicating other factors interacting with Ca nutrition. The results suggest interactions with K, either by K displacing Ca from the exchange complex, or a direct competition with Ca uptake into the plant. Crop load can also affect fruit quality, but co-variate analysis indicated that this was not a factor in the absence of fruit responses to Ca.
- The absence of increasing xylem Ca with increasing soil solution Ca above a certain concentration suggests limitations to Ca uptake because of tree factors. Rootstock genetics have been suggested as one of the main causes for differences between adjacent trees in respect to fruit quality and Ca concentration.
- Most typical avocado producing soils in Australia have a higher selectivity for Ca and K. This is common amongst most soils, and is related to the divalent charge of Ca. There were differences between the typical avocado soils in relation to Ca/K affinity, which allows general recommendations for Ca/K to be made. Soils such as the WA gravelly loam are less likely to have Ca displaced from the exchange complex by K fertilisers, compared with soils such as the Mareeba Kandasol and the Childers Ferrosol. Therefore, more care needs to be taken with the latter soils, since K fertilisers can more easily displace Ca from the exchange complex and decrease soil solution Ca if adequate Ca fertilisation is not maintained.
- Trees with higher yield generally produced fruit with less body rots and stem end rots, as well as less tree variation in the severity of rots, thus highlighting the importance of crop load in avocado fruit quality. This effect appears to be greater in low-yield years, which could result in lower average quality, and greater variation in quality in these years.
- The relationship between crop load and quality has been demonstrated by comparing the yield/quality relationship between trees within the experimental site. To confirm the commercial potential of this approach, we need to demonstrate that improving production practices on low-yielding orchards will increase quality.
- South African experience indicates that higher fruit N is associated with lower fruit quality. However, reducing N application rates to improve quality are likely

to reduce yield under typical Australian conditions. This needs to be investigated further.

- Management practices (other than N) to improve yield are likely to also improve quality.

7 Technology transfer

Relatively little technology transfer has occurred during this project because of the lack of clear results. We preferred to defer publication of results until the end of the project to obtain a more complete picture of Ca nutrition. A summary of the project findings and recommendations will be published in the next edition of Talking Avocados (summer 2007). At least one other Talking Avocados article will be published in the next 6 months.

The following presentations and publications were made:

Hofman, P.J., Searle, C., Marques, J.R., Stubbings, B., Moody, P. (2005) "Improving avocado fruit quality through tree nutrition; present knowledge and future challenges". Presentation to the Australia/New Zealand Avocado conference, Tauranga, September 2005.

Hofman, P.J. (2006) The role of rootstocks and nutrition on the quality of Hass avocado Part one: Uptake of minerals into the roots and leaves of rootstock seedlings. Talking Avocados 16(3): 26-28.

Hofman, P.J. (2005) "Optimising the postharvest qualities of Hass avocado through improved nutrition". Presentation at the Avocado Field Day at Bundaberg on 25th November 2005.

Hofman, P.J. and Marques, J.R. (2007) The challenge of improving avocado fruit quality through tree nutrition – Part 1. Talking Avocados 2007 summer edition (in press).

8 Recommendations

This project did not identify specific Ca nutrition recommendations because of insufficient and inconsistent treatment responses. Extensive Ca research in South Africa came to similar conclusions. However, the project identified several factors relating to Ca nutrition that provides guidance to growers. These are:

- Given the highly weathered nature and associated low CEC of most avocado producing soils, regular, smaller applications of Ca are required to maintain adequate concentrations in the soil solution during the critical fruit growth stage. Single applications during the non-fruiting period are likely to have little effect on fruit Ca nutrition.
- The results confirmed the interaction between K and Ca. The field trials suggested that the leaf K recommendations could be reduced with minimal impact on yield, but this needs to be further investigated. In the interim, it is recommended that K fertilisation occur during and non-fruiting period to minimise leaching of Ca from the soil profile, and preventing Ca uptake into the plant.
- The positive relationship between tree yield and fruit quality can be utilised by growers by selectively harvesting highly yielding blocks or high yielding trees for specific markets with higher fruit quality demands or greater times from harvest to market.

In relation to future research:

- The potential for reducing leaf K recommendations and confining K nutrition to the non-fruiting period should be investigated.
- The relationship between yield and quality should be confirmed and exploited. The main practices here are likely to be irrigation and N nutrition. We may also need to consider the impact of heavy pruning on the yield and quality in normally high yielding orchards the year after pruning. Specific practices just before and after pruning could be developed to rapidly re-establish optimum crop load, or develop recommendations for handling of fruit from the first season after heavy pruning because of the increased risk of rots and flesh disorders.

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10 Literature cited

Alves ME, Lavorenti A (2003). Potassium-calcium exchange in electropositive oxisols: description of exchange sites. *Australian Journal of Soil Research* **41**, 1423-1438.

Appel C, Lena QM, Rhue D, Reve W (2003). Selectivities of potassium-calcium and potassium- lead exchange in two tropical soils. *Soil Science Society America Journal* **67**, 1707-1714.

Arpaia ML, Meyer JL, Witney GW, Bender GS, Stottlemyer DS, Robinson PR (1996). The Cashin Creek nitrogen fertilizer trial - what did we learn? *California Avocado Society Yearbook* **80**, 85-98.

Baker AS, Smith RL (1974). Preparation of solutions for atomic absorption analyses of Fe, Mn, Zn and Cu in plant tissue. *Journal of Agricultural and Food Chemistry* **22**, 103-107.

Bangerth F (1979). Calcium-related physiological disorders of plants. *Annual Review of Phytopathology* **17**, 97-122.

Barber SA (1995). 'Soil nutrient bioavailability.' (John Wiley & Sons: New York, USA)

Barnard RO (1989). Cation distribution during soil profile amelioration with lime and gypsum. *South African Avocado Grower's Association Yearbook* **12**, 43-47.

Bower JP (1985). The calcium accumulation pattern in avocado fruit as influenced by long term irrigation regime. *South African Avocado Grower's Association Yearbook* **8**, 97-99.

Brady NC (1974). 'The nature and properties of soils.' (Macmillan Publishing CO., Inc.: New York)

Brady NC (1990). 'The nature and properties of soils.' (MacMillan Publishing: New York)

Broadbent P, Trochoulias T, Baigent D, Abbott T (1989). Effect of soil management on avocados in a krasnozem soil. *Scientia Horticulturae* **38**, 87-104.

Bruce RC (1999). Calcium. In 'Soil analysis an interpretation manual'. (Eds KL Peverill, LA Sparrow and DJ Reuter). (CSIRO: Victoria, Australia)

Bruce RC, Warrell LA, Bell LC, Edwards DG (1989). Chemical attributes of some Queensland acid soils. 1. solid and solution phase compositions. *Australian Journal of Soil Research* **27**, 333-351.
Carson CD, Dixon JB (1972). Potassium selectivity in certain montmorillonitic soil clays. *Soil Science Society of America Proceedings* **36**, 838-843.
Drake SR, Larsen FE, Fellman JK, Higgins SS (1988). Maturity, storage quality, carbohydrate, and mineral content of 'Goldspur' apples as influenced by rootstock. *Journal of the American Society for Horticultural Science* **113**, 949-952.
Du Plessis SF, Koen TJ (1987). Comparison of different calcium sources on avocado production. *South African Avocado Grower's Association Yearbook* **10**, 49-51.
Eaks IL (1985). Effect of calcium on ripening, respiratory rate, ethylene production, and quality of avocado fruit. *Journal of the American Society for Horticultural Science* **110**, 145-148.
Edmeades DC (1980). Calcium magnesium exchange equilibria in a range of New Zealand soils. *Australian Journal of Soil Research* **18**, 251-255.
Edmeades DC, Wheeler DM, Clinton OE (1985). The chemical composition and ionic strength of soil solutions from New Zealand topsoils. *Australian Journal of Soil Research* **23**, 151-165.
Evangelou VP, Marsi M (2003). Influence of ionic strength on sodium-calcium exchange of two temperate climate soils. *Plant and Soil* **250**, 307-313.
Fallahi E, Rodney DR (1992). Tree size, yield, fruit quality, and leaf mineral nutrient concentration of 'Fairchild' mandarin on six rootstocks. *Journal of the American Society for Horticultural Science* **117**, 28-31.
Filep G (1999). 'Soil chemistry: processes and constituents.' (Hungary)
Gillman GP, Bristow KL, M.J. H (1989). Leaching of applied calcium and potassium from an oxisol in humid tropical queensland. *Australian Journal of Soil Research* **27**, 183-198.
Goedert WJ, Corey RB, Syers JK (1975). Lime effects on potassium in soils of Rio Grande Do Sul, Brazil. *Soil Science* **120**, 107-111.
Goulding KWT (1983). Thermodynamics and potassium exchange in soils and clay minerals. *Advances in Agronomy* **36**, 215-264.
Granger RL, Looney NE (1983). Radio-calcium uptake by 'Spartan' and 'Delicious' apple as influenced by rootstock and BA and GA_3 to activate growth of lateral buds. *HortScience* **18**, 314-316.
Haas ARC (1950). Rootstock influence on the composition of scion avocado leaves. *California Avocado Society Yearbook* **34**, 149-152.
Himelrick DG, McDuffie RF (1983). The calcium cycle: uptake and distribution in apple trees. *HortScience* **18**, 147-151.
Hisenger L (2002). Potassium. In 'Encyclopedia of soil science'. (Ed. M Dekker). (USA)
Hofman PJ, Fuchs Y, Milne DL (2002a). Harvesting, packing, postharvest technology, transport and processing. In 'The avocado; botany, production and uses'. (Eds AW Whiley, B Schaffer and BN Wolstenholme) pp. 363-402. (CAB International: Oxon, UK)
Hofman PJ, Ledger SN (2001). Rots and bruising main quality problems. *Talking Avocados* **12**, 20-22.
Hofman PJ, Mullen C (2005). 'The role of rootstocks and nutrition in the quality of Hass avocado. Final report of project AV00013.' Horticulture Australia Ltd, Sydney, Australia.
Hofman PJ, Vuthapanich S, Whiley AW, Klieber A, Simons D (2002b). Tree yield and fruit minerals concentrations influence ‘Hass’ avocado fruit quality. *Scientia Horticulturae* **92**, 113-123.
Isbell RF (1996). 'The Australian soil classification.' (Australia)

Jakobsen ST (1993). Nutritional disorders between potassium, magnesium, calcium and phosphorus in soil. *Plant and Soil* **154**, 21-28.
Kirkman JH, Basker A, Surapaneni A, MacGregor AN (1994). Potassium in the soils of New Zealand. *New Zealand Journal of Agricultural Research* **37**, 207-227.
Kopittke PM, Menzies NW, Fulton IM (2004). Gypsum solubility in seawater, and its application to bauxite residue amelioration. *Australian Journal of Soil Research* **42**, 953-960.
Kopittke PMS, H.B.//Menzies, N.W. (2005). Effect of ionic strength and clay mineralogy on Na-Ca exchange and the SAR-ESP relationship. *European Journal of Soil Science* **In press**.
Kruger FJ, Snijders B, Mathumbu JM, Lemmer D, Malumane R (2004). Establishing appropriate maturity and fruit mineral content norms for the main avocado export cultivars. *South African Avocado Growers Association Yearbook* **27**, 10-16.
Lahav E, Bareket M, Zamet D (1976). Potassium fertiliser experiment with avocado trees on heavy soils. *California Avocado Society Yearbook* **60**, 181-186.
Lahav E, Whiley AW (2002). Irrigation and mineral nutrition. In 'The Avocado: botony, production and uses'. (Eds AW Whiley, B Schaffer and BN Wolstenholme) pp. 259-297. (CABI Publishing: Oxon, UK)
Leigh RA (2001). Potassium homeostasis and membrane transport. *Journal of Plant Nutrition and Soil Science* **164**, 193-198.
Levy GJ, van der Watt HVH, Shainberg I, du Plessis HM (1988). Potassium-calcium and sodium-calcium exchange on kaolinite and kaolinitic soils. *Soil Science Society of America Journal* **52**, 1259-1264.
Lindsay WL (1979). 'Chemical equilibria in soils.' (New York: USA.)
Malavolta E (1985). Potassium status of tropical and subtropical region soils. In 'Potassium in ariculture'. (Ed. RD Munson). (Soil Science Society of America: Wisconsin, USA)
Marques JR, Hofman PJ, Wearing AH (2003). Rootstocks influence 'Hass' avocado fruit quality and fruit minerals. *Journal of Horticultural Science and Biotechnology* **78**, 673-679.
Marschner H (1986). 'Mineral nutrition of higher plants.' (Academic Press: London)
Marschner H (1995). 'Mineral nutrition of higher plants.' (Academic Press: Great Britain.)
Martinie GD, Schilt AA (1976). Investigation of the wet oxidation efficiencies of perchloric acid mixtures. *Analytical Chemistry* **48**, 70-74.
McBride MB (1994). 'Environmental chemistry of soils.' (New York, USA)
McLaughlin MJ, Reuter DJ, Rayment GE (1999). Soil tTesting-principles and concepts. In 'Soil analysis an interpretation manual'. (Eds P K.L., LA Sparrow and R D.J.). (CSIRO: Victoria, Australia)
Mengel K (1985). Potassium movement within plants and its importance in assimilate transport. In 'Potassium in agriculture'. (Ed. RD Munson). (Soil Science Society of America: Wisconsin, USA.)
Menzies N, Guppy C (2000). In-situ soil solution extraction with polyacrylonitrile hollow-fibers. *Communications in Soil Science and Plant Analysis* **31**, 1875-1886.
Menzies NW, Bell LC (1988). Evaluation of the influence of sample preparation and extraction technique on soil solution composition. *Australian Journal of Soil Research* **26**, 451-465.
Menzies NW, Bell LC, Edwards DG (1994). Exchange and solution phase chemistry of acid, highly weathered soils. I Characteristics of soils and the effects of lime and gypsum amendments. *Australian Journal of Soil Research* **32**, 251-267.
Moody PW (1994). Chemical fertility in krasnozems: A review. *Australian Journal of Soil Research* **32**, 1015-1041.

Nelson RM, Donkin DJ, Bezuidenhout JJ, Eksteen GJ, Huysamer M (2000). Evaluation of avocados exported to Europe and the UK during the 1999 season. *South African Avocado Growers' Association Yearbook* **23**, 21-29.
Newett S, Whiley A*, et al.* (2001). 'Avocado Information Kit. Agrilink Series QAL 9906.' (Department of Primary Industries, Queensland: Brisbane Australia)
Parkhurst D (2003). 'PhreeqcI version 2.12.' (http://water.usgs.gov/owq/software.html: Accessed October 2005).)
Pearson RW (1971). Introduction to symposium – The soil solution. *Soil Science Society of America Proceedings* **35**, 417-420.
Penter MG, Stassen PJC (2000). The effect of pre- and postharvest calcium applications on the postharvest quality of Pinkerton avocados. *South African Avocado Growers' Association Yearbook* **23**, 1-7.
Poss R, Fardeau JC, Saragoni H (1997). Sustainable agriculture in the tropics: the case of potassium under maize cropping in Tago. *Nutrient Cycling in Agroecosystems* **46**, 205-213.
Poss R, Fardeau JC, Saragoni H, Quantin P (1991). Potassium release and fixation in Ferralsols (Oxisols) from Southern Togo. *Journal of Soil Science*, 649-660.
Reuter DJ, Robinson JB (1997). 'Plant analysis an interpretation manual (second edition).' (CSIRO Publishing: Collingwood, Australia)
Shainberg I, Alperovitch NI, Keren R (1987). Charge density and Na-K-Ca exchange on smectites. *Clays and Clay Minerals* **35**, 68-73.
Shainberg I, Oster JD, Wood JD (1980). Sodium/calcium exchange in montmorillonite and Illite suspensions. *Soil Science Society of America Journal* **44**, 960-964.
Sparks DL, Huang PM (1985). Physical chemistry of soil potassium. In 'Potassium in agriculture'. (Ed. RD Munson). (Soil Science Society of America: Wisconsin, USA.)
Sposito G (1989). 'The Chemistry of Soils. Oxford University Press, New York.'
Steel RDG, Torrie JHT (1980). 'Principles and procedures of statistics: a biometrical approach.' (Mcgraw-Hill Book Company: New York)
Sumner MEM, W.P. (1996). Cation exchange capacity and exchange coefficients. In 'Methods of soil analysis part 3: Chemical methods'. (Soil Science Society of America and American Society of Agronomy: Madison, USA)
Tan KH (1993). 'Principles of Soil Chemistry, 2nd ed. Marcel Dekker, New York.'
Taylor RM, McKenzie RM, Fordham AW, Gillman GP (1983). Oxide minerals. In 'Soils: an Australian viewpoint'. (Ed. CSIRO). (Melbourne)
Thorp TG, Hutching D, Lowe T, Marsh KB (1997). Survey of fruit mineral concentrations and postharvest quality of New Zealand-grown 'Hass' avocado (*Persea americana* Mill.). *New Zealand Journal of Crop and Horticultural Science* **25**, 251-260.
van Olphen H (1977). 'An Introduction to Clay Colloidal Chemistry, John Wiley & Sons, New York.'
Vanselow AP (1932). Equilibria of the base-exchange reactions of bentonites, permutites, soil colloids and zeolites. *Soil Science* **33**, 95-113.
Volz RK, Ferguson IB, Hewett EW, Woolley DJ (1994). Wood age and leaf area influences fruit size and mineral composition of. *Journal of Horticultural Science* **69**, 385-395.
Vuthapanich S (2001). Preharvest practices affecting postharvest quality and minerals composition of 'Hass' avocado fruit. PhD thesis, University of Queensland.
White A, Woolf AB, Hofman PJ, M.L. A (2005). 'The International Avocado Quality Manual.' (HortResearch: Auckland, New Zealand)

White J (2002). Potassium distribution in Ferrosols and its influence on rain-fed crop production in the South Burnett region of Queensland. PhD thesis, University of Queensland.

Willingham SL (2003). The role of rootstocks, nutrition and antifungal compounds in resistance of avocado to anthracnose. *Talking Avocados* **14**, 23-27.

Willingham SL (2005). 'New strategies for the control of avocado fruit diseases. Final report on AV01004.' Department of Primary Industries and Fisheries, Brisbane.

Witney GW, Hofman PJ, Wolstenholme BN (1990a). Mineral distribution in avocado trees with reference to calcium cycling and fruit quality. *Scientia Horticulturae* **44**, 279-291.

Witney GW, Hofman PJ, Wolstenholme BN (1990b). Mineral distribution in avocado trees with reference to calcium cycling and fruit quality. *Scientia Horticulturae* **44**, 279-291.

Wolstenholme BN (2004). Nitrogen - the manipulator element: managing inputs and outputs in different enviroments. *South African Avocado Grower's Association Yearbook* **27**, 62-78.

Wolt J (1994). 'Soil solution chemistry, applications to environmental science and agriculture.' (John Wiley & Sons: New York, USA)

Appendices

Appendix 1 - Field layouts of 'Hass' avocado trees from 2002 to 2004.

Each treatment was applied to plots of five trees, with the middle three ones being the experimental trees, and the two outer ones being guard trees between each treatment.

Season 2002-3

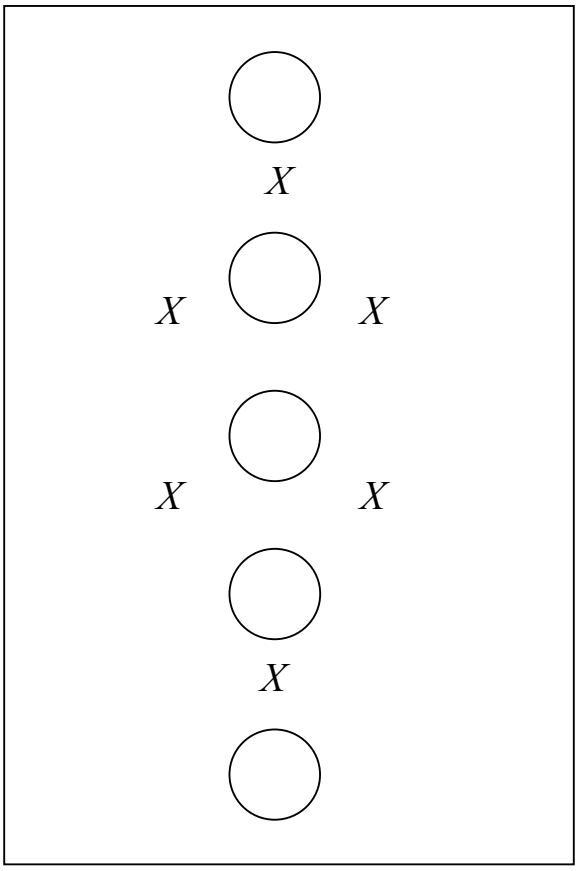
Row 1	Row 2	Row 3	Row 4	Row 5	Row 6
Guard	Guard	Guard	Guard	Guard	Guard
2-Ca+2-K	Control	12-Ca	2-Ca+2-K	1-Ca+2-K	12-Ca
1-Ca+2-K	6-Ca	1-Ca	6-Ca	Control	2-Ca
Control	1-Ca	1-Ca+2-K	1-Ca	2-Ca	2-Ca+2-K
1-Ca	3-Ca	Control	2-Ca	12-Ca	3-Ca
2-Ca	2-Ca+2-K	3-Ca	Control	3-Ca	6-Ca
6-Ca	1-Ca+2-K	2-Ca+2-K	1-Ca+2-K	6-Ca	1-Ca
12-Ca	2-Ca	6-Ca	3-Ca	1-Ca	1-Ca+2-K
3-Ca	12-Ca	2-Ca	12-Ca	2-Ca+2-K	Control
Guard	Guard	Guard	Guard	Guard	Guard

Season 2003-4

Row 1	Row 2	Row 3	Row 4	Row 5	Row 6
Guard	Guard	Guard	Guard	Guard	Guard
1-Ca+4-K	Control	12-Ca	1-Ca+4-K	1-Ca+2-K	12-Ca
1-Ca+2-K	6-Ca	1-Ca	6-Ca	Control	4-K
Control	1-Ca	1-Ca+2-K	1-Ca	4-K	1-Ca+4-K
1-Ca	3-Ca	Control	4-K	12-Ca	3-Ca
4-K	1-Ca+4-K	3-Ca	Control	3-Ca	6-Ca
6-Ca	1-Ca+2-K	1-Ca+4-K	1-Ca+2-K	6-Ca	1-Ca
12-Ca	4-K	6-Ca	3-Ca	1-Ca	1-Ca+2-K
3-Ca	12-Ca	4-K	12-Ca	1-Ca+4-K	Control
Guard	Guard	Guard	Guard	Guard	Guard

Appendix 2 - Field layout of soil sampling points

The ‘X’ represents the sampling points within each plot of five avocado trees (represented by the circles), with the middle three ones being the experimental trees, and the two outer ones being guard trees between each treatment.



Appendix 3 - Field layout of 'Hass' avocado trees in the 2004-5 season.

Each treatment was applied to plots of five trees, with the middle three ones being the experimental trees, and the two outer ones being guard trees between each treatment. The 'X' represents a non experimental plot. As far as possible the treatments coincided with the same treatments applied in previous years.

Row 1	Row 2	Row 3	Row 4	Row 5	Row 6
Guard	Guard	Guard	Guard	Guard	Guard
X	X	X	X	X	X
X	12-Ca	12-Ca(G)	12-Ca	Control	X
Control	Control	X	X	X	X
X	6-Ca	Control	X	12-Ca(G)	6-Ca
X	X	6-Ca	Control	6-Ca	12-Ca
6-Ca	X	X	X	12-Ca	12-Ca(G)
12-Ca	X	12-Ca	6-Ca	X	X
3-Ca	12-Ca(G)	X	12-Ca(G)	X	Control
Guard	Guard	Guard	Guard	Guard	Guard

Appendix 4 - Field layout of 'Hass' avocado trees in the 2005-6 season.

Each treatment was applied to plots of five trees, with the middle three ones being the experimental trees, and the two outer ones being guard trees between each treatment. As far as possible the treatments coincided with the same treatments applied in previous years.

Row 1	Row 2	Row 3
Guard	Guard	Guard
Control	9-Ca	Control
3-K	9-Ca+3-K	9-Ca+3-K
9-Ca	Control	9-Ca
9-Ca+3-K	3-K	3-K
9-Ca	9-Ca	3-K
3-K	9-Ca+3-K	Control
Control	Control	9-Ca
9-Ca+3-K	3-K	9-Ca+3-K
Guard	Guard	Guard

Appendix 5 - Correlations season 2003-4.

Linear correlations (correlation coefficient, r) between 'Hass' avocado tree yield, plant minerals, and quality attributes of ripe fruit harvested in 2004. Correlations are based on means of 13 (ripening time) or 7 (flesh minerals) fruit per tree from 144 trees.

Variable 1	Variable 2	F pr.	r	Direction
Flesh Ca	Flesh N	<0.001	0.40	-
Flesh Ca	Flesh K	<0.001	0.42	-
Flesh Ca	Flesh B	<0.001	0.25	-
Flesh Ca	Can. Vol.	0.014	0.20	-
Flesh Ca	Av. fruit mass	<0.001	0.33	-
Flesh N	Yield/can.vol	<0.001	0.26	-
Flesh N	Canopy vol	<0.001	0.45	+
Flesh N	Aver fruit mass	<0.001	0.40	+
Yield	Flesh Ca	0.756	0.00	
Yield	Flesh N	0.093	0.11	-
Yield	Flesh K	0.696	0.00	
Yield	Acceptable fruit	0.013	0.19	+
Yield	Flesh Mg	0.011	0.20	-
Yield	Body rots	0.038	0.15	-
Yield	Stem end rots	0.832	0.00	
Yield	Diff. discol	0.019	0.18	-
Yield	Vasc browning	0.102	0.00	
Yield	DTES-eth	0.003	0.23	+
Flesh Ca	Acceptable fruit	<0.001	0.30	+
Flesh Ca	Body rots	<0.001	0.35	-
Flesh Ca	Stem end rots	0.015	0.19	+
Flesh Ca	Diffuse disc.	0.002	0.24	-
Flesh Ca	Vasc browning	0.198	0.00	
Flesh Ca	DTES-eth	<0.001	0.35	+
Flesh Ca	Skin colour	<0.001	0.28	-
Flesh N	Acceptable fruit	<0.001	0.32	-
Flesh N	Body rots	<0.001	0.26	+
Flesh N	Stem end rots	<0.001	0.27	-
Flesh N	Diff. Disc.	0.003	0.22	+
Flesh N	Vasc browning	0.262	0.00	

Variable 1	Variable 2	F pr.	r	Direction
Flesh N	DTES-eth	<0.001	0.27	-
Flesh K	Acceptable fruit	0.066	0.13	+
Flesh K	Body rots	0.031	0.15	+
Flesh K	Stem end rots	<0.001	0.37	-
Flesh K	Diff. Disc.	0.003	0.23	+
Flesh K	Vasc browning	<0.001	0.28	-
Flesh K	DTES-eth	<0.001	0.45	-
Flesh K	N/Ca	<0.001	0.55	+
Flesh N/Ca	Body rots	<0.001	0.32	+
Body rots	SER	0.001	0.26	+
Body rots	Flesh (Mg+K)/Ca	<0.001	0.28	+
Body rots	Av. fruit mass	<0.001	0.30	+
Body rots	Yield/c. vol	0.004	0.22	-
Body rots	Flesh K	0.037	0.14	+
Diff. Discol.	Av. fruit mass	<0.001	0.33	+
DETS-eth	Acceptable fruit	0.642	0.00	
DETS-eth	Body rots	0.869	0.00	
DETS-eth	Stem end rots	<0.001	0.56	+
DETS-eth	Diffuse disc.	<0.001	0.28	-

Appendix 6 - Correlations season 2004-5.

Linear correlations (correlation coefficient, r) between 'Hass' avocado tree yield, plant minerals, and quality attributes of ripe fruit harvested in 2005. Correlations are based on means of 20 (ripening time) or 10 (flesh Ca and N) fruit per tree from 72 trees.

Variable 1	Variable 2	F pr.	r	Direction
Soil Ca	Ex-Ca	<0.001	0.44	+
Soil Ca	Sap Ca	0.755	0.00	
Soil Ca	Leaf-Dec Ca	0.745	0.00	
Soil Ca	Leaf Ca	0.757	0.00	
Soil Ca	Fruitlet Ca	0.388	0.00	
Soil Ca	Flesh Ca	0.334	0.00	
Ex-Ca	Sap Ca	0.577	0.00	
Ex-Ca	Leaf-Dec Ca	0.459	0.00	
Ex-Ca	Leaf Ca	0.703	0.00	
Ex-Ca	Fruitlet Ca	0.437	0.00	
Ex-Ca	Flesh Ca	0.630	0.00	
Sap Ca	Leaf-Dec Ca	0.794	0.00	
Sap Ca	Leaf Ca	0.164	0.00	
Sap Ca	Fruitlet Ca	0.009	0.29	+
Sap Ca	Flesh Ca	0.057	0.19	+
Leaf-Dec Ca	Fruitlet Ca	0.954	0.00	
Leaf-Dec Ca	Flesh Ca	0.305	0.00	
Leaf Ca	Flesh Ca	0.281	0.00	
Soil Ca	Soil Mg	<0.001	0.75	+
Soil Ca	Soil K	<0.001	0.50	+
Ex Ca	Ex Mg	0.434	0.00	
Ex Ca	Ex K	0.589	0.00	
Soil Mg	Sap Mg	0.892	0.00	
Soil K	Sap K	0.288	0.00	
Soil K	Leaf K	0.033	0.22	+
Soil K	Flesh K	0.630	0.00	
Sap K	Leaf K	0.331	0.00	
Sap K	Flesh K	0.622	0.00	
Leaf K	Flesh K	0.822	0.00	
Soil Ca	Leaf Mg	0.002	0.35	-
Soil Ca	Leaf-Dec K	0.021	0.25	+
Soil Ca	Leaf K	<0.001	0.41	+

Variable 1	Variable 2	F pr.	r	Direction
Soil Ca	Flesh K	0.712	0.00	
Soil Ca	Flesh K	0.712	0.00	
Soil Ca	Leaf N	0.829	0.00	
Soil Ca	Flesh N	0.938	0.00	
Sap Ca	Sap Mg	<0.001	0.79	+
Sap Ca	Sap K	<0.001	0.62	+
Flesh Ca	Flesh N	<0.001	0.49	-
Flesh N	Flesh K	<0.001	0.56	+
Flesh N	Flesh Mg	0.302	0.00	
Leaf N	Flesh N	0.091	0.16	+
Leaf-Dec Ca	Yield	0.722	0.00	
Leaf Ca	Yield	0.397	0.00	
Sap Ca	Yield	0.313	0.00	
Fruitlet Ca	Yield	0.258	0.00	
Flesh Ca	Yield	0.095	0.16	+
Flesh N	Yield	0.015	0.26	-
Body rots	Yield	0.003	0.32	-
Tissue break.	Yield	<0.001	0.40	-
Diffuse disc.	Yield	<0.001	0.47	-
% accept fruit	Yield	<0.001	0.39	+
DTES	Yield	0.196	0.00	
Diff discol	Fruit no	<0.001	0.49	-
Body rots	Fruit no	0.008	0.29	-
Tissue break.	Fruit no	<0.001	0.45	-
% accept fruit	Fruit no	<0.001	0.40	+
Flesh Ca	Av. fruit mass	0.440	0.00	
Flesh N	Av. fruit mass	<0.001	0.44	+
Fruitlet Ca	% accept fruit	0.651	0.00	
Fruitlet Ca	Body rots	0.488	0.00	
Fruitlet Ca	Diffuse disc	0.027	0.23	-
Fruitlet Ca	DTES	0.018	0.25	+
Flesh Ca	% accept fruit	0.019	0.25	+
Flesh Ca	Body rots	0.174	0.00	
Flesh Ca	SE rots	0.809	0.00	
Flesh Ca	Diffuse disc.	0.151	0.00	
Flesh Ca	Tissue break	0.029	0.23	-
Flesh Ca	DTES	0.039	0.21	+

Variable 1	Variable 2	F pr.	r	Direction
Leaf N	% accept fruit	0.727	0.00	
Leaf N	% accept fruit	0.727	0.00	
Flesh N	% accept fruit	0.017	0.25	-
Flesh N	Body rots	0.138	0.00	
Flesh N	SE rots	0.656	0.00	
Flesh N	Diffuse disc.	0.078	0.17	+
Flesh N	Tissue break	<0.001	0.37	+
Flesh N	DTES	0.010	0.28	-
Flesh K	Body rots	0.199	0.00	
Flesh K	SE rots	0.601	0.00	
Flesh K	Diffuse disc	0.316	0.00	
Flesh K	% accept fruit	0.135	0.00	
Flesh K	Tissue break	0.097	0.00	
Flesh K	Yield	0.002	0.34	
Flesh K	Av. fruit mass	0.026	0.24	
Flesh K	Fruit no	<0.001	0.37	
DTES	Body rots	<0.001	0.56	+
DTES	SE rots	<0.001	0.69	+
DTES	Diffuse disc	0.013	0.27	-
DTES	% accept fruit	<0.001	0.45	-
DTES	Av. fruit mass	0.002	0.34	-
DTES	Fruit no	0.075	0.18	+

Appendix 7 - Correlation season 2005-6.

Linear correlations (correlation coefficient, r) between 'Hass' avocado tree yield, plant minerals, and quality attributes of ripe fruit harvested in 2006. Correlations are based on means of 20 (ripening time) or 10 (flesh Ca and N) fruit per tree from 72 trees.

Variable 1	Variable 2	F pr.	r	Direction
Soil Ca	Flesh Ca	0.895		
Sap Ca	Flesh Ca	0.082		
Leaf Ca	Flesh Ca	0.934		
Flesh Ca	Soil K	0.561		
Flesh Ca	Leaf K	0.183		
Flesh Ca	Sap K	0.071		
Flesh Ca	Flesh K	0.013	0.23	-
Flesh Ca	Flesh N	0.266		
Soil K	Flesh Ca	0.561		
Flesh K	Flesh N	0.052		
Flesh Ca	Av fruit mass	<0.001	0.42	-
Flesh Ca	Fruit no	0.034	0.22	
Flesh Ca	Body rots	0.018	0.25	-
Flesh Ca	Stem end rots	0.701		
Flesh Ca	Diffuse disc.	0.003	0.33	-
Flesh Ca	Ripening time	0.022	0.24	+
Flesh Ca	Dry matter	0.673		
Flesh Ca	Skin colour	0.246		
Ripening time	Dry matter	0.846		
Ripening time	Body rots	0.357		
Ripening time	Stem end rots	0.340		
Ripening time	Diff. discolour.	0.878		
Yield	Flesh Ca	0.166		
Yield	Leaf Ca	0.289		
Yield	Flesh K	0.377		
Yield	Flesh N	0.955		
Yield	Fruit DM	0.718		
Yield	Skin colour	0.201		
Yield	Av. fruit mass	0.273		
Yield	Body rots	0.152		
Yield	Stem end rots	0.786		
Yield	Diff. discol	0.878		
Yield	Ripening time	0.725		

Appendix 8 - Calculated basal nutrients for the pot trial (Chapter 5)

Nutrient	**Form**	**Rate kg/ha**	**Wt. form/pot (g)**	**Weight of form in stock solution g/L**
N	NH_4NO_3	120	0.604	120.8
P	$NaH_2PO_4.2H_2O$	100	0.890	178
K	KCl	50	0.168	33.6
Ca	$CaCl_2.2H_2O$	60	0.388	77.6
Mg	$MgSO_4.6H_2O$	15	0.249	49.8
Zn	$ZnSO_4.7H_2O$	2.5	0.0194	3.8
Cu	$CuSO_4.5H_2O$	2	0.0138	2.76
B	H_3BO_3	0.3	0.00303	0.606
Mo	$Na_2MoO_4.2H_2O$	0.2	0.00089	0.178

Note: Calculations assume 6000cm^3 pot and 5ml of each nutrient added.