Nutrient requirement and distribution of intensively grown 'Brookfield Gala' apple trees

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DECLARATION

I, the undersigned , hereby declare that the work contained in this thesis is my own original work and has not previously, in its entirety or in part, been submitted at any university for a degree.

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    Signature   Date

SUMMARY

'Brookfield Gala' apple trees were planted out in July 2003 in a Dundee soil form, consisting of well-aerated sandy loam soil. During the first 12 months trees received young tree solutions high in nitrogen. The nutrient solution of the 2nd leaf trees was based on a yield estimation of 10 ton. ha^{-1} plus 30%. Nutrient solutions for the 3rd leaf trees were based on 25 ton. ha^{-1} yield estimations and adapted upwards.

Seasonal uptake and distributions were determined for macro and micro elements, using two- and three-year-old apple trees during the seasons 2004/2005 and 2005/2006. In the bearing apple trees the macro nutrient accumulated rapidly from late winter to late autumn. Prior to leaf drop most of the N, P, S, Mg and a small portion of K were redistributed back into the permanent parts of the tree. On the other hand, all Ca in the leaves was lost through leaf drop. Apple fruit contains comparatively large quantities (±60.2%) of K, which are removed during harvest.

Guidelines for minimum and maximum nutritional requirements based on the amount necessary to produce 1 kg fruit were determined. For the 3rd leaf trees the minimum macro nutrient requirements (g. kg^{-1} yield) of N, P, K, Ca, Mg and S were ±1.7, ±0.3, ±2.3, ±0.5, ±0.2 and ±0.2, respectively. The maximum nutrient requirements (g. kg^{-1} yield) for N, P, K, Ca, Mg and S were ±2.6, ±0.4, ±3.3, ±1.9, ±0.4 and ±0.2, respectively. For the 3rd leaf trees the minimum micro nutrient requirements (mg. kg^{-1} yield) of Na, Mn, Fe, Cu, Zn, B and Mo were ±75.1, ±1.3, ±28.7, ±0.9, ±3.0, ±5.7 and ±0.3, respectively. The maximum nutrient requirements (mg. kg^{-1} yield) of Na, Mn, Fe, Cu, Zn, B and Mo were ±102.9, ±7.8, ±32.6, ±1.1, ±6.5, ±7.6 and ±0.3, respectively.

Labelled N uptake and distribution for two- and three-year-old apple trees were also determined during the same seasons. The labelled N uptake and distribution results indicated that there was a low labelled N uptake in the initial growth stages, suggesting the importance of internal N reserves for plant development at the beginning of the season. In the active growing period more than 60% of the labelled N was found in the new growth. Uptake efficiency improved as the trees grew older.

The effect of different nutrient levels on tree growth, yield and fruit quality was assessed: lower (80%) than the standard (100%) and three higher (120%, 140% and 160%). Results indicated that different nutrient levels had no effect on yield, blush or TSS during the 18 months of application over two bearing seasons. The application of biological products (humic acid, and compost plus compost extract) over a period of 18 months had a significant influence on the TSS, malic acid and citric acid concentrations. A tendency towards an increase in total fine root number and length occured with the addition of biological ameliorant.

OPSOMMING

'Brookfield Gala' appelbome is in Julie 2003 in 'n Dundee grond bestaande uit sanderige leemgrond wat goed deurlug is, uitgeplant. Gedurende die eerste 12 maande het die bome 'n jongboom oplossing wat hoog is in stikstof ontvang. Die oplossing vir die 2de blad boompies is gebaseer op 'n opbrengs skatting van 10 ton.ha^{-1} plus 30% meer. Die voedingoplossing vir die drie-jaar-oue boompies is gebaseer op 'n 25 ton.ha^{-1} opbrengs skatting.

Twee- en drie-jarige appelbome is gedurende die 2004/2005 en 2005/2006 seisoene gebruik om die seisoenale opname en verspreiding van makro- en mikro-elemente vas te stel. In vrugdraende appelbome het die makro- voedingselemente akkumulasie vinnig vanaf laatwinter tot laat herfs toegeneem. Tydens blaarval word die meeste van die N, P, S, Mg en 'n klein gedeelte K herversprei na die permanente dele van die boom. Al die Ca in die blare gaan egter verlore tydens blaarval. Die appelvrug bevat relatief groot hoeveelhede (omtrent 60.2%) K wat tydens die oes verwyder word.

Riglyne vir die minimum en maksimum voedingsvereistes gebaseer op die hoeveelheid benodig om 1 kg vrugte te produseer, is vasgestel. Vir die derde-blad bome was die minimum makro voedingselemente vereiste (g.kg^{-1} opbrengs) van N, P, K, Ca, Mg en S, onderskeidelik ±1.7, ±0.3, ±2.3, ±0.5, ±0.2 en ±0.2. Die maksimum voedingselemente vereistes (g.kg^{-1} opbrengs) vir N, P, K, Ca, Mg, en S was onderskeidelik ±2.6, ±0.4, ±3.3, ±1.9, ±0.4, en ±0.2. Vir die derde-blad bome was die minimum mikro voedingselemente vereiste (mg.kg^{-1} opbrengs) van Na, Mn, Fe, Cu, Zn, B, en Mo, onderskeidelik ±75.1, ± 1.3, ± 28.7, ± 0.9, ±3.0, ± 5.7 en ± 0.3. Die maksimum voedingselemente vereiste (mg.kg^{-1} opbrengs) van Na, Mn, Fe, Cu, Zn, B, Mo was onderskeidelik ±102.9, ±7.8, ±32.6, ±1.1, ±6.5, ±7.6 en ±0.3.

Gemerkte N-opname en-verspreiding vir twee- en drie-jaar-oue appelbome is ook gedurende dieselfde seisoen vasgestel. Die gemerkte N-opname en-verspreidings resultate toon dat daar lae gemerkte N opname was gedurende die aanvanklike groeistadiums wat die belangrikheid van interne N reserwes vir plantontwikkeling aan die begin van die seisoen beklemtoon. Gedurende die aktiewe groei-periode is meer as 60% gemerkte N in die nuwe groei gevind. Opnamedoeltreffendheid het verbeter soos die bome ouer geword het.

Die effek van verskillende voedingstofvlakke op boomgroei, opbrengs en vruggehalte is bestudeer; die een laer (80%) as die standaard (100%) en drie hoër (120%, 140% en 160%). Die resultate toon dat die verskillende voedingstofvlakke geen effek op opbrengs, kleur en TOS gedurende die 18 maande oor twee opbrengs-seisoene van die toediening gehad het nie. Die toediening van biologiese produkte (soos humiensuur en kompos plus kompos-ektrak) oor 'n periode van 18 maande het 'n groot invloed gehad op die verbetering van TOS, appelsuur en sitroensuur konsentrasie. Daar was ñ tendens van toename in fyn wortel aantal en lengte met die byvoeging van biologiese ameliorante.

Dedicated to my lovely parents Gersom and Ida

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General introduction

Accurate water and nutrient fertiliser management are essential to enable the manipulation of reproductive and vegetative development as well as fruit quality in deciduous fruit trees (Tagliavini & Marangoni, 2000). It is, therefore, very important to know the tree's mineral requirement and the phenological stage at which a certain element is taken up in order to supply nutrients at the right time to the soil in order for the nutrients to benefit the physiological processes taking place in the tree.

This study commenced with a literature review of existing information of nutrient requirements, seasonal uptake, and nutrient distributions in different tree parts, biological ameliorants and labelled nitrogen studies. Mineral nutrient functions and deficiencies as well as factors affecting nutrient uptake were also reviewed. This study was initiated in order to obtain information on the uptake at different phenological stages and the annual nutrient requirements of young and bearing 'Brookfield Gala' apple trees. This was done for the macro and micro elements because of the important functions and roles they play in fruit tree production, such as synthesis, energy processes, enzyme activation and osmotic regulation (Marschner, 1993). Numerous studies on nutrient uptake, distribution and requirements have been carried out by other researchers on apples (Batjer *et al*., 1952; Terblanche, 1972; Haynes & Goh, 1980); grape vines (Conradie, 1981); peaches (Stassen, 1987); kiwi vines (Kotzé & De Villiers, 1989) and pears (Stassen & North, 2005) to determine the nutrient requirements and uptake of the fruit trees**.** Most of the studies were, however, done in young trees in sand culture, or trees planted in less dense planting systems.

Since nitrogen plays on overriding role in plant growth ^{15}N studies were done in addition to the above studies in order to get a picture of the movement of nitrogen over the season (Millard, 1996). Labelled N studies have been used effectively to quantify the timing of nitrogen uptake (Weinbaum *et al*., 1978; Muñoz *et al.*, 1993) and the significance of N storage, which serves as a reservoir for nitrogen prior to the onset of tree uptake of external nitrogen sources (Millard, 1996).

The nutrient solution that was used was adopted from studies carried out on pears (Stassen & North, 2005). This solution is indicated as the 100% solution and was compared against 80%, 120%, 140% and 160% solutions to determine whether yield and quality can be improved by

decreasing or increasing the nutrient levels. The following question was addressed: Is the theoretical standard (100%) really the ideal nutrient solution?

The advantages of biological ameliorants were also widely studied (Smith, 2001). Here the following question was addressed: Can fruit trees perform maximally with an 'ideal' fertiliser solution and daily fertigation alone, or does the addition of biological ameliorants result in a complimentary improvement in yield and fruit quality through root proliferation and soil environment improvement?

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Chapter 1

Nutrient uptake and distribution, and the management of fruit crops: Literature Review

1.1   Introduction

Deciduous fruit production in South Africa, specifically in the Western Cape Province, is faced with acidic, often shallow (30–50 cm), and inherently infertile soils (Huysamer, 1997). These poor soils need to be rectified and managed properly to improve yields. As a result of these poor soils, some farmers are moving away from conventional microirrigation and broadcasting fertiliser application. A system whereby nutrients and water are directly added to the root zone through a drip irrigation application is currently gaining favour. Fertigation permits the application of nutrients in solution exactly and uniformly to the area where the active roots are concentrated. This increases the efficiency of fertiliser application, reduces leaching and allows nutrients to be applied accurately, to the benefit of the trees (Imas, 1999).

Accurate water and nutrient fertilizer management is essential in modern high density plantations to enable the manipulation of reproductive and vegetative development as well as fruit quality in deciduous fruit trees (Tagliavini & Marangoni, 2000). Mineral nutrition is one of the important factors in fruit tree production since minerals are responsible for several functions like energy processes, enzyme activation and osmotic regulation of the membranes (Faust, 1989; Marschner, 1993). Therefore it is very important to determine the mineral requirements of trees and at what phenological stage a certain element is taken up in order to supply nutrients to the soil at the right time to benefit the physiological processes taking place in the tree at such time. According to Stassen *et al*. (1999) the phenological period and rate of uptake determine the application time and the quantity of nutrient to be applied to achieve optimal production and fruit quality. Nitrogen is the most critical of all the nutrients and it must be managed carefully as it determines the balance between the reproductive and vegetative growth. If nitrogen is applied at the wrong time it may negatively influence phenological and physiological plant processes (Stassen *et al*., 1981b; Faust, 1989). For optimal yield and fruit quality a guideline for tree nutrient requirement at appropriate phenological stages should be determined and applied.

Apple trees require 16 elements for successful completion of their life cycle (Salisbury & Ross, 1992). Among these elements are carbon, hydrogen and oxygen, which are important non-mineral elements and major constituents of organic materials (Neilsen & Neilsen, 2003). Mineral elements are divided into two groups: macro elements comprising nitrogen, phosphorus, potassium, calcium, magnesium and sulphur, and micro elements comprising iron, manganese, copper, zinc, boron, molybdenum and chloride (Salisbury & Ross, 1992). The annual requirement for fertiliser application depends on total requirements, and on the natural supply from the soil through mineralisation and decomposing organic materials. It is difficult to calculate the total nutrient requirements for apple trees since it is necessary to account for nutrients contained in the perennial framework of the trunk and roots as well as the nutrients contained in leaves, new shoots and roots, which are produced annually (Neilsen & Neilsen, 2003). Most of the nutrients removed from the soil are through fruit harvesting so the need to replace nutrients is largely a function of crop yield. Losses by leaching can also take place under conditions of high rainfall or irrigation in more sandy and gravel soil types (Kotze, 2001). Haynes & Goh (1980) estimated a 40% loss of nitrogen supply through leaching in irrigation water. Furthermore, nutrients are removed by pruning and a certain amount is fixed as part of the permanent structure of the tree (Stassen, 1987; Stassen & North, 2005). There is also a positive balance through remobilisation from the leaves before they drop (Terblanche, 1972; Stassen, 1987; Millard, 1996). Thunderstorms can also release nitrogen into the soil (Stassen, 1987; Marschner, 1993). Depending, therefore, on the situation in the orchard, these positive and negative aspects must be balanced out in order to determine the actual nutrient requirements of an orchard.

1.2   Nutrient requirements

Nutrient functions are well studied (Mengel & Kirkby, 1982; Taiz & Zeiger, 1991; Salisbury & Ross, 1992; Marschner, 1993; Mohr & Schopfer, 1994; Neilsen & Neilsen, 2003). The specific nutrient requirements for optimal fruit production and quality do, however, need to be determined, especially for higher density plantings. An effective method for determining tree nutrient requirements is one based on whole tree mineral analysis (Weinbaum et al., 2001). Various studies have been carried out on apples (Batjer et al., 1952; Haynes & Goh, 1980), grape vines (Conradie, 1981), peach (Stassen, 1987), kiwi vines (Kotzé & De Villiers, 1989a; 1989b) mango (Stassen et al., 1997a; 1997b) and pear (Stassen & North, 2005). According to Stassen (1987) and Weinbaum et al. (2001) this method takes into account mineral nutrient

losses caused by removal of fruit and pruned wood, the part of the nutrient content from leaves that does not migrate, and nutrients that are fixed in permanent parts of the tree (older wood and roots). Trees are excavated and divided into the different tree parts (roots, stems, leaves, shoots and fruits) at different stages during the year. Each fresh tree portion is weighed and a sample is milled, dried and weighed again. The dry samples are then sent to the laboratory for mineral analysis. Results of the analysis of mineral elements can be used as a guideline to determine tree requirements by determining the nutrients lost by the removal of fruits, removal of wood (summer and winter pruning), leaf drop and minerals fixed in the permanent parts and used for new growth. These amounts must be put back into the soil to support plant growth.

Terblanche (1972), Titus & Kang (1982), Conradie (1981) and Stassen *et al*. (1997b) report that N, P and K are translocated back from the leaves to the permanent parts before leaf drop, but the immobile Ca and, to an extent, the moderately mobile Mg are not redistributed or translocated from leaves to the permanent parts. Nutrient loss through leaf drop can be regarded as temporary since the leaves decompose and are mineralised if not blown away by the wind or a blower (Stassen, 1987). In medium to high potential soils where mulches are used and nutrients supplied through fertigation and hydroponics there is no need to compensate for leaf loss because the nutrients are mineralised back into the soil (Stassen, 1987). According to Stassen & North (2005), in low potential soils with no mulches and where fertiliser is applied by hand, it is very important to consider losses through the leaves and to compensate for leaching and inefficiency of placement of leaf content (50% of all minerals besides Ca and Mg [100%]). The minimum requirement can be used under medium to high potential soil conditions with mulches and where fertiliser is applied through the water to the root zone (Stassen & North, 2005).

To determine a better annual tree mineral requirement without tree removal the mineral losses through fruit and wood (summer and winter pruning) removal must be combined and expressed per kilogram macro elements or gram micro elements per ton of fruit harvested (Stassen & North, 2005). Stassen (1987) indicates that the quantity of elements lost or fixed, expressed as kilograms fruit, can be used as guidelines for application.

1.2.1 Nitrogen

Nitrogen (N) is a major constituent of amino acids, proteins, nucleic acids and other organic compounds and therefore plays a major role in plant metabolic processes (Salisbury & Ross, 1992: Neilsen & Neilsen, 2003). In apple trees the N requirement is higher than the requirement for any other nutrients. Nitrogen is required to support new tissue growth such as developing leaves, shoots and fruit (Neilsen & Neilsen, 2003). Stassen *et al.* (1999) report that nitrogen deficiency causes poor vegetative and reproductive growth and leads to small fruits. It also reduces the differentiation of reproductive buds. Hewitt & Smith (1975) and Faust (1989) indicate that excess N results in vigorous growth, increased water shoots, induced fruit drop and increased physiological disorders in fruits. High levels of N induce fruit drop and stimulate vigorous growth, and result in Ca translocation to new growth at the expense of the fruit (Stassen *et al.,* 1999; Jackson, 2003). Nitrogen also reduces fruit colouring and the shelf life of fruits. Stassen *et al.* (1983) suggest that the N application should be done in instalments due to the fact that nitrogen leaches easily from the soil and it stimulates growth.

Nitrogen application to the soil will be beneficial to the tree if it is applied at the following stages: (1) 50%, divided into two or more installments of the annual requirement, in early and late spring and (2) the other 50% in autumn, after termination of shoot growth or formation of terminal buds, especially in early ripening peaches (Stassen, 1987). In the case of vigorous shoot growth during spring the quantity (some instalments) of N application can be reduced or omitted to control the competition between the reproductive and vegetative growth (Hewitt & Smith 1975; Stassen *et al.*, 1983). This however means that the initial calculations of requirements may be overestimated (Stassen *et al.,* 1999). Summer N application to full bearing trees should be avoided because it stimulates growth causing the development of water shoots that shade the tree; and retards termination of shoot growth which affects the fruit quality negatively (Stassen *et al.*, 1983). Thus the N is used for regrowth during the post-harvest period instead of building reserves. Stassen *et al.* (1983) suggest that summer N application can be given to young trees to stimulate growth so that they can fill their allocated tree volume faster, but the tree must become dormant during winter. The autumn N application is very important because it is accumulated by the tree's permanent parts as reserves and redistributed in the early season from the permanent structure for new growth when uptake is otherwise insufficient (Stassen *et al.*, 1981b). Terblanche (1972) (working with apples) and Stassen *et al.* (1981b) (working with peaches) report that inadequate autumn

N has negative effects on the tree. It causes premature leaf drop, reduces N and starch reserves, increases delayed foliation, and leads to poor quality flowers, poor fruit set and poor growth the following season. Insufficient N applied during autumn cannot be compensated for by simply applying N in the early part of the following season. The reason for this is that uptake during the period when leaves are still developing is not very effective (Faust, 1989). Nevertheless, in situations, where postharvest N application cannot be done (e.g. lack of sufficient irrigation water) N is applied as a foliar spray in the form of urea in spring. This is, however, a distinctly second best option.

1.2.1 Phosphorus

The phosphorus (P) requirements of apple trees are small relative to other nutrients (Jackson, 2003). P is a factor in energy transfer and is a constituent of nucleic acids (Taiz & Zeiger, 1991; Salisbury & Ross, 1992). P is mostly required at stages of meristematic activity when roots and shoots emerge, particularly at planting (Neilsen & Neilsen, 2003). Hansen (1980) found, in a pot experiment, that the total P uptake is about 50% lower in fruiting than in non-fruiting trees. Nevertheless, annual P requirements can be high early in the season when cell division is taking place in developing leaves, shoots and fruitlets.

Phosphorus is immobile in the soil. It can be supplied as a reservoir application during soil preparation in the feeder root layer so as to be available when needed by the tree (Stassen *et al*., 1983; Stassen, 1987; Faust, 1989; Stassen *et al*., 1999). Thereafter it can be applied as a partial maintenance supplementation according to leaf and soil analysis (Stassen *et al*., 1997b). Kotzé (2001) suggests that sufficient P (30 mg. kg $^{-1}$, Bray II extraction method) must be applied during soil preparation. With fertigation and hydroponics systems P can be applied more often to the root zone at different phenological phases to support growth because of the massive, shallow root development, especially under mulch (Stassen *et al*., 1999). Shear & Faust (1980) and Marschner (2002) indicate that P deficiency is harmful to a wide range of metabolic processes. It delays plant growth, causes weak root growth, and reduces fruit size and quality of the fruit. Excess P causes toxicity to roots and also reduces the iron (Fe) uptake (Mohr & Schopfer, 1994).

1.2.3 Potassium

The potassium (K) demand of apple trees is similar in quantity to the total N demand. The leaf concentration is second to N and the fruit concentration exceeds that of all other mineral

nutrients (Neilsen & Neilsen, 2003). Potassium is the most abundant cation in the cytoplasm and plays an important role in pH stabilisation, osmoregulation, enzyme activation, protein synthesis, stomatal movement, photosynthesis and cell extension (Faust, 1989). Neilsen & Neilsen (2003) also report that K is mobile in the phloem, resulting in a good supply of potassium to fleshy fruits. Whole tree partitioning studies indicate that fruiting trees have a higher K uptake per unit of root dry mass than non-fruiting trees (Neilsen & Neilsen, 2003). Therefore heavy crop load reduces leaf potassium concentration. It is very important to apply the correct amount of K required according to leaf and soil analyses. If it is applied at higher rates it inhibits the uptake of Ca, causing bitter pit in apples (Shear & Faust, 1980). Using the fertigation and hydroponics systems K can be applied more often to the root zone at the fruit development stage. Potassium deficiency is harmful to the physiological functions as well as fruit development, while excess K stimulates a number of physiological disorders (Shear & Faust, 1980; Stassen *et al*., 1999).

1.2.4   Calcium

Calcium (Ca) is the most important mineral element determining the post-harvest quality of fruits, especially in apples and pears that are stored for longer periods (Faust, 1989). It is also important in other fruit types since high Ca levels delay fruit ripening. The apple tree wood contains more Ca than any other mineral element, with the result that orchard requirements to maintain top and root structures are higher than for all other nutrients (Neilsen & Neilsen, 2003). Calcium serves important functions within the plant, including the regulation of cellular behaviour and maintenance of cell integrity and membrane permeability (Mengel & Kirkby, 1982; Tromp, 2005). Calcium is immobile and moves slowly in the soil. Therefore Faust (1989) and Stassen *et al*. (1999) suggest that Ca levels should be rectified during soil preparation and thereafter application can be done according to the soil and leaf analyses norms. Kotzé (2001) recommends that the basic cation saturation of Ca in soils should be 70% for sand, 75% for loam and 80% for clay soils. According to Stassen *et al.* (1983) there is a correlation between Ca and Mg, and an annual supplement of lime is essential for maintaining a suitable soil pH as well as for supplementing Ca. The type of lime to be applied depends on the Mg levels of the soil. If the Mg level is high then calcitic lime must be used. If the Mg level is low then dolomitic lime, or a mixture of calcitic and dolomitic lime, should be used (Kotzé, 2001). Where the pH is correct or high, gypsum can be applied to raise low Ca levels (Kotzé, 2001). Calcium can be applied through hydroponics and fertigation in the early fruit development phase in order to improve the quality in the fruits

(Stassen *et al*., 1999). Calcium deficiency is manifested in retarded growth and necrosis of shoots and root tips (Tromp, 2005). Tromp (2005) further states that low Ca concentrations in the fruit lead to Ca related disorders, such as bitter pit, water core and senescent breakdown in apple fruit.

1.2.5 Magnesium

Magnesium is required and taken up by fruit trees in lower quantities than Ca. The Mg uptake can be reduced by competing cations such as K^+, NH_4^+, Ca^{2+} and Mn^{2+}, as well as H^+ (Marschner, 1993). However, K plays the major role in suppressing Mg uptake because most orchards are fertilized with high quantities of this element (Mengel & Kirkby, 1982). Magnesium is a constituent of the chlorophyll molecule and this ion serves important biochemical functions in the activation of enzymes involved in phosphorylation, activation of ribulose bisphosphate carboxylase, oxygenase and protein synthesis (Mengel & Kirkby, 1982; Marschner, 1993). Kotzé (2001) recommends basic cation saturation in soils of Mg saturation of 16%. Magnesium deficiency inhibits CO_2 assimilation, reduces photosynthesis and is detrimental to metabolic processes (Shear & Faust. 1980; Marschner, 1993; Stassen *et al*., 1999). Excess Mg prevents Ca uptake and therefore the correct quantities must be given to reduce Ca related disorders (Shear & Faust, 1980).

1.2.6 Sulphur

The sulphur (S) requirement of apple trees is similar to the amount of P required. Sulphur is structurally incorporated into sulphur-containing amino acids, proteins and co-enzymes (Neilsen & Neilsen, 2003). The uptake and availability of S is not influenced by soil pH and it is thus taken up readily over a range of orchard soil conditions (Mengel & Kirkby, 1982). In the tree it is incorporated into certain amino acids (e.g. cysteine, methionine) and subsequently becomes part of certain enzymes, vitamins and oils (Mengel & Kirkby, 1982). Once in these complex molecules, S is not easily mobilised within the plant. Deficiency symptoms therefore occur in young tissues before older ones (Shear & Faust, 1980). Senescing leaves efficiently retrieve sulphur that is transported from the leaves to the rest of the plant.

1.2.7 Micro elements

Micro elements are required in smaller quantities than the macro elements. Therefore foliar sprays or soil applications can be given to the plants when needed. The majority of

micronutrients are phloem immobile and most deficiency symptoms appear on new leaves, near the shoot tips (Neilsen & Neilsen, 2003). Manganese (Mn) in the plant participates in several important processes, including photosynthesis, and nitrogen and carbohydrate metabolism (Mengel & Kirkby, 1982; Marschner, 2002). It is generally considered to be somewhat immobile in the plant, and it is preferentially supplied to young growing tissue. Mn deficiency manifests itself on the leaves, as irregular shaped light green spots in the margins and between veins of basal shoots (Shear & Faust, 1980).

Iron (Fe) is associated with chloroplasts where it plays some role in the synthesis of chlorophyll. A small percentage of Fe complexes with proteins to form important enzymes (Mengel & Kirkby, 1982; Tisdale *et al.*, 1985).

Although zinc (Zn) is needed in small amounts in the tree it has been identified as a component of almost 60 enzymes, and therefore plays a role in many plant functions (Marschner, 1993). Of particular interest is its role as an enzyme co-factor in producing the growth hormone indoleacetic acid (IAA) (Mengel & Kirkby, 1982). This is the most probable explanation for the shortened internodes and small leaves observed with zinc deficiency.

Boron (B) is involved in several processes within the plants, including protein synthesis, transport of sugars, metabolism of plant hormones and fertilisation (Marschner, 2002; Jackson, 2003). Because these functions are vital to meristematic tissue, boron deficiency is particularly damaging to actively growing shoots and root tips (Shear & Faust, 1980). Boron moves almost exclusively with the transpiration stream in the xylem; it is virtually absent from the phloem and is thus relatively immobile within the plants (Mengel & Kirkby, 1982).

Copper (Cu) is located in the chloroplasts where it participates in photosynthesis reactions (Mengel & Kirkby, 1982). It is also found in enzymes involved with protein and carbohydrate metabolism.

Molybdenum (Mo) is an essential component of two enzymes involved in nitrogen metabolism (Mengel & Kirkby, 1982). Therefore Mo deficiency symptoms sometimes resemble nitrogen deficiency.

Stassen *et al.* (1999) suggest that B and Zn should be applied before fertilisation and fruit set in order to support cell division. This can be done in the form of soil or leaf applications. Zinc may be applied in autumn as a post-harvest application, but the most effective time for application is in the spring, before buds open (Herrera, 2001). Chelated forms of zinc and iron must be used for soil application. These formulations dissolve slowly in the soil and can be used by trees before being bound to the soil particles (Herrera, 2001). Iron, Mn, Cu and Mo foliar application is needed at cell division, enlargement and growth (Stassen *et al.*, 1999). Each element needs to be supplied in the right quantity in order to avoid deficiencies or surpluses. Some elements affect the uptake of others, reduce productivity and become toxic (Tisdale *et al.*, 1985). Leaf and soil mineral analysis should be used for the fine-tuning of the crop nutrient requirement.

1.3 Leaf and soil nutrient concentration

Nutrient analysis of soil and plant tissue should be an integral part of any tree crop management. According to Faust (1989) leaf analysis is the most convenient and the most accurate guide in determining the nutritional status of trees, while soil analysis estimates the ability of the soil to supply plant nutrients. Thus, when tissue and soil analyses are carried out timeously, deficiency and excess can be detected before symptoms can be seen, and adjustments can be made. Leaf nutrient concentration reflects factors influencing nutrient availability, the supply of nutrients from the soil, as well as variation of climate and crop load (Mengel & Kirkby, 1982; Faust, 1989). Neilsen & Neilsen (2003) report that nutrient concentration is not stable within the season because the rate of nutrient supply and internal tree cycling changes throughout the period of annual leaf and shoot development. Some nutrient concentrations such as nitrogen, phosphorus, potassium and zinc decrease while other nutrient concentrations such as calcium and magnesium increase over the growing season. Faust (1989) and Neilsen & Neilsen (2003) suggest that leaf samples for analysis should be collected at the most stable stage (between 110 and 125 days after full bloom) since this is the best way of establishing the leaf nutritional concentration status. In South Africa, the end of January was found to be the best time for leaf analysis of deciduous fruit trees (Kotzé, 2001). In order to obtain a consistent and representative sample 25–50 leaves should be collected from 20–25 randomly selected trees annually from the same cultivar/rootstock, with leaves collected around the tree from the mid-shoot portion of the current season's extension growth from shoots of representative vigour (Neilsen & Neilsen, 2003).

Various researchers have established leaf and soil norms for different fruit types and for crop loads and these can be used under normal conditions (Faust, 1989; Neilsen & Neilsen, 2003). According to Stassen *et al.* (1981b) and Faust (1989) these norms are used as a tool to adjust the quantity of nutrients to be applied. Neilsen & Neilsen (2003) and Assis & Filho (2004) report that leaf nutrient concentration can be interpreted using a Diagnosis and Recommendation Integrated System (DRIS). The DRIS approach is based on the comparison of nutrient ratios between sample plants and a high yielding subgroup (Assis & Filho, 2004). They also suggest that this method is less affected by sampling time and tissue ageing.

1.4 Root studies

The root system plays a major role in the absorption and translocation of water and nutrients from the soil throughout the tree (Faust, 1989; Atkinson *et al.*, 2003; Neilsen & Neilsen, 2003). Apple cultivars are usually budded to clonal rootstock, which are selected on the basis of precocity, ability to reduce scion vigour and resistance to pests, rather than their ability to take up water and nutrients (Atkinson *et al.*, 2003; Neilsen & Neilsen, 2003). Atkinson (1980) reports that apple tree roots are non-uniformly distributed within the exploitable soil volume, and can sometimes penetrate to a depth exceeding 1–2 m and, without competition from other trees, promote a lateral spread exceeding that of the top branches. Despite the ability of roots to extend over great distances and to great depths apple root density is generally low, frequently of a magnitude less than that of Graminaceae species, with which apple is often interplanted (Neilsen & Neilsen, 2003). Atkinson (1980) also reports that planting density influences root distribution. Roots are deeper and more laterally restricted when trees are planted more closely together. Neilsen & Neilsen (2003) suggest that roots proliferate when nutrient and water conditions are favourable, such as beneath drip emitters through which nutrients are applied.

Adequate nitrogen application stimulates primary absorbing root growth. In contrast, excess N suppresses root growth and stimulates shoot growth (Kolesnikov, 1971). In addition, K and P promote root system branching (Faust, 1989) and K increases the root weight more efficiently than it does the above-ground portion of the tree (Kolesnikov, 1971). Calcium is essential for the growth of shoot tips: when it is in short supply the roots and shoot tips often die back (Faust, 1989). Nutrient uptake by the roots occurs by direct root interception, by mass flow of dissolved nutrients in water absorbed by the plant and by diffusion if a

concentration gradient for the specific ion develops around the root hair zone (Salisbury & Ross, 1969; Taiz & Zeiger, 1991; Neilsen & Neilsen, 2003). Apple is likely to access fewer nutrients by direct interception due to lower root density and because, in general, apple trees are grown in infertile soils (Jackson, 2003).

1.5   Nutrient uptake

Salisbury & Ross (1969), Taiz & Zeiger (1991) and Marschner (1993) report that plants take up nutrients from the soil through their root system by means of diffusion from an area of a higher concentration (soil) to a lower concentration (plant roots) as well as by mass flow of nutrient solution. After absorption by the root system the nutrients are transported in the xylem vessels to areas where they are needed (Salisbury & Ross, 1969; Taiz & Zeiger, 1991). Different factors such as root volume, soil temperature, soil pH, water, oxygen, carbon dioxide and microbial activities affect nutrient uptake by plants. High nutrient uptake is promoted by optimum moisture conditions, a large well developed root system that can explore the soil well, and sufficient photosynthesis that supplies the roots with adequate carbohydrates for optimum root metabolism (Faust, 1989). Low nutrient uptake can result from poor soil aeration, low moisture conditions, or low metabolic activity of the roots.

Temperature plays a large role in nutrient absorption: higher temperatures (about 24°C) increase the uptake and lower temperatures (about 10°C) reduce the uptake. According to Salisbury & Ross (1969), increased absorption with increasing temperature occurs because of the increased rate of diffusion of nutrients from the soil to the roots, as well as increased respiration. At high temperatures of about 40°C, nutrient uptake and respiration are reduced while the cell membrane becomes more permeable and some nutrients leak out.

The pH of the soil also plays a huge role in nutrient uptake. At lower pH the hydrogen ions usually decrease the absorption of cations and increase the absorption of anions. At higher pH the opposite happens because the hydroxyl or bicarbonate ions compete with anions such as nitrate, chloride and phosphate (Marschner, 1993). Soil pH (acidity or alkalinity) and the balance between elements will affect the availability of nutrient elements in the soil (Faust, 1989; Marschner, 1993). Calcareous soils (pH > 7.5, KCl) render Fe and Zn unavailable for uptake by the tree.

Furthermore, waterlogged or poorly aerated soils reduce oxygen around the roots and therefore reduce nutrient uptake.

1.5.1 Nitrogen

Nitrogen studies have received much attention in the past since N is considered the most important nutritional factor in the growth and development of apple trees (Titus & Kang, 1982). Nitrate and ammonium are the major sources of inorganic N taken up by the roots of higher plants (Faust, 1989; Marschner, 1993; Neilsen & Neilsen, 2003). To a lesser extent, apple roots are also capable of absorbing organic nitrogen compounds, including urea, glutamate and aspartate (Neilsen & Neilsen, 2003). Soil nitrogen availability for plant growth is dependent on both organic and inorganic soil properties and on factors determining microbial activity (Neilsen & Neilsen, 2003). Mengel & Kirkby (1982) report that nitrate is taken up more often since it occurs naturally in soil solutions at a higher concentration than ammonium.

In the soil, nitrates are present almost entirely in solution and thus the majority of the nitrate moves to the tree root by mass flow, although a diffusion gradient may arise when depletion zones develop around roots (Marschner, 2002). In contrast, ammonium is adsorbed to the soil cation-exchange complex and can also be fixed within the lattices of certain 2:1 layers of clay minerals, such as illite and vermiculite, often competing with potassium for such sites (Neilsen & Neilsen, 2003). Ammonium uptake by roots is both by mass flow and by diffusion (Taiz & Zeiger, 1991).

Microorganisms influence the nitrate concentrations in soil solution as a result of mineralisation of organic matter and the conversion of ammonium to nitrate (nitrification), nitrate uptake by microorganisms and plants and nitrate leaching by water from precipitation or irrigation (Taiz & Zeiger, 1991; Neilsen & Neilsen, 2003). Titus & Kang (1982) and Stassen *et al*. (1983) suggest that trees can take up N from the soil throughout the season as long as the leaves are active and the soil temperature is conducive to root activity. Nitrogen absorbed by the roots is mostly utilised in the roots, which requires a substantial amount of carbohydrates (Faust, 1989). As a result the N uptake efficiency (NUE) is high when the tree produces photosynthates (Faust, 1989). According to Weinbaum *et al*. (1978), who studied uptake and measured nitrogen utilisation efficiency in plum, N is not taken up before rapid shoot growth begins, it decreases when leaves are senescing, and ceases when leaves drop.

Several researchers agree that in the early season fruit trees rely on N reserves built up in the post-harvest season (Terblanche, 1972; Stassen *et al.*, 1981a; 1981b; Titus & Kang, 1982; Millard, 1996; Stassen *et al.*, 1999). Stassen *et al.* (1981a) report on two stages during which N is taken up by peach trees. The first stage is three weeks before bud break until three weeks before shoot extension growth stops and the second stage is three weeks before and after final leaf drop. Therefore N needs to be applied to the soil in early spring and after formation of the terminal bud. Proper timing for the application of N fertiliser is when the sink demand is high as this ensures better interception, and less leaching, and improves yield and fruit quality (Klein & Weinbaum, 2000).

1.5.2   Phosphorus

Phosphorus solubility and mobility are low in most soils and hence P needs to be applied with soil preparations in the root zone in order for the plant roots to take it up when needed (Stassen *et al.*, 1983; Stassen, 1987; Stassen *et al.*, 1997b; Neilsen & Neilsen, 2003). The combination of a low P concentration in soil and the low rooting density of apple trees causes P uptake mainly by desorption from the soil matrix, followed by diffusion to tree roots (Neilsen & Neilsen, 2003). Consequently, soil properties such as low temperature, moisture content and pH that reduce desorption and diffusion also reduce phosphorus uptake (Taiz & Zeiger, 1991; Salisbury & Ross, 1992). Taiz & Zeiger (1991) indicate that the association of vesicular-arbuscular mycorrhizae with plant roots facilitate the uptake of P.

Nowadays, with a hydroponics systems and fertigation, it is believed that P application can becomes less problematic because it can be directly added to the shallow root zone (Stassen *et al.*, 1999; Stassen & North, 2005). Roots are also stimulated to proliferate near the soil surface, especially in mulched orchards (Atkinson, 1980). Conradie (1981) found that grape vines take up phosphorus at two stages: from three weeks after bud break until veraison and then from five weeks after harvest until leaf drop. Stassen & Stadler (1988) agree with this finding for peach trees. Terblanche (1972) found three stages of P uptake in apple trees: during shoot elongation, six to nine weeks before the beginning of leaf senescence, and during leaf senescence.

1.5.3   Potassium

Due to incorporation within the soil mineral structure the total K content of the soil can be high while the soil solution concentration is low. Soluble K is equivalent to absorbed K on

negatively charged exchange sites on the surface of clay mineral and organic matter (Neilsen & Neilsen, 2003). The K supply to plant roots depends on the diffusion flux that a soil can maintain in the direction of plants (Neilsen & Neilsen, 2003). In an experiment carried out by Tromp (1980), in which he subjected apple trees to a range of environmental conditions, he found that K uptake was linearly related to the metabolic activity. Potassium is mobile in the soil and is transported to the meristematic tissues (Mengel & Kirkby, 1982). According to Conradie (1981) potassium is taken up by grape vines three weeks after bud break until four to five weeks after harvest. No uptake was noticed during leaf drop. Terblanche (1972) indicates two stages of K uptake in apple trees, namely at shoot elongation and at leaf drop. In the case of peach trees, Stassen & Stadler (1988) indicate uptake three weeks after bud break until harvest and then at leaf drop.

1.5.4 Calcium

Most soils contain large quantities of calcium as a constituent of calcium carbonate, silicate, sulphate and phosphate minerals (Neilsen & Neilsen, 2003). Calcium comprises the bulk of exchangeable cations (65–85 %) adsorbed to organic matter and inorganic soil colloids and has the highest concentration (50–100 mg.kg^{-1}) of any cation in soil solution (Neilsen & Neilsen, 2003). Kotzé (2001) recommends the exchangeable cations of Ca to be between 70 and 80%, according to soil texture. Thus the plant requirement for calcium is satisfied by mass flow of water to the roots (Taiz & Zeiger, 1991). Calcium infiltration into the soil is very slow and therefore it needs to be applied as early as possible, preferably before an orchard is planted (Faust, 1989). Especially in soils with at least 10% clay, or more, Ca in the soil needs to be rectified at soil preparation by applying lime to the soil in order for Ca to be available for plant uptake by the young root tips when needed (Kotzé, 2001). There are two types of lime that can be applied to the soil, namely calcitic or dolomitic lime. Dolomitic lime should only be applied if the Mg level of the soil is low, while when Mg is adequate calcitic lime should be applied (Kotzé, 2001). Gypsum can also be applied to increase the percentage of Ca saturation when the pH is correct or high (Kotzé, 2001). Conradie (1981), working on grape vines, and Stassen & Stadler (1988), working on peaches, reported two stages in which Ca is taken up, namely after bud break until véraison in grape vines, or until harvest in peach trees and again six weeks before leaf drop.

1.5.5   Magnesium

Magnesium can be found in different forms in the soil, for example as unavailable Mg contained in the soil mineral structure, exchangeable Mg adsorbed on organic matter and clay minerals, and soluble Mg dissolved in the soil solution (Neilsen & Neilsen, 2003). Thus the soil solution concentration of Mg is high and Mg can be made available to the roots through mass flow. Magnesium is needed, and taken up by fruit trees, in lower quantities than Ca (Faust, 1989). According to Conradie (1981) Mg is taken up in the grape vines after bud break until véraison. Stassen & Stadler (1988) report that Mg in peach trees is taken up after bud break until harvest.

1.5.6   Sulphur

Sulphur is taken up from the atmosphere in small amounts by plants in the form of sulphur dioxide or hydrogen sulphide, but the majority is taken up by the roots (Faust, 1989; Westerman *et al*., 1999). The uptake and assimilation of S by plants is determined by the metabolic needs of the total plant, which differs between species (Westerman *et al*., 1999). According to Westerman *et al*. (1999) the root uptake of sulphur is an active process facilitated by a sulphate transporter, which is controlled by the sulphur content. Part of the S applied to well drained soils ends up in sulphate form. Sulphur is oxidised by soil bacteria and fungi, and the oxidised sulphate ions are absorbed by plants (Tisdale *et al*., 1985). The most abundant reservoir of S in soil is in the organic form, such as lipids, amino acids and proteins (Mengel & Kirkby, 1982). These compounds are broken down by microorganisms to inorganic sulphates, e.g. SO_4. Mengel & Kirkby (1982) indicate that a substantial amount of the total S exists in this form, which is readily available to plants and actively taken up by the roots. Furthermore, Tisdale *et al*. (1985) indicate that sulphates are moderately mobile and may be adsorbed on clay minerals, particularly the kaolinitic type, and on hydrous oxides of aluminium and, to a lesser extent, iron. If the soils are irrigated the sulphides can leach into the subsoil where they are available for root uptake. Westerman *et al*. (1999) suggest that thiol compounds like glutathione play a role in the coordination between sulphur assimilation in the shoot and the rate of sulphate uptake by the roots, by acting as signal modulating sulphate transport.

1.5.7   Micro elements

Micro elements are taken up by the plant roots by mass flow and by diffusion (Salisbury & Ross, 1992). Micronutrients are relatively immobile once they are incorporated into the soils

(Tisdale *et al*., 1985). Boron, however, is moderately mobile and moves out of the rooting depth of coarse textured, acidic soils, and soils that have low organic matter content (Tisdale *et al*., 1985). The most commonly used B fertilizer is borax applied to the soil. The problem with this is that it is very easily leached from sandy soils and at the higher pH of calcareous soils it is unavailable to the plant roots (Marschner, 2002). For this reason foliar application is often more efficient than broadcasting application to correct B deficiency. The availability of microelements for plant uptake increases as the soil pH decreases, except for Mo (Tisdale *et al*., 1985). Copper exists mainly as a divalent cation (Cu^{++}) and is bound tightly to soil exchange sites. Its concentration in the soil solution is low and it does not move readily through the soil with leaching (Mengel & Kirkby, 1982). However, it can be replaced from exchange sites by hydrogen ions (H^+) and is therefore more available in low pH soils. Zinc and Cu can become toxic to plant growth if soil concentrations are excessive. These elements become toxic because they compete at the carrier sites for plant root uptake with other micronutrients and hence induce Fe and Mn deficiency symptoms (Tisdale *et al.*, 1985).

Iron is one of the most abundant minerals in the soil; it constitutes about five percent of the weight of the earth crust (Mengel & Kirkby, 1982). Despite this abundance Fe deficiency is common because of its unavailability to plants. Most Fe exists as insoluble minerals. Only a very small amount exists in the soluble form as $Fe(OH)_2^+$, $FeOH^{++}$, Fe^{+++} and Fe^{++} (Mengel & Kirkby, 1982). The concentration of these soluble forms is pH dependent; Fe concentration reaches a maximum at a low pH value (pH 3, KCl) and a minimum at a pH of about 6.5 to 7.5 (KCl).

The amount of Mn in the soil varies widely from one soil to another although there is usually an adequate amount to supply the limited requirements of fruit trees (Mengel & Kirkby, 1982). The most important form taken up by the roots is Mn^{++}, but also the oxides of Mn^{+++} and Mn^{++++} (Mn_2O_3, MnO_2, etc.). The inter-conversion of these various forms is controlled by oxidation–reduction reactions in the soil (Mengel & Kirkby, 1982). Therefore, factors such as pH, organic matter and soil moisture strongly influence Mn availability. Manganese deficiency is often found in high pH soils with a high organic matter level.

Terblanche (1972) reports that Mn, Zn, Fe and Cu follow a similar uptake pattern. From the beginning of the season until cessation of shoot extension growth these elements do not show any significant uptake. Manganese, Zn, Fe and Cu are actively taken up after completion of

shoot extension until the beginning of leaf ageing of the oldest leaf and during leaf drop (Terblanche, 1972). Boron is actively taken up during three stages: shoot elongation, six to nine weeks before leaf ageing of the oldest leaves, and during leaf drop (Terblanche, 1972).

1.6   Nutrient translocation

Translocation of ions in the xylem vessels to the above-ground parts is passive (Taiz & Zeiger, 1991). Nutrients are transported to the leaves through the transpiration stream, which is influenced by water loss through the leaves (transpiration) (Taiz & Zeiger, 1991; Salisbury & Ross, 1992). From the leaves most minerals are rapidly redistributed via the phloem to other plant parts such as the growing shoot tips and fruits, which usually exhibit only minimal transpiration (Tromp, 2005). The movement of immobile nutrients such as calcium is slowed by ion-exchange in the xylem, even though their concentrations are high in the leaves, resulting in physiological disorders such as bitter pit in apple (Tromp, 2005). Tromp (1979) conducted an experiment to determine the importance of phloem transportation of cations (Ca, K, P and N) and found that the accumulation of N, K and P was concentrated above the girdling ring whereas depletion was found below the ring. In contrast, calcium redistribution is not affected by the phloem flow interruptions. Absorbed inorganic nitrogen is transported to the upper parts in organic forms like amides and amino acids. Although the concentration of minerals in fruits varies a great deal with fruit species, a common factor is that, compared with mobile nutrients (e.g. K), the concentrations of immobile nutrients (especially Ca, and to a lesser degree Mg) are much lower than in leaves (Tromp, 2005). Therefore, when an inadequate nutrient supply of a certain element occurs the mobile nutrients are translocated from mature tissue to young growing parts, causing the visibility of deficiency symptom in older leaves. With immobile elements the symptoms are first noticed in young tissues.

1.7   Seasonal changes and accumulation of nutrients

1.7.1   Nitrogen

Nitrogen assimilated by leaves is stored as leaf protein, but it can be mobilised and withdrawn from apple leaves before leaf abscission (Neilsen & Neilsen, 2003). Titus & Kang (1982) and Millard (1996) report that 23–50% nitrogen is redistributed from the leaves before senescence, as early as the cessation of shoot growth or as late as the onset of leaf senescence, but it is predominant three to four weeks before leaf drop. Stassen *et al.* (1981a) and Neilsen & Neilsen (2003) report that nitrogen withdrawn from the leaves in autumn is stored in the

woody parts of the tree as proteins or amino acids, which are later broken down and redistributed to support new growth the following spring.

The total tree nitrogen level in peach increases rapidly from three weeks before bud breaks and reaches a peak three weeks before termination of shoot extension growth (Stassen *et al.*, 1981a). It then remains constant until three weeks before leaf drop to three weeks after final leaf drop, when a second increase is observed. The nitrogen level of the permanent structures (bark, wood and roots) follows the same pattern during the season (Stassen *et al.*, 1981a). More nitrogen is accumulated in the roots than in the bark and the wood. The nitrogen content in the roots, bark and the wood of peach decreases by the end of July (Southern hemisphere) for three weeks and then begins to increase three weeks before bud break and continues to increase until three weeks after bud break. Three weeks after bud break the nitrogen content starts to decrease in the permanent parts and reaches minimum levels 18 weeks after bud break in the case of the bark and wood, and 12 weeks in the case of the roots, in order to support new growth such as leaves, fruit and new shoots (Stassen *et al.*, 1981a). The nitrogen content in the permanent parts starts to increase before termination of shoot growth (nine weeks in the roots and three weeks in the bark and wood). Three weeks before and after leaf drop the nitrogen levels in the roots, wood and bark increase, followed by a reduction until six weeks after bud break when the study was ended. The nitrogen content in the new growth increases from bud break and reaches a maximum three weeks before termination of shoot extension growth, followed by a decrease until completion of leaf drop, and then remains constant until bud break, until another increase. Stassen *et al.* (1981a) indicate that the highest content of nitrogen is accumulated in the leaves until three weeks before the termination of shoot extension growth. The nitrogen content in the new shoots increases from six weeks after bud break until final leaf drop and remains constant for about nine weeks, after which it drops again from three weeks before bud break. The nitrogen content in the fruit increases quickly until nine weeks before harvest and then it remains constant. Stassen (1980) and Stassen *et al.* (1981a; 1981b) indicate that a decrease in total nitrogen takes place in the permanent parts (roots, wood and bark) at the expense of at least 65% increase in nitrogen content in new growth 3–12 weeks after bud break. At this stage the reserves in the permanent parts decrease and are used for cell development in leaves and fruits that become strong sinks, increasing the tree nitrogen demand and allowing for more uptake from the soil (Stassen *et al.*, 1981b).

Stassen *et al*. (1997) report that nitrogen is accumulated in the developing leaves of mango trees. Three weeks before the termination of shoot extension growth the nitrogen content in new growth starts to drop and nitrogen taken up is stored in the permanent parts as reserves. Researchers have come to the conclusion that a percentage of nitrogen is redistributed back from the leaves to the permanent parts of the tree: ±55% in the case of peaches (Stassen *et al*., 1981a; 1981b) and ±67% in the case of apples (Terblanche, 1972). Neilsen & Neilsen (2003) suggest that nitrogen assimilated by leaves is stored as leaf proteins (predominantly rubisco), but can move from the leaves before leaf abscission to woody tissues. The proteins in woody tissues are later broken down and used as nitrogen reserves to support new root and shoot growth in the following season.

1.7.2   Phosphorus

Phosphorus is accumulated in the permanent structures and retranslocated during the times when demand is higher than uptake (Faust, 1989). Phosphorus uptake by the tree is relatively low and starts increasing three weeks before bud break (when an increase is noticed in the leaves) and a decrease in the permanent parts, especially the roots. This means that P is redistributed from the permanent parts to support the developing organs (leaves, fruits and new growth). Stassen *et al.* (1983) report that P uptake provides 57% P to the new growth while the reserves in the roots support the new shoot growth eight weeks after bud break. The P content increases rapidly three weeks after bud break until harvest, when most of it is accumulated in the leaves and fruits, and less in the new shoots. Accumulation is observed in the roots six weeks before harvest in grape vines (Conradie, 1981) and peaches (Stassen, 1987). However, for apple trees, Terblanche (1972) reports that they reach their maximum level with the cessation of longitudinal growth of the longest shoots, which is followed by a sharp decrease caused by the decrease in leaves. This decrease continues until six weeks after harvest. The phosphorus content of leaves starts decreasing at the beginning of leaf drop. The P content in the total tree decreases after harvest. This is caused by the removal of fruits that contain a relatively large amount of phosphorus. Stassen (1987) and Terblanche (1972) agree that the P content of the whole tree increases at leaf drop. The P taken up at this stage is accumulated more in the roots and a decrease in the leaves is observed. However, Conradie (1981) reports that the grape vine P content decreases with leaf drop, which is opposite to the findings in apple and peach trees. Terblanche (1972) indicates that ±29% of the P content of apple trees is lost at leaf drop while the rest is translocated back to the permanent parts, especially to the roots.

1.7.3   Potassium

Three weeks after bud break the total K content of the tree increases and the leaf K also increases due to redistribution from permanent parts (Stassen, 1987). Conradie (1981) indicates that there is no accumulation of K in the grape vines 22 days after harvest, but rather in the new growth. According to Terblanche (1972) there is an increase in K content of the apple tree after bud break. Stassen *et al*. (1983) report that in full-bearing peach trees ±40% of the K requirement for growth is obtained from reserves eight weeks after bud break. The K content increases three weeks after bud break until harvest. Stassen (1987) indicates that there is an accumulation at this stage that accounts for ±53% in leaves and ±29% in the fruits. Terblanche (1972) noticed that of the ±68% of the K content in apple trees, ±32% was accumulated in the leaves and ±36% in the fruits at harvest. Conradie (1981) found that ±66% of K is found in bunches and ±10% in the leaves of grape vines. Most of this nutrient is accumulated in fruits, and in the absence of fruit it is stored in the leaves (Faust, 1989). After harvest the total tree shows a reduction in the K content due to the fruit removal. Nine weeks after harvest until the end of leaf drop the K content in the tree decreases due to leaf loss. There is also an increase in the roots, which could arise from the translocation of K from the leaves to the permanent parts, especially to the roots. Stassen *et al.* (1983) indicate that potassium is accumulated mostly in the permanent structures where it is later used for bud development as well as for new growth.

1.7.4   Calcium

Different seasonal patterns have been observed; in apples it ranges from the bulk of inflow of Ca occurring in the four to six week period of cell division following bloom (Wilkinson, 1968) to a steady increase throughout the growing season (Faust, 1989). Calcium accumulation in the total tree is relatively low until three weeks after bud break, and this is followed by a rapid accumulation until harvest. A high content of Ca accumulates in the leaves (at least more than ±60%) while the root reserves decrease at this stage (Terblanche, 1972; Conradie, 1981 and Stassen, 1987). Faust (1989) suggests that the accumulation of Ca in the leaves takes place throughout the growing season because Ca is translocated via the transpiration stream. The accumulation of Ca in fruits takes place in the first part of fruit growth and starts decreasing with fruit maturation (Faust, 1989). The Ca content of the whole tree remains constant from harvest until the beginning of leaf drop. This means that a small amount is removed at harvest but it does not have an effect on the content of the whole tree. An increase occurs three to nine weeks after harvest, at which time the Ca is accumulated in

the roots. According to Stassen (1987), at this stage an increase of ±16% Ca is taken up in peach trees. Conradie (1981) observed a smaller amount of accumulation, namely ±12% Ca, as the first uptake in grape vines. Terblanche (1972) reports a similar amount of accumulation during the post-harvest and pre-harvest periods of apples (81%). Calcium is lost through leaf drop, which reduces the total tree content. Terblanche (1972) noticed that more Ca is lost from the tree than what was in the leaves before leaf drop. He therefore suggests that Ca moves from the permanent parts before leaf drop and is lost through leaf drop. Conradie (1981) also found that at least ±54% of total tree Ca is lost through leaf drop.

1.7.5   Magnesium

According to Conradie (1981) the Mg content does not show a significant increase during the 22 days after bud break. Thereafter the Mg content starts to increase in the whole tree, with a redistribution of Mg from the roots to the leaves (Conradie, 1981). Stassen (1987) indicates that three weeks after bud break the Mg content of the tree increases rapidly until harvest. The Mg content in the leaves increases during this period and the root content also start to increase from three weeks before the termination of shoot extension to six weeks before the end of leaf drop. Magnesium accumulates in leaves and in a case of need it is translocated from older leaves to younger leaves (Faust, 1989). Stassen (1987) found that the concentration of Mg in the leaves increases during the last six weeks before leaf drop and it is lost through leaf drop. Terblanche (1972) found that Mg can move from the permanent parts to the leaves, where it is lost at leaf drop. Conradie (1981) reported a loss of about 44% of the tree Mg content that is linked to leaf loss. Terblanche (1972) and Conradie (1981) report that there is an uptake of Mg after harvest.

1.7.6   Sulphur

Sulphur is accumulated in new growth, leaves, shoots and fruits during the active growth period. After leaf drop it is accumulated in the permanent parts of the tree as reserves that can be used early in the season to support new growth (Faust, 1989). The importance of S has not been clearly recognised by researchers, therefore there is not much information available with regard to this mineral element.

1.7.7   Micro nutrients

Seventeen days before bud break Mn is accumulated in the permanent parts, of which the roots host almost 50% of the total tree content, the bark almost 25%, and the wood 3%

(Terblanche, 1972). After bud break a reduction of Mn content in the permanent parts takes place, which indicates redistribution to new growth in order to support growth and development. Terblanche (1972) indicates that at termination of the longest shoot elongation about 50% of the Mn content is found in the new growth and that most of this nutrient is accumulated in the leaves. The permanent parts start accumulating Mn just before leaf drop. Major quantities of Mn are accumulated in the roots during the rest period as well as early in the season, while the leaves make a huge contribution to the Mn content of the total tree during the active growing season. In contradiction, Kotzé & De Villiers (1989b) found that there is no indication of translocation of micronutrients from the permanent parts of the kiwi vines to new growth during the early part of the growing season.

According to Terblanche (1972) the amount of Zn taken up during the shoot elongation period is sufficient to support new growth, thus no redistribution from the permanent parts takes place. Zinc is significantly redistributed after cessation of shoot extension growth, when a reduction in the permanent parts takes place to support new growth. However, Kotzé & De Villiers (1991) found that in kiwi vines the rate of Zn absorption into roots remains constant from before bud break until early March, and increases very markedly thereafter until the middle of July. Furthermore, the rate of absorption of Zn remains at a low level from before bud break until the beginning of March, whereafter a fourfold increase takes place until the beginning of July (after leaf drop) (Kotzé & De Villiers, 1991). Smith *et al.* (1987) report that most of the Cu and Zn in field-grown kiwifruit accumulates during the first four weeks after leaf emergence, whereas the rate of accumulation of Mn, Fe and B is similar throughout the growing season. Kotzé & De Villiers (1989b) and Smith *et al.* (1987) agree that the accumulation of copper by the leaves increases sharply before harvest.

Boron accumulates mostly in the bark and roots during the rest period while in the growing season it accumulates in the leaves and fruits. During the shoot extension period, the B needed for new growth comes from the redistribution from one-year wood (Terblanche, 1972).

Copper is accumulated mostly in the roots while the Cu in the wood and bark is equally accumulated. The roots store most of the Fe during the rest period and after cessation of shoot extension growth (Terblanche, 1972).

Kotzé & De Villiers (1989b) show that ±16% Zn assimilated from bud break to harvest is transported to the leaves compared to ±49% Mn, ±46% B and ±55% Fe. Furthermore, a large fraction of Zn is retained in the permanent part of the kiwi vine, confirming the low mobility of Zn. During the active growth period Fe redistribution takes place from the permanent parts to support new growth (Terblanche, 1972). Smith *et al*. (1987) and Kotzé & De Villiers (1989b) agree that no migration of micronutrients is observed from the leaves prior to harvest but substantial amounts of Mn, Zn and Fe are redistributed from the leaves after harvest, before leaf drop. There is, however, some indication of an increased content of these nutrients in the permanent parts of the kiwi vine and at least some of these nutrients might be transported out of the leaves before senescence (Kotzé & De Villiers, 1989b). These findings do not concur with the findings of Terblanche (1972), who suggests that Mn, Zn and Fe migrate from the permanent parts to the apple leaves and are lost through leaf drop. Boron and Cu in new growth migrate to permanent parts before leaf drop, increasing the quantities of the elements in the total tree. The fruit is a relatively unimportant sink for micronutrients except in the case of B (Kotzé & De Villiers, 1989b). In the case of B, ±70% of this nutrient assimilation in the period up to harvest is accumulated in new growth (Kotzé & De Villiers, 1989b). Furthermore, Raven (1980) reports that the quantity of B taken up by the roots and subsequently transported to the shoots and leaves is closely related to the rate at which plants transpire.

1.8   Organic ameliorants

Biological ameliorants such as humic acid, compost and compost extract have advantages that can influence deciduous fruit production. They improve the uptake of nutrients by improving the root system and soil environment, which can lead to improved quality and increased yields (Schupp, 2001). They improve the soil structure and texture, which leads to an improvement in aeration and moisture holding capacity (Schupp, 2001; Smith, 2001). Organic material mulches can improve growth and yield of apples planted in high density systems (Neilsen *et al*., 2004). This improvement is related to the release of nutrients in the applied organic material, which can improve orchard soil nutrient availability and soil biological activity. Neilsen *et al*. (2004) furthermore state that mulches can buffer against moisture stress resulting from inadequate irrigation. However, mulches can be ineffective in orchards with good nutrient management and frequent irrigation which leaches N excessively from the root zone (Neilsen *et al*., 2004).

1.8.1   Humic acid

Humic acid is a fraction of humic substances produced by the decay of organic matter. It is composed of long-chain molecules of high molecular weight, it is dark brown in colour and soluble in alkaline solution (Obreza *et al*., 1989). According to Davies *et al*. (2001) humic acid can act as a photosensitiser, retain water, bind to clays, act as a plant growth stimulant, and scavenge toxic pollutants. Humic acid plays a role in the soil's physical, chemical and biological properties. Obreza *et al*. (1989) and Davies *et al*. (2001) report that humic acid modifies the soil structure and texture, thus improving the aeration and moisture holding capacity. Obreza *et al*. (1989) suggest that humic acid changes the CEC (cation exchange capacity) of the soil, making nutrients more available in the form that can be taken up by plants. Davies *et al*. (2001) report that humic acid acts as a plant growth regulator by supplying a precursor of hormones. Therefore humic acid inhibits indoleacetic acid (IAA) oxidase activity, increases the IAA concentration, and thus stimulates root development, which results in an increases in the absorption area of nutrients (Davies *et al*., 2001). This consequently improves the uptake of nutrients due to a better root system and availability of nutrients, resulting in improved fruit quality and increased yields.

Chen & Aviad (1990) and Fernandez-Escobar *et al*. (1996) report that the application of humic substances stimulates vegetative growth. This growth-promoting activity seems to be caused by plant hormone-like material present in the humic substances (O' Donnell, 1973; Casenave de Sanfilippo *et al*., 1990). However, in an experiment conducted by Fernandez-Escobar *et al*. (1996), no effect was observed on yield, even in experiments where fruit size was improved and, in an experiment that continued for two seasons, when vegetative growth was promoted. The stimulating effect of humic substances on plant growth is related to the enhanced uptake of mineral nutrients. Increases in the uptake of macro and micro elements influenced by humic substances have been reported in different plant species (Rauthan & Schnitzer, 1981; Chen & Aviad, 1990; Fagbenro & Agboole, 1993). Humic substances are usually applied to the soil and favourably affect the soil structure and soil microbial population. Foliar sprays of these substances also promote growth in a number of plant species such as tomato, cotton and grapes (Brownell *et al.,* 1987). However, Pilanali & Kaplan (2003) report that high rates of humic acid inhibit the nutrient uptake by strawberry leaves. This is supported by Casenave de Sanfilippo *et al*. (1990), who suggest that this inhibition is due to an increased content of auxin- and gibberelin-like substances present in humic acid. Spraying with fulvic acid also increases the yield of wheat grown under dry

conditions (Xudan, 1986). Sánchez-Sánchez *et al*. (2002) report that the addition of humic substances to lemon trees improves the uptake of Fe and Cu. It also improves the fruit weight and the vitamin C content in the fruits.

1.8.2 Compost

Compost is generally produced from organic materials, such as livestock manure, sewage solids, wood chips, livestock beddings, tree leaves, crop residues and lawn clippings (Schupp, 2001). Therefore, compost is the remains of organic waste in the soil that contain a low amount of nutrients and a high amount of organic matter, and which can act as a nutrient buffer and improve the soil structure for a year or two after application (Smith, 2001). The compost supplies nutrients and organic matter and, importantly, attracts beneficial microorganisms and sustains their life in the soil (Amlinger *et al*., 2003). These microbes are important for the good structure of the soil, for nutrient cycling and for the good health of plants (Dumontet *et al*., 1999; Hoistink & Krause, 2003; Fichtner *et al*., 2004). Schupp (2001) reports that compost application increases the soil pH and CEC of plots. Despite the variability in the compost there are some important aspects such as nutrient content, salt index, moisture content and percentage of non-compostable substances (soil) that need to be taken into account.

High quality compost consists of many compounds that influence the biological processes in the soil positively, thus improving the physical and chemical soil characteristics (Obreza *et al.*, 1989). The humates, which are the organic substances that remain in the soil after the breakdown of organic matter, improve the soil structure, resulting in a soil that is easier for the plant roots to penetrate. The optimal soil texture also has a pronounced effect on the water storing capacity of the soil, which is important in dry areas and in coarse texture sandy soils (Stuckey & Hudak, 2001). With improved root growth, the stability of trees increases. The larger soil volumes explored by the roots lead to better nutrient status and less water stress. Organic molecules act as sites for cation exchange, thus increasing the adsorption and retention of nutrients in the soil (Schupp, 2001).

According to Smith (2001) compost should be considered as a soil modifier and not a fertiliser because it contains low quantities of nutrients and a high organic content. Nutrients are released slowly by soil organisms by the degradation of organic matter. Compost salts are referred to as fertiliser components, such as N, P, K, Zn, Na, Cl, etc., which can be beneficial

to trees if supplied in diluted solutions (Smith, 2001). Compost with a salt index of more than 4 can, however, be harmful to trees if incorporated with the soil or applied as mulch at the base of the tree (Smith, 2001). Therefore, it is necessary to test the compost components to ensure that trees will not be damaged. Moisture can vary between 50–60% in compost. Compost soil amendments are found to be effective when the soil is poor in nutrients before the application of compost (Roe, 1998) but have little or no effect if the soil is relatively nutrient rich (Gilman, 2004; Ferrini *et al.*, 2005). Rose & Wang (1996) report that compost and municipal sludge increase growth in most ornamental plants, but that high salt concentration results in negative responses in some species. Watson (2002) observed more roots in replaced soil amended with compost than in the surrounding soil 14 years after replacement of the soil, but that root growth in the soil beyond the zone of replaced soil was not affected. Compost contributes to both increased growth and a higher content of nutrients in apple trees in the establishment phase (Moran & Schupp, 2003). Medina *et al.* (2004) report that trees planted in a poor soil respond well to amendment with favourable microorganisms, especially if the soil is also amended with organic materials as food for the microorganisms.

1.8.3   Compost extract

The term compost extract refers to a wide variety of organic slurries. They contain living organisms and can function as fertiliser (Houghton, 2003). As the use of compost extract is still relatively new, limited information exists. It is, however, believed that a compost extract does have some benefits, like soil pest control, disease control as well as modification of soil structure and texture to improve nutrient uptake (Houghton, 2003). Compost extract can be applied as foliar feeding directly to the leaves, in the drip area, directly on the soil or on top of the compost, making it more effective to control pests and disease**.**

1.9   Use of labelled nitrogen

Elements can exist in both stable and unstable (radioactive) forms. Most elements of biological interest (e.g. C, H, O, N, and S) have two or more stable isotopes, with the lightest of these present in much greater abundance than the others. Among the stable isotopes the most useful as biological tracers are the heavy isotopes of carbon and nitrogen (Doucett, 2001). These two elements are found in the earth, the atmosphere, and in all living organisms. Variation in ^{15}N abundance of various components of the biosphere is typical

within 1 or 2% of that of atmospheric N_2 (0.3663 atom % ^{15}N) (Junk & Svec, 1958). This variation results from isotopic discrimination (Shearer & Kohl, 1993). Labelled nitrogen is used in tracing studies to investigate nitrogen cycling in crop plants. ^{15}N-labelled fertiliser (urea, ammonium nitrate, etc.), either 2–5% enriched or 0.36% depleted in ^{15}N, is applied (De Niro, 1987; Nadelhoffer *et al.*, 2004). The tracer yields allow for quantification of the fate of the added fertiliser containing ^{15}N.

Isotope studies have been used effectively to quantify the timing of nitrogen uptake (Weinbaum *et al.*, 1978; Muñoz *et al.*, 1993) and the significance of N storage, which serves as a reservoir for nitrogen prior to the onset of tree uptake of external nitrogen sources (Millard, 1996). Labelling forest trees with ^{15}N, the heavier and less abundant of the two stable isotopes of nitrogen (^{14}N and ^{15}N), has provided information about the fates of N inputs to forests (Nadelhoffer *et al.*, 2004). Prediction of the movement of the stable isotope ^{15}N into ecosystem pools can be tested because changes in $^{15}N/^{14}N$ ratios in vegetation and soil pools can be easily detected (Nadelhoffer *et al.*, 2004). Using a biogeochemical process model to interpret the redistributions of field-applied ^{15}N tracers provides an opportunity to test model formulations of C/N interactions with more sensitivity than can be achieved with non-isotope models (Currie *et al.*, 2004). Sensitivity is greater because the background variability in field-measured $^{15}N/^{14}N$ ratios is small compared to the $^{15}N/^{14}N$ ratios of tracers applied experimentally. Stable isotopically labelled products can provide accurate and non-radioactive *in vivo* studies of both nutrition and metabolism (Currie *et al.*, 2004).

Other stable isotope techniques rely on adding trace amounts of compounds that are artificially enriched in the rare (heavy) isotope of the element of interest. These are referred to as isotope tracer techniques (Doucett, 2001). For example, without isotopes the independent measurement of the processes of microbial production of ammonium (NH_4^+) through mineralisation and the consumption of NH_4^+ through immobilisation and nitrification are not possible because all these processes occur simultaneously. By adding $^{15}NH_4^+$ to soil and monitoring the rate at which it is diluted by the more abundant $^{14}NH_4^+$ one can measure the rate of mineralisation of soil organic matter – a rate that is independent of nitrification and immobilisation (the NH_4^+ consuming processes) (Doucett, 2001). By adding ^{15}N as NH_4^+ or NO_3^- and monitoring both ^{15}N and ^{14}N in the soil, it is possible to quantify each of these microbial transformations, *in situ*.

1.10 Influence of mineral nutrition on fruit quality

Optimum mineral nutrient application contributes to positive fruit quality, maintains spur quality, as well as fruit, vegetative and root growth (Faust, 1989; Mengel & Kirkby, 1982). Nitrogen supplied in the correct amount in autumn or summer, after shoot extension growth, results in an increase in fruit set in young peach trees (Stassen *et al*., 1981b). Nitrogen is needed in active cell division and fruit development processes (Mengel & Kirkby, 1982). Phosphorus is found in ATP molecules that store energy from photosynthesis and the breakdown of sugar (Salisbury & Ross, 1992). This energy is very mobile and can therefore be transported to sites requiring a great deal of energy, such as expanding shoots, leaves and developing fruit. Calcium is involved in cell elongation, cell division, germination and pollen growth (Mengel & Kirkby, 1982; Faust, 1989). One of Ca most important functions is the maintenance of cell integrity. When it is deficient the cells become leaky and lose control over the import and export of nutrient elements, leading to tissue breakdown. Boron and Zn are needed for pollen tube formation and hence need to be supplied in correct amounts for fertilisation to take place (Mengel & Kirkby, 1982).

There is little doubt that applied fertilisers are able to influence post-harvest fruit quality and, in some case, fruit maturation and ripening (Tromp, 2005). According to Faust (1989), an oversupply of nitrogen can lead to vigorous growth and poor fruit quality characteristics. A typical effect can be reduced firmness at harvest or, after storage, reduced red colour formation due to ethylene production, and delayed ripening (Faust, 1989; Tromp, 2005). Various researchers (Shear & Faust, 1980; Faust, 1989; Marcelle, 1995; Tromp, 2005) agree that high amounts of N reduce fruit firmness, favour the development of bitter pit, internal breakdown and scald in apple, and core breakdown in pear, and generally increase the susceptibility of fruits to pathogens. An undersupply of nitrogen leads to poor tree growth and reduces yield because of fewer and smaller fruit (Neilsen & Neilsen, 2003).

Marcelle (1995) reports that K favours fruit quality with respect to fruit size, taste (acidity), aroma, colour and the risk of low-temperature breakdown. High rates of K increase the K/Ca ratio and increase the susceptibility of the fruit to bitter pit, core flush, internal breakdown, senescent breakdown, scald and pathogens, and should therefore be avoided (Marcelle, 1995; Tromp, 2005). Fruit respiration can be increased by high rates of K, which can lead to early fruit ripening.

Calcium is also one of the important elements that play a large role in fruit quality and the storage ability of fruits. Calcium affects fruit senescence and quality by changing intracellular and extracellular processes, and the rate of fruit softening depends on fruit Ca content (Mason *et al.*, 1975; Fallahi *et al.,* 1987). High levels of fruit Ca inhibit ripening and reduce the susceptibility to senescence disorders such as bitter pit, water core, and senescence breakdown in apple, and cork spot in pear (Tromp, 2005).

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Chapter 2

Seasonal uptake, distribution and requirements of macro and micro elements by intensively grown apple trees

2.1 Seasonal uptake and distribution of macro elements in two- and three-year-old apple trees

Abstract

The seasonal uptake of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S), as well as their distribution, were determined for two- and three-year-old 'Brookfield Gala' apple trees on M793 rootstock grown under field conditions. Trees were planted at a spacing of 4 x 1.25 m and trained to a central leader system, with laterals bent horizontally according to the solaxe principle. Two-year-old trees were excavated at the beginning of bud-break, 6 weeks later, mid-summer, harvest and early winter. The three-year-old trees were excavated during late winter (trees in dormant state), mid-summer, harvest, late autumn (before leaf drop), and again during late winter. Trees were divided into different tree parts: roots, leaves, fruit, rootstock, current year wood, trunk and canopy branches, at excavation, and analysed for the different macro nutrients. Results were used to determine the macro element uptake and distribution within the tree. In the bearing apple trees the nutrient accumulation increased rapidly from late winter to late autumn. During leaf drop most of the N, P, S, Mg and a small portion of K were redistributed back into the permanent parts of the tree. On the other hand, all Ca in the leaves was lost through leaf drop. Apple fruit contains comparatively large quantities of K ($\pm$60.2%), which is removed during harvest.

Keywords: nutrient management, nutrient accumulation, remobilisation of elements

2.1.1 Introduction

Essential macro elements, such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S), play many important roles in plants, as constituents of plant tissues and of buffer systems: they activate enzymes, and regulate osmotic pressure and membrane permeability (Kozlowski *et al.*, 1991; Salisbury & Ross, 1992; Marschner, 1993). An insufficient supply, application at wrong phenological stages and the mobility of macro elements may cause deficiency and stimulate disorders that are usually characteristic for that element (Tromp, 2005). An excess, on the other hand, may stimulate growth, causing an imbalance in the nutrients (Marschner, 1993). It is therefore important to know when certain macro elements are taken up during the different phenological stages and to which organs/tissues they are distributed.

Weinbaum *et al.* (2001) suggested that the sequential excavation of trees coupled with biomass determinations and nutrient analysis is the only method that can reliably indicate the seasonal patterns of tree nutrient uptake. Various studies have been conducted using this principal to determine the seasonal uptake and distribution patterns of macro elements in apples (Batjer *et al.,* 1952; Mason & Whitfield 1960; Meynhardt *et al.* 1967; Terblanche, 1972; Haynes & Goh, 1980), peach (Stassen *et al.*, 1981a; Stassen *et al.*, 1983), grape vines (Conradie, 1981), kiwi vines (Kotzé & De Villiers, 1989), mango (Stassen *et al.*, 1997) and pear (Stassen & North, 2005). Terblanche (1972) found three periods of N and P uptake in apples: during shoot elongation, six to nine weeks before the beginning of leaf senescence, and during leaf drop. Stassen *et al.* (1981a) reported two periods in which N increased rapidly in the trees as a whole. The first period commenced three weeks before bud-break and reached a maximum three weeks before termination of shoot extension growth, while the second period is three weeks before final leaf drop until three weeks after final leaf drop. With apples, Meynhardt *et al.* (1967) found a relatively sharp increase in the total P content of the above-ground portion of the tree from 14 days after bud-break until after cessation of shoot elongation. This was followed by a further, less definite, increase until the beginning of leaf senescence. Mason &Whitfield (1960) found that P uptake started at a stage equivalent to the end of October in the Southern hemisphere and reached a maximum in January. Conradie (1981) found two periods of uptake in grape vines: just after bud-break until véraison and again five weeks after harvest until the leaf drop period. Mason & Whitfield (1960) reported that K, Ca and Mg are taken up during most of the shoot-elongation period.

Terblanche (1972) found that Ca and Mg were taken up during the same periods as N and P, however the trends differed. Ca and Mg were taken up at a higher rate at nine weeks before the beginning of leaf drop and at a lower rate in the leaf drop period than N and P. Furthermore, Terblanche (1972) reported two periods of K uptake: the first was during most of the shoot-elongation period and the second was during the leaf drop period. In grape vines, Conradie (1981) found only one period of K uptake (soon after bud-break until after harvest), whereas there were two peaks of Ca and Mg uptake: the first from bud-break to véraison, and a less noticeable peak during the six-weeks period before leaf drop for Ca and during the leaf drop period for Mg.

Nitrogen assimilated by the leaves is stored as leaf protein, but it can be mobilised and withdrawn from apple leaves before leaf abscission (Neilsen & Neilsen, 2003). Titus & Kang (1982) and Millard (1996) reported that 23–50% nitrogen is redistributed from the leaves before senescence, as early as the cessation of shoot growth or as late as the onset of leaf senescence, but it was predominant three to four weeks before leaf drop. Different researchers report that N, P and K are redistributed back from the leaves to the permanent parts before the end of leaf drop and stored as reserves to support new growth in the following season when root and leaf activities are not conducive to support new growth (Terblanche, 1972; Conradie, 1981; Titus & Kang, 1982; Stassen *et al.*, 1983; Millard, 1996; Neilsen & Neilsen, 2003).

Most of the studies that have been carried out to date were done in wider-spaced orchards or in sand culture with young trees. Little research was done on newer generation higher-density orchard systems under more intensive water and nutrient management. The objective of this study was to determine the uptake and distribution of N, P, K, Ca, Mg and S in young and bearing apple trees in a higher-density commercial orchard under drip fertigation.

2.1.2 Material and methods

2.1.2.1 Experimental site

'Brookfield Gala' apple trees (Granny Smith as pollinators) budded on M 793 rootstock were planted in July 2003 on a well drained, well aerated loamy sand soil of the Dundee form (Macvicar *et al.*, 1977) in the Greyton area near Genadendal in the Western Cape Province. The area is situated 34º03' S, 19º37' E and 33 m above sea level. The Dundee soil form

contains a proportion of stone, clay and silt, with ±57% fine sand and ±130 mm.m^{-1} water holding capacity (Table 1). The trees were irrigated daily with two Netafim 2.3 l.h^{-1} pressure compensated emitters per tree, spaced at 60 cm on either side of the trunk. Irrigation was applied to meet the daily requirements, based on long-term evaporation data and by using water sensors for daily scheduling.

2.1.2.2 Soil preparation

Preplant soil preparation was done by cross-ripping the soil to a depth of 800 mm. Calcitic lime was mixed into the soil horizons to obtain a pH of ±5.5 (KCl). Rectification of phosphorus to ±30 mg. kg^{-1} (Bray II, as extraction method) was also done. Table 2 indicates the pH, carbon percentage and percentage of elements that contributed to the cation exchange capacity in the top and sub soil (0–60 cm) after preplant soil rectification. The organic fraction of the soil was improved by adding sawdust (25 L/ tree) before the first ridging and then rotten straw was applied before the second ridging.

2.1.2.3 Tree training, pruning and thinning

Trees from a nursery were cut back to 1.2 m height for uniformity among all plants. Tree spacing was 4 m x 1.25 m. Trees were planted in a NE–SW row orientation and trained to a central leader spindle with lateral shoots bent horizontally according to the French solaxe principle (Lauri & Lespinasse, 2000). Pruning was done by removing upright water shoots during summer. Strong limbs and those on top of one another as well as those with narrow crotch angles were removed during winter. During the 2004/2005 and 2005/2006 seasons the trees were thinned according to a tree potential to two fruit/cluster for the first 50% of the shoot length from the stem and to three fruit/cluster for the terminal 50% of the available lateral branches.

2.1.2.4 Nutrient management

During the first 12 months the trees received a young-tree solution high in nitrogen (solution prepared by Omnia fertilisers, Epsom Downs Park, Bryston, South Africa). This was applied to ensure vigorous growth in order to fill the allocated space between trees as soon as possible. After 12 months the annual nutrient requirement was adjusted for apples based on the results obtained by Stassen & North (2005) on pears for an estimated yield of 10 t/ha (see Tables 3 and 4) plus a 30% increase of all elements. The 30% increment in all nutrients was given because the trees were still between the young and the bearing stages and it was

necessary to stimulate some growth to fill the allocated space. The yield for the 2nd leaf trees was 2.02 t.ha^{-1}. These annual amounts were divided percentage-wise (Table 5) according to the phenological demand for apple trees as found previously in the Villiersdorp area, according to the principal explained by Stassen et al. (1999). The 3rd leaf nutrient solution were based on yield estimations of 25 ton.ha^{-1} and later adapted to the real yield of 45 ton.ha^{-1}. A computer programme compiled by a private irrigation consultant was used to calculate the daily nutrient solution from available fertilisers using the above information. No foliar applications of nutrients were made in this trial.

2.1.2.5 Water management

Long-term evaporation data from two nearby weather stations and apple crop factors (Kotze *et al.*, 1998) were used to determine the monthly and annual water requirements. Watermark sensors (Irrometer Co., Riverside, CA, USA) were installed at depths of 20 cm, 40 cm, 60 cm and 80 cm, and used to adjust and manage the predetermined amount of water as necessary.

2.1.2.6 Water and nutrient application

The experimental site was situated at the lower terrain, SW of a hill, 35 m higher than the orchard level. Water and nutrients were mixed in a 10 000 L tank according to the computer calculations based on the tree phenological stage. The solution flowed gravitationally downhill at 220 kpa. At the orchard an AQ 516 Aquarius, 5 program 16 zone controller, was programmed to give signals to a Netafim Aqua Pro DC solenoid that opens and closes the electronic valve for the determined duration to apply the correct amount of water. Water and nutrients were filtered with an Arkal filter (120 mesh and 130 micron) before application. The system was flushed every six weeks with water to prevent chemical buildup in the root area.

2.1.2.7 Experimental design and plant sampling

Three trees were excavated at the beginning of bud-break (the end of the late winter phenological stage), 6 weeks after bud-break, mid-summer, harvest (2nd week of February) and early winter (before any natural leaf drop, i.e. the same phenological period as late autumn) for the two-year-old trees during the 2004/2005 season. The three-year-old trees were excavated in late winter, at mid-summer, harvest, late autumn and again in late winter during the 2005/2006 season. Three single-tree plots replicated in a randomised complete block design were sampled per date. At excavation the scion was separated from the

rootstock in the field and the roots were carefully excavated by hand. The excavated trees were divided into the following parts: trunk, rootstock, canopy branches, current year wood, thick roots (5 mm and above), thin and medium roots (0–5 mm), leaves, fruit, pruning shoots and pruning leaves, depending on the phenological stage. Samples were then cut into smaller parts using a saw for the woody parts and pruning scissors for the smaller parts. Roots were washed to remove soil particles. Leaves, shoots, fruitlets and fine root samples were dried at 65ºC in a convection oven for 24 h. Woody tissue and coarse roots were dried at 65ºC in a convection oven to constant weight (± 0.1%) (Neilsen *et al.*, 2001). Total fresh and dry masses for all the tree part samples were recorded. After drying, samples were milled into finer particles.

2.1.2.8 Milling of samples

An IKA universal grinder M20 (IKA-WERKE GMBH & CO.KG, Staufen, Germany) was used to mill the samples. The first six excavation samples were directly milled using this method. The last four excavation samples were first run through a LV15M type condux (Condux-Werke Wolfgang bei Hanau, Federal, Germany) that chops the samples into smaller parts. After this the samples were placed in a ZM 1 type Retsch (supplied and serviced by Monitoring & Control Laboratories (Pty) (Ltd)) containing a 0.50-mm size sieve that grinds the sample into finer particles.

2.1.2.9 Analysis of samples

Mineral analysis of macro elements was performed by a commercial analytical laboratory (Bemlab Pty. Ltd, Strand, South Africa). Samples were analysed for N, P, K, Ca, Mg and S. Nitrogen was analysed using a nitrogen analyser (LECO FP528 Nitrogen analyzer, LECO Cooperation, St. Joseph, Michigan, USA) and all other nutrients using an ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometer) (Varian MPX-OEX, Varian, Inc. Corporate, Palo Alto, California, USA). Results were expressed as percentages of dry mass. Data were then multiplied by the dry mass of each part to determine the content (in grams) of elements in each tree part. Although the experimental trees were selected for uniformity variation still occurred, and some trees were bigger than others. One can correct this by fitting a smooth curve through the data but then each data point is the average of the three. Another solution was to use a tree part that reflects the total mass of the tree accurately. Such a part is the trunk (the central leader from the graft union to the terminal point), used as a basis to equilibrate tree mass where differences in tree size occurred. This method gave a

growth curve very similar to the fitted curve (allometric function: $\ln(y) = ax^b$) on the original data (Appendix, Figure 1a). For the purpose of this study the trunk equilibrated data were used. The permanent parts include the canopy branches, rootstock and trunk. The pruning includes shoots and leaves.

2.1.3 Results and discussion

2.1.3.1 Nitrogen

In the young two-year-old trees the nitrogen content increased from ±14.9 g at bud-break to ±61.8 g at early winter (Table 6a, and Appendix, Fig. 2a and b). The N content of the new growth increased from 0 to ±16.7 g. This comprised 27.0% of the total N in the tree. The leaves contained the highest amount of N of the new growth. In the tree as a whole the leaves, prunings, permanent parts and roots contributed ±16.0%, ±22.5%, ±30.1% and ±20.4% to total N early in winter, respectively. The total increase in N/tree was 55.3 g over the season (total nitrogen taken up at different stages plus the nitrogen removed through pruning and fruit at harvest). Uptake during the first six weeks was ±4.2 g, therefore ±7.6% of the total uptake until early winter. The increase from six weeks after bud-break until harvest was ±10.1 g, therefore ±18.3 % of the pre-harvest uptake. The post-harvest period uptake was 61.8 g – (29.2 – 1.3 g (fruit) – 7.1 g (prunings) = 20.8 g) = 41 g, therefore ±74.1% of the total N taken up.

Nitrogen content of the three-year-old apple trees is summarised in Table 6b and depicted in the Appendix, Fig. 2c and d. The total increase in N/ tree was 84.0 g from late winter to late autumn (total nitrogen uptake from the first late winter to late autumn plus nitrogen removed through pruning at mid-summer and fruit at harvest). The increase from late winter to mid-summer was ±18.6 g, therefore 22.1% of the total uptake to late autumn. These findings are in agreement with those of Terblanche (1972), Stassen *et al.* (1981a), Millard (1996) and Neilsen & Neilsen (2003). N reserves from the permanent structure were translocated to support the new growth. From mid-summer to harvest ±19.7 g N was taken up, contributing to 23.5% of the pre-harvest value. The increase from late winter to harvest was ±38.3 g; therefore the pre-harvest uptake of N was ±45.6%. During the post-harvest period the uptake was 99.8 g – (74.3 g – 20.2 g (fruit) = 54.1 g) = 45.7 g, therefore 54.4%. This is in contrast to the 74.1% N that was taken up during this period in the two-year-old trees where yield was low (2.02 t/ha). With harvest, 20.2 g N was removed in the harvested fruit from the tree. The

N content in the leaves increased to 31.4 g from harvest to late autumn. In the period from late autumn to late winter the total N in the tree as a whole decreased by ±11.4 g. This means that 20.0 g (63.7%) N in the leaves was redistributed especially to the permanent parts, the roots and new shoots before the end of leaf drop. At this stage uptake could not play a significant role because the leaves were inactive (Faust, 1989). The ±63.7% redistribution from the leaves recorded in this study is comparable to the ±67% found by Terblanche (1972) and slightly higher than the ±55% found by Stassen *et al.* (1981a). Part of the post-harvest N for storage as reserve N therefore comes from redistribution from the leaves (Mason & Whitfield, 1960; Terblanche, 1972; Stassen *et al.*, 1981a). During harvest ±27.2% of the N content was in the fruit, ±29.2% in the permanent parts and ±16.2% in the roots.

Ferguson *et al.* (1987) found that 43% of the total nitrogen content of field grown kiwifruit was in the roots at harvest, 23% in the leaves, 8% in the current shoots and ±13% in the fruit. This is in agreement with the findings of Kotzé & De Villiers (1989): in kiwifruit vines planted in plastic pots the roots contained ±44% N at harvest, ±25% of which was in the leaves and ±8% was in the shoots, except for the fruits that only contained ±8%. The leaf content of ±23.8% at harvest found in the present study agrees well with this. However, the fruit nitrogen content of ±27.2% was higher than the ±13% and ±8% reported above. The root total nitrogen content of ±16.2% at harvest was lower than the ±43% and ±44% reported above but compares well with the ±14% found by Buwalda & Smith (1987) in 1–5-year-old kiwifruit vines. During late winter ±78.7% of the total N in the tree was in the permanent parts and ±21.3% in the roots. Titus & Kang (1982), Stassen *et al.* (1981b) and Millard (1996) also discuss the role of the permanent structures to provide N for the first few weeks when the leaves are still sinks. In this study the period late winter to mid-summer (± 4 months) was too long to accurately show the real value of permanent structures as a source of N.

2.1.3.2 Phosphorus

The results of this study show an increase in phosphorus content of 6.1 g from bud-break to early winter in the two-year-old trees (Table 7a, and Appendix, Fig. 3a and b). In the new growth the P content increased from 0 to ±1.7 g, thus contributing to ±23.3% of the total P in the tree. It was established that the new shoots contained the highest amount of P of the new growth (12.3%). The leaves, pruning, permanent parts and roots contributed ±11.0 g, ±19.2 g, ±31.5 g and ±26.0 g of P content, respectively. Furthermore, the P uptake during the first six

weeks after bud-break was ±0.2 g, which represented ±3.3% of the total uptake until early winter. The increase from beginning of bud-break to harvest was 3.5 g – 2.0 = 1.5 g, resulting into ±24.6% of pre-harvest P uptake. The post-harvest P uptake was 7.3 g – (3.5 -0.2 – 0.6 = 2.7 g) = 4.6 g (±75.4%).

In the three-year-old apple trees the total P content uptake was 12.8 g from late winter to late autumn (Table 7b, and Appendix, Fig. 3 c and d). The increase from late winter to mid-summer was ±2.5 g, comprising ±19.5% of the total uptake to late autumn. The uptake of P from mid-summer to harvest was ±4.3 g (±33.6%). Therefore the pre-harvest uptake of P was ±6.8 g (±53.1%), while ±6.0 g (±46.9%) of P was taken up in the post-harvest period. These results show that more P was taken up in the two-year-old trees (±75.4%) compared to in the three-year-old trees. During fruit harvesting ±3.3 g (±29.5%) of P was removed from the tree. It was further observed that the P content in the leaves increased from ±1.6 g to ±3.3 g (±23.7%) from harvest to late autumn. A decrease of ±13.9 g –11.9 g = 2.0 g of P was observed in the total tree during late autumn to late winter. This result indicates that ±1.3 g (±39.4%) of P in the leaves was redistributed to the permanent parts. Therefore ±60.6% was lost through leaf drop, which is in contrast with the ±30% found in apple by Terblanche (1972) and the ±31% in grape vine found by Conradie (1981). This differences in the leaf lost might have been due to the fact that Terblanche (1972) worked in a controlled environment and all fallen leaves were analysed. At harvest, the P content was ±29.5% (fruit), ±32.1% (permanent parts) and ±19.6% (roots). The root and fruit P content in the present study compares well to the ±19.2%; ±34.1% P in the grape vine roots and in the bunches found by Conradie (1981), however, the ±27.3% in the leaves at harvest is higher than the findings of the present study. During late winter ±74.8% of total P in the tree was in the permanent parts and ±25.2% in the roots. The total tree P content decreased in winter. This is in agreement with the findings of Conradie (1981) who reported that the grapevine P content decreased with leaf drop. It was, however, opposite to the findings of Stassen (1987) for peach and Terblanche (1972) for apple trees. The differences between the current study and Terblanche (1972) study might be due to the fact that he worked on younger trees in pot that was fertilised with the Hoagland solution.

2.1.3.3 Potassium

The K content in the two-year-old trees showed an increase of 34.6 g from the period of bud-break to early winter (Table 8a, and Appendix, Fig. 4a and b). The K content in the new

growth increased from 0 to ±11.1 g, which accounted for ±34.7% of the total K. The highest proportion of K of the new growth was in the leaves. The contribution to K in the tree as a whole was as follows: leaves (±24.1%), prunings (±27.2%), permanent parts (±25.0%) and roots (±13.1%). No uptake was noticed in the first six weeks after bud-break as total K did not increase in the early season but rather K reserves were redistributed from the permanent parts to support new growth. Stassen *et al.* (1983) found that in full-bearing peach trees ±40% of the requirement for new growth during the first eight weeks after bud-break was obtained from reserves. The results of the present study show that from six weeks after bud-break until harvest ±14.6 g K was taken up, accounting for 42.2% pre-harvest uptake. The increase from harvest to early winter was ±20.0 g, and therefore 57.8% was taken up during the post-harvest period.

The findings of this study indicate that in the three-year-old tree the K content increase was 75.1 g from late winter to late autumn (Table 8b, and Appendix, Fig. 4c and d). The increase from late winter to mid-summer was ±16.7 g, therefore ±22.2% of the uptake to late autumn. In the period mid-summer to harvest ±40.8 g (54.3%) K was taken up. After fruit removal the total tree K content was 73.3 g – 44.1 g = 29.2 g, indicating an uptake of ±17.6 g (±23.4%) in the post-harvest period. The K content uptake in the post-harvest period was lower than in the two-year-old trees (±57.8%) compared to the three-year-old trees. At harvest ±60.2% K was removed from the tree as the element was contained in the fruits. As the season progressed from harvest to late autumn the K content in the leaves increased to ±22.7 g, while the tree total K content decreased by 46.8 g – 26.9 g = 19.9 g from late autumn to late winter. This indicates that ±2.8 g (±12.3%) K from the leaves was redistributed to the permanent structure.

These results are not consistent with the findings of Conradie (1981) who found 13.6% K loss through leaf drop in grape vines. The contribution of K at harvest in the fruit, permanent parts and roots was 60.2%, 15.6% and 5.2%, respectively. The K in the fruit compares well to the 66.1% found by Conradie (1981) in grapes. It is, however, higher than the 28.9% in peach found by Stassen and Stadler (1988) and the 36% in apples found by Terblanche (1972). Conradie (1981) reported that 10.7% K was in the leaves at harvest and 6.9% in the roots. This compares well with the 5.2% K found in the roots and 17.1% K in the leaves at harvest in the present study. In their studies with apples, Haynes & Goh (1980) reported that the major K loss was through fruit harvest. During late autumn 48.5% of the total K was in the leaves. According to Faust (1989) fruit is a strong sink of K and in the absence of fruit K is

accumulated mostly in the leaves. This was also observed by the increase in K levels in the leaves following harvest. During the late winter 81.4% total K in the tree was in the permanent parts and 18.6% in the roots. The K content in this study decreased towards late winter. This is in agreement with the findings of Conradie (1981) and Stassen & Stadler (1988) who reported that the K content of the tree started to decrease from six weeks prior to completion of leaf drop. However, this study's findings were in contrast to the findings of Terblanche (1972) who reported a pronounced increase until final leaf drop.

2.1.3.4 Calcium

The total increase in the Ca per tree was 41.6 g (total uptake over the period of bud-break until winter plus the Ca present in the prunings and fruit removed at harvest) from bud-break to early winter in the two-year-old trees (Table 9a, and Appendix, Fig. 5a and b). The Ca content of new growth increased from 0 to ±10.8 g, comprising ±24.1% of the total Ca in the tree. The leaves and the new shoots contained equal amounts of total tree Ca, namely ±5.4 g (±12.1%). In the tree as a whole, the leaves, prunings, permanent parts and roots contributed ±12.1%, ±21.0%, ±45.5% and ±9.4%, respectively to the total tree Ca content. No uptake was noticed in the first six weeks after bud-break but rather the Ca reserves were redistributed from the permanent parts to support new growth. The increase in the Ca content from six weeks after bud-break until harvest was ±11.6 g, therefore resulting in ±27.9% of pre-harvest uptake. During the post-harvest period the total uptake was ±30.0 g (±72.1%) of the total tree Ca.

The Ca content of the three-year-old apple trees is summarised in Table 9b and depicted in the Appendix, Fig. 5c and d. The total increase in Ca/tree was 40.1 g (total uptake from the first late winter to late autumn plus Ca contained in the prunings at mid-summer and fruit removed at harvest) from late winter to late autumn. An increment of ±4.3 g (10.7%) of Ca content was observed from late winter to mid-summer. The Ca content uptake from mid-summer to harvest was 43.1 − (34.3 − 7.1 = 27.2) = ±15.9 g, therefore ±39.7% of the Ca content of pre-harvest uptake. During the post-harvest period 62.0 − (43.1 −1.0 = 42.1) = ±19.9 g (±49.6%) of Ca was taken up. This is in contrast to the ±72.1% of Ca that was taken up during this period in the two-year-old trees. With fruit harvest, only ±1.0 g (±2.3%) of Ca was removed from the tree.

Kotzé & De Villiers (1989) found ±3% Ca in kiwi fruit at harvest, which compares well with results of the present study. However, the ±58% in the leaves and the ±30% in the roots that they found were higher than the ±39.7% in leaves and ±10.0% in roots found in the present study. Conradie (1981) reported that at harvest grape bunches contained ±7.7% Ca: ±46.4% in the leaves and ±19.8% in the roots. The Ca content in the leaves increased to ±24.1 g (±38.9%) from harvest to late autumn. From late autumn to late winter the total Ca in the tree as a whole decreased by ±28.5 g. This means that all the Ca present in leaves at this stage is lost through leaf drop. These results clearly show that more Ca content was lost than was present in the leaves. This supports the findings of Terblanche (1972) who reported that just before the end of leaf drop some of the Ca in the permanent parts is redistributed to the leaves and gets lost at leaf drop. Conradie (1981) also reported that all Ca present in the leaves at leaf drop was lost by the grape vine. During harvest ±2.3% of the Ca content was in the fruit, ±40.8% in the permanent parts and ±10.0% in the roots. During the late winter ±89.0% of the total Ca in the tree was in the permanent parts and ±11.0% in the roots.

2.1.3.5 Magnesium

The whole tree Mg content in the young two-year-old trees was 8.3 g from bud-break until early winter (Table 10a, Appendix, Fig. 6a and b). In the new growth the Mg content increased from 0 to ±2.8 g, thus contributing ±32.6% of the tree Mg content. The highest proportion of the new growth Mg content was found in the leaves. The leaves, prunings, permanent parts and roots contributed ±17.4%, 27.9%, 26.7% and 12.8%, respectively to the whole tree Mg content. No uptake was noticed in the first six weeks as Mg reserves were redistributed from the permanent parts to support new growth. The increase from six weeks after bud-break until harvest was ±2.3 g, therefore ±27.7% of pre-harvest uptake. During the post-harvest period the total Mg uptake was ±6.0 g (±72.3%).

The total Mg content uptake in the three-year-old trees was 9.5 g from late winter to late autumn (Table 10b, and Appendix, Fig. 6c and d). From late winter to harvest the Mg content in the tree increased by ±6.1 g, contributing ±64.2% to the pre-harvest uptake. During the post-harvest period ±3.4 g Mg (±35.8%) was taken up. Stassen & Stadler (1988), working with peach trees, also reported that little uptake was found in the post-harvest period. This is in contrast to the ±72.3% of Mg that was taken up during this period in the two-year-old trees. At harvest ±2.0 g (±20.8%) Mg was removed in fruit from the tree. It was also observed that the Mg content in the leaves increased to ±44.5% from harvest to late autumn. The total tree

Mg content decreased by ±3.2 g during late autumn to late winter. These results indicate that ±1.7 g (±34.7%) Mg in the leaves was redistributed to the permanent parts. This finding is higher than the findings of Conradie (1981), who reported that loss associated with leaf drop amounted to approximately 44.3% of the total Mg absorbed during the season. However, it is in contrast to the findings of Terblanche (1972), who found that Mg can even move from the permanent structure to the leaves of apple trees and become lost through leaf drop. During harvest ±20.8% of the Mg content was in the fruit, ±28.1% in the permanent parts, and ±8.3% in the roots. These findings compare well with the findings of Conradie (1981), namely 15.4% in the bunches and 36.8% in the leaves. By late winter ±85.9% of the total Mg in the tree was in the permanent parts and ±14.1% in the roots.

2.1.3.6 Sulphur

The S content in the two-year-old trees increased by ±2.5 g from bud-break to early winter (Table 11a, and Appendix, Fig. 7a and b). The S content in the new growth increased from 0 to ±0.7 g, which accounted for ±23.3% of the tree total S. Of the new growth, the leaves contained the highest amount of S. The contribution to S in the tree was as follows: leaves (±13.3%), prunings (±20.0%), permanent parts (±30.0%) and roots (±26.7%). No uptake was observed early in the season as redistribution of reserves from the permanent parts to new growth played a big role from the beginning of bud-break until mid-summer. The S content increased by 0.7 g from mid-summer to harvest, therefore ±28.0% was taken up in the pre-harvest period. The post-harvest uptake was 1.8 g (±72.0%).

The total increase in S content of the three-year-old trees (Table 11b, and Appendix, Fig. 7c) was 5.5 g from late winter to late autumn. The increase from late winter to mid-summer was ±2.1 g, contributing ±38.2% of the pre-harvest uptake. From mid-summer to harvest ±2.0 g (±36.4%) S was taken up. Therefore the pre-harvest uptake was 4.1 g (74.5%), while 1.4 g (25.5%) was taken up during the post-harvest period. This is in contrast to the 72.0% S that was taken up during this period in the two-year-old trees. At harvest, ±1.4 g S was present in the fruit that was removed from the tree. From harvest to late autumn the S content in the leaves increased to ±1.7 g (±28.8%), while the total tree S content decreased by ±0.5 g from late autumn to late winter. This result indicates that ±1.2 g (±70.6%) S in the leaves was redistributed to the permanent structure. At this stage uptake could not play a significant role because the leaves were inactive (Faust, 1989). At harvest the fruit, permanent parts and roots contributed about ±23.7%, ±33.9% and ±18.6%, respectively to the total tree S content. In the

late winter ±75.9% of the total S in the tree was in the permanent parts and ±24.1% in the roots.

The macro nutrient levels found in the leaves at harvest (close to 31 January) were within the norms given by Faust (1989) and Kotzé *et al.* (2001) (data not shown).

2.1.4 Conclusions

In the two-year-old apple trees the macro nutrients N, P, K, Ca, Mg, S accumulated very slowly from bud-break until winter. This increase in the tree accounted for ±29.2 g N, ±3.5 g P, ±19.3 g K, ±18.4 g Ca, ±3.6 g Mg and ±1.7 g S. At harvest, fruit contained approximately ±4.5% N, ±5.7% P, ±11.9% K, ±1.1% Ca, ±2.8% Mg and ±5.9% S of the total content of each of these elements in the tree at that stage. These young trees continued taking up nutrients throughout the season because they were still growing, to fill the space allocated to them. It was previously reported by various researchers that nutrient reserves play a big role in the early season to support new growth (Mason & Whitfield, 1960; Terblanche, 1972; Conradie, 1981; Stassen *et al.*, 1981b; Titus & Kang, 1982; Stassen *et al.*, 1983; Stassen & Stadler, 1988; Kotzé & De Villiers 1989; Millard, 1996). Similar observations were made in the present study.

The N uptake in the 3rd leaf tree was ±22.1% and ±23.5% for the period from late winter to mid-summer and mid-summer to harvest, respectively, making a total of ±45.6% of pre-harvest uptake. During the post-harvest period ±54.4% was taken up. Another ±63.7% of leaf total N was redistributed from the leaves to the trees before the end of leaf drop. At late winter ±70.6% was in the permanent parts while ±29.4% was found in the roots. At harvest, the fruit (±27.2%), leaves (±23.8%), new shoots (3.6%), permanent parts (±29.2%) and roots (±16.2%) contributed to the total tree N content. Early in the season about ±57.8% N was taken up from the soil while ±42.2% was redistributed from the reserves in the permanent parts to support new growth.

The P content uptake in the 3rd leaf trees was ±19.5% and ±33.6% for the period from late winter to mid-summer and mid-summer to harvest, respectively, making a total of ±53.1% of pre-harvest uptake. During the post-harvest period ±46.9% was taken up. About ±39.4% of leaf total P was redistributed from the leaves to the permanent parts. At late winter ±65.5%

was in the permanent parts while ±34.5% was found in the roots. At harvest, the fruit, leaves, new shoots, permanent parts and roots comprised ±29.5%, ±14.3%, ±4.5%, ±32.1% and ±19.6% of the total P, respectively. Early in the season about ±86.2% P was taken up from the soil while ±13.8% was redistributed from the reserves to the permanent parts to support new growth.

The three-year-old tree K uptake was divided into ±22.2% and ±54.3% for the period from late winter to mid-summer and mid-summer to harvest respectively, making a total of ±76.5% of pre-harvest uptake. During the post-harvest period ±23.4% was taken up. About ±12.3% of leaf total K was redistributed from the leaves to the trees before the end of leaf drop. At late winter ±78.4% was in the permanent parts while ±21.6% was found in the roots. At harvest, the fruit (±60.2%), leaves (±17.1%), new shoots (±2.0%), permanent parts (±15.6%) and roots (±5.2%) contributed to the total tree K content. Early in the season about ±76.6% K was taken up from the soil while ±23.4% was distributed from the reserves in the permanent parts to support new growth.

The total Ca uptake during the 3rd year was divided into ±10.7% and ±39.7% for the period from late winter to mid-summer and mid-summer to harvest respectively, making a total of ±50.4% of pre-harvest uptake. During the post-harvest period ±49.6% was taken up. No redistribution from the leaves to the trees took place. At late winter ±86.0% was in the permanent parts while ±14.0% was found in the roots. At harvest, the fruit, leaves, new shoots, permanent parts and roots contained ±2.3%, ±39.7%, ±7.2%, ±40.8% and ±10.0% of the total Ca, respectively. Early in the season about ±33.1% Ca was taken up from the soil while ±66.9% was redistributed from the reserves in the permanent parts to support new growth.

Magnesium uptake in the 3rd leaf trees was divided into ±27.4% and ±36.8% for the period from late winter to mid-summer and mid-summer to harvest, respectively, making a total of ±64.2% of pre-harvest uptake. During the post-harvest period ±35.8% was taken up. A redistribution of ±34.7% of Mg from the leaves to the tree was observed. At late winter ±76.6% was in the permanent parts while ±23.4% was found in the roots. At harvest the fruit (±20.8%), leaves (±37.5%), new shoots (5.2%), permanent parts (±28.1%) and roots (±8.3%) contributed to the total tree Mg content. Early in the season about ±65.0% Mg was taken up

from the soil while ±35.0% was redistributed from the reserves in the permanent parts to support new growth.

The S uptake of the three-year-old trees was divided into ±38.2% and ±36.4% for the period from late winter to mid-summer and mid-summer to harvest, respectively, making a total of ±74.5% of pre-harvest uptake. During the post-harvest period ±25.5% was taken up. Another ±70.6% of leaf total S was redistributed from the leaves to the trees before the end of leaf drop. At late winter ±63.6% was in the permanent parts while ±36.4% was found in the roots. At harvest the distribution of S in the fruit, leaves, new shoots, permanent parts and roots was as follows: ±23.7%, ±20.3%, ±3.4%, ±33.9% and ±18.6%, respectively. Results of this study indicate that there was no redistribution from the reserves, but rather all of the S was taken up to support the new growth at the beginning of the season. The period late winter to mid-summer (± 4 months) was too long to accurately show the real value of the permanent structure as a storage site for macro nutrient reserves.

In disagreement with the findings of Terblanche (1972), Conradie (1981) and Stassen and Stadler (1988), the roots in this study had a low nutrient content in comparison with the permanent parts. Ferguson and Turner (1981) suggested that wood and bark are important sites for nutrient reserves in kiwifruit and that nitrogen is readily redistributed to new growth. A similar observation was made in this study. The differences between the current study and Terblanche (1972) study might be due to the fact that he worked on younger trees in pot that was fertilised with the Hoagland solution and he also collected data weekly which could have taken in account any losses from the leaves.

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Table 1: The average percentages stone, clay, silt and sand in the composition of the Dundee loamy sand soil (0–60 cm depth) and mean water holding capacity at the orchard at Greyton

Soil type				Classification				
	Stone	Clay	Silt	Fine sand	Medium sand	Coarse sand	Stone volume	Water-holding capacity
			(%)				(v/v)	(mm/m)
Loam sand	0.75	5.21	9.61	57.4	21.8	5.91	0.34	130.3

Table 2: The pH, carbon (C) percentage and percentages of elements that contributed to the cation exchange capacity in the top and sub soil of the Dundee loamy sand soil form at the orchard at Greyton after pre-plant soil rectification

Depth (cm)	pH (KCl)	C %	Na %	K %	Ca %	Mg %	T-value (cmol.kg^{-1})
0-30	6.1	1.37	5.61	3.20	79.22	11.98	8.47
30-60	4.8	1.49	5.55	2.38	70.09	11.54	5.26

Table 3: The predetermined annual nutrient requirements for apple trees based on a yield of one ton as adopted from Stassen and North (2005)

Macro nutrient (kg element/ton fruit					
N	P	K	Mg	Ca	S
2.3	0.5	1.8	0.5	1.8	1.0
Micro nutrient (g element/ton fruit)					
Mn	Fe	Cu	Zn	B	Mo
0.02	0.13	0.007	0.02	0.01	0.001

Table 4: Predetermined and computed annual nutrient requirements based on estimated yield for two seasons (2004/5 and 2005/6) in Brookfield Gala trees

Estimated fruit yield (ton/ha)	Nutrient levels (kg. ha^{-1}. yr^{-1})											
	N	P	K	Mg	Ca	S	Mn	Fe	Zn	B	Mo	Cu
10 + 30% (2ndleaf)	29.9	6.5	23.4	6.5	23.4	13.0	0.26	1.69	0.26	0.13	0.013	0.09
25 (3rd leaf)	57.5	12.5	45.0	12.5	45.0	25.0	0.50	3.25	0.50	0.25	0.03	0.18

Table 5: Seasonal macro and micro nutrient percentage distribution in nutrient solutions applied to young Brookfield Gala apples trees during the 2004/5 and 2005/6 seasons

Month	N (%)	Ca (%)	K, P and Mg (%)	B, Zn (%)	Fe, Mn (%)
Jan[3]	4.0	0.0	10.0	5.0	12.0
Feb[4]	4.0	0.0	10.0	10.0	10.0
Mar[5]	20.0	12.0	11.0	12.0	10.0
Apr[5]	20.0	8.0	10.0	2.0	10.0
May[5]	5.0	5.0	10.0	2.0	6.0
June[1]	1.0	0.0	1.0	1.0	2.0
July[1]	1.0	0.0	1.0	1.0	1.0
Aug[1]	1.0	1.0	1.0	1.0	1.0
Sept[2]	10.0	15.0	12.0	15.0	12.0
Oct[2]	15.0	25.0	12.0	15.0	12.0
Nov[3]	15.0	25.0	12.0	18.0	12.0
Dec[3]	4.0	9.0	10.0	18.0	12.0

*Phenological periods: 1- Dormant; 2- Spring; 3- Summer; 4- Harvest; 5- Post-harvest

Table 6: Average nitrogen (N) content in grams (g) and percentage distribution in different parts of Brookfield Gala apple trees at different phenological stages in: a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average N (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter *	%
Fruit	-	-	0.3±0.1	1.6	0.1±0.0	0.5	1.3±0.2	4.5	-	-
Leaves	-	-	1.3±0.2	6.8	8.7±0.6	41.6	4.8±0.8	16.4	9.9±1.8	16.0
New shoots	-	-	1.6±0.1	8.4	1.5±0.0	7.2	1.6±0.6	5.5	6.8±1.3	11.0
Subtotal (new growth)	0	0	3.2±0.4	16.8	10.3±0.6	49.3	7.7±1.5	26.4	16.7±3.2	27.0
Prunings**	-	-	-	-	-	-	7.1±1.3	24.3	13.9±5.1	22.5
Permanent parts***	11.3±1.3	75.8	9.9±1.2	51.8	6.4±0.5	30.6	9.9±1.1	33.9	18.6±1.0	30.1
Roots****	3.6±0.3	24.2	6.0±1.7	31.4	4.2±0.4	20.1	4.5±0.4	15.4	12.6±2.7	20.4
Subtotal (permanent structure)	14.9±1.6	100.0	15.9±2.9	83.2	10.6±0.9	50.7	21.5±2.8	73.6	45.1±8.8	73.0
Total	14.9±1.6	100.0	19.1±3.3	100.0	20.9±1.5	100.0	29.2±4.3	100.0	61.8±12.0	100.0

* early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** permanent parts includes trunk, canopy branches and rootstock
**** roots includes primary and secondary roots

b)

Tree parts	Average N (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	2.7±0.6	4.4	20.2±2.6	27.2	-	-	-	-
Leaves	-	-	27.3±5.0	44.4	17.7±2.3	23.8	31.4±0.1	31.5	-	-
New shoots	-	-	2.2±0.3	3.6	2.7±0.4	3.6	6.7±1.6	6.7	-	-
Subtotal (new growth	0	0	32.2±5.9	52.4	40.6±5.2	54.6	38.1±1.8	38.2	0	0
Prunings**	-	-	6.9±1.4	11.2	-	-	-	-	-	-
Permanent parts***	30.3±3.2	70.6	18.3±2.5	29.8	21.7±3.5	29.2	45.2±4.3	45.3	69.6±5.8	78.7
Roots****	12.6±2.7	29.4	4.1±2.0	6.7	12.0±1.3	16.2	16.5±2.7	16.5	18.8±4.9	21.3
Subtotal (permanent structure)	42.9±5.9	100.0	29.3±6.0	47.7	33.7±4.8	45.4	61.7±7.0	61.8	88.4±10.7	100.0
Total	42.9±5.9	100.0	61.5±11.9	100.0	74.3±10.1	100.0	99.8±8.8	100.0	88.4±10.7	100.0

* late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** permanent parts includes trunk, canopy branches and rootstock
**** roots includes primary and secondary roots

Table 7: Average phosphorus (P) content in grams and percentage distribution in different parts of Brookfield Gala apple trees at different phenological stages in: a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average P (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.0±0.0	0.0	0.0±0.0	0.0	0.2±0.0	5.7	-	-
Leaves	-	-	0.1±0.0	4.5	0.7±0.1	26.9	0.4±0.1	11.4	0.8±0.1	11.0
New shoots	-	-	0.2±0.0	9.1	0.2±0.0	7.7	0.2±0.1	5.7	0.9±0.2	12.3
Subtotal (new growth)	0	0	0.3±0.0	13.6	0.9±0.1	34.6	0.8±0.2	22.8	1.7±0.3	23.3
Prunings**	-	-	-	-	-	-	0.6±0.1	17.2	1.4±0.4	19.2
Permanent parts***	1.5±0.2	75.0	1.1±0.2	50.0	1.0±0.1	38.5	1.4±0.1	40.0	2.3 ±0.1	31.5
Roots****	0.5±0.0	25.0	0.8±0.2	36.4	0.7±0.1	26.9	0.7±0.1	20.0	1.9 ±0.5	26.0
Subtotal (Permanent structure)	2.0±0.3	100.0	1.9±0.4	86.4	1.7±0.2	65.4	2.7±0.3	77.2	5.6 ±1.1	76.7
Total	2.0±0.3	100.0	2.2±0.4	100.0	2.6±0.3	100.0	3.5±0.5	100.0	7.3±1.3	100 .0

* early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
***permanent parts includes trunk, canopy branches and rootstock
**** roots includes primary and secondary roots

b)

Tree parts	Average P (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	0.4±0.1	5.0	3.3±0.1	29.5	-	-	-	-
Leaves	-	-	2.2±0.3	27.5	1.6±0.3	14.3	3.3±0.1	23.7	-	-
New shoots	-	-	0.3±0.1	3.8	0.5±0.1	4.5	1.0±0.2	7.2	-	-
Subtotal (new growth)	0	0	2.9±0.5	36.3	5.4±0.5	48.3	4.3±0.3	30.9	0	0
Prunings**	-	-	1.1±0.2	13.7	-	-	-	-	-	-
Permanent parts***	3.6±0.4	65.5	3.2±0.4	40.0	3.6±0.5	32.1	6.7±0.6	48.2	8.9±0.6	74.8
Roots****	1.9±0.5	34.5	0.8±0.4	10.0	2.2±0.3	19.6	2.9±0.7	20.9	3.0±0.8	25.2
Subtotal (permanent structure)	5.5±0.9	100.0	5.1±1.0	63.7	5.8±0.8	51.7	9.6±1.3	69.1	11.9±1.5	100.0
Total	5.5±0.9	100.0	8.0±1.5	100.0	11.2±1.3	100.0	13.9±1.6	100.0	11.9±1.5	100.0

* late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** permanent parts includes trunk, canopy branches and rootstock
**** roots includes primary and secondary roots

Table 8: Average potassium (K) content in grams and percentage distribution in different parts of Brookfield Gala apple trees at different phenological stages in: a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average K (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.2±0.0	4.3	0.1±0.0	0.8	2.3±0.2	11.9	-	-
Leaves	-	-	0.6±0.0	12.8	6.0±0.3	46.2	3.2±0.4	16.6	7.7±1.1	24.1
New shoots	-	-	0.5±0.0	10.6	1.1±0.0	8.5	1.0± 0.3	5.2	3.4±0.5	10.6
Subtotal (new growth)	0	0	1.3±0.0	27.7	7.2±0.3	55.4	6.5±0.9	33.7	11.1±1.6	34.7
Prunings**	-	-	-	-	-	-	5.0±0.9	25.9	8.7±2.7	27.2
Permanent parts***	4.4±0.4	83.0	2.3±0.1	48.9	4.2±0.3	32.3	6.1±1.0	31.6	8.0±0.7	25.0
Roots****	0.9±0.0	17.0	1.1±0.3	23.4	1.6±0.2	12.3	1.7±0.1	8.8	4.2±0.9	13.1
Subtotal (permanent structure)	5.3±0.4	100.0	3.4±0.4	72.3	5.8±0.5	44.6	12.8±2.0	66.3	20.9±4.4	65.3
Total	5.3±0.4	100.0	4.7±0.4	100.0	13.0±0.8	100.0	19.3±2.9	100.0	32.0±6.0	100 .0

* early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** permanent parts includes trunk, canopy branches and rootstock
**** roots includes primary and secondary roots

b)

Tree parts	Average K (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	3.4±0.4	9.4	44.1±2.1	60.2	-	-	-	-
Leaves	-	-	16.8±2.2	46.5	12.5±1.8	17.1	22.7±1.4	48.5	-	-
New shoots	-	-	1.6±0.3	4.4	1.5±0.2	2.0	3.4±0.7	7.3	-	-
Subtotal (new growth)	0	0	21.8±2.9	60.3	58.1±4.1	79.3	26.1±2.1	55.8	0	0
Prunings**	-	-	3.6±0.7	10.0	-	-	-	-	-	-
Permanent parts***	15.2±1.7	78.4	9.6±0.2	26.7	11.4±1.7	15.6	16.4±1.5	35.0	21.9±1.4	81.4
Roots****	4.2±0.9	21.6	1.1±0.4	3.0	3.8±0.3	5.2	4.3±1.0	9.2	5.0±1.4	18.6
Subtotal (permanent structure)	19.4±2.6	100.0	14.3±1.3	39.7	15.2±2.0	20.7	20.7±2.6	44.2	26.9±2.8	100.0
Total	19.4±2.6	100.0	36.1±4.2	100.0	73.3±6.1	100.0	46.8±4.7	100.0	26.9±2.8	100.0

* late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** permanent parts includes trunk, canopy branches and rootstock
**** roots includes primary and secondary roots

Table 9: Average calcium (Ca) content in (g) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Ca (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.0±0.0	0.0	0.0±0.0	0.0	0.2±0.0	1.1	-	-
Leaves	-	-	0.2±0.0	2.9	3.3±0.2	26.8	2.6±0.5	14.1	5.4±1.0	12.1
New shoots	-	-	1.1±0.1	16.2	1.0±0.0	8.1	1.2±0.4	6.5	5.4±1.0	12.1
Subtotal (new growth)	0	0	1.3±0.1	19.1	4.3±0.2	35.0	4.0±0.9	21.7	10.8±2.0	24.1
Prunings**	-	-	-	-	-	-	3.4±0.4	18.5	9.4±3.2	21.0
Permanent parts***	6.3±0.5	85.1	4.3±0.2	63.2	6.5±0.5	52.8	9.2±2.0	50.0	20.4±2.3	45.5
Roots****	1.1±0.1	14.9	1.2±0.2	17.6	1.5±0.1	12.2	1.8±0.1	9.8	4.2±1.1	9.4
Subtotal (Permanent structure)	7.4±0.6	100.0	5.5±0.4	80.9	8.0±0.6	65.0	14.4±2.4	78.3	34.0±6.6	75.9
Total	7.4±0.6	100.0	6.8±0.5	100.0	12.3±0.8	100.0	18.4±3.3	100.0	44.8±8.6	100.0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Ca (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	0.2±0.0	0.6	1.0±0.2	2.3	-	-	-	-
Leaves	-	-	11.1±1.7	32.4	17.1±1.6	39.7	24.1±2.2	38.9	-	-
New shoots	-	-	1.7±0.3	5.0	3.1±0.2	7.2	5.3±1.0	8.5	-	-
Subtotal (new growth)	0	0	13.0±2.0	38.0	21.2±2.0	49.2	29.4±3.2	47.4	0	0
Prunings**	-	-	7.1±1.9	20.7	-	-	-	-	-	-
Permanent parts***	25.8±3.3	86.0	13.0±2.4	37.9	17.6±2.1	40.8	27.8±4.0	44.8	9.8±0.6	89.0
Roots****	4.2±1.1	14.0	1.2±0.4	3.5	4.3 ±0.5	10.0	4.8 ±1.1	7.7	3.7±1.2	11.0
Subtotal (Permanent structure	30.0±4.4	100.0	21.3±4.7	62.0	21.9±2.6	50.8	32.6±5.1	52.6	33.5±1.8	100.0
Total	30.0±4.4	100.0	34.3±6.7	100.0	43.1±4.6	100.0	62.0±8.3	100.0	33.5±1.8	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary r

Table 10: Average magnesium (Mg) content in (g) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Mg (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.0±0.0	0.0	0.0±0.0	0.0	0.1±0.0	2.8	-	-
Leaves	-	-	0.1±0.0	7.7	0.9±0.1	37.5	0.6±0.1	16.7	1.5±0.3	17.4
New shoots	-	-	0.2±0.0	15.4	0.3±0.0	12.5	0.2±0.1	5.6	1.3±0.3	15.1
Subtotal (new growth)	0	0	0.3±0.0	23.1	1.2±0.1	50.0	0.9±0.2	25.0	2.8±0.6	32.6
Prunings**	-	-	-	-	-	-	0.9±0.1	25.0	2.4±0.9	27.9
Permanent parts***	1.1±0.1	84.6	0.7±0.1	53.8	0.9±0.1	37.5	1.4±0.2	38.9	2.3±0.1	26.7
Roots****	0.2±0.0	15.4	0.3±0.1	23.1	0.3±0.0	12.5	0.4±0.0	11.1	1.1±0.2	12.8
Subtotal (Permanent structure)	1.3±0.1	100.0	1.0±0.2	76.9	1.2±0.1	50.0	2.7±0.3	75.0	5.8±1.2	67.4
Total	1.3±0.1	100.0	1.3±0.2	100.0	2.4±0.2	100.0	3.6±0.5	100.0	8.6±1.8	100.0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Mg (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	0.2±0.0	2.7	2.0±0.2	20.8	-	-	-	-
Leaves	-	-	3.3±0.5	45.2	3.6±0.4	37.5	4.9±0.7	44.5	-	-
New shoots	-	-	0.5±0.1	6.8	0.5±0.1	5.2	1.1±0.3	10.0	-	-
Subtotal (new growth)	0	0	4.0±0.6	54.8	6.1±0.7	63.5	6.0±1.0	54.5	0	0
Prunings**	-	-	1.2±0.2	16.4	-	-	-	-	-	-
Permanent parts***	3.6±0.4	76.6	1.9±0.2	26.0	2.7±0.4	28.1	4.1±0.2	37.3	6.7±0.5	85.9
Roots****	1.1±0.2	23.4	0.2±0.1	2.7	0.8±0.0	8.3	0.9±0.3	8.2	1.1±0.3	14.1
Subtotal (Permanent structure)	4.7±0.6	100.0	3.3±0.5	45.2	3.5±0.4	36.5	5.0±0.5	45.5	7.8±0.8	100.0
Total	4.7±0.6	100.0	7.3±1.1	100.0	9.6±1.1	100.0	11.0±1.5	100.0	7.8±0.8	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

Table 11: Average sulphur (S) content in (g) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average S (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.0±0.0	0.0	0.0±0.0	0.0	0.1±0.0	5.9	-	-
Leaves	-	-	0.1±0.0	5.6	0.4±0.0	40.0	0.2±0.0	11.8	0.4±0.1	13.3
New shoots	-	-	0.1±0.0	5.6	0.0±0.0	0.0	0.1±0.0	5.9	0.3±0.1	10.0
Subtotal (new growth)	0	0	0.2±0.0	11.1	0.4±0.0	40.0	0.4±0.0	23.6	0.7±0.2	23.3
Prunings**	-	-	-	-	-	-	0.4±0.1	23.5	0.6±0.2	20.0
Permanent parts***	1.4±0.4	77.8	1.0±0.1	55.6	0.3±0.0	30.0	0.6±0.1	35.3	0.9±0.1	30.0
Roots****	0.4±0.1	22.2	0.6±0.3	33.3	0.3±0.0	30.0	0.3±0.0	17.6	0.8±0.2	26.7
Subtotal (Permanent structure)	1.8±0.6	100.0	1.6±0.4	88.9	0.6±0.0	60.0	1.3±0.2	76.4	2.3±0.5	67.4
Total	1.8±0.6	100.0	1.8±0.4	100.0	1.0±0.0	100.0	1.7±0.2	100.0	3.0±0.7	100 .0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average S (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	0.2±0.0	4.7	1.4±0.2	23.7	-	-	-	-
Leaves	-	-	1.8±0.3	41.9	1.2±0.1	20.3	1.7±0.2	28.8	-	-
New shoots	-	-	0.1±0.0	2.3	0.2±0.0	3.4	0.3 ±0.1	5.1	-	-
Subtotal (new growth)	0	0	2.1±0.3	48.9	2.8±0.3	47.5	2.0±0.3	33.9	0	0
Prunings**	-	-	0.4±0.1	9.3	-	-	-	-	-	-
Permanent parts***	1.4±0.2	63.6	1.3±0.1	30.2	2.0±0.2	33.9	2.8±0.2	47.5	4.1±0.4	75.9
Roots****	0.8±0.2	36.4	0.5±0.2	11.6	1.1±0.3	18.6	1.1±0.2	18.6	1.3±0.3	24.1
Subtotal (Permanent structure)	2.2±0.4	100.0	2.2±0.3	51.1	3.1±0.5	52.5	3.9±0.4	66.1	5.4±0.7	100.0
Total	2.2±0.4	100.0	4.3±0.7	100.0	5.9±0.8	100.0	5.9±0.7	100.0	5.4±0.7	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

2.2 Seasonal uptake and distribution of micro nutrients in two-and three-year-old apple trees

Abstract

The seasonal uptake and distribution of sodium (Na), manganese (Mn), zinc (Zn), iron (Fe), copper (Cu), boron (B) and molybdenum (Mo) were determined for two- and three-year-old 'Brookfield Gala' apple trees on M793 rootstock grown under field conditions. Trees planted at a spacing of 4 x 1.25m and trained to a central leader system using the solaxe principle were excavated at different phenological stages. The two-year-old trees were excavated at the beginning of bud-break, six weeks after bud-break, mid-summer, harvest and early winter. The three-year-old trees were excavated at late winter, mid-summer, harvest, late autumn, and again at late winter. Trees were divided into different tree parts (roots, leaves, fruit, rootstock, current-year wood, trunk, canopy branches) at excavation and analysed for the different micro nutrients. Chemical analysis was used to determine the micro element uptake and distribution within the tree. In the two-year-old apple trees the Na, Mn, Fe, Cu, Zn, B and Mo accumulated rapidly from the beginning of bud-break to harvest. In the young bearing apple trees the nutrients accumulated rapidly from late winter to harvest. Among the micro nutrients involved in this study only Mn uptake took place during the post-harvest period. B and Mo were found in high concentrations in the fruit, contributing to the reduction in the nutrient content after harvest. In this study it was also found that a portion of Mn (±25.2%), Fe (±100.0%), Cu (±100.0%) and B (±35.4%) was redistributed from the leaves to the permanent parts before the end of leaf drop. The period late winter to mid-summer (± 4 months) was too long to show the real value of the permanent structure as a storage site for reserves.

Keywords: micro-element accumulation, nutrient redistribution from leaves

2.2.1 Introduction

Judicious mineral nutrition is an important factor in fruit tree production since it is responsible for several functions such as energy processes, enzyme activation and osmotic regulation of the membranes (Mengel & Kirkby, 1982; Faust, 1989; Taiz & Zeiger, 1991; Marschner, 1993; Neilsen & Neilsen, 2003). Micro elements are needed in smaller quantities, therefore foliar sprays or soil application can be given to the plants when needed to avoid deficiencies and abnormal growth (Kotze & De Villiers, 1991).

Apart from a study by Terblanche (1972) on apples and two studies on kiwi vines (Kotze & De Villiers, 1989; Kotze & De Villiers, 1991) few studies have been conducted to determine the different seasonal uptake and distribution patterns of micro elements. Terblanche (1972) reports that Mn, Zn and Cu are taken up slowly during the shoot elongation period but after completion of shoot elongation they are actively taken up at two stages: from cessation of shoot elongation until the beginning of leaf aging of the oldest leaf and then again during the leaf drop period. Furthermore, Fe does not show any uptake during the shoot elongation period but follows the same pattern as Mn, Zn and Cu. At termination of the longest shoot elongation about 50% of Mn is found in new growth and most of this nutrient is accumulated in the leaves (Terblanche, 1972). Major quantities of Mn are accumulated in the roots during the rest period as well as early in the season, while the leaves make a huge contribution to the Mn content of the total tree during the active growing season. In contradiction, Kotzé & De Villiers (1989) found that there is no indication of translocation of micronutrients from the permanent parts of the kiwi vines to new growth during the early part of the growing season. According to Terblanche (1972) Zn is significantly redistributed after cessation of shoot extension growth when a reduction in the permanent parts takes place to support new growth. However, Kotzé & De Villiers (1991) found that in kiwi vines the rate of Zn absorption into roots remained constant from before bud-break until early March, and increased significantly thereafter until the middle of July. Furthermore, the rate of absorption of Zn remained at a low level from before bud-break until the beginning of March, after which a four-fold increase takes place until the beginning of July (after leaf drop) (Kotzé & De Villiers, 1991). Smith *et al.* (1987) reported that most of the copper and the zinc in field-grown kiwifruit accumulate during the first four weeks after leaf emergence, whereas the rates of accumulation of Mn, Fe and B are similar throughout the growing season. Kotzé & De Villiers (1989) and Smith *et al.* (1987) agree that the accumulation of copper by the leaves

increases sharply before harvest. Boron accumulates mostly in the bark and roots during the rest period while in the growing season it accumulates in leaves and fruits. During the shoot extension period the B needed for new growth comes from the redistribution from one-year wood (Terblanche, 1972). Copper is accumulated mostly in the roots while the Cu in the wood and bark is equally accumulated. The roots store most of the Fe during the rest period and after cessation of shoot extension growth (Terblanche, 1972).

Kotzé & De Villiers (1989) found that ±16% of Zn assimilated from bud-break to harvest is transported to the leaves compared to ±49% Mn, ±46% B and ±55% Fe. Furthermore, a large fraction of Zn is retained in the permanent part of the kiwi vine, confirming the low mobility of Zn. During the active growth period Fe redistribution takes place from the permanent parts to support new growth (Terblanche, 1972). Smith *et al*. (1987) and Kotzé & De Villiers (1989) agree that no migration of micronutrients is detected from the leaves prior to harvest, but substantial amounts of Mn, Zn and Fe are redistributed from the leaves after harvest, before leaf drop. However, there is some indication of an increase in the content of these nutrients in the permanent parts of the kiwi vine and at least some of these nutrients might be transported out of the leaves before senescence (Kotzé & De Villiers, 1989). These findings disagree with the findings of Terblanche (1972), who suggests that Mn, Zn and Fe migrate from the permanent parts to the apple leaves and are lost through leaf drop. B and Cu in the new growth migrate to the permanent parts before leaf drop, increasing the quantity of these elements in the total tree. The fruit is a relatively unimportant sink for micronutrients except in the case of B (Kotzé & De Villiers, 1989). In the case of B, ±70 % of this nutrient's assimilation in the period up to harvest is accumulated in new growth (Kotzé & De Villiers, 1989). Furthermore, Raven (1980) reports that the quantity of B taken up by the roots, and subsequently transported to the shoots and leaves, is closely related to the rate at which plants transpire.

All these studies were conducted in sand culture. Not much research has been carried out in commercial higher-density orchards. The objective of this study is to determine the uptake and distribution of Na, Mn, Fe, Zn, Cu, B and Mo in young non-bearing and bearing apple trees in a commercial high-density orchard under drip fertigation.

2.2.2 Material and methods

2.2.2.1 Orchard cultural practices

'Brookfield Gala' apple trees on M 793 rootstock were planted in July 2003 on a well drained, well aerated loamy sand soil of the Dundee form (Macvicar *et al.*, 1977) in the Greyton area near Genadendal in the Western Cape Province. The area is situated 34º03' S, 19º37' E and 33 m above sea level. Granny Smith trees were planted as cross pollinators. The trees were fertigated daily with two Netafim 2.3 l.h^{-1} pressure compensated emitters per tree, spaced at 60 cm on either side of the trunk. Water and nutrient requirements were calculated as previously described in Section 2.1.

The single-tree plots were replicated three times in a randomised complete block design. Trees from the nursery were cut back to 1.2 m height for uniformity among all trees. The trees were planted at a spacing of 4m x 1.25 m, as in the rest of the orchard, and trained as a central leader spindle with lateral shoot bent horizontally according to the solaxe principle (Lauri & Lespinasse, 2000). The soil preparation, tree training, water and nutrient management, plant sampling and the milling of samples have been described earlier (see Section 2.1).

2.2.2.2 Analysis of samples

Mineral analysis of micro elements was performed by a commercial analytical laboratory (Bemlab Pty. Ltd, Strand, South Africa). Samples were analysed for Na, Mn, Zn, Fe, Cu, B and Mo. All nutrients were analysed using ICP-OES (Inductively Coupled Plasma-Optical Emission Spectrometer) (Varian MPX-OEX, Varian, Inc. Corporate, Palo Alto, California, USA). Results were expressed as mg/kg dry weight (DW) for all micro elements except Mo, which was expressed in µg/kg. Data were then converted to the micro element content in milligrams for each tree part using the dry weight. Three trees were removed on a specific excavation date and the central leader mass above the graft union was used to equilibrate the tree size as previously discussed (see Section 2.1). The permanent parts include the canopy branches, rootstock and trunk. The pruning includes the shoots and leaves.

2.2.3 Results and discussion

2.2.3.1 Sodium

Results showed that the Na content of the two-year-old trees increased from ±246.9 mg at bud-break to ±1294.6 mg in early winter (Table 1a, and Appendix, Fig. 8a and b). The Na content of the new growth increased from 0 to ±218.3 mg. This comprised 16.9% of the total Na in the tree. The leaves contained the highest amount of Na of the new growth. In the tree as a whole, the leaves, prunings, permanent parts and roots contributed ±9.3%, 14.2%, ±34.6% and ±34.2% of the total Na in early winter, respectively. The total increase in Na/tree was 1154.2 mg over the season. No uptake was noted during the first six weeks, and therefore the reserves must have played a role in supplying new growth with Na. The increase from six weeks after bud-break until harvest was ±858.0 mg, therefore 74.3% of pre-harvest uptake. The post-harvest period uptake was 1294.6 mg – (1100.8 – 24.3 – 78.1 = 998.4 mg) = 296.2 mg, contributing 25.7% of the total Na taken up.

The Na content of the three-year-old apple trees is summarised in Table 1b and depicted in Appendix, Fig. 8c and d. The total increase in Na/ tree was 2974.1 mg from late winter to late autumn. The increase from late winter to mid- summer was ±94.3 mg, therefore 3.2% of pre-harvest uptake. From mid-summer to harvest 3617.0 – (1144.6 – 176.8 = 967.8) = ±2649.2 mg was taken up, contributing to 89.1% of pre-harvest uptake. During the post-harvest period the uptake was 3124.4 mg – (3617.0 mg – 723.2 mg = 2893.8 mg) = 230.6 mg, therefore 7.8% of post-harvest uptake. This is lower than the 25.7% Na that was taken up during this period in the two-year-old trees. With harvest, ±723.2 mg of Na was removed in the harvested fruit from the tree. In the leaves the Na content increased to 451.2 mg from harvest to late autumn. From late autumn to late winter the total Na in the tree as a whole decreased by ±1384.5 mg. This means that all Na present in the leaves was lost during leaf drop. Furthermore, the permanent structure showed a decline in Na content. This can be explained as follows: just before the end of leaf drop the Na moved out of the permanent structure to the leaves and was lost through the leaves. During harvest, ±20.0% of the Na content was in the fruit, ±36.9% in the permanent parts and ±15.1% in the roots. During late winter ±75.9% of the total Na in the tree was in the permanent parts and ±24.1% in the roots. In this study the period late winter to mid-summer (± 4 months) was too long to accurately show the real value of the permanent structures as a source of Na reserves.

2.2.3.2 Manganese

No Mn was taken up during the first six weeks in the two-year-old trees, but redistribution from the permanent parts took place in order to support new growth (Table 7a, and Appendix, Fig. 3a and b). Terblanche (1972) reports that at least 71% of the Mn reserves are redistributed to new growth early in the new season. The Mn content increase was 188.2 mg from six weeks after bud-break to early winter. The new growth Mn content increased from 0 to ±55.0 mg, thus contributing ±30.9% of the total Mn in the tree. It was established that the leaves contained the highest amount of Mn of the new growth. The leaves, prunings, permanent parts and roots contributed ±21.5 mg, ±24.4 mg, ±30.6 mg and ±14.2 mg of Mn content, respectively. The Mn content increased from six weeks after bud-break to harvest by ±64.2 mg, therefore ±34.1% of pre-harvest uptake. The post-harvest Mn uptake was 124.0 mg (±65.9%).

In the three-year-old apple trees the total Mn content uptake was 203.1 mg from late winter to late autumn (Table 2b, and Appendix, Fig. 9c and d). The increase from late winter to mid-summer was ±126.7 mg, contributing to ±62.4% of the pre-harvest uptake. From mid-summer to harvest no Mn was taken up but rather a portion was lost through summer pruning. The Mn post-harvest uptake was ±76.4 mg (±37.6%). These results show that more Mn was taken up in the two-year-old trees (±65.9%) compared to the third-year-old trees. During fruit harvesting ±17.4 mg (±9.8%) Mn was removed from the tree. It was further observed that the Mn content in the leaves increased to ±161.5 mg from harvest to late autumn. Kotzé & De Villiers (1989) reported that in kiwi vines at harvest the leaves showed a significant decrease in Mn content that coincided with a significant increase in the permanent parts. In the present study the same observation was made in the roots. A decrease of ±237.2 mg – 116.4 mg = 120.8 mg Mn was observed in the total tree during late autumn to late winter. This result indicated that ± 40.7 mg (±25.2%) Mn in the leaves was redistributed to the permanent parts. This redistribution was less than the ±45.5% found by Terblanche (1972). At harvest the Mn content was ±9.8% (fruit), ±18.0% (permanent parts) and ±5.7% (roots). Kotzé & De Villiers (1989) reported that in kiwi vines at harvest the leaves contained ±49% Mn, the roots ±40% and the fruit ±1%. However, in the present study the leaves contained ±63.9% Mn, which is higher than ±49%. While the ±5.7% in the roots is lower than in the above findings but the fruit 1% Mn is lower than the ±9.8% found in the present study. During late winter ±84.1% total Mn in the tree was in the permanent parts and ±15.9% in the roots. According to Terblanche (1972) the roots are the most important source in the rest period and early in the

season while the leaves play a major role in the active growing season until the beginning of leaf drop. The largest amount of Mn was found in the leaves throughout the growing season in the three-year-old apple trees. Thus the leaves played a very important part while the roots did not play a significant role, but rather the permanent parts. This is in agreement with the findings of Terblanche (1972) for apple trees.

2.2.3.3 Iron

The Fe content in the two-year-old trees increased by 1394.7 mg during the period from bud-break to early winter (Table 3a, and Appendix, Fig. 10a and b). In the new growth the Fe content increased from 0 to ±241.9 mg, which accounted for ±15.8% of the total Fe. The highest proportion of Fe of the new growth was in the new shoots. The contributions to the Fe content in the tree as a whole were as follows: leaves (±7.1%), prunings (±14.0%), permanent parts (±53.3%) and roots (±16.9%). The redistribution of Fe reserves took place early in the season since no uptake was noted during the first six weeks after bud-break. Results of the present study show that from six weeks after bud-break until harvest ±212.1 mg Fe was taken up, accounting for ±15.2% pre-harvest uptake. The increase from harvest to early winter was ±1182.6 mg, therefore ±84.8% of the post-harvest period uptake.

Results of this study show that the increase in the Fe content in the three-year-old trees (as a whole) from late winter to late autumn was 1008.2 mg (Table 3b, and Appendix Fig. 10c and d). The increase in the total Fe/ tree from mid-summer to harvest was ±381.8 mg, resulting in 37.9% of the pre-harvest uptake. During the period harvest to late autumn the Fe content increased by ±626.4 mg, accounting for 62.1% of the post-harvest uptake. However, Kotzé & De Villiers (1989) reported that the Fe content of the kiwi vine increases rapidly from bud-break until the beginning of December and thereafter at a slower rate until the end of March. In the present study ±210.3 mg Fe was removed from the tree with fruit harvest. From harvest to late autumn the leaf Fe content increased to ±480.3 mg. From late autumn to late winter the total increase in Fe in the tree was ±157.4 mg. This means that no Fe was lost at leaf drop. This finding disagrees with the findings of Terblanche (1972) who reported that ±19.78% Fe is lost through leaf drop. During harvest ±17.7% of the Fe content was in the fruit, ±41.3% in the permanent parts and ±19.5% in the roots. The 30% in the kiwi vine roots found by Kotzé & De Villiers (1989) was higher than the findings of the present study. During the late winter ±78.4% of the total Fe in the tree was in the permanent parts and ±21.6% in the roots.

2.2.3.4 Copper

The total increase in the Cu/tree was 39.2 mg from bud-break to early winter in the two-year-old trees (Table 4a, and Appendix, Fig. 11a and b). The Cu content of new growth increased from 0 to ±7.4 mg (±16.7% of the total Cu in the tree). The new shoots contained the highest portion of Cu of the new growth. In the tree as a whole the leaves, prunings, permanent parts and roots contributed ±6.1%, ±15.3%, ±52.8% and ±15.1%, respectively, to the total tree Cu content. The increase in tree Cu content in the first six weeks was ±3.2 mg (±8.2% of the total uptake). The increase in the Cu content from six weeks after bud-break until harvest was ±7.4 mg, therefore ±18.9% was taken up. During the post-harvest period the total uptake was ±28.6 mg (±73.0% of the total tree Cu).

The Cu content of the three-year-old apple tree is summarised in Table 4b and depicted in Appendix, Fig. 11c and d. The total increase in Cu/ tree was 34.4 mg from late winter to late autumn. No uptake of Cu was observed from late winter to mid-summer, suggesting that the reserves might have played a large role. The Cu content uptake from mid-summer to harvest was ±13.7 mg (±39.8% of pre-harvest uptake). During the post-harvest period ±20.7 mg (±60.2%) of Cu was taken up. This is in contrast to the ±73.0% of Cu that was taken up during this period in the two-year-old trees. Kotzé & De Villiers (1989) has reported that the Cu content of the kiwi vine increases continuously from bud-break until harvest. With fruit harvest, ±11.8 mg (±28.9%) of Cu was removed from the tree. At late autumn ±20.7% of the total Cu was in the leaves. From late autumn to late winter the total Cu in the tree as a whole increased by ±37.4 mg. This means that the nett loss of Cu during leaf drop was zero. This is in contradiction to the findings of Terblanche (1972) who reported that at least 2.9% of the total Cu taken up during the season was lost through leaf drop. During harvest ±28.9% of the Cu content was in the fruit, ±45.0% in the permanent parts and ±11.7% in the roots. Kotzé & De Villiers (1989) have also reported that in kiwi vines the roots contributed ±75.0% Cu, the leaves ±17.0% and the fruit ±2.0% to the total uptake of ±59.6 mg from dormancy to harvest. They found the root content to be higher than the ±11.7% found in the present study. During the late winter ±90.3% of total Cu in the tree was in the permanent parts and ±9.7% in the roots.

2.2.3.5 Zinc

The whole tree Zn content in the young two-year-old trees increased by 144.2 mg from bud-break to early winter (Table 5a, and Appendix, Fig. 12a and b). The new growth Zn content

increased from 0 to ±38.9 mg, thus contributing ±25.6% of the tree Zn content. The leaves contained the highest proportion of the new growth Zn content. The contribution of leaves, prunings, permanent parts and roots was ±14.8%, 21.3%, 36.1% and 17.0%, respectively, to the whole tree Zn content. The Zn pre-harvest uptake was 51.2 mg (35.5%) while the post-harvest uptake was 93.0 mg (64.5%). Kotzé & De Villiers (1991) reported that the rate of absorption of Zn in kiwi vines remains at a low level from before bud-break until the beginning of March, after which there is a four-fold increase until the beginning of July (after leaf drop).

The Zn uptake of the three-year-old apple tree was 86.4 mg from late winter to late autumn (Table 5b, and Appendix Fig. 12c and d). From late winter to mid-summer the tree Zn content increased by ±7.5 mg (±8.7% of total pre-harvest uptake). The increase in the Zn content from mid-summer to harvest was ±67.0 mg (±77.5%) while the post-harvest period uptake was ±11.9 mg (±13.8%). This is in contrast to the 64.5% Zn that was taken up during this period in the two-year-old trees. Kotzé & De Villiers (1989) reported that the Zn content in kiwifruit vine increases rapidly from bud-break until the beginning of January and thereafter no significant changes were observed for the rest of the growing season. In the present study ±10.0 mg Zn was removed from the tree during harvest. It was also observed that the Zn content in the leaves increased to ±34.4% from harvest to late autumn. The total tree Zn content decreased by ±63.8 mg during late autumn to late winter. This result indicates that all Zn present in the leaves was lost through leaf drop. This finding is in contradiction to the findings of Terblanche (1972) who indicated a loss of ±42.9% Zn through leaf drop. During harvest ±6.2% of the Zn content was in the fruit, ±44.8% in the permanent parts and ±14.5% in the roots. The ±6.2% Zn content of the fruit found in this study was comparable to the 4% found by Kotzé & De Villiers (1989) in kiwi fruit. At late winter ±75.1% of the total Zn in the tree was in the permanent parts and ±24.9% in the roots.

2.2.3.6 Boron

The B content in the two-year-old trees increased by 147.8 mg from bud-break to early winter (Table 6a, and Appendix, Fig. 13a and b). New growth B content increased from 0 to ±42.0 mg, which accounted for ±28.8% of the tree total B content. The contribution to B in the tree was as follows: leaves (±14.7%), prunings (±24.1%), permanent parts (±34.4%) and roots (±12.7%). The tree B content increase in the first six weeks was ±4.1 mg (±2.8%) of total B

uptake. During the period six weeks after bud-break to harvest the B uptake was ±33.8 mg (±22.9%) while ±109.9 mg (±74.4%) B was taken up during the post-harvest period.

The total increase in the B content of the three-year-old trees (Table 6b, and Appendix, Fig. 13c and d) was 174.3 mg from late winter to late autumn. No uptake of B was observed from late winter to mid-summer as B reserves were redistributed from the permanent parts to support new growth. From mid-summer to harvest ±110.9 mg (±63.6%) B was taken up in the pre-harvest period. During the post-harvest period (189.2 – 103.0 = 86.2), 149.6 – 86.2 = 63.4 mg was taken up (therefore ±36.4% B). This is lower than the ±74.4% B that was taken up during this period in the two-year-old trees. Kotze & De Villiers (1989) reported that the B content of the kiwi vine increases continuously from bud-break until the end of March. However, Terblanche (1972) reports three stages of uptake in apples: the shoot elongation period, six to nine weeks before aging of the oldest leaves, and during the leaf drop period. In the present study ±103.0 mg B was removed from the tree during harvest. Boron was found in high concentrations in the fruit, contributing to the reduction in the nutrient content after harvest. This agrees with the findings of Buwalda & Smith (1987) and Kotze & De Villiers (1989) who found that the fruit is an important sink for B. From harvest to late autumn the B content in the leaves increased to ±44.6 mg (±29.8%), while the total tree B content decreased by ±28.8 mg from late autumn to late winter. This result indicates that ±15.8 mg (±35.4%) B in the leaves was redistributed to the permanent structure. However, this redistribution is greater than the 29.8% found by Terblanche (1972). The fruit, permanent parts and roots contributed about ±54.4%, ±21.4% and ±5.5%, respectively, to the total tree B content at harvest. This is in agreement with the findings of Kotze & De Villiers (1989) who found that the B accumulation up to harvest was about 70% in new growth of kiwi vines. In the late winter ±82.2% of total B in the tree was in the permanent parts and ±17.8% in the roots. Terblanche (1972) found that during the dormant period a high content of B is found in the roots and the bark while during the active growing season the fruit and the leaves make large contributions.

2.2.3.7 Molybdenum

Analyses of Molybdenum were carried out but results were very inconsistent: some replications had concentrations ten times higher than others for some tree parts. Requirements were, however, calculated for this element.

2.2.4 Conclusions

In the 2nd leaf apple trees the Na, Mn, Fe, Cu, Zn and B accumulated rapidly from the beginning of bud-break until early winter. This accumulation in the tree accounted for ±1100.8 mg Na, ±75.0 mg Mn, ±431.3 mg Fe, ±18.8 mg Cu, ±78.6 mg Zn and ±56.9 mg B. At harvest, fruit contained respectively ±2.2% Na, ±4.3% Mn, ±2.0% Fe, ±4.8% Cu, ±2.5% Zn and ±15.1% B of the total content of each of these elements in the tree. These young trees continued taking up nutrients since they were still growing.

In the bearing 3rd leaf apple trees the Na uptake was divided into ±3.2% and ±89.1% for the period from late winter to mid-summer and mid-summer to harvest respectively, making a total of ±92.2% of pre-harvest uptake. During the post-harvest period ±7.8% was taken up. No re-distribution of Na was observed in this study from the leaves to the trees by end of leaf drop. At late winter ±57.8% was in the permanent parts while ±42.2% was found in the roots. At harvest the fruit (±20.0%), leaves (±23.8%), new shoots (±4.2%), permanent parts (±36.9%) and roots (±15.1%) contributed to the total tree Na content. Early in the season about ±37.6% Na was taken up from the soil while ±62.4% was redistributed from the reserves in the permanent parts to support new growth. Manganese content uptake in the 3rd leaf tree was ±62.4%, which it was taken up during the period from late winter to mid-summer—no uptake was noted from mid-summer to harvest. During the post-harvest period ±37.6% was taken up. Another ±25.2% Mn was redistributed from the leaves to the trees. At late winter ±78.1% was in the permanent parts while ±21.9% was found in the roots. The Mn distribution in the fruit, leaves, new shoots, permanent parts and roots was as follows: ±9.8%, ±63.9%, ±2.7%, ±18.0% and ±5.7%, respectively at harvest. At the beginning of the season about ±71.5% Mn was taken up from the soil while ±28.5% was redistributed from the reserves in the permanent parts. No uptake was observed in the 3rd leaf trees Fe content until mid-summer thereafter ±37.9% was taken up from mid-summer to harvest. During the post-harvest period ±62.1% was taken up. Results of this study showed that a ±100.0% Fe re-distribution from the leaves to the permanent parts took place. At late winter ±79.5% was in the permanent parts while ±20.5% was found in the roots. At harvest the fruit (±17.7%), leaves (±18.5%), new shoots (±2.9%), permanent parts (±41.3%) and roots (±19.5%) contributed to the total tree Fe content. All Fe in the new growth at the beginning of the season was derived from reserves since no uptake was observed.

No uptake was observed in the 3rd leaf apple trees Cu content until mid-summer but thereafter ±39.8% was taken up from mid-summer to harvest. During the post-harvest period ±60.2% was taken up. Results of this study showed a ±100.0% Cu re-distribution from the leaves to the permanent structure. At late winter ±81.5% was in the permanent parts while ±18.5% was found in the roots. The Cu content at harvest was distributed as follows: new shoots, permanent parts and roots, ±28.9% in the fruit, ±10.0% in the leaves, ±4.4% in the new shoot, ±45.0% in the permanent parts and ±11.7% in the roots. All Cu in the new growth at the beginning of the season was derived from reserves since no uptake was observed. The 3rd leaf tree Zn content uptake was divided into ±8.7% and ±77.5% for the period from late winter to mid-summer and mid-summer to harvest, respectively, making a total of ±86.2% of pre-harvest uptake. During the post-harvest period ±13.8% was taken up. No Zn re-distribution from the leaves to the permanent structure was observed by the end of leaf drop. At late winter ±76.1% was in the permanent parts while ±23.9% was found in the roots. At harvest the fruit (±6.2%), leaves (±29.1%), new shoots (5.4%), permanent parts (±44.8%) and roots (±14.5%) contributed to the total tree Zn content. Early in the season about ±13.6% Zn was taken up from the soil while ±86.4% was distributed from the reserves in the permanent parts to support new growth. The B uptake in the 3rd leaf trees was ±63.6% of which it was taken up from mid-summer to harvest, while no uptake was noted from late winter to mid-summer. During the post-harvest period ±36.4% was taken up. Another ±35.4% of leaf total B was redistributed from the leaves to the trees by end of leave drop. At late winter ±81.5% was in the permanent parts while ±18.5% was found in the roots. At harvest the distribution of B in the fruit, leaves, new shoots, permanent parts and roots was as follows: ±54.4%, ±15.4%, ±3.3%, ±21.4% and ±5.5%, respectively. At the beginning of the season all B in the new growth was redistributed from the reserves. In contrast to the findings of Terblanche (1972) and Kotze & De Villiers (1989), the roots in the present study had a low micro nutrient content in comparisons to that in the permanent parts.

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Table 1: Average sodium (Na) content in (mg) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Na (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	3.0±0.8	1.2	0.9±0.4	0.1	24.3±2.4	2.2	-	-
Leaves	-	-	14.2±0.4	5.8	57.8±5.1	8.8	27.9±3.5	2.5	119.9±4.7	9.3
New shoots	-	-	24.2± 0.1	10.0	43.5±0.7	6.6	64.8±17.6	5.9	98.4±24.3	7.6
Subtotal (new growth)	0	0	41.4±1.3	17.1	102.2±6.2	15.6	117.0±23.5	10.6	218.3±29.0	16.9
Prunings**	-	-	-	-	-	-	78.1±9.1	7.1	184.4±63.2	14.2
Permanent parts***	182.1±24.0	73.8	135.0±17.9	55.6	263.4±52.2	40.2	472.4±30.8	42.9	448.5±52.0	34.6
Roots****	64.8±13.3	26.2	66.4±6.9	27.3	289.8±13.7	44.2	433.3±24.8	39.4	443.4±112.0	34.2
Subtotal (Permanent structure)	246.9±37.3	100.0	201.4±24.8	82.9	553.2±65.9	84.4	983.8±64.7	89.4	1076.3±227.2	83.1
Total	246.9±37.3	100.0	242.8±26.1	100.0	655.4±72.1	100.0	1100.8±88.1	100.0	1294.6±256.2	100.0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Na (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	19.5±4.7	1.7	723.2±70.0	20.0	-	-	-	-
Leaves	-	-	168.2±25.4	14.7	860.0±530.6	23.8	451.2±49.9	14.4	-	-
New shoots	-	-	63.2±10.7	5.5	153.3±21.2	4.2	222.3±33.8	7.1	-	-
Subtotal (new growth)	0	0	250.9±40.8	21.9	1736.5±621.8	48.0	673.5±83.7	21.5	0	0
Prunings**	-	-	176.8±48.7	15.4	-	-	-	-	-	-
Permanent parts***	606.9±78.6	57.8	625.0±49.8	54.6	1333.9±78.4	36.9	1795.4±178.2	57.5	1320.7±120.8	75.9
Roots****	443.4±112.0	42.2	91.9±31.9	8.0	546.6±39.3	15.1	655.5±211.6	21.0	419.2 ±107.5	24.1
Subtotal (Permanent structure)	1050.3±190.6	100.0	893.7±130.4	78.1	1880.5±117.7	52.0	2450.9±389.8	78.5	1739.9±228.3	100.0
Total	1050.3±190.6	100.0	1144.6±171.2	100.0	3617.0±739.5	100.0	3124.4±473.5	100.0	1739.9±228.3	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

Table 2: Average manganese (Mn) content in (mg) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Mn (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter *	%
Fruit	-	-	0.7±0.2	2.8	0.1±0.0	0.1	3.2±0.7	4.3	-	-
Leaves	-	-	3.2±0.5	12.9	65.4±3.9	73.5	20.7±4.7	27.6	38.3±7.9	21.5
New shoots	-	-	3.1± 0.1	12.5	3.7±0.2	4.2	2.9±1.0	3.9	16.7±3.8	9.4
Subtotal (new growth)	0	0	7.0±0.8	28.2	69.2±4.1	77.8	26.8±6.4	35.7	55. 0±11.7	30.9
Prunings**	-	-	-	-	-	-	17.6±1.7	23.5	43.4±14.5	24.4
Permanent parts***	23.6±4.5	86.4	12.6±0.7	50.8	16.4±1.2	18.4	24.7±5.4	32.9	54.5±3.7	30.6
Roots****	3.7±0.2	13.6	5.2±2.7	21.0	3.4±0.3	3.8	5.9±0.2	7.9	25.3±6.5	14.2
Subtotal (Permanent structure)	27.3±4.7	100.0	17.8±3.4	71.8	19.8±1.5	22.2	48.2±7.3	64.3	123.2±24.7	69.1
Total	27.3±4.7	100.0	24.8±4.2	100.0	89.0±5.6	100.0	75.0±13.7	100.0	178.2±36.4	100 .0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Mn (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	3.0±0.3	1.2	17.4±3.1	9.8	-	-	-	-
Leaves	-	-	169.5±11.7	70.0	113.8±8.9	63.9	161.5±39.2	68.1	-	-
New shoots	-	-	4.8±0.3	2.0	4.8±0.4	2.7	10.1±2.1	4.3	-	-
Subtotal (new growth)	0	0	177.3±12.3	73.2	136.0±12.4	76.3	171.6±41.3	72.3	0	0
Prunings**	-	-	27.1±4.4	11.2	-	-	-	-	-	-
Permanent parts***	90.3±11.4	78.1	36.7±6.0	15.1	32.0±5.8	18.0	55.0±10.2	23.2	97.9±11.2	84.1
Roots****	25.3±6.5	21.9	1.2±0.4	0.5	10.2±0.7	5.7	10.6±0.7	4.5	18.5±4.4	15.9
Subtotal (Permanent structure)	115.6±17.9	100.0	65.0±10.8	26.8	42.2±6.5	23.7	65.6±10.9	27.7	116.4±15.6	100.0
Total	115.6±17.9	100.0	242.3±23.1	100.0	178.2±18.9	100.0	237.2±52.2	100.0	116.4±15.6	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

Table 3: Average iron (Fe) content in (mg) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Fe (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	2.3±0.6	1.0	1.1±0.2	0.5	8.6±1.3	2.0	-	-
Leaves	-	-	9.8±1.1	4.5	37.2±2.0	16.8	49.1±8.1	11.4	108.2±14.2	7.1
New shoots	-	-	10.1± 0.8	4.6	18.2±2.3	8.2	15.7±3.0	3.6	133.7±37.4	8.7
Subtotal (new growth)	0	0	22.2±2.5	10.1	56.5±4.5	25.5	73.4±12.4	17.0	241.9±51.6	15.8
Prunings**	-	-	-	-	-	-	73.4±12.0	17.0	215.2±89.0	14.0
Permanent parts***	198.7±37.2	77.3	142.2±33.7	64.9	102.2±10.0	46.2	206.9±15.1	48.0	816.2±83.4	53.3
Roots****	58.2±2.5	22.7	54.8±10.9	25.0	62.6±4.5	28.3	77.6±10.9	18.0	258.6±77.5	16.9
Subtotal (Permanent structure)	256.9±39.7	100.0	197.0±44.6	89.9	164.8±14.5	74.5	357.9±38.0	83.0	1290.0±249.9	84.2
Total	256.9±39.7	100.0	219.2±47.1	100.0	221.3±19.0	100.0	431.3±50.4	100.0	1531.9±301.5	100 .0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Fe (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	19.0±2.6	2.1	210.3±29.2	17.7	-	-	-	-
Leaves	-	-	254.2±51.5	28.4	219.1±28.0	18.5	480.3±17.8	30.0	-	-
New shoots	-	-	25.7±3.6	2.9	34.9±4.3	2.9	44.8±9.6	2.8	-	-
Subtotal (new growth)	0	0	298.9±57.7	33.4	464.3±61.5	39.1	525.1±27.4	32.8	0	0
Prunings**	-	-	89.0±20.2	10.0	-	-	-	-	-	-
Permanent parts***	1004.0±127.9	79.5	456.5±9.7	51.0	490.8±68.3	41.3	825.6±109.8	51.5	1380.2±212.1	78.4
Roots****	258.6±77.5	20.5	49.9±17.0	5.6	232.0±21.6	19.5	252.5±103.4	15.7	380.4±134.0	21.6
Subtotal (Permanent structure)	1262.6±205.4	100.0	595.4±46.9	66.6	722.8±89.9	60.9	1078.1±213.2	67.2	1760.6±346.1	100.0
Total	1262.6±205.4	100.0	894.3±104.6	100.0	1187.1±151.4	100.0	1603.2±240.6	100.0	1760.6±346.1	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

Table 4: Average copper (Cu) content in (mg) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Cu (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.5±0.1	3.1	0.0±0.0	0.0	0.9±0.1	4.8	-	-
Leaves	-	-	1.9±0.2	11.8	3.2±0.2	28.1	1.3±0.3	6.9	2.7±0.5	6.1
New shoots	-	-	0.7±0.0	4.3	0.9±0.1	7.9	0.8±0.3	4.3	4.7±1.1	10.6
Subtotal (new growth)	0	0	3.1±0.3	19.2	4.1±0.3	36.0	3.0±0.7	16.0	7.4±1.6	16.7
Prunings**	-	-	-	-	-	-	2.2±0.3	11.7	6.8±2.4	15.3
Permanent parts***	11.6±0.9	89.9	9.8±0.7	60.9	5.9±0.2	51.8	11.2±0.5	59.6	23.4±0.8	52.8
Roots****	1.3 ±0.1	10.1	3.2±1.4	19.9	1.4±0.2	12.3	2.4±0.1	12.8	6.7±2.0	15.1
Subtotal (Permanent structure)	12.9±1.0	100.0	13.0±2.1	80.8	7.3±0.4	64.0	15.8±0.9	84.0	36.9±5.2	83.3
Total	12.9±1.0	100.0	16.1±2.4	100.0	11.4±0.7	100.0	18.8±1.6	100.0	44.3±6.8	100 .0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Cu (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	1.2±0.2	3.8	11.8±0.6	28.9	-	-	-	-
Leaves	-	-	9.5±0.4	30.2	4.1±0.6	10.0	10.3±0.6	20.7	-	-
New shoots	-	-	1.6±0.3	5.1	1.8±0.2	4.4	3.7±1.1	7.4	-	-
Subtotal (new growth)	0	0	12.3±0.9	39.0	17.7±1.4	43.3	14.0±1.7	28.1	0	0
Prunings**	-	-	4.3±1.0	13.7	-	-	-	-	-	-
Permanent parts***	29.5±2.1	81.5	14.1±2.0	44.8	18.4±4.5	45.0	28.5±1.1	57.2	78.7±2.1	90.3
Roots****	6.7±2.0	18.5	0.8±0.3	2.5	4.8±1.2	11.7	7.3±0.6	14.7	8.5 ±2.0	9.7
Subtotal (Permanent structure)	36.2±4.1	100.0	19.2±3.3	61.0	23.2±5.7	56.7	35.8±1.7	71.9	87.2±4.1	100.0
Total	36.2±4.1	100.0	31.5±4.2	100.0	40.9±7.1	100.0	49.8±3.4	100.0	87.2±4.1	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

Table 5: Average zinc (Zn) content in (mg) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average Zn (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	0.7±0.2	2.4	0.1±0.0	0.2	2.0±0.4	2.5	-	-
Leaves	-	-	2.1±0.3	7.1	30.5±2.0	51.3	17.9±3.4	22.8	22.5±4.3	14.8
New shoots	-	-	3.0±0.3	10.1	5.5±0.3	9.2	4.6±1.1	5.9	16.4±3.1	10.8
Subtotal (new growth)	0	0	5.8±0.8	19.5	36.1±2.3	60.7	24.5±4.9	31.2	38.9±7.5	25.6
Prunings**	-	-	-	-	-	-	17.6±1.5	22.4	32.4±11.0	21.3
Permanent parts***	22.7±1.8	82.8	14.2±1.5	47.8	9.6±1.4	32.9	31.3±6.5	39.8	54.8±6.2	36.1
Roots****	4.7±0.2	17.2	9.7±4.0	32.7	3.8±0.4	6.4	5.2±0.3	6.6	25.9±9.1	17.0
Subtotal (Permanent structure)	27.4±2.0	100.0	23.9±5.5	80.5	23.4±1.8	39.3	54.1±8.3	68.8	113.1±26.4	74.4
Total	27.4±2.0	100.0	29.7±6.3	100.0	59.5±4.1	100.0	78.6±13.2	100.0	152.0±33.8	100 .0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average Zn (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	1.9±0.2	1.6	10.0±2.3	6.2	-	-	-	-
Leaves	-	-	46.6±4.0	40.2	46.6±5.6	29.1	55.8±8.5	34.4	-	-
New shoots	-	-	6.7±0.3	5.8	8.7±0.9	5.4	14.1±2.7	8.7	-	-
Subtotal (new growth)	0	0	55.2±4.5	47.7	65.3±8.8	40.7	69.9±11.2	43.1	0	0
Prunings**	-	-	22.6±3.8	19.5	-	-	-	-	-	-
Permanent parts***	82.4±11.5	76.1	35.0±5.5	30.2	71.7±14.2	44.8	67.4±14.6	41.6	73.8±3.6	75.1
Roots****	25.9±9.1	23.9	3.0±0.8	2.6	23.2±1.4	14.5	24.8±4.2	15.3	24.5±3.5	24.9
Subtotal (Permanent structure)	108.3±20.6	100.0	60.6±10.1	52.3	94.9±15.6	59.3	92.2±18.8	56.9	98.3±7.1	100.0
Total	108.3±20.6	100.0	115.8±14.6	100.0	160.2±24.4	100.0	162.1±30.0	100.0	98.3±7.1	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

Table 6: Average boron (B) content in (mg) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf trees

a)

Tree parts	Average B (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud-break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter*	%
Fruit	-	-	1.3±0.4	5.6	0.4±0.1	1.0	8.6±0.4	15.1	-	-
Leaves	-	-	5.2±0.4	22.5	14.4±0.5	37.6	6.7±0.8	11.8	21.4±2.4	14.7
New shoots	-	-	2.4± 0.1	10.4	3.8±0.0	9.9	4.2±1.5	7.4	20.6±2.1	14.1
Subtotal (new growth)	0	0	8.9±0.9	38.5	18.6±0.6	48.6	19.5±2.7	34.3	42.0±4.5	28.8
Prunings**	-	-	-	-	-	-	12.5±2.2	22.0	35.1±10.1	24.1
Permanent parts***	16.0±0.8	84.2	10.9±0.6	47.2	14.4±1.7	37.6	19.9±3.2	35.0	50.1±4.8	34.4
Roots****	3.0±0.2	15.8	3.3±0.7	14.3	5.3±0.4	13.8	5.0±0.1	8.8	18.5±4.8	12.7
Subtotal (Permanent structure)	19.0±1.0	100.0	14.2±1.3	61.5	19.7±2.1	51.4	37.4±5.5	65.7	103.7±19.6	71.2
Total	19.0±1.0	100.0	23.1±2.2	100.0	38.3±2.7	100.0	56.9±8.2	100.0	145.7±24.1	100 .0

* Early winter (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

b)

Tree parts	Average B (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn*	%	Late winter	%
Fruit	-	-	7.7±0.7	8.3	103.0±3.4	54.4	-	-	-	-
Leaves	-	-	31.6±3.3	33.9	29.2±2.0	15.4	44.6±2.3	29.8	-	-
New shoots	-	-	5.0±0.6	5.4	6.2±0.7	3.3	13.1±2.0	8.8	-	-
Subtotal (new growth)	0	0	44.3±4.6	47.6	138.4±6.1	73.1	57.7±4.3	38.6	0	0
Prunings**	-	-	14.8±2.8	15.9	-	-	-	-	-	-
Permanent parts***	81.4±11.7	81.5	30.7±2.4	33.0	40.4±5.6	21.4	75.6±9.3	50.5	99.3±2.6	82.2
Roots****	18.5±4.8	18.5	3.3±1.3	3.5	10.4±1.3	5.5	16.3±3.8	10.9	21.5±5.8	17.8
Subtotal (Permanent structure)	99.9±16.5	100.0	48.8±6.5	52.4	50.8±6.9	26.9	91.9±13.1	61.4	120.8±8.4	100.0
Total	99.9±16.5	100.0	93.1±11.1	100.0	189.2±13.0	100.0	149.6±17.4	100.0	120.8±8.4	100.0

* Late autumn (before any natural leaf drop)
** includes pruning shoots as well as leaves
*** Permanent parts includes trunk, canopy branches and rootstock
**** Roots includes primary and secondary roots

2.3 Guidelines for macro element requirements of young and bearing apple trees

Abstract

Accurate water and nutrient management are essential to enable the manipulation of reproductive and vegetative development as well as fruit quality. Little information exists on this topic in higher-density apple orchards in their second to third year under fertigation drip irrigation. Brookfield Gala apple trees on M793 planted at 4 x 1.25 m and trained to a central leader system using the solaxe principle were excavated at various stages over two seasons. These trees were divided into different tree parts: roots, leaves, fruit, rootstock, new shoots, trunk and canopy branches. The macro nutrients N, P, K, Ca, Mg and S were analysed. The requirements for 2nd leaf apple trees that are still growing and must fill their allocated space are presented in grams per tree (g tree^{-1}). Annual requirements of the 3rd leaf trees at a commercial bearing stage (45.2 t/ha) were determined by calculating losses and fixture. Guideline minimum and maximum nutritional requirements based on the amount necessary to produce 1 kg fruit were determined.

Keywords: nutrient management, nutrient solutions, leaf nutrient remobilisation, nutrient losses

2.3.1 Introduction

Accurate water and nutrient fertilizer management are essential to enable the manipulation of reproductive and vegetative development as well as fruit quality in deciduous fruit trees (Tagliavini & Marangoni, 2000). Therefore it is very important to know the trees' mineral requirements and at what phenological stage a certain element is taken up in order to supply nutrients to the soil at the right time to benefit the physiological processes taking place in the tree. Nitrogen is the most critical of all the nutrients and it must be managed carefully because it determines the balance between the reproductive and vegetative growth. If it is applied at wrong times it may influence phenological and physiological plant processes (Stassen *et al.,* 1981b; Faust, 1989). Nutrient requirement determination in apple trees is not easy since numerous factors are involved, such as fixture in the permanent parts, leaf loss, fruit loss and losses through pruning (Neilsen & Neilsen, 2003). One method of determining tree nutrient requirement is to base it on whole tree mineral analysis (Weinbaum *et al.,* 2001). Several studies have been conducted on the determination of nutrient requirement by different fruit trees (Batjer *et al.,* 1952 for apple trees; Haynes & Goh, 1980 for apple trees; Stassen, 1987 for peach, and Stassen & North, 2005 for pear). This method takes into account mineral nutrient losses that arise from removal of fruit and pruned wood from the orchard, part of the dropped leaf content and nutrients fixed in permanent parts of the tree (older wood and roots) (Stassen, 1987; Stassen & North, 2005).

Terblanche (1972) and Stassen (1987) report that N, P and K are translocated back from the leaves to the permanent parts before the end of leaf drop but Ca and Mg do not move back; Ca and Mg move from the permanent parts to the leaves and are lost at leaf drop. However, in Section 2.1 it was determined that only Ca is not redistributed to the permanent parts, and ±34.7% of Mg was redistributed before end of leaf drop. Nutrient loss from leaf drop is regarded as temporary since the leaves decompose and are mineralised if not blown away by the wind or a blower (Stassen, 1987). In medium to high potential soils where mulches are used and nutrients supplied through fertigation and hydroponics there is no need to compensate for leaf loss (Stassen, 1987). In low potential soils, however, with no mulches and where the fertiliser is applied manually, it is very important to consider loss by the leaves to compensate for leaching and inefficiency of placement (50% of all minerals except Ca and Mg at 100%) (Stassen & North, 2005). The minimum requirement can be used under medium

to high potential soil conditions with mulches and where fertiliser is applied through the water to the root zone (Stassen *et al.,* 1999).

The objective of this study is to determine the macro nutrient requirements for young and bearing apple trees in a commercial high-density orchard under drip fertigation.

2.3.2 Material and methods

2.3.2.1 Orchard cultural practices

'Brookfield Gala' apple trees on M 793 rootstock were planted in July 2003 on a well drained, well aerated Dundee (Macvicar *et al*., 1977), loamy sand soil in the Greyton area near Genadendal in the Western Cape Province. The area is situated at 34º03' S, 19º37' E, and 33 m above sea level. Granny Smith trees were planted as cross pollinators. The trees were fertigated daily with two Netafim 2.3 l.h^{-1} pressure compensated emitters per tree, spaced at 60 cm on either side of the trunk. Water and nutrient requirements were provided to meet daily requirements, as described previously (Section 2.1).

The single-tree plots were replicated three times in a randomised complete block design. Trees received from the nursery were cut back to 1.2 m height for uniformity among all trees. The trees were planted at a spacing of 4 m x 1.25 m, like the rest of the orchard, and trained as a central leader spindle with secondary branches bent according to the solax principle (Lauri & Lespinasse, 2000). The water and nutrient management, plant sampling and the milling of samples were previously described (Section 2.1)

2.3.2.2 Analysis of samples

Mineral analysis was done as previously discussed in Section 2.1. The data received from the laboratory, i.e. percentage. (see Section 2.1) were then converted to the actual macro element content in grams for each tree part based on the dry mass of that part. Three trees were taken out at specific phenological stages of which the average tree part was used in all calculations. The permanent parts include canopy branches, rootstock, trunk and roots. The 2nd leaf permanent part fixture was determined by dividing the total nutrients content over the year by the age of the tree. The 3rd leaf tree permanent part fixture was determined by subtracting the 2nd leaf tree permanent part content from the 3rd leaf tree permanent part nutrient content. The value at harvest was used, before reserves were built up during the post-harvest period.

2.3.3 Results and discussion

2.3.3.1 Nutrient requirements

The elements N, P, K and S have been shown to migrate back to the permanent tree parts just before leaf drop (Terblanche, 1972; Conradie, 1981; Stassen *et al.*, 1981a; Stassen, 1987). Similar data are reported in Section 2.1. Terblanche (1972), Stassen *et al.* (1981a) and Conradie (1981) found that Ca and Mg are not remobilised to the permanent parts but rather all nutrients present in the leaves are lost at leaf drop. However, the results in Section 2.1 indicate that only Ca is not remobilised to the permanent parts while about 34.7% Mg is remobilised. For this study we accepted a 100% loss of Ca and Mg from the leaves during leaf drop for the 2nd leaf apple trees. For the N, P, K and S it was assumed that approximately 50% migrates back into the tree before leaf drop. In Section 2.1 it was determined that N, P, K, Mg and S are redistributed to the permanent parts just before the end of leaf drop, however in lower quantities than previously reported, except for N. Therefore for the 3rd leaf trees the actual losses through leaf drop obtained in Section 2.1 were used for the nutrient requirements calculations.

Maximum loss was calculated by adding the amount of nutrient in the fruit and permanent parts at harvest, summer and winter prunings as well as leaves at early winter. Minimum loss excluded the losses due to leaf drop and prunings. Table 1 a–f illustrates how the calculation was done. Only maximum loss per tree was determined for the 2nd leaf trees because only a few fruit were harvested, accounting for an average of 1.01 kg yield/tree. However maximum and minimum nutrient requirements for the 3rd leaf 'Brookfield Gala' apple trees were calculated for each element based on the average yield of 22.6 kg fruit per tree. For the 2nd leaf trees the maximum nutrient losses per tree of N, P, K, Ca, Mg and S were ±34.5 g, ±3.7 g, ±23.8 g, ±23.9 g, ±5.8 g and ±1.8 g, respectively (Table 1). For the 3rd leaf trees the minimum nutrient requirements (g. kg^{-1} yield) of N, P, K, Ca, Mg and S were ±1.7, ±0.3, ±2.3, ±0.5, ±0.2 and ±0.2, respectively. The maximum nutrient requirements (g. kg^{-1} yield) for N, P, K, Ca, Mg and S were ±2.6, ±0.4, ±3.3, ±1.9, ±0.4 and ±0.2, respectively (Table 1). The total nitrogen requirement of apple trees is high compared to other nutrients. The total nitrogen content of apple trees shows some variation, ranging from 2 g per tree at planting for high-density apple plantings of trees on dwarf rootstock up to 890 g per tree for standard 30-year-old trees (Batjer *et al.*, 1952; Neilsen & Neilsen, 2003). Greenham (1980) and Haynes & Goh (1980) reported that about 25–26 kg nitrogen is removed annually in fruit and prunings

per hactor in 14–21 year old mature trees. Furthermore, when the fixture in permanent parts is included, the annual removal was estimated as 33 kg ha^{-1} from 9–12-year-old Cox's Orange Pippin/M7 (Greenham, 1980) and 52 kg ha^{-1} from 30-year-old Delicious apple trees (Batjer *et al.*, 1952). Batjer *et al.* (1952) found a 2.7 g.kg^{-1} nitrogen requirement in 30 year-old Delicious apple trees while Haynes & Goh (1980) found 1.3 g. kg^{-1} in 14-year-old Golden Delicious apple trees. These finding are similar to the findings of the present study. Furthermore, Neilsen & Neilsen (2003) estimated an N requirement of 2.8 g at end of year one while they estimated a requirement of 10.5 g for end of year three only based on nitrogen removed in fruit and senescent leaves in dwarf apple trees. The two-year estimation requirements compares well to the 1.7 g. kg^{-1} (min); 2.6 g. kg^{-1} (max); obtained in the present study for the 3rd leaf trees. The present study N requirements for the 3rd leaf trees were also similar to the findings of Stassen & North (2005) who found 1.5 g. kg^{-1} (min); 2.3 g. kg^{-1} (max) in the nine-year-old Forelle pear trees on Quince A rootstock.

The P needed to produce 1 kg fruit in the three-year-old trees was found to be between 0.3 g.kg^{-1} and 0.4 g.kg^{-1}. This finding compares well to the 0.4 g.kg^{-1} found by Batjer *et al.* (1952), although it was higher than the 0.2 g.kg^{-1} found by Haynes & Goh (1980). Furthermore, findings of the present study findings were similar to the 0.3 g.kg^{-1} (Quince A) but lower than the 0.5 g.kg^{-1} or 0.6 g.kg^{-1} (BP1) found by Stassen & North (2005). The K requirements of apple trees are similar in magnitude to the N requirements, with leaf concentration second to nitrogen and fruit concentration higher than all other elements (Neilsen & Neilsen, 2003). Similar observations were made in the current study. Terblanche (1972), Conradie (1981), Batjer *et al.* (1952), Haynes & Goh (1980) and Neilsen & Neilsen (2003) found that fleshy fruits are high in K. This is because the fruit is a strong sink for K, and K is mobile within the phloem. Batjer *et al.* (1952) and Haynes & Goh (1980) found the K requirements for apple trees to be 3.2 g.kg^{-1} and 2.2 g.kg,$^{-1}$, respectively. The same requirements determinations were found in the present study. The minimum K requirement to produce 1 kg fruit in the present study was similar to the maximum requirements obtained by Stassen & North (2005), while the maximum requirements were higher.

The annual calcium requirement to produce 1 kg fruit in the 3-year-old tree was found to be between 0.5 g.kg^{-1} to 1.9 g.kg^{-1}, which is lower than the requirement found by Stassen & North (2005) of 1.6 g.kg^{-1} or 3.0 g.kg^{-1} (Quince A) and 1.75 g.kg^{-1}, 3.61 g.kg^{-1} (BP1). The calcium requirement of 3.7 g.kg^{-1} found by Batjer *et al.* (1952) was higher than that found in

the present study. However, it was similar to the findings of Haynes & Goh (1980) of 1.8 g. kg^{-1}. Many researchers have found that the fruit contains low amounts of calcium due to the restricted phloem loading (Batjer *et al.*, 1952; Haynes & Goh, 1980; Jackson, 2003; Neilsen & Neilsen, 2003; Tromp, 2005). The fruit relies on phloem supply and often experience difficulties obtaining sufficient amounts of Ca (Neilsen & Neilsen, 2003). Results presented Section 2.1 are in accordance with these findings. However, the bark of the tree is reported to be an important source of Ca (Terblanche, 1972; Conradie, 1981; Stassen *et al.*, 1981a).

Haynes & Goh (1980) found the Mg requirements of apple trees to be 0.2 g.kg^{-1}, which compared well with the present findings. The Mg requirement of the 30-year-old trees was 0.6 g.kg^{-1}, which is similar to the BP1 findings of Stassen & North (2005). However, the Quince A finding of 0.4 g.kg^{-1} was comparable to the 0.4 g. kg^{-1} found in the present study. Furthermore, the S requirement found by Haynes & Goh (1980) was 0.2 g.kg^{-1}, which again is similar to the findings of the present study.

2.3.4 Conclusions

The basic nutrient requirements of 'Brookfield Gala' apple trees may be calculated using these results, especially in compiling nutrient mixtures for fertigation and hydroponic systems. Under medium to high potential soil conditions, where mulches and fertigation are used, the minimum nutrient requirements may be used (Stassen & North, 2005). For the 3rd leaf apple trees the minimum nutrient requirement (g.kg^{-1} yield) for N, P, K, Ca, Mg and S are respectively ±1.7, ±0.3, ±2.3, ±0.5, ±0.2 and ±0.2. The maximum requirements must be used in low potential soils where fertilizers are distributed manually to compensate for leaching and inefficiency of placement (Stassen *et al.,* 1999). There are, however, some conditions that need to be considered when applying the above recommendations, such as fertilisers applied during soil preparation and the results of soil and leaf analysis (Faust 1989; Stassen *et al.,* 1999). Soil and leaf analysis can be used as a tool to adjust the nutrients to be applied (Faust 1989; Stassen *et al.*, 1999).

The nutrient loss of the 2nd leaf apple trees through pruning was higher than the loss in the 3rd leaf trees due to more vigorous growth that was stimulated by high nitrogen levels required to fill their allocated space. The nutrient requirements of the 30-year-old trees planted at a spacing of 124 trees ha^{-1} as proposed by Batjer *et al.* (1952) were similar to the maximum

requirements emerging from the present study, or sometimes higher. While the 14-year-old trees planted at a spacing of 500 trees ha^{-1} requirements determinations by Haynes & Goh (1980) were falling in the same categories as the minimum requirement obtained in this study.

Furthermore, the rootstock also plays a role in the nutrient requirements. The nutrient requirements of a dwarfing rootstock were lower than the vigorous rootstock nutrient requirements (Stassen & North, 2005). The nutrient requirement determinations in the BPI proposed by Stassen & North (2005) were higher than those found in the present study, while those of Quince A were comparable to those found in the current study where M793 rootstock was used.

The commercial recommendation for the apple industry for two-year-old trees is 17 g N/tree/month (Kotzé, 2001). Over a period of six months (Sept–Feb) that is equivalent to a requirement of 102 g/tree/year. According to this study a two-year-old tree requires 34.5 g/tree. Furthermore, Kotzé (2001) recommends that a two-year-old apple tree should receive 90 g K/tree/year. The current study showed that the need for K is 23.8 g/tree/year. Industry recommends that apple trees bearing 45 t/ha, and growing normally, should be fertilised with 110 kg N/ha (Kotzé, 2001). According to this study the annual requirement of apple trees bearing 45 t/ha is between 79.0 kg N/ha minimum and 115kg N/ha maximum. Neilsen *et al.* (2001) recommended that 4-year-old Elstar (33000 trees/ha) requires 65.0 kg N/ha and Batjer *et al.* (1952) showed that 30-year-old Delicious (124 trees/ha) bearing 44.8 t/ha needs 110.5 N kg/ha. It is clear that higher-density apple trees under intensive cultural conditions need less kg N/ha. The minimum recommendation reported in this study of 79.0 kg N/ha is lower than the general industry recommendation but similar to that of 65 kg N/ha for high-density apple orchards.

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Table 1: Macro nutrient requirements in grams (g) for 2nd leaf tree, based on g/tree, and 3rd leaf, based on 22.6 kg fruit. tree^{-1} or 45.2 t.ha^{-1} of: a) Nitrogen, b) Phosphorus, c) Potassium, d) Calcium, e) Magnesium, f) Sulphur

a)

Nitrogen (N) (g)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	1.3±0.2	20.2±2.6
2. Leaves	5.0±0.9	11.3±0.1
3. Prunings	21.0±5.9	6.9±1.4
B. Fixed		
4. Permanent parts*	7.2±0.7**	19.3±6.0***
Total A + B (max loss) (g)	34.5±7.7	57.7±10.1
1 + 4 (min loss) (g)		39.5±8.6
Max. loss g.kg^{-1}****		2.6
Min. loss g.kg^{-1}****		1.7

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf from 3rd leaf tree permanent parts content
**** g/kg fruit harvested per tree

b)

Phosphorus (P) (g)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	0.2±0.0	3.3±0.1
2. Leaves	0.4±0.0	2.0±0.1
3. Prunings	2.0±0.5	1.1±0.2
B. Fixed		
4. Permanent parts*	1.1±0.1**	3.7±1.1***
Total A+B (max loss) (g)	3.7±0.6	10.1±1.5
1 + 4 (min loss) (g)		7.0±1.2
Max. loss g.kg^{-1}****		0.4
Min. loss g.kg^{-1}****		0.3

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf from 3rd leaf tree permanent parts content
**** g/kg fruit harvested per tree

c)

Potassium (K) (g)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	2.3±0.2	44.1±2.1
2. Leaves	3.9±0.5	20.0±1.2
3. Prunings	13.7±3.3	3.6±0.7
B. Fixed		
4. Permanent parts*	3.9±0.5**	7.4±2.5***
Total A + B (max loss) (g)	23.8±4.5	75.1±6.5
1 + 4 (min loss) (g)		51.5±4.6
Max. loss g.kg^{-1}****		3.3
Min. loss g.kg^{-1}****		2.3

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf from 3rd leaf tree permanent parts content
**** g/kg fruit harvested per tree

d)

Calcium (Ca) (g)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	0.2±0.0	1.0±0.2
2. Leaves	5.4±1.0	24.1±2.2
3. Prunings	12.8±3.6	7.1±1.9
B. Fixed		
4. Permanent parts*	5.5±1.0**	10.9±3.3***
Total A + B (max loss) (g)	23.9±5.6	43.1±7.6
1 + 4 (min loss) (g)		11.9±3.5
Max. loss g.kg^{-1}****		1.9
Min. loss g.kg^{-1}****		0.5

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf from 3rd leaf tree permanent parts content
**** g/kg fruit harvested per tree

e)

Magnesium (Mg) (g)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	0.1±0.0	2.0±0.2
2. Leaves	1.5±03	3.2±0.5
3. Prunings	3.3±1.0	1.2±0.2
B. Fixed		
4. Permanent parts*	0.9±0.1**	1.7±0.6***
Total A + B (max loss) (g)	5.8±1.4	8.1±1.5
1+4 (min loss) (g)		3.7±0.8
Max. loss g.kg^{-1}****		0.4
Min. loss g.kg^{-1}*****		0.2

*Permanent parts include roots, rootstock, trunk and canopy branches
**2nd leaf permanent parts total per tree are divided by tree age
***3rd leaf permanent parts are obtained by subtracting 2nd leaf from 3rd leaf tree permanent parts content
****g/kg fruit harvested per tree

f)

Sulphur (S) (g)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	0.1±0.0	1.4±0.2
2. Leaves	0.2±0.0	0.5±0.1
3. Prunings	1.0±0.3	0.4±0.1
B. Fixed		
4. Permanent parts*	0.5±0.0**	2.2±0.2***
Total A + B (max loss) (g)	1.8±0.3	4.5±0.6
1 + 4 (min loss) (g)		3.6±0.4
Max. loss g.kg^{-1}****		0.2
Min. loss g.kg^{-1}****		0.2

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf from 3rd leaf tree permanent parts content
**** g/kg fruit harvested per tree

2.4 Guidelines for micro element requirements of young and bearing apple trees

Abstract

The correct nutrient balance and the correct amount of nutrients at a specific phenological stage are important to optimise plant processes. Furthermore, there are disadvantages involved in both the under and over application of nutrients, to the trees as well as to the environment. This situation forces us to manage nutrient application in close association with the requirement of the tree. This information can be used to prepare specific nutrient solutions for certain development stages of apple trees. 'Brookfield Gala' apple trees on M793 planted at 4 x 1.25 m and trained to a central leader system using the solaxe principle were excavated at various stages over two seasons. These trees were divided into different tree parts: roots, leaves, fruit, rootstock, new shoots, trunk and canopy branches, and analysed for micro nutrients (Na, Mn, Fe, Cu, Zn, B and Mo). Nutrient losses and fixture per tree were determined for the 2nd leaf apple trees. Annual requirements of the 3rd leaf tree at a commercial bearing stage (45.2 t/ha) were determined by calculating losses from the tree and fixture within the framework. Guideline minimum and maximum nutritional requirements based on yield were determined.

Keywords: nutrient management, nutrient solutions, leaf nutrient remobilisation, nutrient losses

2.4.1 Introduction

For optimal yield and fruit quality the micro nutrient requirements of the tree should be determined and must be adhered to in order to avoid deficiencies and toxicity, and to improve the storage quality of fruit (Shear & Faust, 1980; Mengel & Kirkby, 1982; Marschner, 1993). The majority of micro nutrients are phloem immobile and most deficiency symptoms appear on new leaves, near the shoot tips (Neilsen & Neilsen, 2003). Although the role of micro nutrients in fruit nutrition is small the importance in cell division, fruit set and fruit quality cannot be ignored (Brown & Hu, 1996). Micro elements are needed in concentrations equal to or less than 100 mg.kg^{-1} of dry matter (Salisbury & Ross, 1992). They are nevertheless essential to fruit growth for the following reasons: a deficiency of the element makes it impossible for the plant to complete its life cycle, the deficiency must be specific for the element in question and the element must be directly involved in the nutrition of the plant (Arnon & Stout, 1939). Furthermore, since the requirements for micro nutrients are so low they can be rectified by foliar sprays when needed by the apple tree.

Apart from a study by Stassen & North (2005) on pears, few studies have been conducted to determine the micro nutrient requirements. The objective of this study is to determine the micro nutrient requirements of young and bearing apple trees in a high-density commercial orchard under drip fertigation.

2.4.2 Material and methods

2.4.2.1 Orchard cultural practices

'Brookfield Gala' apple trees on M 793 rootstock were planted in July 2003 on a well-drained, well-aerated Dundee, loamy sand soil (Macvicar *et al*., 1977) in the Greyton area near Genadendal in the Western Cape Province. The area is situated 34º03' S, 19º37' E, and 33m above sea level. 'Granny Smith' trees were planted as cross pollinators. Water and nutrient requirements were calculated to meet daily requirements, as described previously (Section 2.1).

The single-tree plots were replicated three times in a randomised complete block design. Trees received from the nursery were cut back to 1.2 m height for uniformity among all trees. The trees were planted at a spacing of 4 m x 1.25 m, as the rest of the orchard, and trained as a central leader spindle with secondary branches bent according to the solaxe principle (Lauri &

Lespinasse, 2000). The water and nutrient management, plant sampling and the milling of samples were as discussed previously (Section 2.1)

2.4.2.2 Analysis of samples

Mineral analysis was done as previously discussed (Section 2.2). The data received from the laboratory (mg.kg^{-1} except Mo, µg.kg^{-1}), were then converted to the actual micro element content in milligrams for each tree part based on the dry mass of that part. Three trees were taken out at a specific excavation date, and the average of the tree part was used in all calculations. The permanent parts included the canopy branches, rootstock, trunk and roots. The 2nd leaf permanent part fixture was determined by dividing the total nutrients over the year by the age of the tree. The 3rd leaf tree permanent part fixture was determined by subtracting the 2nd leaf tree permanent part content from the 3rd leaf tree permanent part nutrient content. The nutrient value at harvest was used, before reserves were built up during the post-harvest period.

2.4.3 Results and discussion

2.4.3.1 Nutrient requirements

Cu, B and Mo have been shown to migrate back to the permanent tree parts just before leaf fall but Mn, Zn and Fe do not migrate to any significant extent (Terblanche, 1972). For this study we accepted a 100% loss of Mn, Zn, Fe and Na from the leaves during leaf drop for the 2nd leaf apple trees. For Cu, B and Mo it was assumed that approximately 50% migrate back into the tree before leaf drop. The findings in Section 2.2 revealed that the micro nutrients Mn, Fe, Cu, B and Mo are redistributed to the permanent parts just before the end of leaf drop. Therefore for the 3rd leaf trees the actual losses by leaf drop obtained in Section 2.2 were used for the calculations. Maximum loss was calculated by adding the amount of nutrients in the fruit and permanent parts at harvest, the winter and summer prunings, as well as the leaf content at early winter. Minimum loss excluded the losses due to leaf drop and prunings. Table 1 a–g illustrates how the calculations were done. Only maximum loss per tree was determined for the 2nd leaf trees because these trees still had to increase in volume to fill the space allocated to them. However, maximum and minimum nutrient requirements for the 3rd leaf 'Brookfield Gala' apple trees were calculated for each element based on the average yield of 22.6 kg fruit per tree. For the 2nd leaf trees the maximum nutrient loss per tree of Na, Mn, Fe, Cu, Zn, B and Mo was ±859.6 mg, ±117.8 mg, ±541.3 mg, ±18.1 mg, ±92.8 mg, ±79.4 mg and ±2.2 mg, respectively (Table 1). For the 3rd leaf trees the minimum

nutrient requirements (mg.kg^{-1} yield) of Na, Mn, Fe, Cu, Zn, B and Mo were ±75.1, ±1.3, ±28.7, ±0.9, ±3.0, ±5.7 and ±0.3, respectively. The maximum nutrient requirements (mg.kg^{-1} yield) of Na, Mn, Fe, Cu, Zn, B and Mo were ±102.9, ±7.8, ±32.6, ±1.1, ±6.5, ±7.6 and ±0.3, respectively (Table 1).

The 3rd leaf tree B requirements of 5.7 mg.kg^{-1} (min) and 7.6 mg.kg^{-1} (max) found in the present study were comparable to the B requirement findings by Stassen & North (2005) of 5.8 mg.kg^{-1} (min) and 7.0 mg.kg^{-1} (max) in the 9-year-old 'Forelle' on Quince A pear trees. The micro nutrients requirements of Mn, Fe, Cu and Zn in the present study were lower than the results found by Stassen & North (2005) in the Quince A and the BP1 pear trees.

2.4.4 Conclusion

In the present study Na, Fe and B were found in high concentrations in the fruit. This agrees with the findings of Buwalda & Smith (1987) and Kotze & De Villiers (1989), who found that the fruit is an important sink for B. High concentrations of Na and Fe were found in the leaves (Section 2.2). This indicates that the leaves are an important sink of those nutrients. Furthermore, in section 2.2 it was also found that a portion of Mn, Fe, Cu, B and Mo was redistributed from the leaves to the permanent parts before the end of leaf drop. These results differ from those previously reported by Terblanche (1972), where movement of Mn from the permanent parts of the tree to the leaves was observed before leaf drop. However, no Zn and Na redistributions were observed in the present study.

For the 3rd leaf trees the minimum nutrient requirements (mg.kg^{-1} yield) of Na, Mn, Fe, Cu, Zn, B and Mo were ±75.1, ±1.3, ±28.7, ±0.9, ±3.0, ±5.7 and ±0.3, respectively. The maximum nutrient requirements (mg.kg^{-1} yield) of Na, Mn, Fe, Cu, Zn, B and Mo were ±102.9, ±7.8, ±32.6, ±1.1, ±6.5, ±7.6 and ±0.3, respectively (Table 1). The rootstock also plays a role, as was observed in the cases of the Quince A and BP1 findings of Stassen & North (2005), where more nutrients were required in the vigorous pear trees than in the dwarfing trees.

The maximum loss can be used for compiling a nutrition mixture for fertigation and hydroponic systems. There are, however, some conditions that need to be considered when rectifying nutrient loss, such as the fertilizer applied during soil preparation and the results of

soil and leaf analysis (Stassen *et al.,* 1999; Stassen & North, 2005). Soil and leaf analysis can be used as a tool to adjust the nutrients to be applied (Faust, 1989; Kotzé, 2001).

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Table 1: Micro nutrient requirements in milligrams (mg) for 2nd leaf tree, based on mg/tree, and 3rd leaf, based on 22.6 kg fruit. tree $^{-1}$ or 45.2 t.ha^{-1} of: a) a) Sodium, b) Manganese, c) Iron, d) Copper, e) Zinc, f) Boron, g) Molybdenum

a)

Sodium (Na) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	24.3 ±2.4	723.2±70.0
2. Leaves	119.9±4.7	451.2±49.9
3. Prunings	262.5±67.9	176.8±48.7
B. Fixed		
4. Permanent parts*	452.9±23.9**	974.8±93.5***
Total A + B (max loss) (g)	859.6±98.9	2326.0±262.1
1 + 4 (min loss) (g)		1698.0±163.5
Max. loss mg.kg^{-1}****		102.9
Min. loss mg.kg^{-1}****		75.1

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
**** mg/kg fruit harvested per tree

b)

Manganese (Mn) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	3.2 ±0.7	17.4 ±3.1
2. Leaves	38.3±7.9	121.1±29.4
3. Prunings	61.0±16.1	27.1 ±4.4
B. Fixed		
4. Permanent parts*	15.3 ±2.8**	11.6 ±7.3***
Total A + B (max loss) (g)	117.8±27.5	177.2±44.2
1 + 4 (min loss) (g)		29.0 ±10.4
Max. loss mg.kg^{-1}****		7.8
Min. loss mg.kg^{-1}****		1.3

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
**** mg/kg fruit harvested per tree

c)

Iron (Fe) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	2.3 ±0.6	210.3±29.2
2. Leaves	108.2±14.2	0.0 ±0.0
3. Prunings	288.5±92.3	89.0 ±20.2
B. Fixed		
4. Permanent parts*	142.3±2.2**	438.3±49.8***
Total A + B (max loss) (g)	541.3±109.3	737.6±98.6
1 + 4 (min loss) (g)		648.6±79.0
Max. loss mg.kg^{-1}****		32.6
Min. loss mg.kg^{-1}****		28.7

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
**** mg/kg fruit harvested per tree

d)

Copper (Cu) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	0.9±0.1	11.8±0.6
2. Leaves	1.4±0.3	0.0 ±0.0
3. Prunings	9.0±2.8	4.3 ±1.0
B. Fixed		
4. Permanent parts*	6.8±0.3**	9.6 ±4.5***
Total A + B (max loss) (g)	18.1±3.5	25.7 ±6.1
1 + 4 (min loss) (g)		21.4 ±5.1
Max. loss mg.kg^{-1}****		1.1
Min. loss mg.kg^{-1}****		0.9

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
**** mg/kg fruit harvested per tree

e)

Zinc (Zn) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	2.0 ±0.4	10.0±2.3
2. Leaves	22.5±4.3	55.8±8.5
3. Prunings	50.0±12.5	22.6±3.8
B. Fixed		
4. Permanent parts*	18.3±3.1**	58.4±21.4***
Total A+B (Max loss) (g)	92.8±20.3	146.8±36.0
1+4 (Min loss) (g)		68.4±23.7
Max. loss mg.kg^{-1}****		6.5
Min. loss mg.kg^{-1}****		3.0

*Permanent parts include roots, rootstock, trunk and canopy branches
**2nd leaf permanent parts total per tree are divided by tree age
***3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
****mg/kg fruit harvested per tree

f)

Boron (B) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	8.6 ±0.4	103.0±3.4
2. Leaves	10.7±1.2	29.0 ±1.5
3. Prunings	47.6±11.4	14.8 ±2.8
B. Fixed		
4. Permanent parts*	12.5±1.6**	25.9±7.4***
Total A + B (max loss) (g)	79.4±14.6	172.7±15.1
1 + 4 (min loss) (g)		128.9±10.8
Max. loss mg.kg^{-1}****		7.6
Min. loss mg.kg^{-1}****		5.7

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
**** mg/kg fruit harvested per tree

(g)

Molybdenum (Mo) (mg)	2nd leaf	3rd leaf
	Harvest: 06/02/2006	Harvest: 07/02/2007
A. Lost		
1. Fruit	0.2±0.0	5.0±0.2
2. Leaves	0.2±0.0	0.3±0.0
3. Prunings	0.9±0.2	0.2±0.1
B. Fixed		
4. Permanent parts*	0.8±0.1**	2.2±0.6***
Total A + B (max loss) (g)	2.1±0.3	7.7±0.9
1 + 4 (min loss) (g)		7.2±0.8
Max. loss mg.kg^{-1}****		0.3
Min. loss mg.kg^{-1}****		0.3

* permanent parts include roots, rootstock, trunk and canopy branches
** 2nd leaf permanent parts total per tree are divided by tree age
*** 3rd leaf permanent parts are obtained by subtracting 2nd leaf permanent parts from 3rd leaf tree
**** mg/kg fruit harvested per tree

Chapter 3

Using ^{15}N enriched fertilizer to optimise N management of young 'Brookfield Gala' apple trees

Abstract

Nitrogen management in a deciduous fruit orchard to meet the plant's needs and avoid environmental contamination requires that plant demand is understood and that application methods are efficient. In this study 'Brookfield Gala' apple trees on M793, planted at 4 x 1.25 m, received the standard nutrient solution through fertigation. Twenty-four trees were also fed with ^{15}N enriched ammonium sulphate at four phenological stages: spring (16/09/2004), 20 days later (05/10/2004), summer (15/12/2004) and at harvest (01/02/2005). Three trees were excavated in October 04, December 04, February 05, May 05 and the last 12 were excavated in December 05 during the following season. After excavation the trees were divided into different tree parts and samples were analysed for total N and labelled N. Uptake and distribution of N were calculated. Results indicated that there was a low labelled-N uptake in the initial growth stages, suggesting the importance of internal N reserves for plant development at the beginning of the season and low leaf and root activities. Low temperatures as well as leaching influenced the N uptake. In the active growing period more than 60% labelled N was found in the new growth. This trend changed in early winter as reserves started building up in the permanent parts. Very low labelled-N content was found in samples of the first two applications, excavated in December 05, due maybe to leaching caused by high rainfall early in the season. Uptake efficiency improved as the trees grew older.

Keywords: labelled nitrogen, nitrogen, fertilisation management, seasonal ^{15}N patterns

3.1 Introduction

Management of nitrogen (N) in a deciduous fruit orchard to meet the plants' needs and avoid environmental contamination requires that the plant demand is understood and that application methods are efficient (Tagliavini *et al.*, 1996). Understanding the demand for N includes the recognition that N can affect tree growth and development both in the current and the following years (Weinbaum *et al.*, 1987). Neilsen *et al.* (2001) indicate that storage and remobilisation are the key processes involved in year-to-year responses of deciduous trees to N status. Nitrogen is considered to be in storage if it can be remobilised from one tissue and subsequently used for the growth of other tissues (Millard, 1988). Nitrogen is stored as amino acids or proteins in roots in deciduous trees over the winter (Tromp, 1983) and in bark (Titus & Kang, 1982; Millard & Proe, 1991). During summer, N is stored in leaves primarily as rubisco (Titus & Kang, 1982; Millard, 1996). Remobilisation of N occurs during periods of senescence and growth (Millard, 1996). During leaf senescence much of the N stored in the leaves during summer is withdrawn and stored over winter in woody tissues, and subsequently remobilised and used for growth in spring (Millard, 1996). The annual cyclic nature of N transformations in the apple can be summarised in three steps: (1) N is mobilised in the autumn from senescing leaves to storage tissues, (2) N is conserved largely as proteins that undergo little modification during the dormant period, and (3) this N is then reutilised in the spring through storage protein hydrolysis to supply N for developing tissues (Titus & Kang, 1982).

Application of nitrogen influences tree growth and development during the current year and in the following growing season (Weinbaum *et al.*, 1987). Several factors affect N-fertiliser use efficiency, including the plant demand for N (Weinbaum *et al.*, 1992), the form of N applied (Baker & Mills, 1980), the application method (Sanchez *et al*, 1995), and the rate and timing of application (Stassen *et al.*, 1981b; Conradie, 1991; Sanchez *et al.*, 1992). Fertiliser use efficiency is defined as the fraction of applied fertilizer that is absorbed and used by a specific plant (Weinbaum *et al.*, 1978). Fertilizer not absorbed by the target plants can be taken up by weeds, lost in the atmosphere as gases, incorporated into stable organic fractions in soil, or leached below the rooting zone (Barker & Mills, 1980). Titus & Kang (1982) and Stassen *et al.* (1983) suggest that trees can take up N from the soil throughout the season as long as the leaves are active and soil temperature is conducive to root activity. Nitrogen absorbed by the roots is mostly utilised in the roots, which require substantial amount of carbohydrates (Faust, 1989). As a result, N uptake efficiency (NUE) is high when the tree produces photosynthates

(Faust, 1989). Weinbaum *et al*. (1978) studied N uptake and measured its utilisation efficiency in plum. He found that N is not taken up before rapid shoot growth begins; it decreases when leaves are senescing and ceases when leaves drop.

The seasonal pattern of N uptake and accumulation in trees reflects their N demand and can be used for timing N application in order to maximise fertilizer uptake (Weinbaum *et al*., 1992). Nitrogen uptake during the season, and partitioning of N to different plant organs, has been investigated in several fruit tree species (Terblanche, 1972; Weinbaum *et al*., 1978; Stassen *et al*., 1981a; Sanchez *et al*., 1992; Muñoz *et al*., 1993). During spring, bud break takes place when conditions for root uptake are not conducive, and at this time N remobilisation is of critical importance in supplying N to the developing tissues. In a study using isotopes, Weinbaum *et al*. (1978) showed that the N uptake and distribution within young non-bearing prune trees varies seasonally in relation to sink demand. They indicated that the uptake efficiency increases by close to tenfold once rapid shoot growth commences in spring and declines proportionally to leaf area during leaf senescence and abscission in the fall. Nitrogen uptake remains fairly constant during the growing season, but its upward translocation and distribution is related to patterns of sink demand within the tree. Nitrogen applied after bloom or during rapid shoot growth satisfies the N demand of new growth in grapes (Conradie, 1991), prunes (Weinbaum *et al*., 1978), pears (Sanchez *et al*., 1990) and apples (Neilsen *et al*., 2001). It has been reported for many fruit crops that after shoot growth termination the leaves change from being a strong sink to being a source of N for reproductive organs (Millard, 1988). Late season application increases the N storage pool that will be remobilised in the following year (Sanchez *et al*., 1991).

The timing of nitrogen application should be optimised for maximising uptake efficiency and minimising leaching, and for correcting transient or localised deficiency related to specific sink demands and processes such as fruit set, root growth, and others (Klein & Weinbaum, 2000). There is ample evidence indicating that early N demand by deciduous and evergreen fruit trees is met from the internal N pool stored within the tree (Terblanche, 1972; Stassen *et al*., 1981a and b; Titus & Kang, 1982; Millard, 1995). Apricot flowers of mature trees acquire up to 16% of their N from the previous autumn's nitrogen application compared to <1% from the winter application (Weinbaum *et al*., 1980). Similar results have been recorded for grapes (Conradie, 1992). Traces of isotopically labelled nitrogen in almonds could be detected within a week after application in the spring, but the bulk of N used for initial growth and

flowering originated from internal pools enriched during the previous year (Weinbaum *et al.*, 1984).

Isotope labelling and nutrient analysis of whole trees that were excavated were used to determine sequential patterns of nutrient uptake in mature trees (Weinbaum *et al.*, 1994). Results of these studies suggest that nutrient uptake does not occur uniformly over the season and that the seasonal periodicity of uptake is conditioned by the kinetics of sink demand for nutrients (Klein & Weinbaum, 2000).

The objective of this study was to determine how labelled N is taken up and distributed to the different tree parts during different phenological stages and how these allocations change during the growing season.

3.2   Material and methods

3.2.1   Orchard culture practices

'Brookfield Gala' apple trees on M 793 rootstock were planted in July 2003 on a well drained, well aerated loamy sand soil of the Dundee soil form (Macvicar *et al.,* 1977), in the Greyton area near Genadendal in the Western Cape Province. The area is situated 34º 03' S, 19º 37' E and 33 m above sea level. The Western Cape Province climate is typically Mediterranean, with warm, dry summers and mild, rainy winters. Near the coast, the summer temperature rises from a pleasant low of 15ºC to 27ºC. Inland temperatures are some 3–5ºC higher. Coastal winters can be 7ºC at night and the temperature rises to 18ºC by day. Away from the beach, it can be 5ºC in the morning and 22º C in the afternoon (SA Weather, 2007). Granny Smith trees were planted as cross pollinators. The trees were fertigated daily with two Netafim 2.3 l.h^{-1} pressure compensated emitters per tree, spaced at 60 cm on either side of the trunk. Tree training, soil preparation, and water and nutrient requirements were determined as previously described (Section 2.1).

3.2.2 ^{15}N application

Ammonium sulphate (($NH_4)_2SO_4$, 29 g) containing 6.15 g labelled N enriched to 10 atom% was applied once per tree in addition to the standard solution, as previously discussed (Section 2.1) at four phenological stages: spring (16/09/2004), 20 days later (05/10/2004), summer (15/12/2004) and at harvest (01/02/2005). At each application date six trees received ^{15}N of

which three trees were excavated within three month after application, on the following dates (13/10/2004; 15/12/2004; 01/02/2005 and 05/05/2005), leaving the other 12 for a final excavation in the next summer (06/12/2005) (three from each of the application treatments). Ammonium sulphate was applied manually under the drippers so that the water could dissolve the granules into the soil.

3.2.3 Experimental design and plant sampling

The single-tree plots were replicated three times in a randomised complete block design. At excavation the scions were separated from the rootstock in the field and the roots were carefully excavated by hand. The excavated trees were divided into the following parts: trunk, rootstock, canopy branches, new shoots, large roots, fine roots, leaves, fruits, pruning shoots and pruning leaves, according to the phenological stage at excavation. Samples were then cut into smaller parts using a saw for the woody parts and pruning scissors for the finer parts. Roots were washed to remove soil particles. Leaves, shoots, fruitlets and fine root samples were dried at 65°C for 24 h. Woody tissues and coarse roots were dried at 65°C to constant weight ($\pm$ 0.1%) (Neilsen *et al.*, 2001). The total fresh and dry weights for all the tree part samples were recorded.

3.2.4 Milling of samples

Samples were milled to finer particles. An IKA universal grinder M20 (IKA-WERKE GMBH &CO.KG, Staufen, Germany) was used to mill samples after the first four excavation dates. The last excavation samples (Dec 05) were first run through a LV15M type condux (Condux-Werke, Wolfgang bei Hanau, Germany) that chops the samples into smaller parts. Samples were then placed in a ZM 1 type Retsch mixer (Monitoring & Control Laboratories (Pty) Ltd. Germany, containing a 0.50-mm sieve to grind the sample into finer particles.

3.2.5 Analysis of samples

Total N and ^{15}N concentrations in samples were determined by Isotope Service (Los Alamos, USA) for the first four excavations. The equipment used comprised the following: an automated mass spectrometer, a Model VG-Isomass and an automated sample processing unit, a Carlo-Erba NA 1500, (gas chromatograph) (VG Isogas, Middlewich, Cheshire, U.K). Weighed samples in tin capsules were loaded into the sample processing unit. The capsules were transferred to a carousel, which drops the capsule into a flowing helium atmosphere in a quartz tube heated to 1020ºC. Just as it drops, a pulse of pure oxygen is emitted. The tin

burns, making the temperature even higher and promoting sample combustion. The combustion products are passed through processing train-water, and absorbed by a Drierite tube. Carbon dioxide is taken up by an absorbent called Carbosorb, and the nitrogen oxides are reduced to N_2 by metallic copper at 600°C. The gas stream exiting the gas chromatograph passes through a thermal conductivity detector, which senses and measures the quantity of total nitrogen. The stream is then sampled by the mass spectrometer and measured a second time. There the nitrogen is separated into its ^{14}N and ^{15}N stable isotopes and their respective contents are expressed as percentages.

The last excavated samples (Dec 05) were subjected to labelled N analysis. (Analyses were carried out at the University of Cape Town (UCT)). Samples (2 and 4 mg) were weighed into tin capsules and then combusted in a flash EA 1112 series elemental analyser (Thermo Finnigan, Italy). The gases were passed through a CO_2 trap to remove CO_2, and fed into a Delta Plus XP isotope ratio mass spectrometer (Thermo Electron, Germany), via a Conflo III gas control device (Thermo Finnigan, Germany). Then nitrogen was separated into its ^{14}N and ^{15}N stable isotopes, and expressed as a percentage.

The labelled N (mg/tree) was calculated according to the following equation:

$$\text{Labelled N (mg/tree)} = \text{tissue N (g)}*1000 \text{ x } \frac{^{15}N \text{ atom \% excess in tissue}}{^{15}N \text{ atom\% excess in fertiliser}}$$

using the atmospheric ^{15}N abundance (0.3663 atom% ^{15}N) as reference to estimate atomic ^{15}N excess (Junk & Svec, 1958).

3.2.6 Soil solution monitoring

Soil suction lysimeters with 2.0 cm diameter porous cups (Irrometer Co. Inc., Riverside, CA) were installed at 30 and 60 cm depth below one of the drip emitters. The suction points were placed at different depths in order to measure the difference in the concentration of the nitrate solutions. The installation and sample collection procedures used in this trial were similar to those described by Neilsen *et al.* (1998). Samples were collected at least twice monthly, between 13 Oct 2004 and 16 May 2005. Thereafter NO_3-N was analysed in the laboratory with a portable ion specific electrode meter (Cardy meter, Horiba Ltd., Kyoto, Japan).

3.3 Results and discussion

3.3.1 Labelled N uptake and distribution

Little labelled N (Table 1) was absorbed from 16/09/2004 to 13/10/2004 (154.4 mg), suggesting the importance of internal N reserves for plant development in spring, as has been reported by different researchers (Titus & Kang, 1982; Millard, 1995; Tagliavini *et al.*, 1997; Menino *et al.,* 2007). It is generally accepted that perennial crops are strongly dependent on stored N during the first weeks after bud-break; while soil derived N is the primary source later in the season (Stassen *et al.*, 1981b; Titus & Kang, 1982; Weinbaum *et al.*, 1984; Millard & Neilsen, 1989; Sanchez *et al.*, 1990). The same observations were made for Section 2.1, Table 6a); little N was taken up from bud-break to six weeks after. The time from 20/09/2004 when bud break took place to 13/10/2004 was also too short to permit significant uptake. Furthermore, the low soil temperatures as well as leaching caused by the heavy rainfall received early in October probably also influenced the low uptake of labelled N. Normally this region receives high rainfall in May to August. During Oct 04, heavy rain of 124 mm fell mainly on 6/10/2004 and 20/10/2004 (Table 2). Faust (1989) reports that N uptake efficiency is high when the trees produce photosynthates, which can support the low labelled N taken up at this point due to low leaf activities. Between 13/10/2004 and 06/12/2005 another 136.5mg labelled N was absorbed. This is still relatively little, indicating that probably by 20/10/2004 little labelled N was left in the soil due to the heavy rainfall received in that month (Table 2).

In Table 3 the labelled nitrogen uptake efficiency (labelled nitrogen taken up by the tree divided by the applied amount) was calculated and expressed as a percentage. The uptake efficiency of 2.5% was very low, probably due to an unfavourable soil temperature and therefore low root activity. From 16/09/2004 to 06/12/2005 the labelled N uptake efficiency was 4.7%. In this study most of the little labelled N absorbed from 16/09/2004 to 13/10/2004 was found in the fine roots, (63.3%) while the permanent structure (canopy branches, rootstock and trunk) contained about 20.1%, and the new growth (fruit, leaves and new shoots) contained 16.6% (Figure 1). However, from 16/09/2004 to 06/12/2005, of all the labelled N taken up the greatest portion was found in the new growth (fruit, leaves, new shoots, pruning shoots and leaves) (51.5%), of which the leaves contained the most (44.2%) (Figure 2). The roots contained the lowest amount of N, namely about 5.0%. It is clear from these results that the high root content of labelled N on 13/10/2004 indicates that the roots were still undergoing new growth.

From 05/10/2004 to 15/12/2004 about 393.9 mg labelled N was absorbed (Table 1). This is an indication that as the season progressed to summer the temperatures increased (Table 2), and the root and leaf activity probably became more effective; hence more labelled N was taken up than at 13/10/2004 (Titus & Kang, 1982; Faust, 1989; Millard, 1996). However, the uptake efficiency of 6.4% (Table 3) at this point was low due to low leaf activities. Furthermore, only 51.0 mg labelled N was absorbed between 15/12/2004 and 06/12/2005. This minimal uptake indicates that less labelled N was left in the soil after the October leaching. The N uptake efficiency of 7.2% (Table 3) at 06/12/2005 is close to the 6.4% on 15/12/2004, indicating that not much N was taken up during the rest of the season. The 6.4% uptake efficiency found in the present study for 15/12/2004 was lower than the 30.5% found in non-bearing prune trees by Weinbaum *et al*. (1978) but it is similar to the 6% found by Menino *et al*. (2007) and the 5% found by Weinert *et al.* (2002) for 1-year-old orange trees.

The distribution pattern on 15/12/2004 was as follows: more than 60% labelled N was in the new growth while the least was present in the roots. The same trend in distribution was observed in the trees on 06/12/2005. The uptake from six weeks after bud break to mid-summer was only 1.8 g (Section 2.1, Table 6a) but the N distributions changed significantly: ±49.3% was now found in the new growth, with the leaves comprising about ±41.6% of the new growth contribution. In comparison to the 16/09/2004 application one can clearly see that early in the season the uptake is very low, probably due to low root activity and few leaves available for photosynthesis. This is supported by the findings of Titus &Kang (1982), Faust (1989) and Muñoz *et al*. (1993).

In the case of trees where labelled N was applied on 05/12/2004 (Table 1) uptake was relatively high (426.1 mg) up to 01/02/2005, while another 620.0 mg was absorbed between 01/02/2004 and 06/12/2005. The N uptake efficiency at 01/02/2005 was about 6.9% while the efficiency at 06/12/2005 was about 17.0% (Table 3). Weinbaum *et al*. (1978) reported an N uptake efficiency ranging from 4.3% at bud swell to 35.9% at shoot growth cessation, which is higher than the findings of the present study. These differences can be attributed by the fact that stone fruits shoot growth cessation takes much longer than the poem fruits. Furthermore the prune trees in the above mentioned study was non-bearing and still growing to fill their allocated space hence took up more N. At harvest the N uptake increased by 8.3 g from mid-summer (Section 2.1, Table 6a). Furthermore, it was previously reported by Weinbaum *et al*. (1978), Sanchez *et al*. (1990), Conradie (1991) and Neilsen *et al*. (2001) that

nitrogen applied after bloom or during rapid shoot growth satisfied the N demand of new growth in different fruit trees. The distribution pattern found in this study is similar to the ones reported by Legaz *et al.* (1981), Muñoz *et al.* (1993) and Menino *et al.* (2007). The new growth (fruit, leaves, new shoots and pruning shoots and leaves) contained about 71.5% of labelled N, followed by the permanent structure (20.8%), while the roots contained the lowest (7.7%) (See Figure 1). The fruit received 44.9% of labelled N, indicating that it is a strong sink for N. Muñoz *et al.* (1993) reports that during the growing season most of the absorbed nitrogen is in the new fruit, leaves and shoots, and only a small amount remains in the root zone. In agreement, Legaz *et al.* (1981) and Menino *et al.* (2007) also found that more than half of the ^{15}N absorbed by the plant is allocated to young organs (new leaves, new branches and fine roots). Similar trends of distribution were found on 06/12/2005 and on 01/02/2005.

For trees where labelled N was applied on 05/02/2005 about 490.5 mg of labelled N was absorbed up to 05/05/2005 (Table 1). Another large amount (380.3 mg) was absorbed between 05/05/2005 and 06/12/2005. The N uptake efficiency for 05/05/2005 was 8.0% while the 06/12/2005 uptake efficiency was 14.2%. On 05/05/2005 the permanent structure (35.1%) and roots (27.5%) contained a higher proportion of labelled N than the new growth (37.4%), indicating translocation of nitrogen to the permanent parts, to be stored as reserves for the next season. Similar observations have been described in Section 2.1, Table 6a, where the N uptake almost doubled from harvest to early winter. Furthermore, the distributions also changed at this stage: the new growth contained ±27.0% N while the permanent structure contained ±73.0% N. This is in agreement with the findings of Terblanche (1972), Stassen *et al.* (1981a; 1981b), Titus & Kang (1982), Tromp (1983), Millard & Proe (1991) and Millard (1995), who report that the permanent structure and roots are a reservoir for reserve N during the winter to support new growth early in the next season. In addition, the 06/12/2005 distribution pattern was similar for all samples taken on the same day, where more than 60% labelled N was found in the new growth and the lowest percentage was present in the roots. This indicates that labelled nitrogen uptake efficiency correlates positively with photosynthesis (Faust, 1989).

3.3.3   Soil solution nitrate

The soil solution NO_3 concentrations within the root zone were within the range (28–224 µg.ml^{-1}) as suggested by Neilsen *et al.* (1993) (Fig. 3). Two peaks occurred during the period of high N application, namely in spring (Oct 04) and during the post-harvest period (March

05). During March the trees received high post-harvest nitrogen applications, which can explain the 210 µg.ml^{-1} in the 30-cm soil depth. One must remember that these trees were under drip irrigation and one would therefore expect a high NO_3 concentration within the root zone (0–600 mm). This is a sandy soil and depths from 600 mm to 900 mm should have been studied to calculate the amount of NO_3 leaching from the root zone. Neilsen *et al.* (1993) found that for apple trees in pots, optimum growth occurred in plants receiving daily fertigation of 56–112 µg.ml^{-1} and lower growth in plants receiving both lower and higher N concentrations ($\leq$ 28µg.ml^{-1} NO_3-N and 224 µg.ml^{-1} NO_3-N). Bhat (1983) reported that N uptake by roots is an active process and is independent of concentration, and maximum uptake by apples can occur at very low soil-solution concentrations (-0.28 ppb). Furthermore, it was suggested that under field conditions plant NO_3 uptake occurs either at a near maximum rate or ceases rapidly and that low uptake is due to the difficulty of maintaining nutrient flux to the plant rather than to a low soil solution concentration (Bhat, 1983).

3.4   Conclusions

The results indicate that there was a low uptake of labelled N in the initial growth stages, which suggests the importance of internal N reserves for plant development at the beginning of the season. Furthermore, early in the season low temperatures in the Genadendal area (on the banks of a river) also possibly caused low root activity and few leaves were available for photosynthesis during this stage. Leaching also probably removed N from the soil. In the active growing period more labelled N was found in the new growth. This trend changed in early winter, as reserves started building up in the permanent parts (permanent structure and roots). Thus the permanent parts contained the most labelled N in proportion to the new growth. Nitrogen uptake efficiency indicates that early in the season the uptake is low due to unfavourable soil temperature and low root and leaf activity. This is in agreement with the findings of Faust (1989) who report that N uptake efficiency is high when the trees produce photosynthates, which can support the low labelled N taken up early in the season. As the season progresses to active growth stages the trees start taking up labelled N more effectively.

Samples from the last two application dates that were excavated in 06/12/2005 had a high labelled-N content, probably because the labelled N was absorbed before the end of leaf drop (mid-July). This was supported by Weinbaum *et al.* (1984), who report that labelled N must

be absorbed by the tree before leaf drop to be able to contribute notably to the N composition of developing blossoms, immature fruits, and the earliest maturing leaves. In general, the tree uptake efficiency in this study was very low – it reached a maximum of 17.0% in summer (Dec 05) for the three-year-old trees. The tree uptake efficiency of the trees might improve as the trees grow older and a bigger root system develops that can take up more N for photosynthate production. This was observed from the N uptake efficiency of trees excavated a little later in the present study. Menino *et al*. (2007) suggest that young orange trees grown under field conditions are dependent on new inputs of N, however the recovery of labelled N is relatively small in the first three years after transplant. Weinbaum *et al*. (1978) report that uptake efficiency increases close to tenfold in mature almond trees once rapid shoot growth has commenced in spring and declines, proportionally to leaf area, during leaf senescence and abscission in autumn.

This study confirmed the annual cyclic nature of N transformations in the apple trees , which can be summarised in two steps, as previously reported by other researchers (Weinbaum *et al.,* 1978; Titus & Kang, 1982; Millard & Proe, 1991; Muñoz *et al*., 1993; Millard, 1996): (1) N is mobilised in the autumn from senescing leaves to storage tissues, and (2) this N is reutilised in the spring through storage protein hydrolysis to supply N for developing tissues.

The soil solution NO_3 concentrations within the root zone were within the suggested range. However, a peak occurred during spring and the post-harvest period due to high N application.

In conclusion, I offer the following recommendation: More sampling dates should be included in a study such as this one so that one can follow the pattern of uptake and distribution more clearly.

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Table 1: Average labelled N uptake and distribution in different tree parts of young 'Brookfield Gala' apple trees that received 6.15g of labelled nitrogen on different dates, and excavated at different phenological stages within three month after application

Application date	16/09/2004		05/10/2004		05/12/2004		05/02/2005	
	Labelled N (mg/tree)		Labelled N (mg/tree)		Labelled N (mg/tree)		Labelled N (mg/tree)	
Excavation date	13/10/2004[1]*	06/12/2005[2]*	15/12/2004[2]*	06/12/2005[2]*	01/02/2005 [3]*	06/12/2005[2]*	05/05/2005[4]*	6/12/2005[2]*
New growth								
Fruit	2.9±1.1	11.9±0.2	2.6±0.8	54.9 ±13.5	44.9 ±23.4	85.9 ±28.9	-	52.8 ±16.1
Leaves	20.0±6.5	128.6±23.4	202.2±10.5	158.5±13.3	65.7±28.3	556.6±139.0	52.4±25.0	391.9±170.2
New shoots	2.8±1.1	9.3±1.1	39.8±2.1	11.9±0.6	49.7±36.9	29.5±1.0	49.4±20.6	32.3±17.0
Total new growth	**25.7±8.7**	**149.8±24.7**	**244.6±13.4**	**225.3±27.4**	**160.3±88.6**	**672.0±168.9**	**101.8±45.6**	**477.0±203.3**
Permanent part								
Trunk	14.7±4.5	28.5±4.3	23.7±1.8	25.4±2.1	26.4±7.3	51.0±9.8	42.2±15.3	48.3±9.9
Canopy branches	-	47.8±0.9	34.7±5.3	56.4±8.7	39.0±14.4	106.4±15.9	82.9±31.4	138.7±50.4
Rootstock	16.3±6.6	21.4±3.5	33.1±3.3	56.6±2.0	23.1±4.7	60.0±24.1	47.1 ±18.3	75.6±29.9
Total	**31.0±11.1**	**97.7±8.7**	**91.5±0.4**	**138.4 ± 12.8**	**88.5±26.4**	**217.6 ±49.8**	**172.2±65.0**	**262.6±90.2**
Roots								
Fine roots	97.7±63.5	2.0±0.7	39.2±11.8	5.4±1.2	11.5±3.6	15.3±4.6	57.0 ±20.3	10.7±4.6
Thick roots	-	12.5±6.3	18.6±4.5	37.9±8.2	21.3±9.3	64.2±4.7	77.9 ±36.7	43.1±15.0
Total	**97.7±63.5**	**14.5±7.0**	**57.8 ±16.3**	**43.3±9.4**	**32.8 ±12.9**	**79.5±9.3**	**134.9±57.0**	**53.8±19.6**
Pruning								
Shoots		25.0±13.1		30.7±3.2	45.2±19.1	63.1±44.5	48.0 ±17.2	70.3±19.6
Leaves		3.9±1.8		7.2±0.5	99.3±38.8	13.9±7.3	33.6 ±15.0	7.1±0.7
Total		**28.9±14.9**		**37.9±3.7**	**144.5±57.9**	**77.0±51.8**	**81.6 ±32.2**	**77.4±20.3**
Total/tree	154.4±83.3	290.9±55.3	393.9±40.1	444.9±53.3	426.1±185.8	1046.1±279.8	490.5±199.8	870.8±333.4

1*- Six weeks after bud-break
2*- Mid-summer
3*- Harvest
4*- Early winter, before normal leaf drop

Table 2: Monthly average soil temperature and rainfall data for the 2004/2005 season at the High noon station in the Caledon district (Supplied by ISCW, Agromet section, Pretoria)

Month	Soil temperature (ºC)	Rainfall (mm)
Sept 04	13.10	40.70
Oct	15.20	124.10
Nov	18.40	1.00
Dec	19.80	24.50
Jan	23.65	24.02
Feb	22.66	16.71
Mar	23.19	12.06
Apr	16.96	45.86
May	16.94	78.25
Jun	9.12	33.60
Jul	11.74	145.23
Aug	11.31	125.80
Sep 05	15.41	56.30
Oct	18.39	39.80
Nov	20.84	10.95
Dec	22.48	8.85

Table 3: Percentage labelled N uptake efficiency of young Brookfield Gala apple trees, applied and excavated at different dates

Application date	16/09/2004		05/10/2004		05/12/2004		05/02/2005	
Excavation date	13/10/2004	06/12/2005	15/12/2004	06/12/2005	01/02/2005	06/12/2005	05/05/2005	06/12/2005
Labelled N uptake efficiency (%)	2.5	4.7	6.4	7.2	6.9	17.0	8.0	14.2
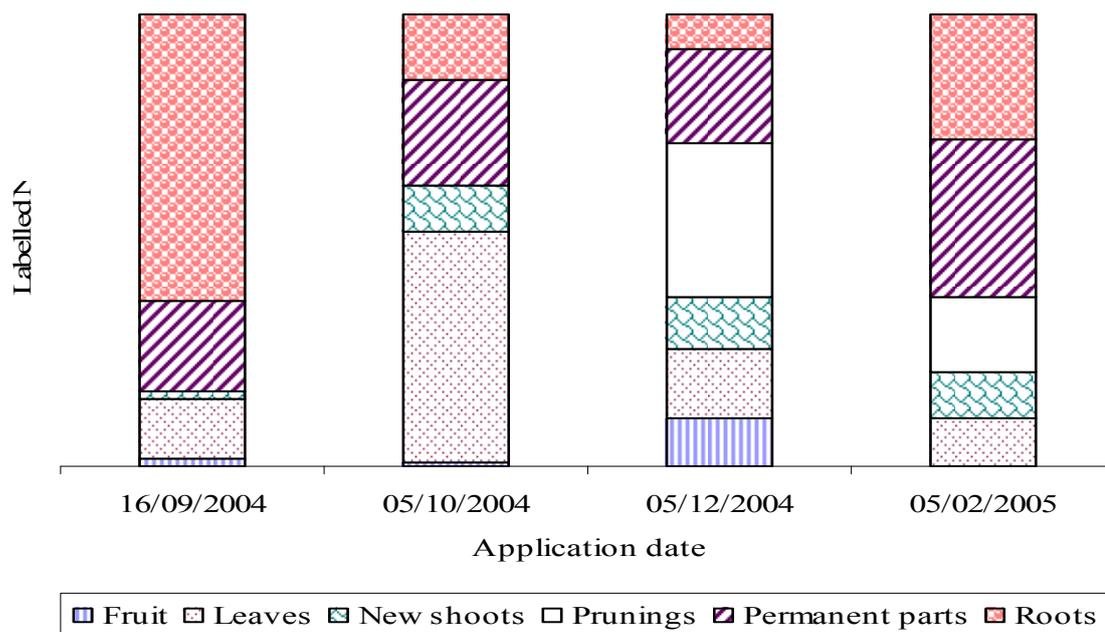
Figure 1: Labelled N distribution in different tree parts of young 'Brookfield Gala' apple trees that received 6.15g of labelled nitrogen on different dates (16 Sept 04; 5 Oct 04; 15 Dec 04 and 1 Feb 05) and were excavated for analysis within three months after application.
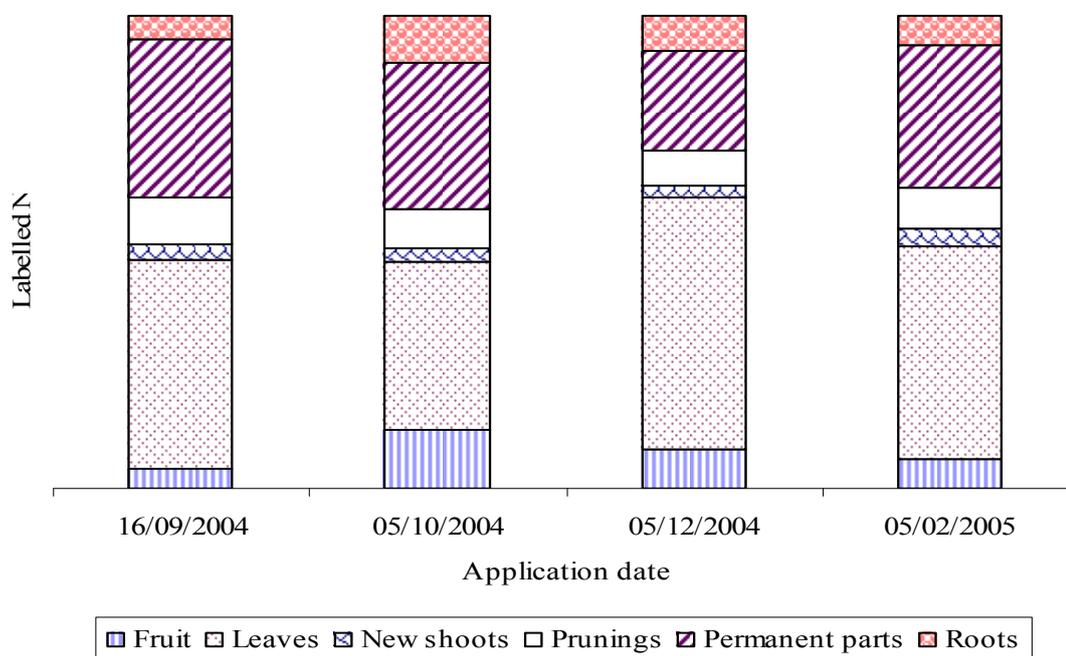
Figure 2: Labelled N distribution in different tree parts of young 'Brookfield Gala' apple trees that received 6.15g of labelled nitrogen on (16 Sept 04; 5 Oct 04; 15 Dec 04 and 1 Feb 05) and were excavated for analysis on 6 Dec 05.
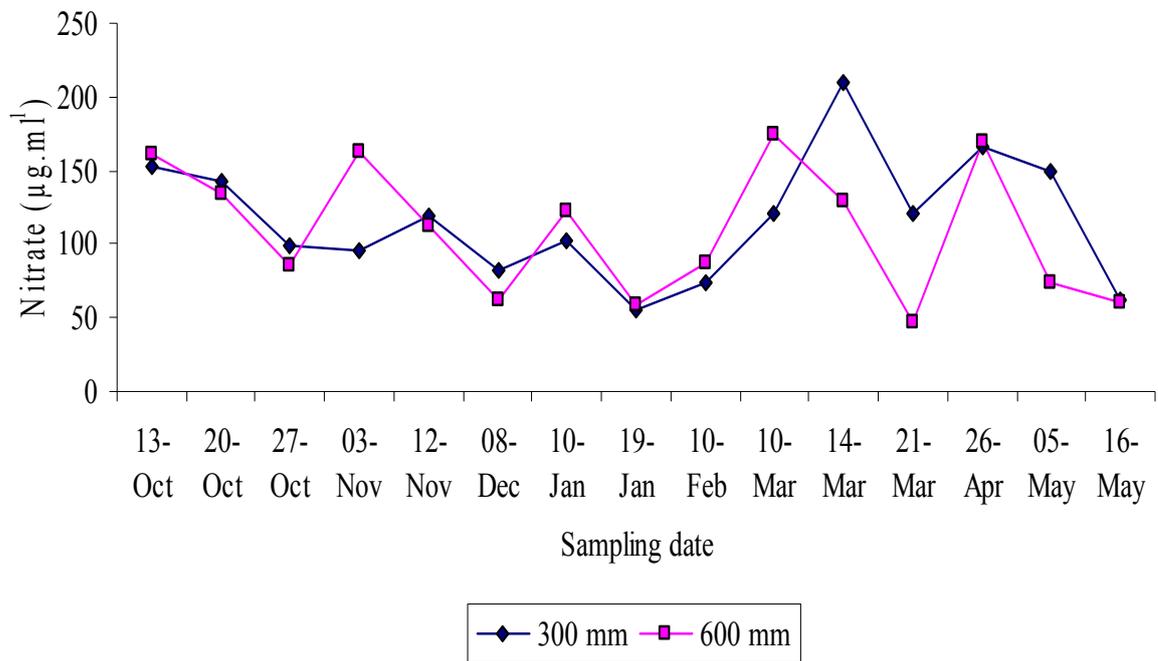
Figure 3: Soil water nitrate concentration at 300 mm and 600 mm soil depth in a drip
irrigation system in the 2004/2005 season.

Chapter 4

The influence of different nutrient levels or biological ameliorants on yield, fruit quality, shoot, fruit and root growth of apple trees

Abstract

In this study two statistical trials were conducted using 'Brookfield Gala' apple trees planted at a spacing of 4 x 1.25 m during July 2003. In the first trial different nutrient levels were applied. This trial was designed as a randomised complete block with five different nutrient levels, which were replicated six times. The second trial was designed as a randomised complete block with three treatments STD (control), STD+HA (humic acid) and STD+C+CE (compost plus compost extract), which were replicated eight times. Results indicated that different nutrient levels had no effect on yield, blush and TSS, but there were differences in fruit size, fruit weight, firmness, starch breakdown, malic acid and citric acid. These differences could not be explained as no definite trend was found with different nutrient levels. No significant difference in the results of root studies was observed among the different nutrient levels. The following tendency was, however, noted: the higher nutrient levels resulted in fewer fine roots than in the case of the control treatment. The application of biological ameliorants such as humic acid, and compost plus compost extract, had a significant influence on the improvement of TSS, malic acid and citric acid. No significant differences in the results of root studies were observed in the biological ameliorant trial although it was noticed that the STD+HA and the STD+C+CE treatments resulted in more root development than in the cases of the STD (control) treatment.

Keywords: nutrient management, humic acid, compost plus compost extract

4.1   Introduction

High density orchards allow early cropping and produce high yields and good fruit quality (Oberhofer, 1989; Wagenmakers, 1991). Adequate mineral nutrition contributes to positive fruit quality, and it maintains spur quality as well as fruit, vegetative and root growth (Mengel & Kirkby, 1982, Faust, 1989). Several studies have been conducted on the nutrient requirements and uptake in more widely spaced apple trees (Batjer *et al*., 1952; Haynes & Goh, 1980) but not much research has been done for higher density orchards under fertigation. The standard fertilizer solution used for high density apple trees in the experiments described here is based on that used for higher density pear trees (Stassen & North, 2005). This study was carried out in order to determine whether the concentration of the standard solution that is used could be increased or decreased in order to achieve improved yield and fruit quality.

Biological ameliorants such as humic acid, compost and compost extract are said to have advantages that can influence deciduous fruit production. They improve the soil structure, which leads to an improvement in aeration and moisture holding capacity (Schupp, 2001; Smith, 2001). Organic mulches improve growth and the yield of apples planted in a high density system (Neilsen *et al*., 2004). This improvement is related to the release of nutrients from the applied organic material, which can improve orchard soil nutrient availability and soil biological activity. However, mulches can be ineffective in orchards with good nutrient management (Neilsen *et al*., 2004). According to Davies *et al*. (2001) humic acid inhibits indoleacetic acid (IAA) oxidase activity; it increases the IAA concentration and thus stimulates root development, which increases the absorption area of nutrients. Consequently, this improves the uptake of nutrients due to a larger root system and availability of nutrients, resulting in improved fruit quality and increased yields. Chen & Aviad (1990) and Fernandez-Escobar *et al*. (1996) report that the application of humic substances stimulates vegetative growth. However, in an experiment conducted by Fernandez-Escobar *et al*. (1996) no effect on yield was observed, even in experiments in which fruit size was improved. Neither was there any effect on yield in an experiment that was continued for two seasons, in which vegetative growth was promoted. Foliar sprays of humic substances also promoted growth in a number of plant species such as tomato, cotton and grapes (Brownell *et al.,* 1987). However, Pilanali & Kaplan (2003) report that high rates of humic acid inhibit nutrient uptake by strawberry leaves. This is supported by Casenave *et al*. (1990), who suggest that this

inhibition is due to an increased content of auxin-like and gibberellin-like substances present in humic acid. Spraying with fulvic acid also increases the yield of wheat grown under dry conditions (Xudan, 1986). Sánchez-Sánchez *et al*. (2002) report that the addition of humic substances to lemon trees improves the uptake of Fe and Cu and it also improves the fruit weight and the vitamin C content of the fruit.

Compost soil amendments were found to be effective when the soil was poor in nutrients prior to the application of compost (Roe, 1998) but they had little or no effect if the soil was relatively rich in nutrients (Ferrini *et al*., 2005; Gilman, 2004). Rose & Wang (1996) report that compost and municipal sludge increase growth in most ornamental plants but that potential high salt concentrations result in negative responses in some species. Watson (2002) observed more roots in replaced soil amended with compost than in the surrounding soil 14 years after replacement of the soil, but root growth in the soil beyond the zone of replaced soil was not affected. Compost contributes to both increased growth and a higher content of nutrients in apple trees in the establishment phase (Moran & Schupp, 2003). Medina *et al*. (2004) observed that a poor soil responded well to amendment with favourable microorganisms, especially if the soil is also amended with organic materials to feed the microorganisms. Compost extract contains living organisms and can function as fertilizer (Houghton, 2003). The potential benefits of compost extract are still emerging and limited information exists. It is, however, believed that benefits could include soil pest control and disease control, as well as modification of soil structure to improve nutrient uptake (Houghton, 2003).

Assessing fruit quality is not simple since there are various factors that have diverse effects on external and internal quality, namely environmental factors, the cultivar and tree management (Kingston, 1992). For instance, excess nitrogen application increases green colouration yet decreases the soluble solids concentration, titratable acidity and fruit firmness (Hikasa *et al*. 1986; Olsen *et al*. 1986). In contrast, increasing exposure to sunlight hastens the development of red colouration and increases fruit size, soluble solids concentration and fruit firmness (Shaw & Rowe, 1982; Barritt *et al*. 1987). As the fruit reach maturity many physical and chemical changes take place (Kingston, 1992). In apple and pear, fruit firmness and titratable acidity decrease while total sugar and the rate of starch breakdown increase (Divikar *et al*. 1981; Mann & Singh, 1985). Apples have a relatively high acid content compared to other fruits (Vangdal, 1985), and consumer acceptability in European countries is closely correlated

to the acid content (Wills *et al.*, 1989). Truter & Hurndall (1988) found that the soluble solids content of Starking Delicious apples varies between 10.8 and 12.2% at the optimum picking stage. Marcelle (1995) reports that the nitrogen status, fruit position in the canopy, watercore, fruit size and fruit temperature are the most important factors that influence fruit firmness. As apples mature so the rate of chlorophyll production decreases, causing a loss in concentration of green colouration and allowing other pigments to appear on the skin and flesh (Olsen, 1982; Wills *et al.*, 1989; Kingston, 1992).

This present study was initiated in order to determine the influence of several nutrient levels on growth and fruit quality, from 20% below the "ideal" nutrient solution to 20, 40 and 60% above. The study was also carried out to determine whether the addition of biological ameliorants lead to a complimentary improvement in yield and fruit quality through root proliferation and soil environmental improvement.

4.2   Materials and methods

4.2.1   Treatments and statistical layout

Trees from the same orchard but a different block as described in Section 2.1 were used. In the first trial different nutrient levels were evaluated in a randomised complete block with five treatments, which were replicated six times. The treatments that were used were the following: one lower than the standard (80%), the standard (100%) and three higher than the standard (120%, 140% and 160%). The standard solution (described in Section 2) was taken as the theoretical "ideal" solution (100%). The concentrations of all the nutrients in the solution were increased or decreased, as indicated by the percentage. In the second trial the biological ameliorants were evaluated in a randomised complete block with three treatments, which were replicated eight times. In this trial all treatments received the standard (100%) nutrient solution through fertigation. The first treatment was a control, only receiving fertigation, and the second received humic acid in addition to fertigation. The third treatment consisted of compost and compost extract in addition to fertigation. The nutrient solutions were prepared as previously described (Section 2). Each experimental unit consisted of eight trees of which five uniform trees were selected for measurements.

A drip fertigation system was used to supply a nutrient solution to the trees once daily. Soil preparation, tree training, pruning, thinning and irrigation scheduling was done in the same

way as described previously (Section 2). During the 2006/2007 season no thinning was done due to low fruit set as a result of cold and misty weather conditions during flowering. Standard practices were carried out as for a commercial orchard.

4.2.2 Application of biological ameliorants

In the 2005/2006 season twenty-five litres (L) of compost/ tree was applied as mulch around the trees on 26/10/2005 followed by another 25 L/ tree application on 01/12/2005. For the 2006/2007 season 25 L/ tree was applied on 22/09/2006 and again on 29/11/2006. Compost was supplied by Reliance Compost (Hermanus, South Africa). This compost was made of vegetable waste and its analysis is presented in Appendix, Table 13.

In the 2005/2006 season 1 L/ tree compost extract was applied around the trees bi-weekly from mid-September 2005 until the end of April 2006. In the 2006/2007 season 1 L/tree compost extract was applied from 22/09/2006 to the end of March 07. The compost extract was prepared on the farm, by brewing 80 L water, 2.4 L compost and 900 ml malose sugar in an aerator (homemade) for 24 hours under normal atmospheric air conditions.

In the 2005/2006 season 50 ml humic acid/ tree was mixed with water in a 5 L container and then applied around the trees once a month from mid-November 2005 to the end of April 2006. In the 2006/2007 season the same amount of humic acid was applied from 22 Sept 06 until the end of March 07. The humic acid was supplied by Agron (Moosrivier, South Africa). The humic acid consisted of a solution of humic acid and 5% K. The pH thereof was 13, 28.

4.2.3 Data recorded

Two branches on each tree of the five experimental trees were tagged. These two branches were measured bi-weekly throughout the season. Twenty-five fruit per replication were tagged after fruit thinning and measured weekly throughout the season. The fruit were measured by using an electronic Cranston diameter gauge (Cranston Machinery Co. Inc., Oregon, USA).

Three days before the first harvesting date a total of 75 fruits per replication were randomly picked. Fruits were evaluated for fresh weight, flesh firmness, total soluble solids (TSS), starch breakdown, malic acid, citric acid and background colour. Quality evaluation was

done on 25 fruits at harvest, after six weeks of cold storage (–0.5 C) and ten days of shelf life at 25°C following cold storage. Flesh firmness was analysed on both pared cheeks using a penetrometer (Southtrade, FT327, Alphonsine, Italy) fitted with an 11 mm tip. The percentage TSS was determined using a hand-held refractometer (PR-1009501, ATAGO Co. Ltd., Tokyo, Japan) and the percentage starch breakdown was determined using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa). Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5–5: dark 0.5 and light 5). Malic acid and citric acid were analysed by using a Metrohm 760 titrator (Swiss Lab, Pty. Ltd., Rivonia, South Africa).

Fifty-leaf samples were randomly collected from each of the treatment blocks on 31 January, over two seasons. The leaves were collected and analysed as described in Section 2.1.

4.2.4   Root studies

Soil profile holes of 1 m wide x 1m deep were made 60 cm away from the tree, followed by working back 20 cm towards the tree with a fork one month prior to harvest. The roots were sprayed with a white, quick drying spray paint to make them more visible. Photographs of the roots were taken within an 80 x 80 cm frame divided into smaller grids of 20 x 20 cm each (Appendix, Figures 14 and 19). Each treatment was replicated three times and the total number of fine roots (0–5 mm diameter) and thick roots (above 5 mm diameter), and the root length within a 20 x 20 cm grid, and 20 cm depth were determined.

4.2.5   Soil samples

Soil samples were collected at 0–300 mm and 300–600 mm depths per replication and thoroughly mixed. The soil mineral analysis for nitrogen and potassium was performed using a commercial analytical laboratory (Bemlab Pty. Ltd., Strand, South Africa). Five grams of air-dried soil was weighed into an extraction bottle. A 50 ml volume of ammonium acetate solution was added and the contents shaken for 30 minutes, then filtered. Nitrogen was analysed using a nitrogen analyser (LECO FP528 Nitrogen analyser, LECO Cooperation, St. Joseph, Michigan, USA) and potassium was analysed using an inductively coupled plasma-optical emission spectrometer (ICP-OES; Varian MPX-OEX, Varian, Inc. Corporate, Palo Alto, California, USA). Results were expressed as % N and in mg/kg for K (Appendix, Table 12).

4.2.10 Data analysis

Analysis of variance was done using the General Linear Model (GLM) procedure in the Statistical Analysis System (SAS) programme version 3.1 (SAS Institute Inc, 2004, Cary, NC).

4.3   Results and discussion

4.3.1.1 Influence of nutrient levels on yield and fruit quality

2005/06 Season

After the first three months of applying different levels of nutrients there was no significant difference in yield, blush colour and TSS (Table 1). Where the nutrient level was increased by 40% (H140) the fruit diameter was significantly lower (Table 1) than that resulting from the other solutions (Treatment L80, S100, H120 and H160). This is also clear from the fruit growth pattern from 82 DAFB (Table 2 and Appendix, Figure 15). This is difficult to explain because the treatment where the nutrient level was 60% higher than the standard (H160) resulted in the same effect as the 80, 100 and 120% levels (Contrast Cubic p=0.0110 and Contrast Quadratic p=0.0385). The 40% higher nutrient level treatment (H140) also resulted in significantly less background colour, firmness and starch breakdown. The malic acid and citric acid were higher than for the 80%, 120% and 160% nutrient solutions but not significantly different from when the standard solution (100%) was used. Fruits analysed after six weeks of cold storage and at shelf life followed the same pattern as fruits analysed at harvest (Appendix, Tables 5 and 6).

2006/07 Season

Due to poor weather conditions during the fruit set period the yield was lower than in the previous season (Table 3). It could perhaps also be an effect of the large crop the previous year (1st crop on very young trees). From Table 3 it is also clear that the fruit diameter and fruit weight induced by the standard nutrient solution (100%) were significantly lower than that which resulted from the other nutrient solutions (L80, H120, H140 and H160). This tendency was found throughout the season (Appendix, Figure 15). There was, however, no real trend in fruit diameter, fruit length and weight in relation to the nutrient level (Contrast Cubic p=<0.0001; p=0.0040; p=<0.0001, respectively). During the season there was again no significant difference in background colour, TSS and sunburn. Differences in malic and citric acid showed no clear trends relative to the level of the nutrient solution although significant

differences occurred. The standard solution resulted in significantly higher malic acid and citric acid than the 80%, 120% (not for citric acid) and 140% solutions, but not in the case of the 160% solution. After six weeks of cold storage (Appendix, Table 7) there was no significant difference in the background colour among all treatments. Fruit from the standard solution (100%) had a significantly lower fruit weight, higher firmness, lower starch breakdown and a higher malic and citric acid than from the 80%, 120%, 140% nutrient solutions. Fruits from the treatment where 60% more nutrients were applied (H160) were significantly less firm and had a higher starch breakdown than fruit from treatment with the standard nutrient solution (100%).

4.3.1.2 Shoot growth (2005/06 and 2006/07)

Different nutrient levels had no influence on final shoot length in either of the two seasons (Table 2) and therefore no effect was seen on shoot growth throughout the two seasons (Appendix, Figure 16).

4.3.1.3 Root growth

No significant difference was observed among the different nutrient levels, although at the higher nutrient levels (H120, H140 and H160) there was a tendency for fewer fine roots than in the control treatment (Table 4). This agrees with the findings of Kolesnikov (1971) who found that excess N suppresses root growth. Furthermore, Kohls & Baker (1989) and Boot & Mensink (1990) report that root hair development is negatively affected by a high NO_3-N supply. These results indicate that high nutrient levels may have an inhibiting effect on the number of the finer, shallow roots.

4.3.2.1 Influence of the biological ameliorant on yield and fruit quality

2005/06 Season

After the first four months of applying the biological ameliorant there was no significant difference in yield, fruit diameter, weight, background colour, fruit firmness, TSS, malic acid and citric acid (Tables 5 and 6). Compost soil amendments are effective when the soil has a poor nutrient status (Roe, 1998) but have little or no effect if the soil is relatively nutrient rich (Gilman, 2004; Ferrini *et al*., 2005). In agreement with this, Neilsen *et al*. (2004) found that mulches are ineffective in a good nutrient-managed orchard. The control treatment where only standard nutrient solution (100%) was given resulted in a significantly higher starch breakdown than the humic acid treatment, but results did not differ significantly from those of

the compost plus compost extract treatment. After six weeks of cold storage no significant differences were found in all variables measured for the different treatments, except in the fruit weight (Appendix, Table 8). The treatment that involved humic acid application resulted in significantly bigger fruits than the control and the compost plus compost extract treatment. This might just be a manifestation of the sampling process. No significant differences were seen following shelf life (Appendix, Table 9).

2006/07 Season

Due to poor weather and wet soil conditions during the fruit set period, yield was lower than the previous season (Table 7). A significant reduction in the yield was observed following the ameliorants application but this cannot be explained. During the season there was no significant difference in the fruit diameter, fruit length, fruit mass, background colour, firmness, starch breakdown and sunburn. Significant differences were observed in the TSS, malic acid and citric acid with the humic acid application and the compost plus compost extract applications resulting in higher TSS than the control treatment. Even though there was no significant difference in the fruit mass and diameter the control treatment was slightly bigger than the other two treatments. A statistical analysis (Table 7) showed that the low TSS and malic acid level in the control treatment was influenced by the bigger fruit mass ($p=<.0001$; $p=0.0033$), however the biological ameliorant treatment effects still remained significant in terms of TSS, malic and citric acid when the fruit mass was used as a covariate ($p=0.0314$; $p=0.0009$; $p=0.0015$). Based on these observations it appears as if biological ameliorants have on influence on the taste of apples. Sánchez-Sánchez et al. (2002) reported that the addition of humic substances to lemon trees improved Fe and Cu uptake, and it also improved the fruit weight and the vitamin C content in the fruits.

After six weeks of cold storage (Appendix, Table 10) the TSS of apples treated with humic acid and those treated with compost plus compost extract was significantly higher than the TSS of the control. However, the malic acid and citric acid of apples treated with the compost plus compost extract were significantly higher than in the control treatment but did not differ significantly from fruit treated with humic acid.

4.3.2.2 Shoot growth (2005/06 and 2006/07)

Different biological ameliorants had no influence on final shoot length in either of the two seasons (Table 6) and therefore no effect was seen on shoot growth throughout the seasons (Appendix, Figure 18).

4.3.2.3 Root growth

No significant differences were observed in the root number or length among all treatments (Table 8 and Appendix, Figure 19). However, a tendency was seen whereby the STD+HA and STD+C+CE treatments had more fine root development than the STD treatment.

4.3.3   Leaf nutrient concentrations

Leaf nutrient analysis (Appendix, Table 11) was carried out to determine the toxicity or deficiency levels in the leaves of Brookfield Gala apple trees. Values obtained from the laboratory were compared to the published nutrient standard guidelines in apples according to Faust (1989) (Northern Hemisphere) and Kotzé (2001) (Southern Hemisphere). Leaf analyses for the 2005/06 season showed that N, P, K, Mg, Cu and B percentages in leaves were in line with the norms set by Faust (1989) and Kotzé (2001). However, the Ca concentrations found on 31 January 2006 were higher than the 1.45–1.60 % range recommended by Kotzé (2001) as well as the 1.8% recommended by Faust (1989). Futhermore, Levin *et al*. (1980) report that the leaf Ca percentage in an orchard where drip irrigation is used ranges from 1.3 to 1.9% (dry weight basis). In the present study the Ca concentration varied from 1.83 to 1.99% for the biological ameliorant treatments, which is close to the above findings. However, the 1.92 to 2.07% range found for the different nutrient levels was higher than the norms reported above. Faust (1989) reported that a leaf Ca concentration above 1.8% is beneficial to the tree because the Ca influx to the tree is continuous throughout the entire season and therefore the fruit will receive enough Ca. The S and Na concentrations were lower than the norms while the Mn, Fe and Zn concentrations were higher than the published norms. The same tendencies in the leaf nutrient concentrations were observed in the 2006/2007 season and the previous season. However, in the 2006/2007 season the Ca concentrations were lower than the norms while the K concentrations were higher than the norms. This is supported by Jackson (2003), who reports that high K concentrations inhibit Ca uptake and cause bitter pit problems in apples.

4.4 Conclusions

During the 2005/2006 season the different nutrient levels had no effect on yield. The yield was between 27 and 33 t/ha for the three-year-old 'Brookfield Gala' trees. Upon looking at the whole picture, no definite trend was observed in fruit quality. During the 2006/2007 season, with the lower yield (5–8 t/ha), the differences in fruit size, firmness, starch breakdown, malic acid and citric acid did not follow any trend. High nutrient levels (20%, 40% and 60% higher than the control) showed a tendency of a decrease on the number of shallow roots (0–400mm). These results might indicate that the 80% nutrient level could also be optimal since this nutrient level did not differ significantly from the two treatments that had better fruit quality over the two seasons, although there was no trend. Furthermore, the leaf nutrient levels of the 80% treatment were within the recommended norms.

During the 2005/2006 season, four months after starting with biological ameliorants, there were no differences between apple trees receiving the standard nutrient and those receiving the treatments where humic acid and compost plus compost extract was applied. Yield differences during 2006/2007 (18 month and two bearing seasons after initial application) cannot really be ascribed to treatment effects because of the effects of weather and wet soil conditions on yield. The application of biological ameliorants led to significantly higher TSS, malic acid and citric acid. This indicates that certain biological products might improve these components and maybe taste of apples. Even though no significant differences were observed in the root number or length among all treatments a tendency was seen whereby the STD+HA and STD+C+CE treatments had more fine root development than the STD treatment.

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Table 1: The effect of differential nutrient levels applied for three months on yield and fruit quality of a 25-fruit sample of Brookfield Gala apple trees at harvest (2005–2006 season)

Treatment	Yield (kg/ tree)	Estimated yield** (t/ ha)	Diameter (mm)	Mass (g)	Colour*** Back	Blush	Firmness (kg)	TSS % Brix)	Starch**** (%)	Malic acid (%)	Citric acid (%)
L80	14.37	27.10	67.50a	136.08a	3.87a	3.86	8.74b	13.43	41.42a	0.43b	0.41b
S100	15.62	29.37	67.00a	133.48a	3.93a	3.77	8.64b	14.28	48.57a	0.45ab	0.43ab
H120	16.10	30.30	66.64a	131.38a	3.96a	4.03	8.76b	13.58	42.07a	0.43b	0.41b
H140	14.81	27.74	63.95b	117.20b	3.32b	4.76	9.69a	13.87	20.17b	0.48a	0.46a
H160	17.51	32.53	67.43a	134.99a	3.72a	4.51	8.68b	13.32	40.33a	0.42b	0.40b
Significance level	*0.6031ns*		*0.0080*	*0.0118*	*0.0199*	*0.5164ns*	*0.0009*	*0.0559ns*	*0.0078*	*0.0100*	*0.0135*
Contrast linear	0.2526		0.1517	0.1338	0.0467	0.1389	0.0916	0.3878	0.0656	0.5959	0.6821
Contrast quadratic	0.8393		0.0385	0.0533	0.9767	0.9356	0.1215	0.0501	0.5734	0.0339	0.0518
Contrast cubic	0.3163		0.0110	0.0149	0.0208	0.3758	0.0005	0.3420	0.0020	0.0621	0.0610
LSD (5%)	*4.32*		*2.01*	*11.02*	*0.40*	*1.38*	*0.48*	*0.69*	*14.63*	*0.03*	*0.03*

* Means within a column followed by different letters are significantly different (P=0.05; LSD)
** Estimated yield is obtained by multiplying the yield (in kg) by 2000 trees/ha
*** Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5–5: dark 0.5 and light 5)
*** Percentage starch breakdown was determined by the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, RSA).

Table 2: The effect of different nutrient levels on final fruit and shoot growth of Brookfield Gala apple trees over two seasons

Treatment	Final fruit growth (05–06 season)*	Final fruit growth (06–07 season)*	Final shoot growth (05–06 season)*	Final shoot growth (06–07 season)*
L80	65.00a	67.61b	27.35	33.45
S100	64.82a	65.67d	26.00	31.65
H120	65.64a	66.99bc	25.71	34.70
H14	61.80b	68.75a	26.75	33.65
H160	64.87a	66.77c	27.01	32.90
Significance level	*0.0012*	*0.0013*	*0.5711ns*	*0.8431ns*
Contrast linear	0.0762	0.2528	0.9756	0.8885
Contrast quadratic	0.4112	0.8056	0.1029	0.7890
Contrast cubic	0.0031	0.0003	0.4136	0.4883
LSD (5%)	*1.61*	*1.09*	*2.03*	*5.88*

* Means within a column followed by different letters are significantly different (P=0.05; LSD)
* Final fruit size and shoot length as adjusted for initial size and length

Table 3: The effect of different nutrient levels on yield and fruit quality of Brookfield Gala apple trees at harvest (2006–2007 season)

Treatment	Trunk circumference (cm)	Yield (kg/tree)	Yield efficiency	Diameter (mm)	Length (cm)	Mass (g)	Background colour**		Firmness (kg)	TSS (% Brix)	Starch*** (%)	Malic acid (%)	Citric acid (%)	Sunburn (%)
							Back	Blush						
L80	20.84	7.43	0.22	70.64ab	62.68ab	152.88b	4.46	2.56	7.23cb	13.5	84.94ab	0.34 b	0.32b	10.83
S100	19.79	4.96	0.16	66.84c	60.46b	132.67c	4.4	3.27	8.38a	14.30	72.30c	0.38a	0.37a	17.17
H120	20.27	6.95	0.22	69.58b	62.92a	145.92b	4.39	2.19	7.23cb	13.63	82.97ab	0.36 b	0.34ab	5.33
H140	20.02	7.76	0.25	71.73a	64.68a	165.58a	4.46	2.62	6.96c	13.67	88.56a	0.34b	0.33b	9.67
H160	20.70	6.40	0.19	69.50b	62.63ab	150.59b	4.41	2.67	7.57b	13.85	79.61bc	0.36ab	0.34ab	11.05
Significance Level	*0.1938ns*	*0.0863ns*	*0.0844ns*	*0.0015*	*0.0315*	*0.0006*	*0.4683ns*	*0.3706ns*	*<0.0001*	*0.0555ns*	*0.0038*	*0.0154*	*0.0115*	*0.4487ns*
Contrast linear	0.9684	0.7467	0.7633	0.2606	0.1316	0.0500	0.5897	0.7150	0.1915	0.9113	0.5094	0.7404	0.9028	0.6099
Contrast quadratic	0.0458	0.7003	0.6717	0.3468	0.9106	0.3066	0.5581	0.8843	0.7653	0.4547	0.8197	0.2695	0.1327	0.7021
Contrast cubic	0.5974	0.0081	0.0066	<0. 0001	0.0040	<0.0001	0.1981	0.2353	<0.0001	0.0128	0.0002	0.0013	0.0012	0.2779
LSD (5%)	*1.01*	*2.10*	*0.06*	*2.10*	*2.44*	*12.66*	*0.10*	*1.08*	*0.50*	*0.55*	*7.77*	*0.03*	*0.03*	*12.73*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)

**Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5–5; dark 0.5 and light 5)

*** Percentage starch breakdown was determined using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Table 4: The effect of different nutrient application levels for 18 months on the growth and distribution of roots a month before harvest in 'Brookfield Gala' apple tree during the 2006/2007 season. Root number is the average per 20 cm^3 and the root length is the average total length per 20 cm^3 soil

Treatment	Fine root number**			Fine root length (cm)			Thick root number***			Thick root length (cm)		
Soil depth (mm)	0–200	200–400	Total****	0–200	200–400	Total****	0–200	200–400	Total****	0–200	200–400	Total****
L80	20.33	19.33	39.67	397.33	404.00	801.33	2.00	2.67	4.67	52.00	66.00	118.00
S100	25.67	19.00	44.67	422.00	399.33	821.33	2.33	2.67	5.00	64.67	94.67	159.33
H120	19.67	17.33	37.00	378.00	336.33	714.33	3.33	1.67	5.00	100.00	54.67	154.00
H140	15.33	18.67	34.00	257.67	305.33	562.67	2.67	2.00	4.67	93.33	62.67	156.00
H160	17.67	16.67	34.33	381.00	316.67	697.33	3.00	2.33	5.33	116.00	83.33	199.33
Significance Level	*0.1242ns*	*0.8421ns*	*0.3959ns*	*0.5031ns*	*0.2317ns*	*0.3566ns*	*0.6108ns*	*0.7169ns*	*0.9909ns*	*0.5005ns*	*0.7294ns*	*0.8044ns*
Contrast linear	0.0754	0.3865	0.1377	0.3784	0.0417	0.1437	0.2738	0.4996	0.7811	0.1090	0.9714	0.3019
Contrast quadratic	0.6458	0.9648	0.7682	0.6413	0.6389	0.6025	0.4983	0.3962	0.9375	0.8359	0.7174	0.9487
Contrast cubic	0.0469	0.7548	0.2511	0.1776	0.3906	0.1890	0.8709	0.6103	0.7116	0.9407	0.2921	0.5591
LSD (5 %)	*7.91*	*6.38*	*13.34*	*217.89*	*114.38*	*296.92*	*2.05*	*1.94*	*3.59*	*89.58*	*74.37*	*148.91*

* Means within a column followed by different letters are significantly different (P =0.05; LSD)
** Fine roots 5 mm diameter and less
*** Thick roots more than 5 mm diameter
**** Total is the total number or length from 0- 400 mm soil depth

Table 5: The effect of biological ameliorants applied for four months on yield and fruit quality of a 25-fruit sample of Brookfield Gala apple trees at harvest (2005–2006 season)

Treatment	Yield (kg/ tree)	Estimated yield** (t/ ha)	Diameter (mm)	Mass (g)	Background Colour *** Back	Blush	Firmness (kg)	TSS % Brix)	Starch**** (%)	Malic acid (%)	Citric acid (%)
STD	12.78	23.86	67.46	135.56	4.11	2.71	8.40	14.15	60.03a	0.43	0.41
STD +HA	13.47	25.17	67.92	138.60	3.89	3.40	8.42	13.74	46.51b	0.45	0.43
STD+C+CE	12.64	23.84	66.58	130.38	4.10	3.51	8.51	14.39	52.85ab	0.47	0.45
Significance Level	*0.8682 ns*		*0.0517ns*	*0.0595ns*	*0.0631ns*	*0.1659ns*	*0.8552ns*	*0.1178ns*	*0.0388*	*0.1125ns*	*0.1036ns*
LSD (5%)	*3.57*		*1.08*	*6.77*	*0.18*	*0.92*	*0.41*	*0.63*	*10.10*	*0.03*	*0.03*

* Means within a column followed by different letters are significantly different (P =0.05; LSD)
**Estimated yield is obtained by multiplying the yield (in kg) by 2000 trees/ha
***Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5–5; dark 0.5 and light 5)
**** Percentage starch breakdown was determined using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Table 6: The effect of different nutrient levels on final fruit and shoot growth of Brookfield Gala apple trees over two seasons

Treatment	Final fruit growth (05–06 season)*	Final fruit growth (06–07 season)*	Final shoot growth (05–06 season)*	Final shoot growth (06–07 season)*
STD	66.63	64.28	28.04	32.61
STD+ HA	67.07	63.94	28.26	31.37
STD+ C+ CE	65.72	64.38	27.80	27.90
Significance Level	*0.0832ns*	*0.7359ns*	*0.9282ns*	*0.2115ns*
LSD (5%)	*1.24*	*1.44*	*2.88*	*4.58*

* Means within a column followed by different letters are significantly different (P =0.05; LSD)
*Final fruit size and shoot length as adjusted for initial size and length

Table 7: The effect of biological ameliorants on yield and fruit quality of Brookfield Gala apple trees at harvest (2006–2007 season)

Treatment	Trunk circumference (cm)	Yield (kg/tree)	Yield efficiency	Diameter (mm)	Length (cm)	Mass (g)	Background Colour**		Firmness (kg)	TSS (% Brix)	Starch*** (%)	Malic acid (%)	Citric acid (%)	Sunburn (%)
							Back	Blush						
STD	20.70	7.48a	0.22a	68.67	61.76	140.46	4.45	2.68	7.76	14.11b	76.30	0.35b	0.34b	20.38
STD +HA	20.36	6.21ab	0.18ab	67.65	61.69	136.58	4.43	3.15	8.18	14.66^a	70.90	0.41a	0.39a	22.51
STD+C+CE	19.63	4.51b	0.15b	66.81	61.44	133.46	4.38	3.84	7.94	15.01a	72.80	0.41a	0.40a	24.52
Significance Level														
TRT	*0.1217ns*	*0.0169*	*0.0330*	*0.1148ns*	*0.9616ns*	*0.3313ns*	*0.5454ns*	*0.0945ns*	*0.2710ns*	*0.0084*	*0.2561ns*	*0.0006*	*0.0008*	*0.5848ns*
Covariate mass	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*<.0001*	*-*	*0.0033*	*0.1716*	*-*
TRT****	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*0.0314*	*-*	*0.0009*	*0.0015*	*-*
LSD (5%)	*1.06*	*1.92*	*0.05*	*1.77*	*2.58*	*9.72*	*0.14*	*1.05*	*0.54*	*0.53*	*6.78*	*0.03*	*0.03*	*8.41*

* Means within a column followed by different letters are significantly different (P=0.05; LSD)

** Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark 0.5 and light 5)

*** Percentage starch breakdown was determined using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

**** Significance level following covariate analysis

Table 8: The effect of biological ameliorants application for 18 months on the growth and distribution of roots a month before harvest in Brookfield Gala apple tree during the 2006/2007 season. Root number is the average per 20 cm^3 and the root length is the average total length per 20 cm^3 soil

Treatment	Fine root number**			Fine root length (cm)			Thick root number***			Thick root length (cm)		
Soil depth (mm)	0–200	200–400	Total****	0–200	200–400	Total****	0–200	200–400	Total****	0–200	200–400	Total****
STD	14.00	15.33	29.33	212.00	217.00	429.00	2.67	1.67	4.33	84.67	47.67	132.67
STD+HA	17.33	19.00	36.33	290.00	354.33	644.33	3.33	2.00	5.33	95.67	71.00	166.67
STD+C+CE	16.00	16.67	32.67	269.67	333.67	603.67	2.33	2.00	4.33	80.33	56.66	136.67
Significance Level	0.5163ns	0.4927ns	0.4821ns	0.2531ns	0.2185ns	0.2040ns	0.6489ns	0.8403ns	0.1600ns	0.9495ns	0.6992ns	0.7228ns
LSD (5%)	7.44	7.91	14.65	113.04	192.62	288.30	2.88	1.77	1.31	135.44	74.23	122.90

* Means within a column followed by different letters are significantly different (P =0.05; LSD)
** Fine roots 5 mm diameter and less
*** Thick roots more than 5 mm diameter
**** Total is the total number or length from 0- 400 mm soil depth

Chapter 5

General conclusions

Young and bearing Brookfield Gala apple trees were studied in the Greyton area near Genadendal in the Western Cape Province. These trees were planted in a well-drained and well aerated Dundee loamy sand soil, which can enhance a good root system and promote healthy tree development. Sequential excavations were done in order to determine the macro and micro nutrient uptake, distribution and requirements in two- and three-year-old apple trees. The following conclusions were drawn from the results of studies performed on the two- and three-year 'Brookfield Gala' apple trees.

A) In the two-year-old apple trees the N, P, K, Ca, Mg and S accumulated very slowly from bud break until early winter. The increase in the tree accounted for ±29.2 g N, ±3.5 g P, ±19.3 g K, ±18.4 g Ca, ±3.6 g Mg and ±1.7 g S. At harvest, fruit contained approximately ±4.5% N, ±5.7% P, ±11.9% K, ±1.1% Ca, ±2.8% Mg and ±5.9% S of the total content of each of these elements in the tree at that stage. These young trees continued taking up nutrients throughout the season because they were still growing to fill the space allocated to them.

In the three-year-old trees it was found that ±54.4%, ±46.9%, ±23.4%, ±49.6%, ±35.8% and ±25.5% of N, P, K, Ca, Mg and S, respectively, was taken up in the post-harvest period. From the total leaf content ±63.7% N, ±39.4% P, ±12.3% K, ±34.7% Mg and ±70.6% S was re-distributed back to the permanent parts before final leaf drop. The following distribution of reserves from the permanent structure took place in order to support new growth: N (±42.2%), P (±13.8%), K (±23.4%), Ca (±66.9%) and Mg (±35.0%). The N distribution at harvest was as follows: in the fruit ±27.2%, leaves ±23.8%, new shoots 3.6%, permanent parts ±29.2% and roots ±16.2%. At harvest the fruit, leaves, new shoots, permanent parts and roots contained ±29.5%, ±14.3%, ±4.5%, ±32.1% and ±19.6% of total P, respectively. The K content distribution at harvest was as follows: in the fruit (±60.2%), leaves (±17.1%), new shoots (±2.0%), permanent parts (±15.6%) and roots (±5.2%). At harvest the fruit, leaves, new shoots, permanent parts and roots contained ±2.3%, ±39.7%, ±7.2%, ±40.8% and ±10.0% of total Ca, respectively. At harvest the fruit (±20.8%), leaves (±37.5%), new shoots (5.2%), permanent parts (±28.1%) and roots (±8.3%) contributed to the total tree Mg content. The S content at harvest was distributed as follows: in the fruit ±23.7%, leaves ±20.3%, new shoots ±3.4%, permanent parts ±33.9% and roots ±18.6%.

B) The micro nutrients Na, Mn, Fe, Cu, Zn and B in the 2nd leaf apple trees accumulated rapidly from beginning of bud break until early winter. This accumulation in the tree accounted for ±1100.8 mg Na, ±75.0 mg Mn, ±431.3 mg Fe, ±18.8 mg Cu, ±78.6 mg Zn and ±56.9 mg B. At harvest, fruit contained ±2.2% Na, ±4.3% Mn, ±2.0% Fe, ±4.8% Cu, ±2.5% Zn and ±15.1% B of the total content of each of these elements in the tree, respectively. These young trees continued taking up nutrients since they were still growing.

In the bearing 3rd leaf apple trees the micro nutrient accumulated rapidly from late winter to late autumn. In the three-year-old trees it was found that ±7.8% Na, ±37.6% Mn, ±62.1% Fe, ±60.2% Cu, ±13.8% Zn and ±36.4% B were taken up in the post-harvest period. From the total leaf content 0% Na, ±25.2% Mn, ±100.0% Fe, ±100.0% Cu, ±0.0% Zn and ±35.4% B was redistributed back to the permanent parts before final leaf drop. The following distributions of reserves from the permanent structure took place in order to support new growth: ±62.4% Na, ±28.5% Mn, ±100.0% Fe, ±100.0% Cu, ±86.4% Zn and ±100.0% B. The Na distribution in the fruit, leaves, new shoots, permanent parts and roots at harvest was as follows: ±20.0%, ±23.8%, ±4.2%, ±36.9% and ±15.1%, respectively. The Mn distribution at harvest in the fruit, leaves, new shoots, permanent parts and roots was ±9.8%, ±63.9%, ±2.7%, ±18.0% and ±5.7%, respectively. At harvest, the fruit (±17.7%), leaves (±18.5%), new shoots (±2.9%), permanent parts (±41.3%) and roots (±19.5%) contributed to the total tree Fe content. The Cu content at harvest was distributed as follows in the fruit (±28.9%), leaves (±10.0%), new shoots (±4.4%) permanent parts (±45.0%) and roots (±11.7%). At harvest the fruit (±6.2%), leaves (±29.1%), new shoots (5.4%), permanent parts (±44.8%) and roots (±14.5%) contributed to the total tree Zn content. The distribution of B at harvest in the fruit, leaves, new shoots, permanent parts and roots was ±54.4%, ±15.4%, ±3.3%, ±21.4% and ±5.5%, respectively.

C) Guidelines for nutrient requirements were determined by calculating losses through fruit removal, leaf fall, pruning, as well as fixture in the permanent parts. Maximum nutrient loss was calculated by adding the amount of nutrient in the fruit and permanent parts at harvest, summer and winter prunings, as well as the leaves at early winter. Minimum loss excluded the losses due to leaf drop and prunings. A two-year-old apple tree needs the following macro nutrients to maintain growth and reproductive development: ±34.5 g N, ±3.7 g P, ±23.8 g K, ±23.9 g Ca, ±5.8 g Mg, ±1.8 g S, ±859.6 mg Na, ±117.8 mg Mn, ±541.3 mg Fe, ±18.1 mg Cu, ±92.8 Zn mg, ±79.4 mg B and ±2.1 mg Mo. For the three-year-old trees it was found that (g.

kg^{-1} & mg. kg^{-1} yield) for N (±1.7g), P (±0.3g), K (±2.3g), Ca (±0.5g), Mg (±0.2g), S (±0.2g), Na (±75.1mg), Mn (±1.3mg), Fe (±28.7mg), Cu (±0.9mg), Zn (±3.0mg), B (±5.7mg) and Mo (±0.3mg) is necessary to produce 1kg of fruit.

D) Labelled N uptake and distribution results indicate that there was a low uptake of labelled N in the initial growth stages, suggesting the importance of internal N reserves for plant development at the beginning of the season. Furthermore, early in the season low temperatures in the Genadendal area (on the banks of a river) also possibly caused low root activity, and there were few leaves for photosynthesis during this stage. Leaching also probably removed N from the soil. In the active growing period more labelled N was found in the new growth. This trend changed in early winter, as reserves started building up in the permanent parts (permanent structure and roots). Thus the permanent parts contained the most labelled N in proportion to the new growth. Nitrogen uptake efficiency indicates that early in the season the uptake is low due to unfavourable soil temperature and low root and leaf activity. As the season progresses to the active growth stages the trees start taking up labelled N more effectively. In general, the tree uptake efficiency in this study was very low; it reached a maximum of 17.0% in summer (Dec 05) in the case of the three-year-old trees. The tree uptake efficiency of the trees might improve as the trees grow older and a bigger root system develops that can take up more N. This was observed from the N uptake efficiency of trees excavated a little later in the present study. This study confirmed the annual cyclic nature of N transformations in the apple trees, which can be summarised in two steps: (1) N is mobilised in the autumn from senescing leaves to storage tissues, and (2) this N is re-utilised in the spring through storage protein hydrolysis to supply N for developing tissues.

E) During the 2005/2006 season the different nutrient levels had no effect on yield. The yield was between 27 and 33 t/ha for the three-year-old Brookfield Gala trees. Overall, no definite trend was observed in fruit quality. During the 2006/2007 season, with the lower yield (5–8 t/ha), the differences in fruit size, firmness, starch breakdown, malic acid and citric acid did not follow any trend. High nutrient levels (20%, 40% and 60% higher than the control) had a tendency towards a decrease in the number of shallow roots (0–400mm). These results indicate that the 80% nutrient level could be the optimum nutrient level since this nutrient level did not differ significantly from the two treatments that resulted in better fruit quality over the two seasons, although no trend was seen. Furthermore, the leaf nutrient levels of the 80% treatment were within the recommended norms.

During the 2005/2006 season, four months after starting with biological ameliorants, there were no differences between apple trees receiving the standard nutrient and those receiving the treatments to which humic acid and compost plus compost extract were applied. Yield differences during 2006/2007 (18 months, and over two bearing seasons after initial application) cannot be ascribed to treatment effects because of the effects of weather and wet soil conditions on yield. The application of biological ameliorants led to significantly higher TSS, malic acid and citric acid. This may indicate that certain biological products might affect the taste of apples. Although there were no significant differences in the statistical analysis results for the roots in these trials, there was a trend towards a greater number of fine roots and roots with increased length in the 0- 400mm cm soil depth.

Appendix

Appendix Table 1: Average dry weight content (trunk equilibrated data) in (g) and percentage distribution in different tree parts of 'Brookfield Gala' apple at different phenological stages in a) 2nd leaf trees, b) 3rd leaf apple trees

a)

Tree parts	Average dry weight (grams per tree or % of dry mass per tree)									
Phenological stage	Beginning of bud break	%	6 weeks after	%	Mid-summer	%	Harvest	%	Early winter	%
Fruit	-	-	9.0±2.0	0.6	9.2±2.8	0.5	240.0±17.8	7.8	-	-
Leaves	-	-	31.2±3.7	2.0	326.4±17.4	17.3	207.6±33.2	6.7	468.4±61.3	8.0
New shoots	-	-	114.3± 2.0	7.3	122.5±0.5	6.5	147.0± 48.1	4.8	656.0±122.2	11.2
Subtotal (new growth)	0	0	154.5±7.7	9.9	458.1±20.7	24.2	594.6±99.1	19.3	1124.4±183.5	19.2
Prunings*	-	-	-	-	-	-	400.2±60.7	13.0	1001.1±344.5	17.0
Permanent parts**	983.1±51.2	81.8	1175.7±80.7	75.4	1114.7±35.2	58.9	1752.3±111.2	56.9	2814.5±97.4	47.9
Roots***	219.4±15.6	18.2	229.9±49.8	14.7	319.1±25.9	16.9	330.9±20.6	10.8	935.8±227.3	15.9
Subtotal (Permanent structure)	1202.5±66.8	100.0	1405.6±130.5	90.1	1433.8±61.1	75.8	2483.4±192.5	80.7	4751.4±669.2	80.7
Total	1202.5±66.8	100.0	1560.1±138.2	100.0	1891.9±81.8	100.0	3078.0±291.6	100.0	5875.8±852.7	100 .0

* includes pruning shoots as well as leaves
** Permanent parts includes trunk, canopy branches and rootstock
*** Roots includes primary and secondary roots

b)

Tree parts	Average dry weight (grams per tree or % of dry mass per tree)									
Phenological stage	Late winter	%	Mid-summer	%	Harvest	%	Late autumn	%	Late winter	%
Fruit	-	-	297.7±28.1	4.4	5878.6±301.0	46.6	-	-	-	-
Leaves	-	-	1015.5±159.5	14.9	926.4±110.9	7.3	1474.0±84.7	13.7	-	-
New shoots	-	-	205.2±32.6	3.0	306.6±48.1	2.4	731.1±211.0	6.8	-	-
Subtotal (new growth)	0	0	1518.4±220.2	22.3	7111.6±460.0	56.3	2205.1±295.7	20.5	0	0
Prunings*	-	-	483.0±91.2	7.1	-	-	-	-	-	-
Permanent parts**	3704.7±250.3	79.8	4517.5±605.5	66.1	4548.3±670.0	36.1	7212.2±287.8	67.3	8164.4±676.5	85.2
Roots***	935.8±227.3	20.2	314.3±156.5	4.6	950.8±73.3	7.5	1310.4±400.4	12.2	1422.9±408.3	14.8
Subtotal (Permanent structure)	4640.5±477.6	100.0	5314.8±856.2	77.8	5499.1±743.3	43.6	8522.6±688.2	79.5	9587.3±1084.8	100.0
Total	4640.5±477.6	100.0	6833.2±1076.4	100.0	12610.7±1203.3	100.0	10727.7±983.9	100.0	9587.3±1084.8	100.0

*includes pruning shoots as well as leaves
** Permanent parts includes trunk, canopy branches and rootstock
*** Roots includes primary and secondary roots

a)
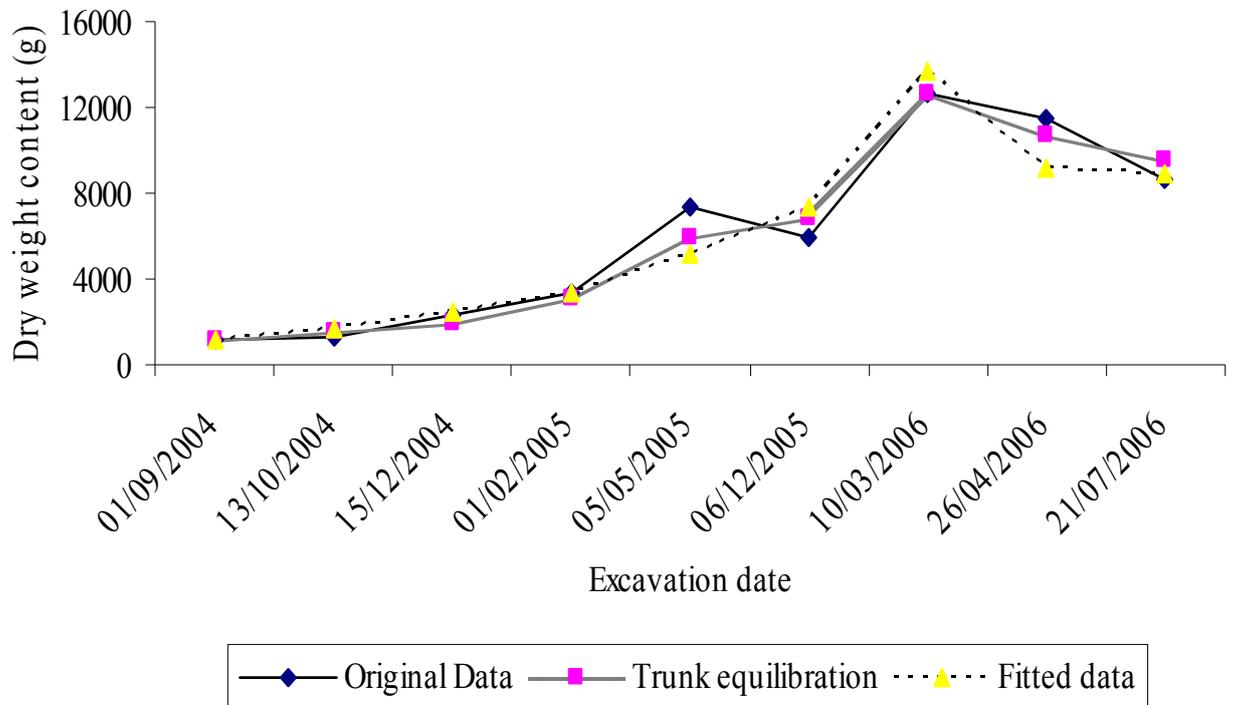
Appendix Figure 1a: Average seasonal accumulation dry weight content (g) in 'Brookfield Gala' apple tree for three senarious: The original data curve, fitted curve $(\ln(y)=ax^b$ and the trunk equilibrated curve

b)
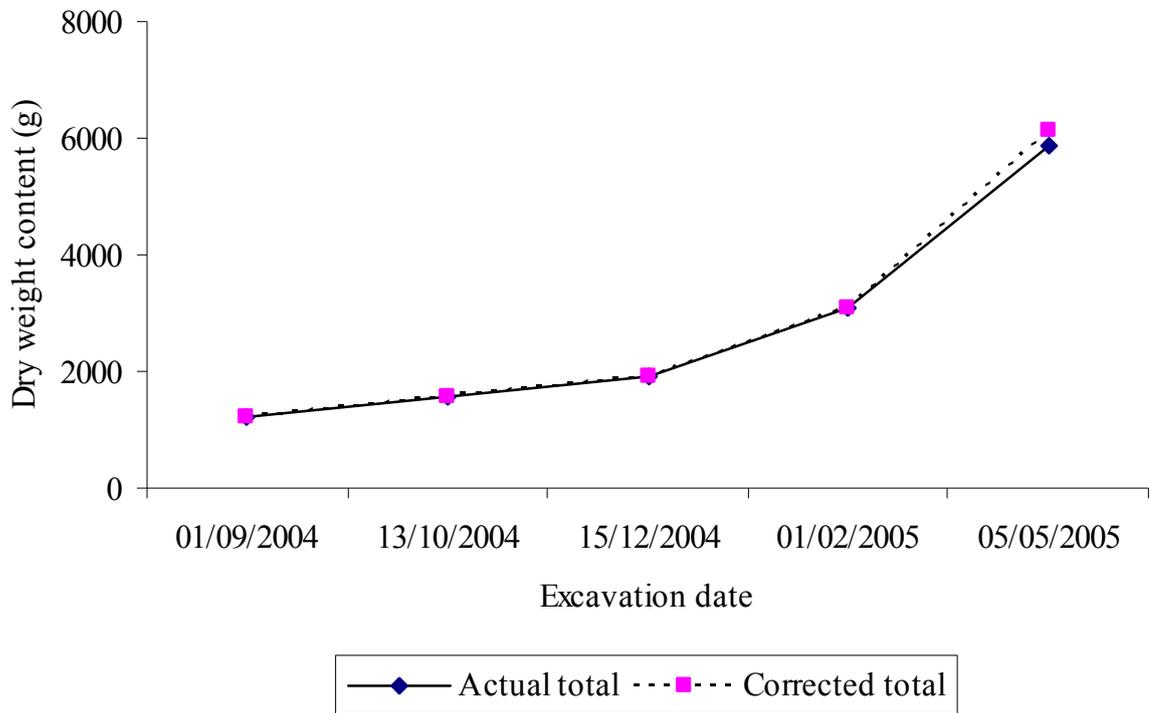
* Corrected total is corrected for fruit removed and leaves that dropped

c)
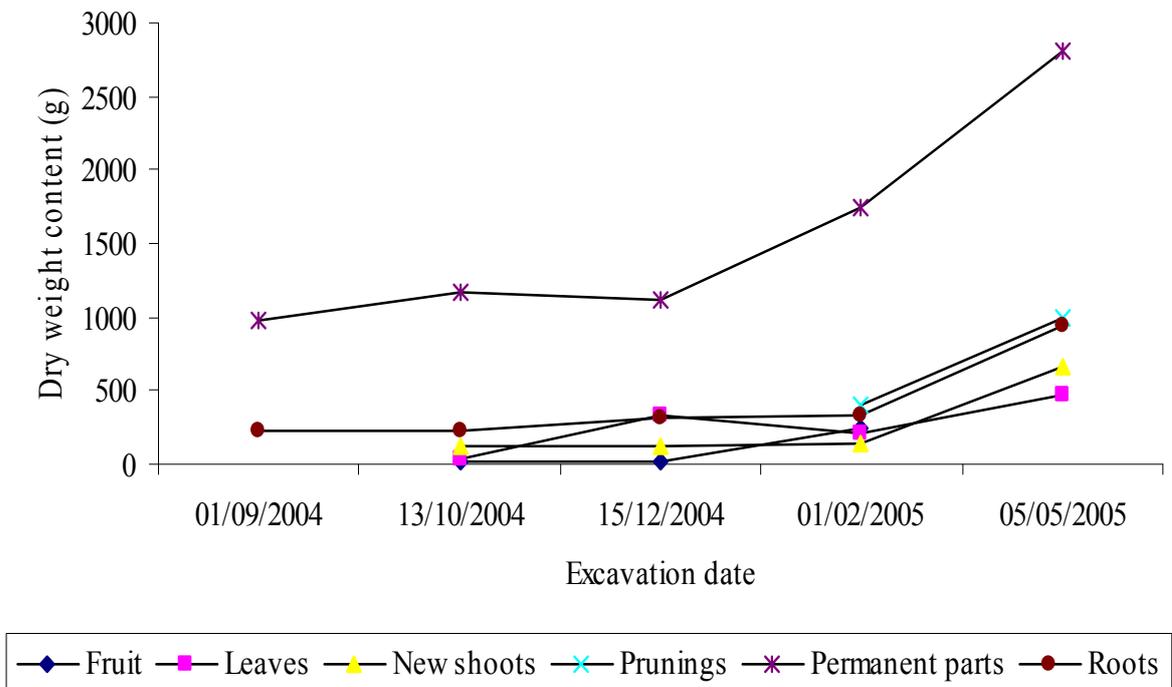
d)
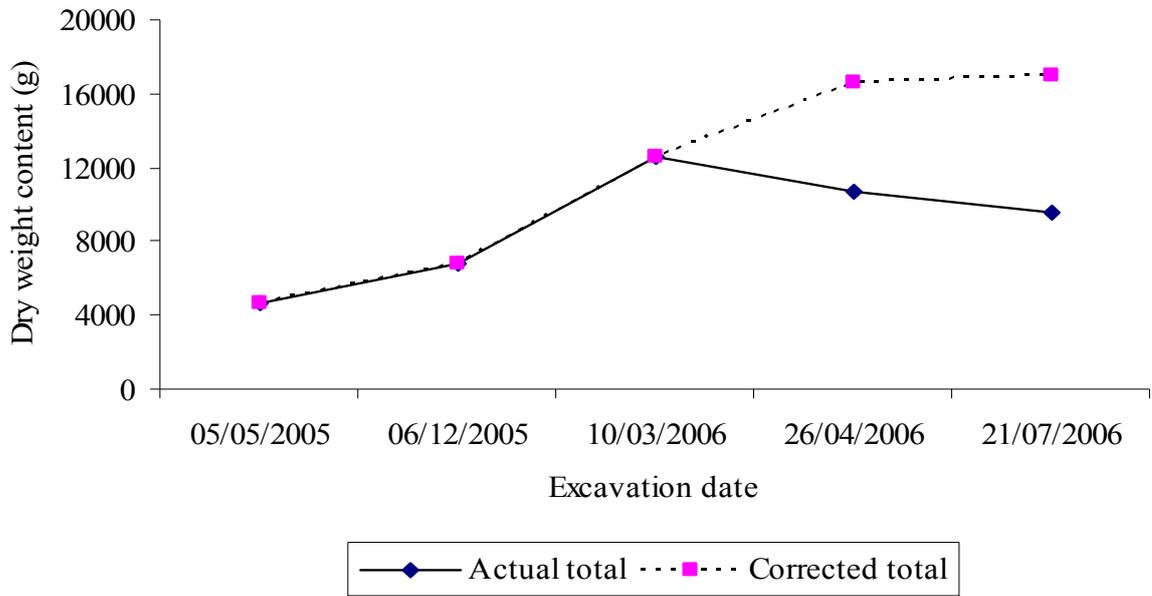
* Corrected total is corrected for fruit removed and leaves that dropped

e)
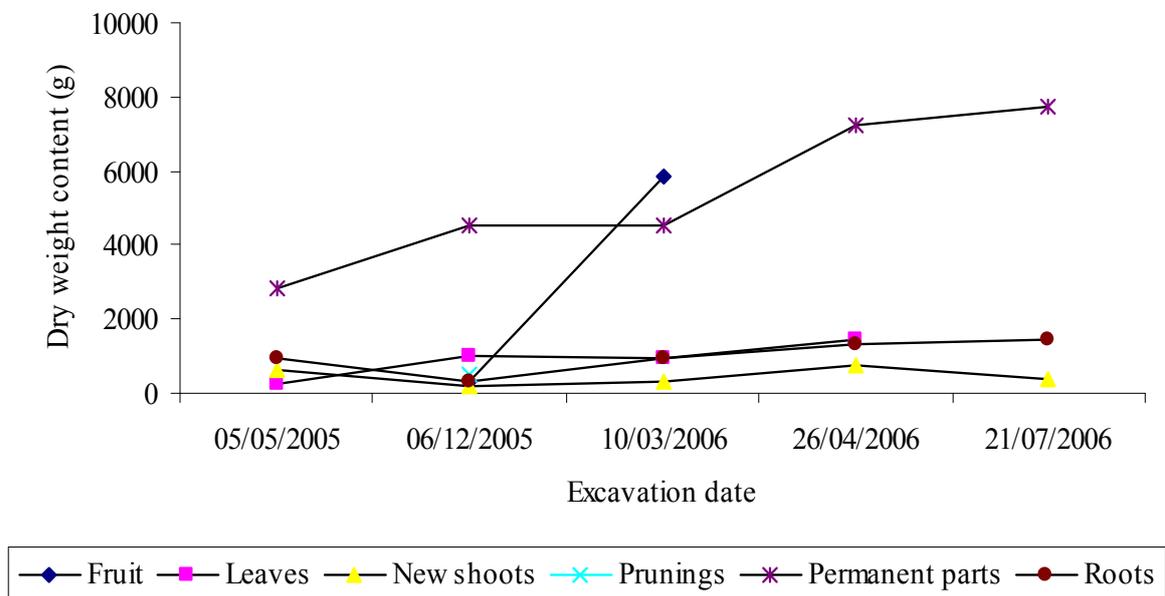
Appendix Figure 1b: Average seasonal accumulation (trunk equilibrated data) of dry weight in a 'Brookfield Gala' apple tree (b) 2nd leaf tree, (c) different parts of 2nd leaf tree, (d) 3rd leaf trees corrected for leaf fall and fruit yield, (e) different parts of 3rd leaf tree
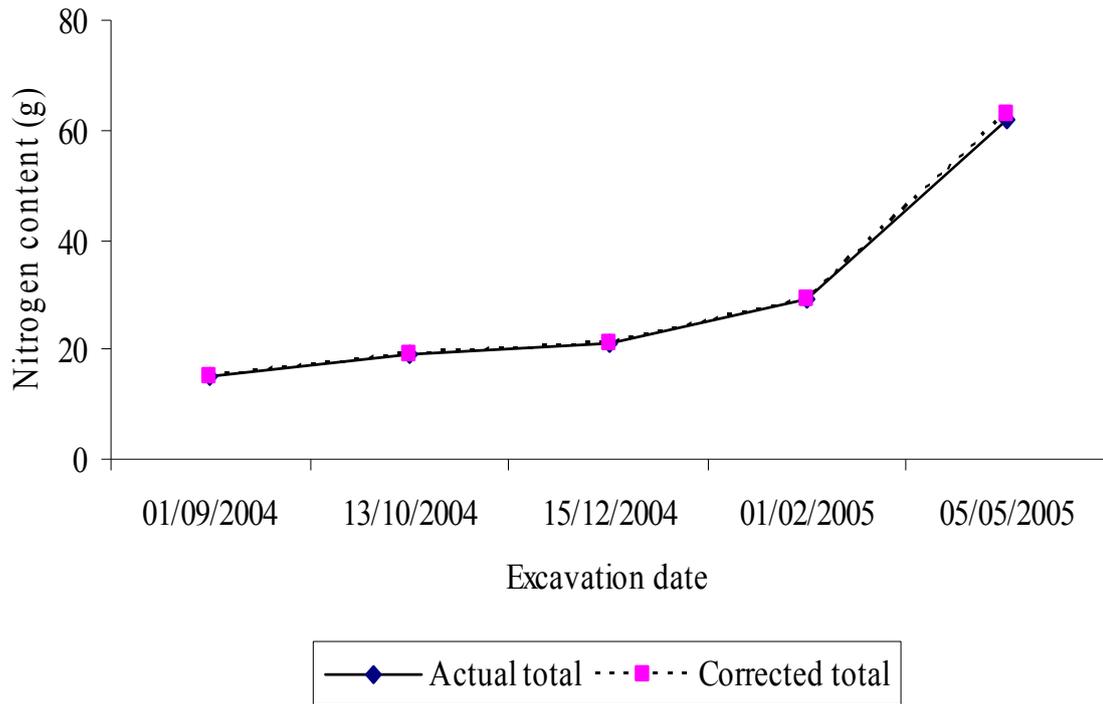
a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
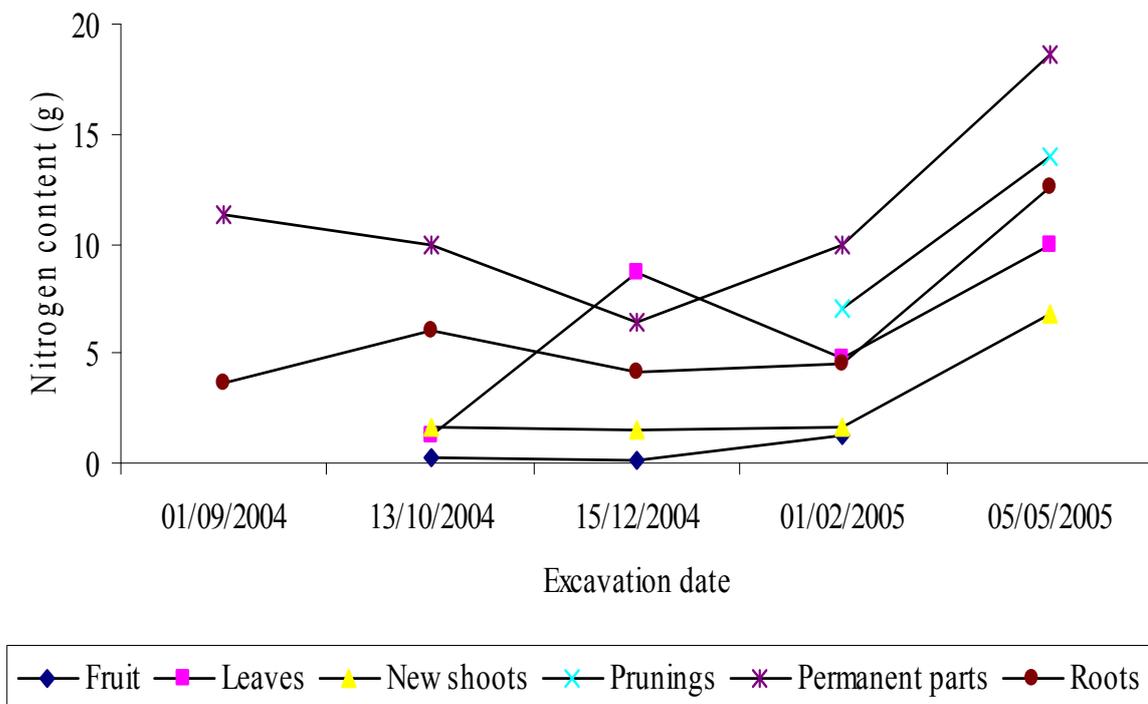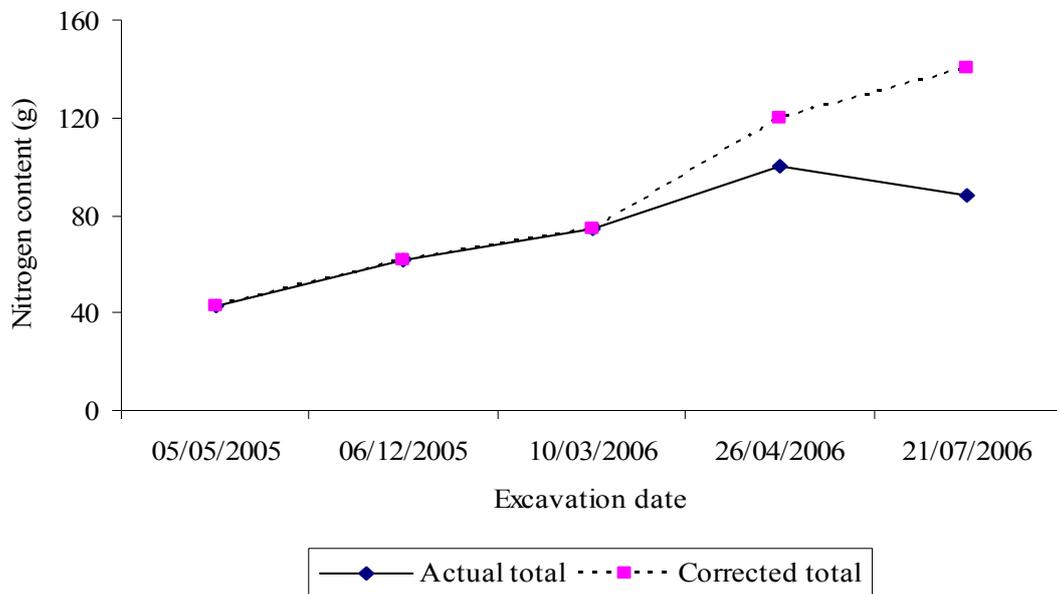
* Corrected total is corrected for fruit removed and leaves that dropped

d)
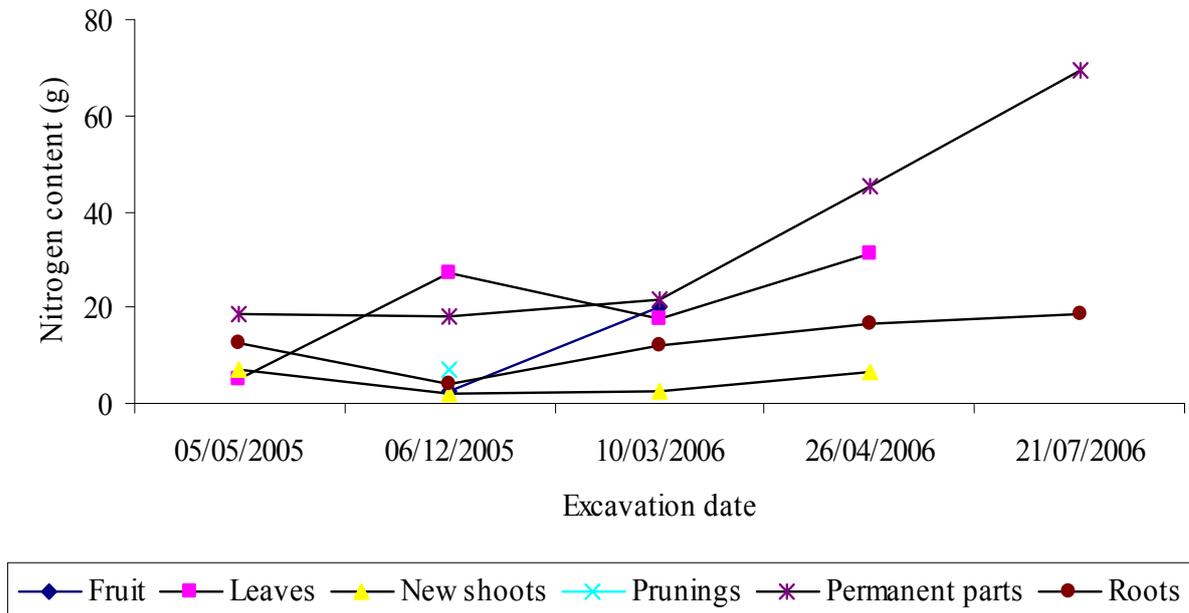
Appendix Figure 2: Average seasonal accumulation of nitrogen in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

Excavation date

* Corrected total is corrected for fruit removed and leaves that dropped

b)

Excavation date

c)
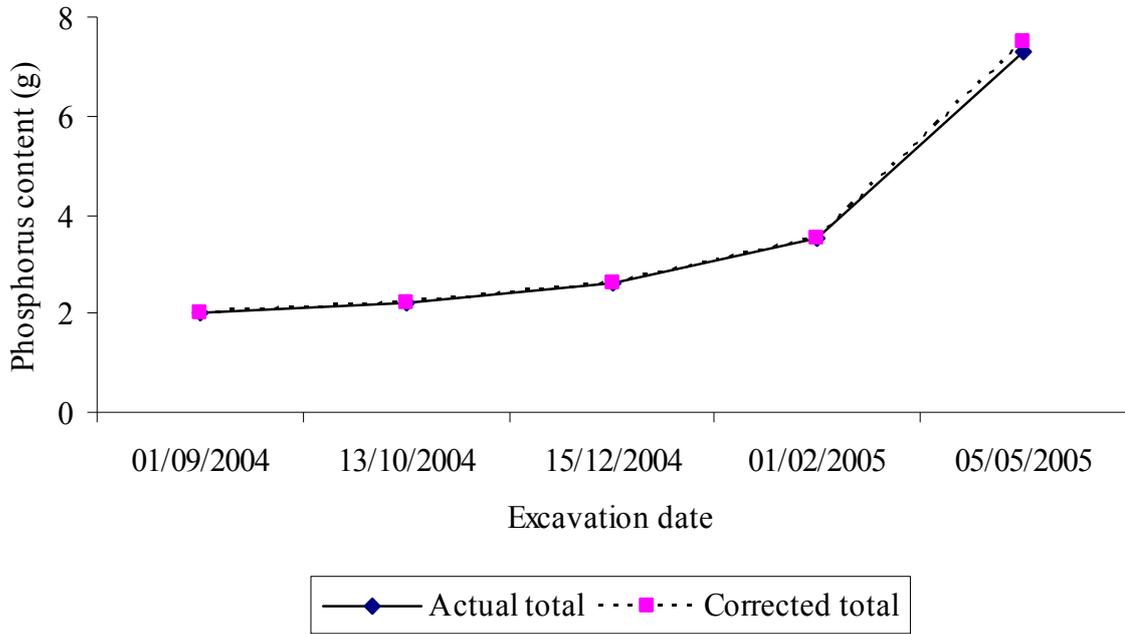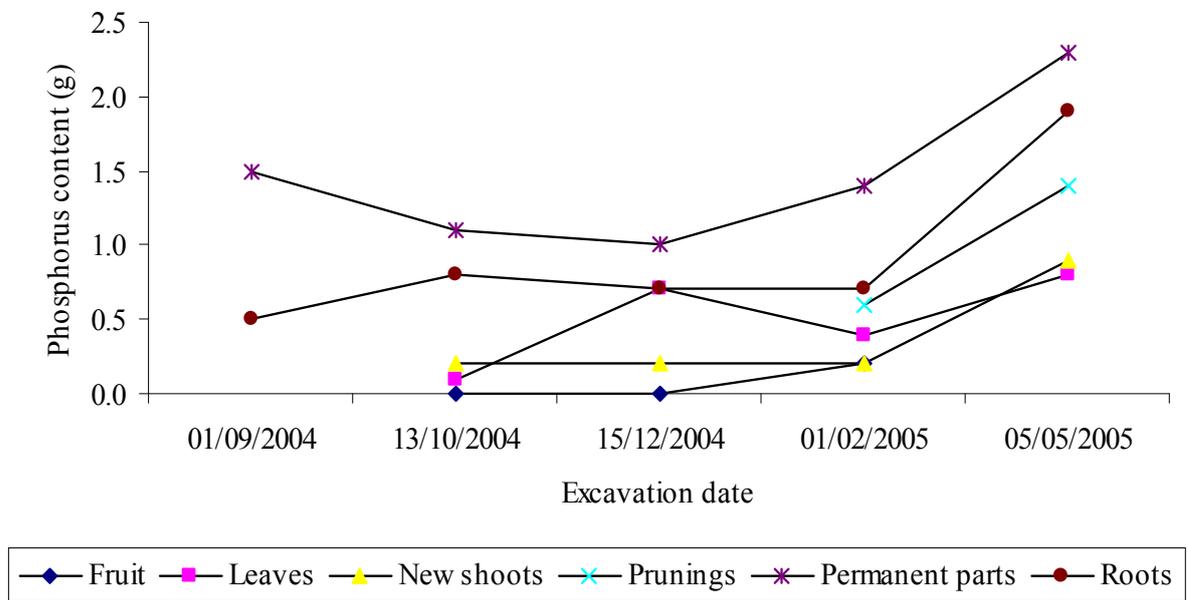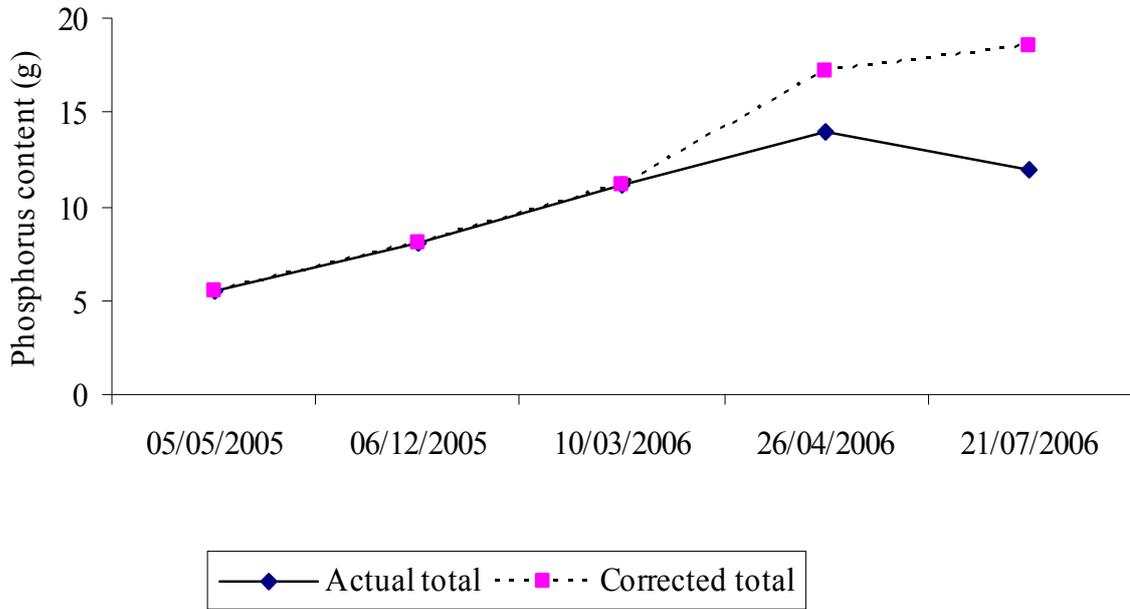
* Corrected total is corrected for fruit removed and leaves that dropped

d)
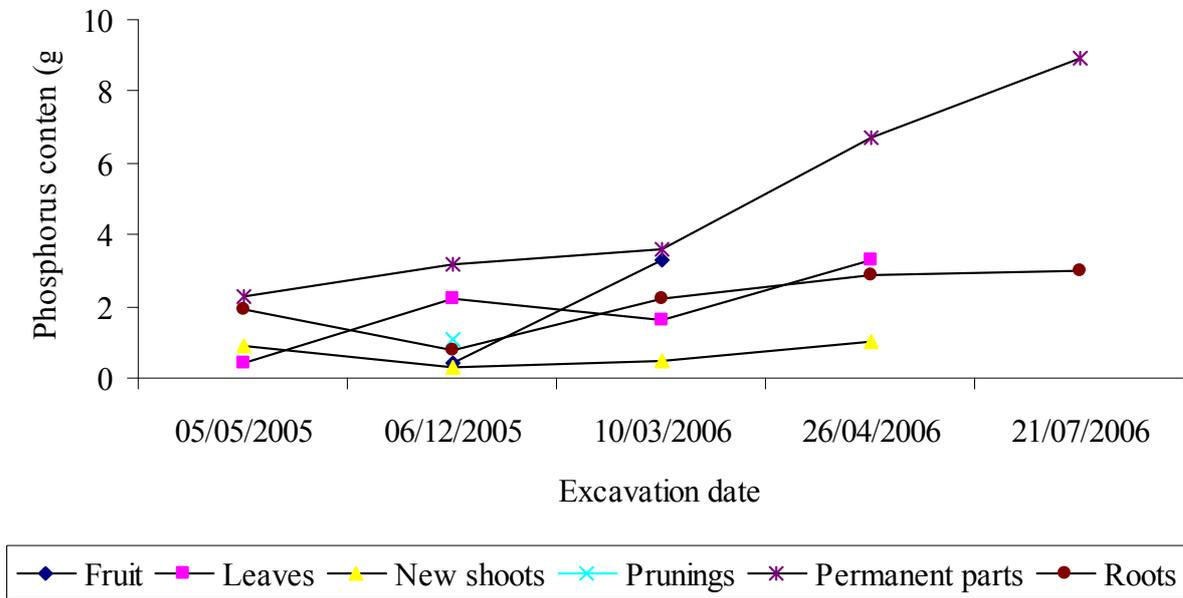
Appendix Figure 3: Average seasonal accumulation of phosphorus in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
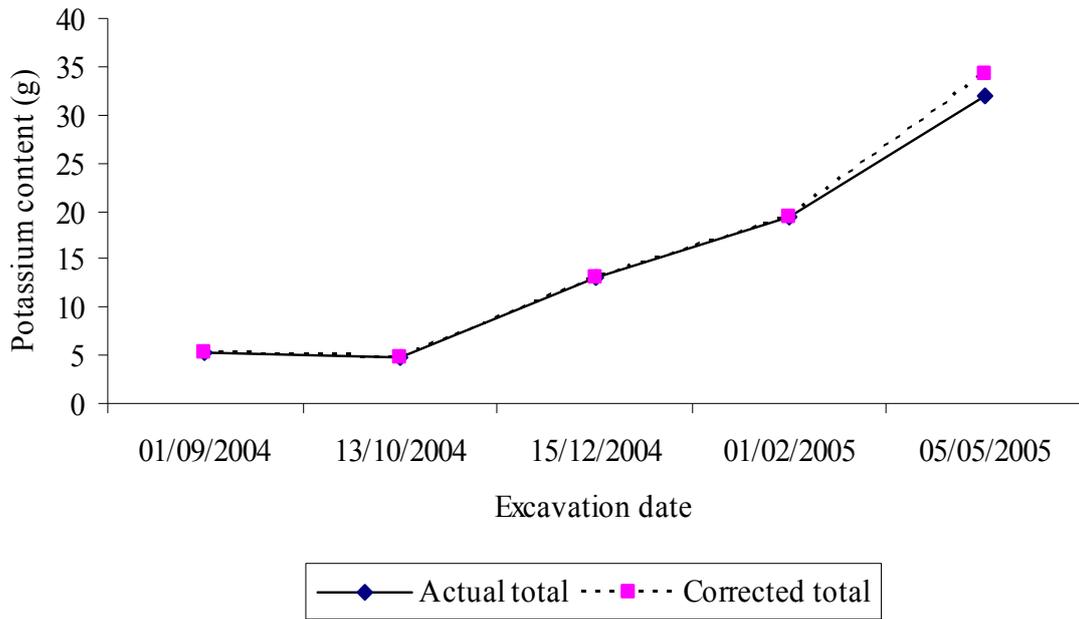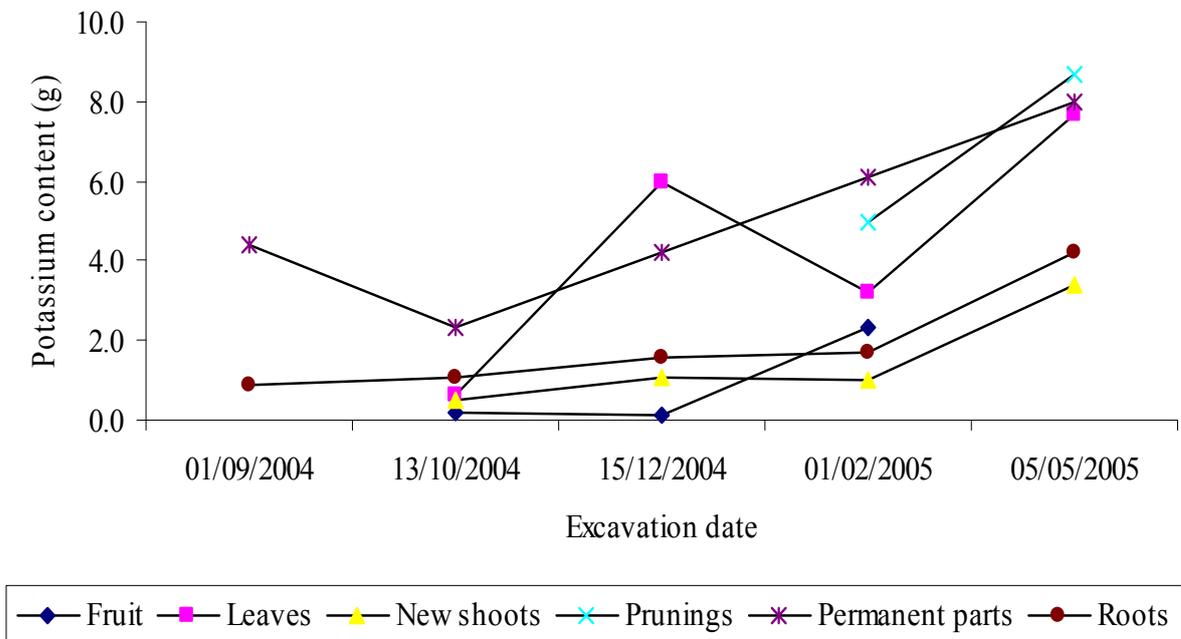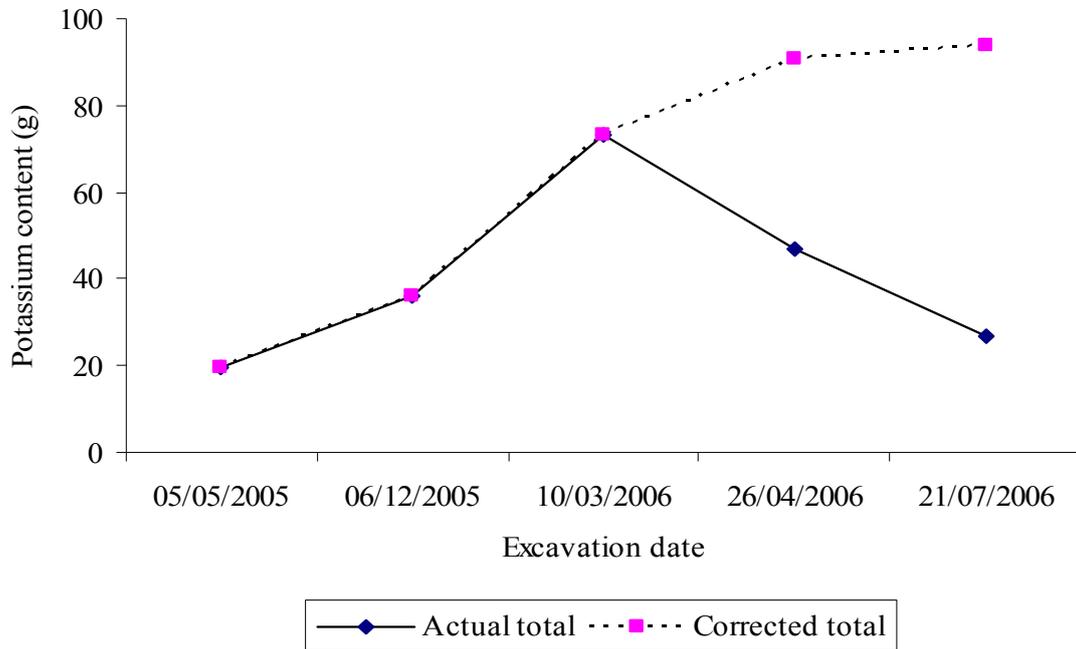
* Corrected total is corrected for fruit removed and leaves that dropped

d
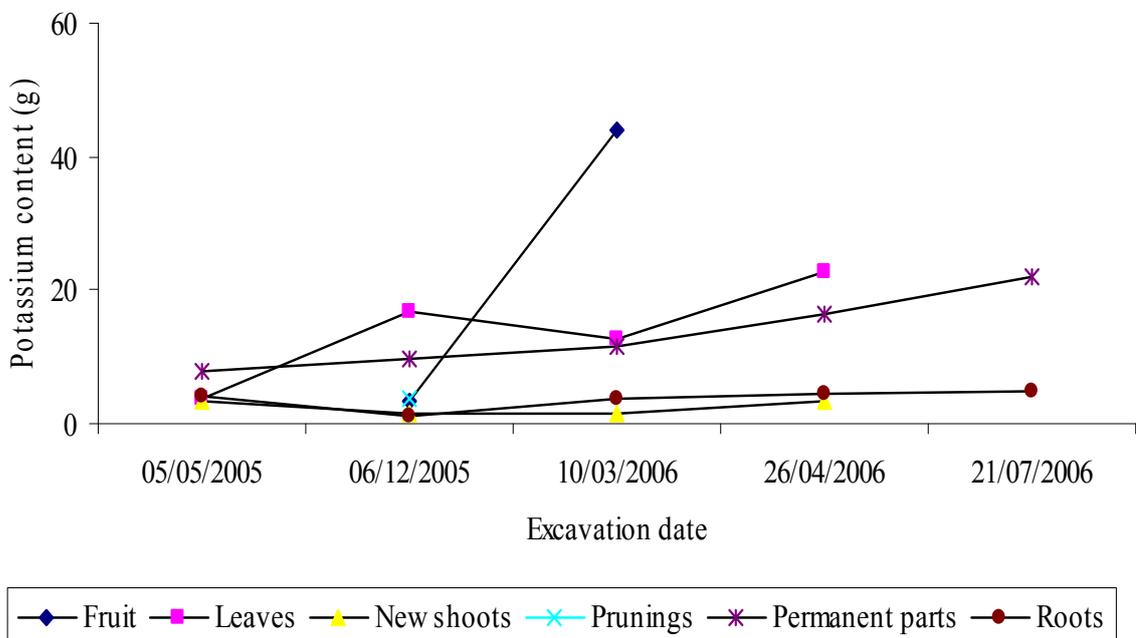
Appendix Figure 4: Average seasonal accumulation of potassium in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
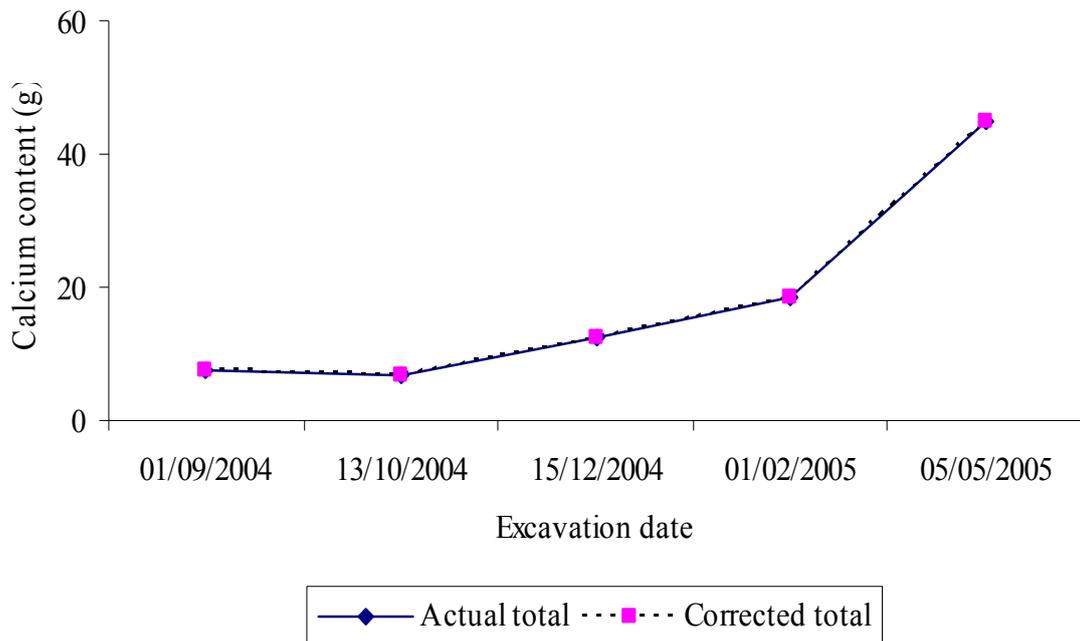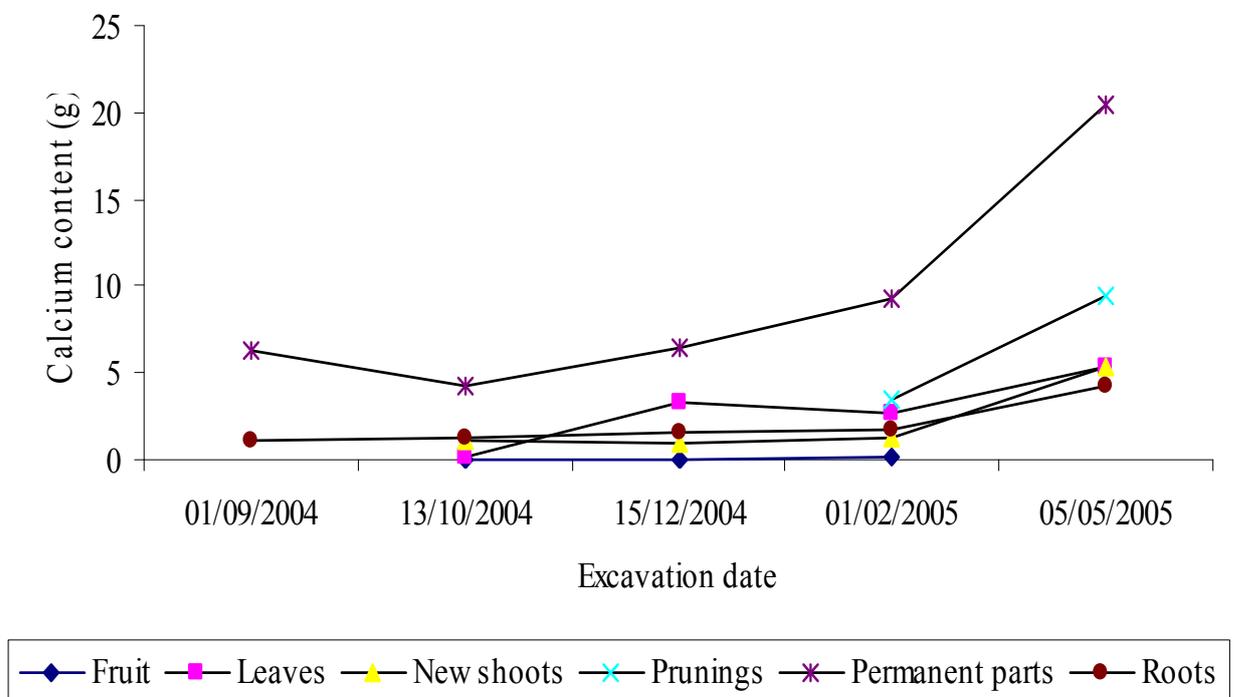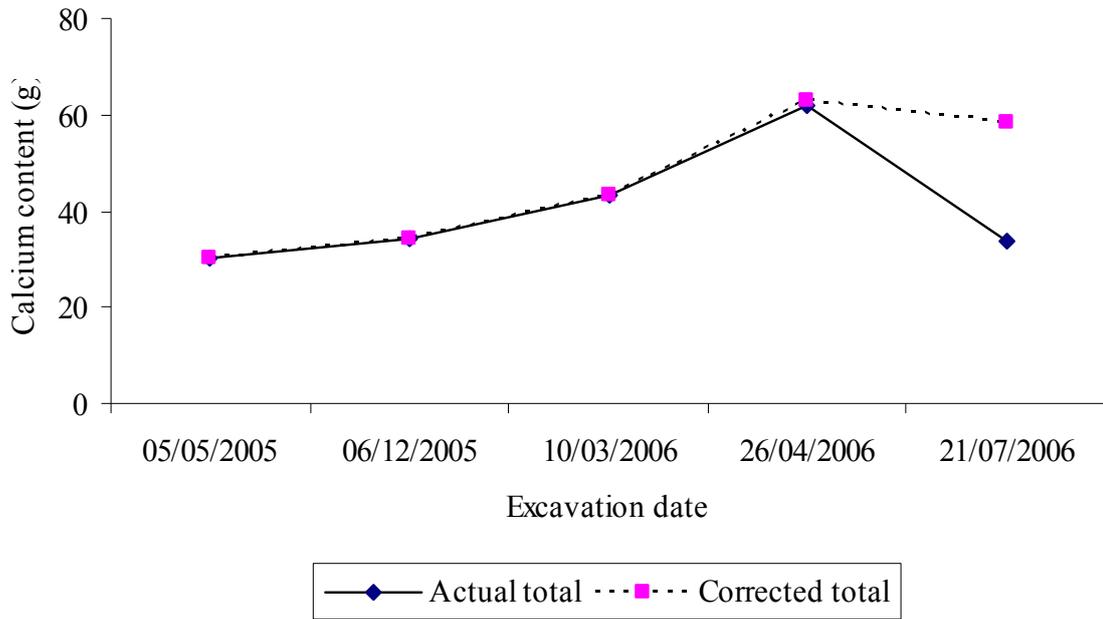
* Corrected total is corrected for fruit removed and leaves that dropped

d)
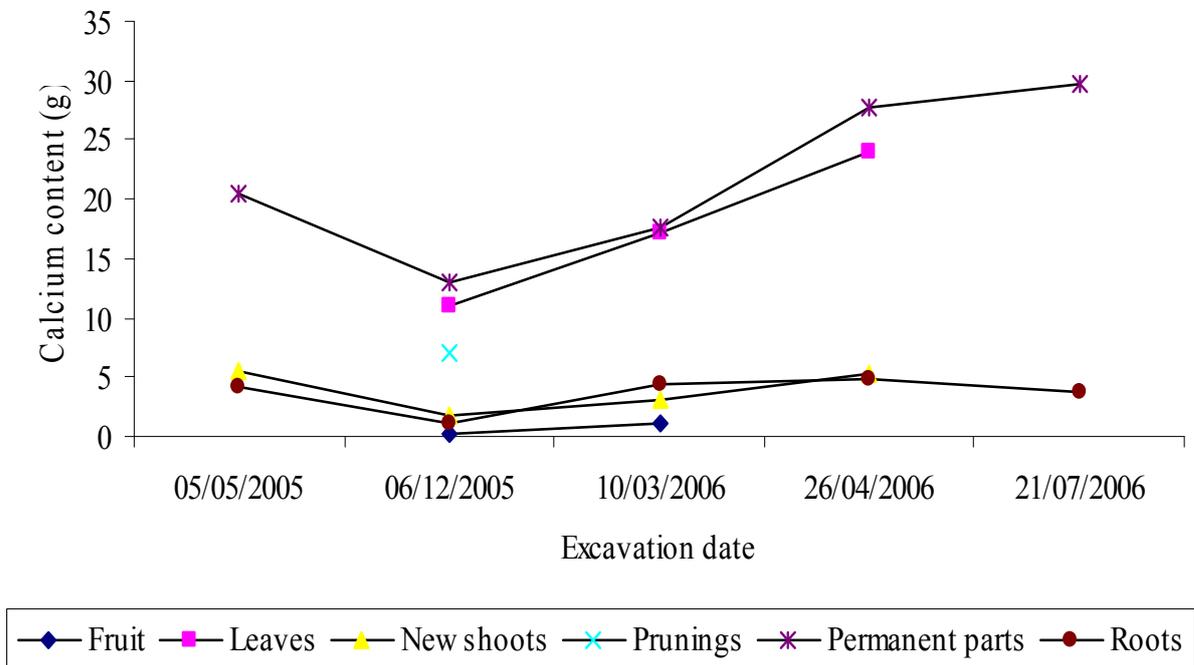
Appendix Figure 5: Average seasonal accumulation of calcium in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
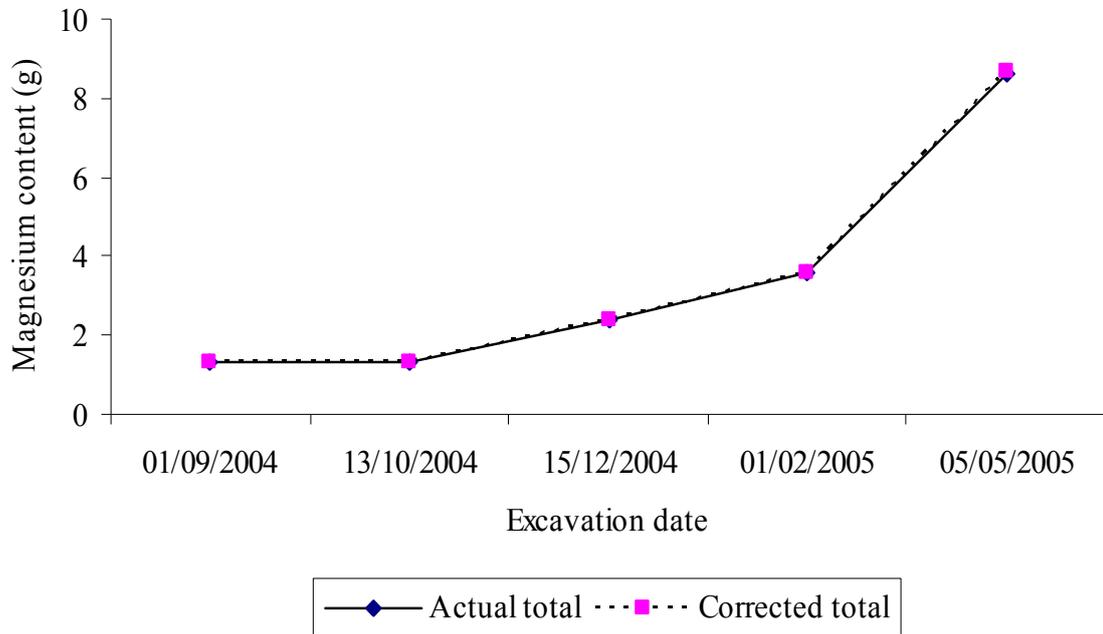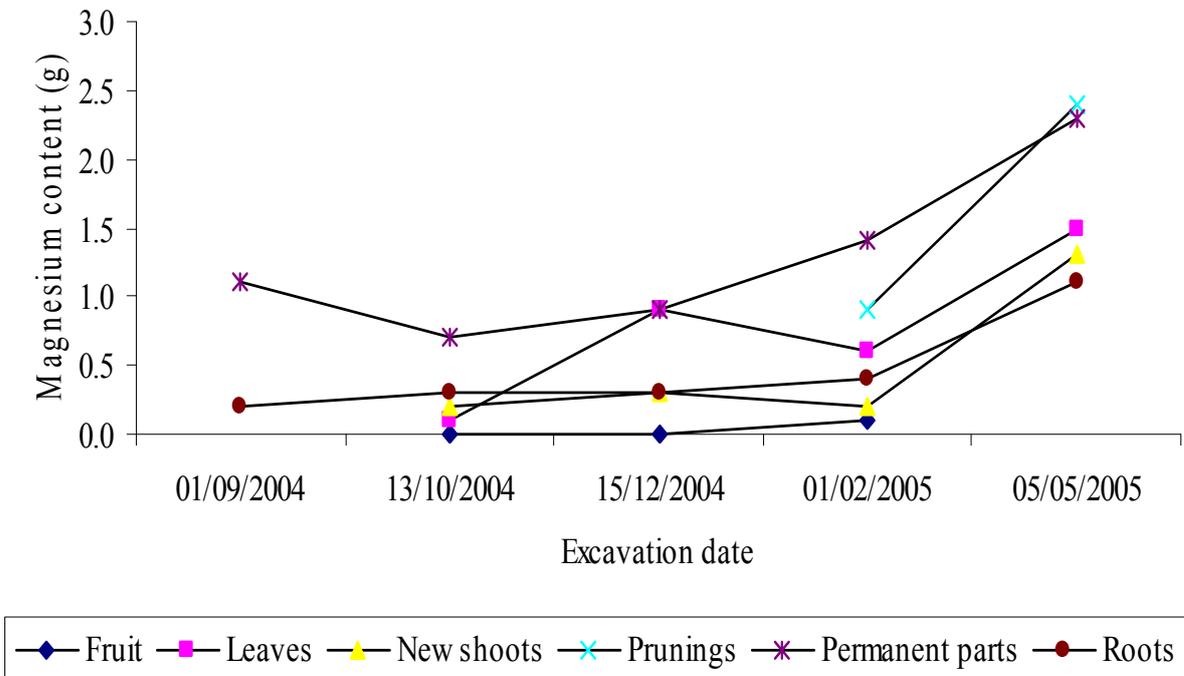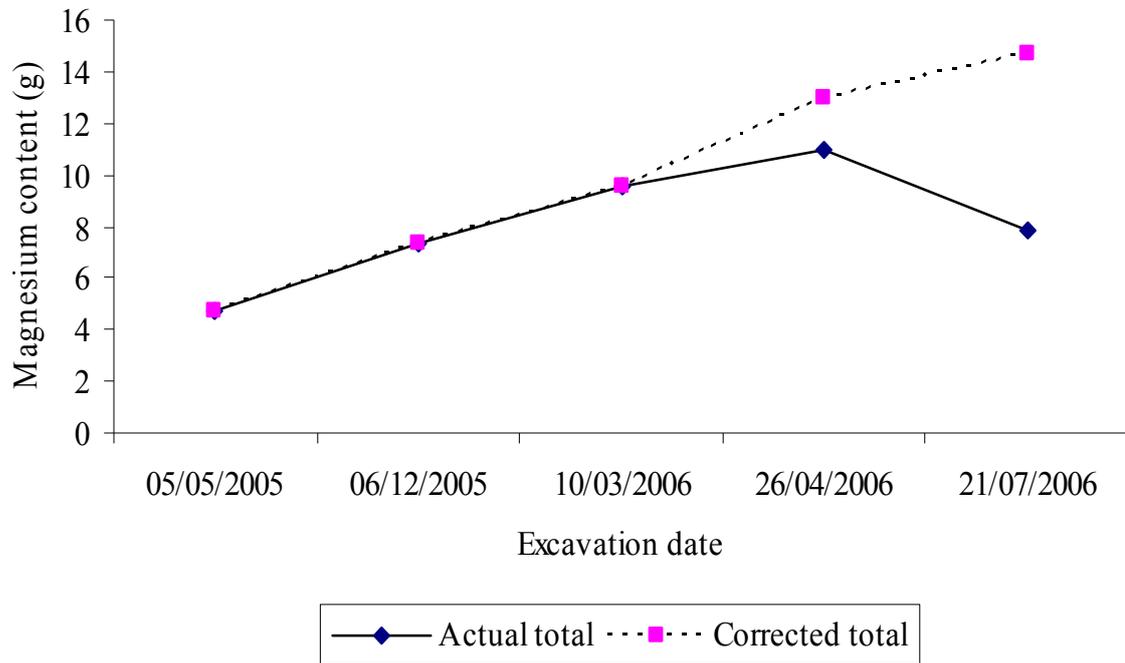
* Corrected total is corrected for fruit removed and leaves that dropped

d)
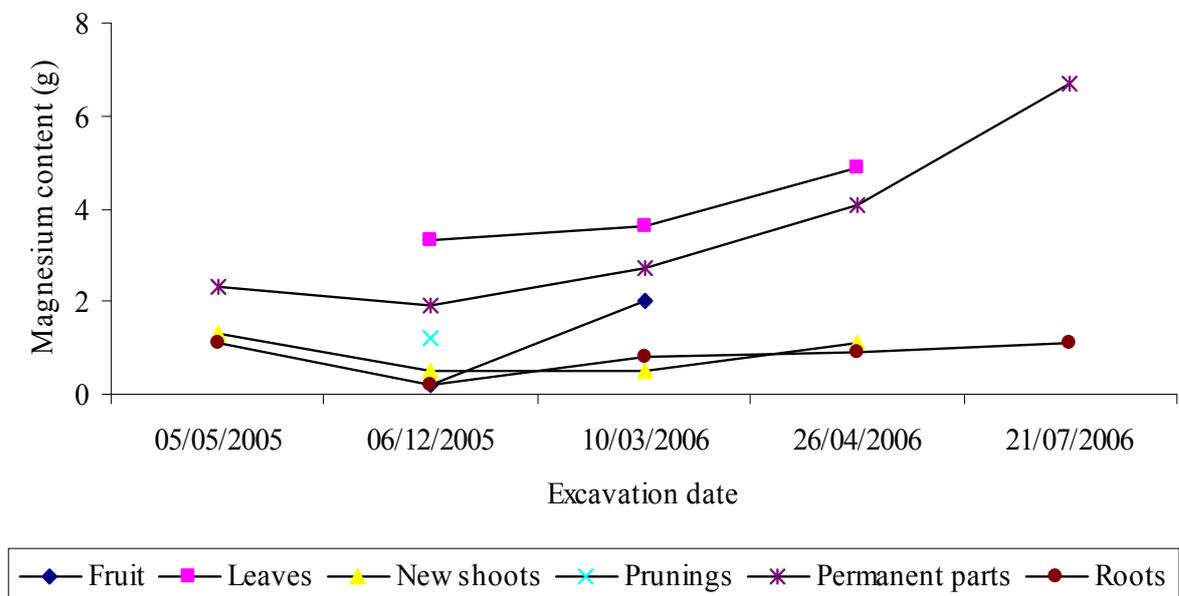
Appendix Figure 6: Average seasonal accumulation of magnesium in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
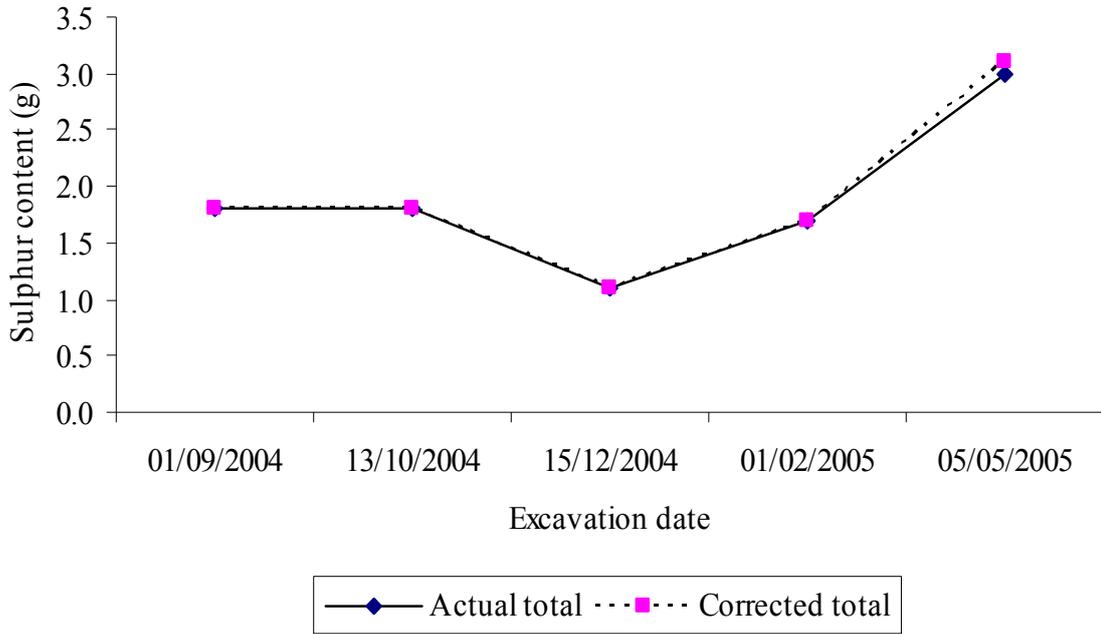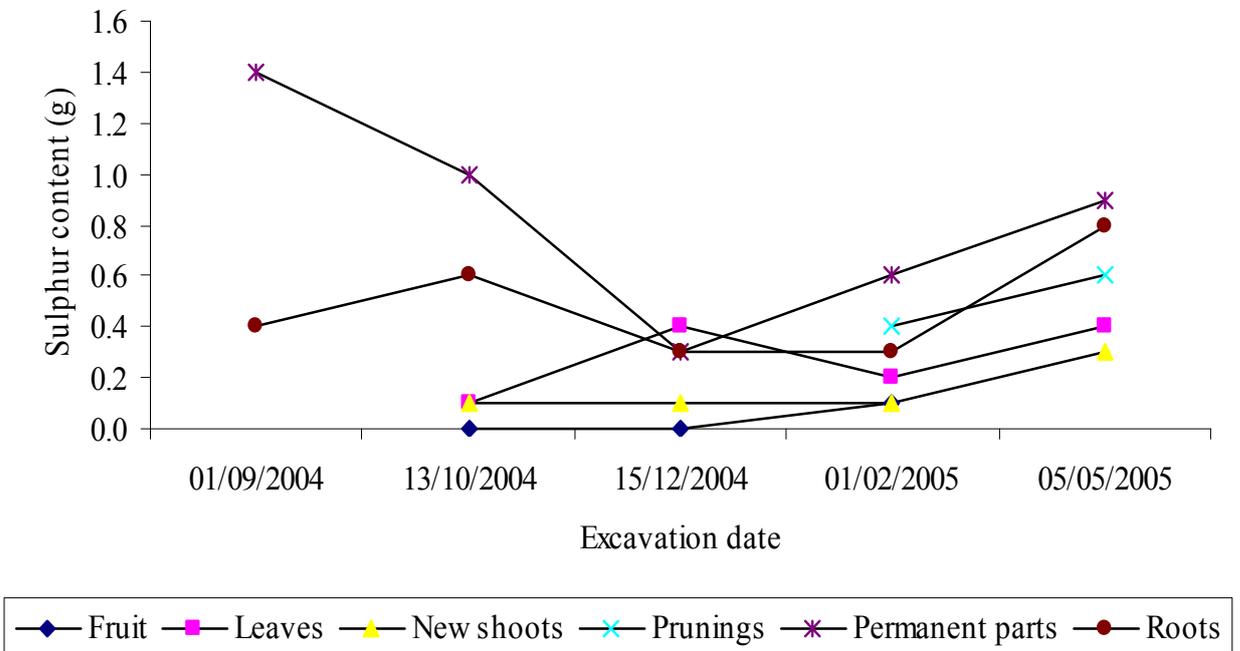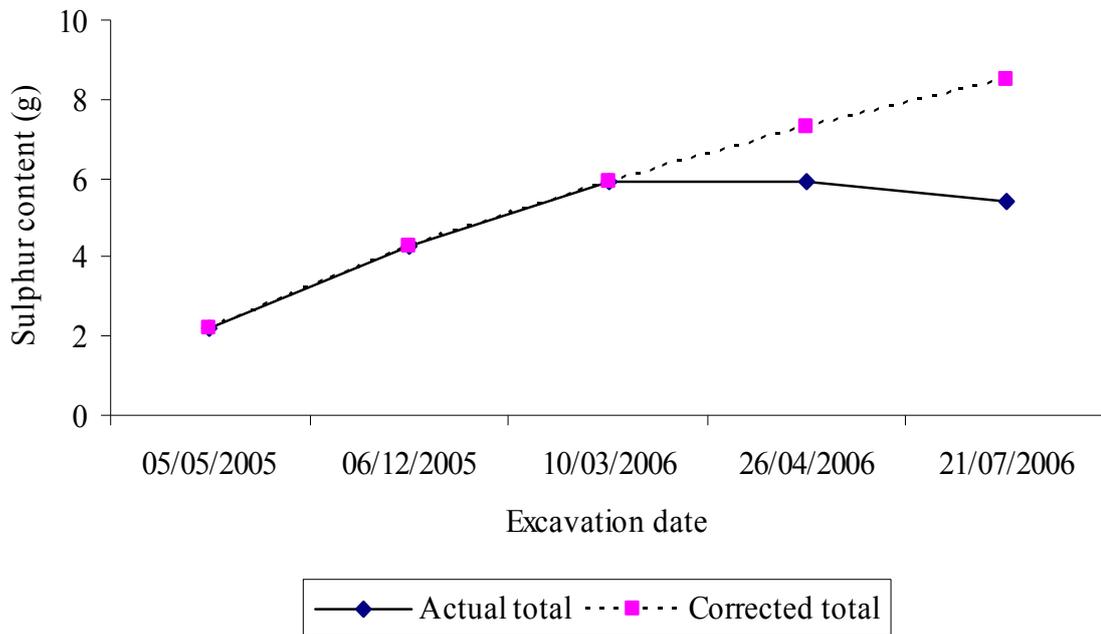
* Corrected total is corrected for fruit removed and leaves that dropped

d)
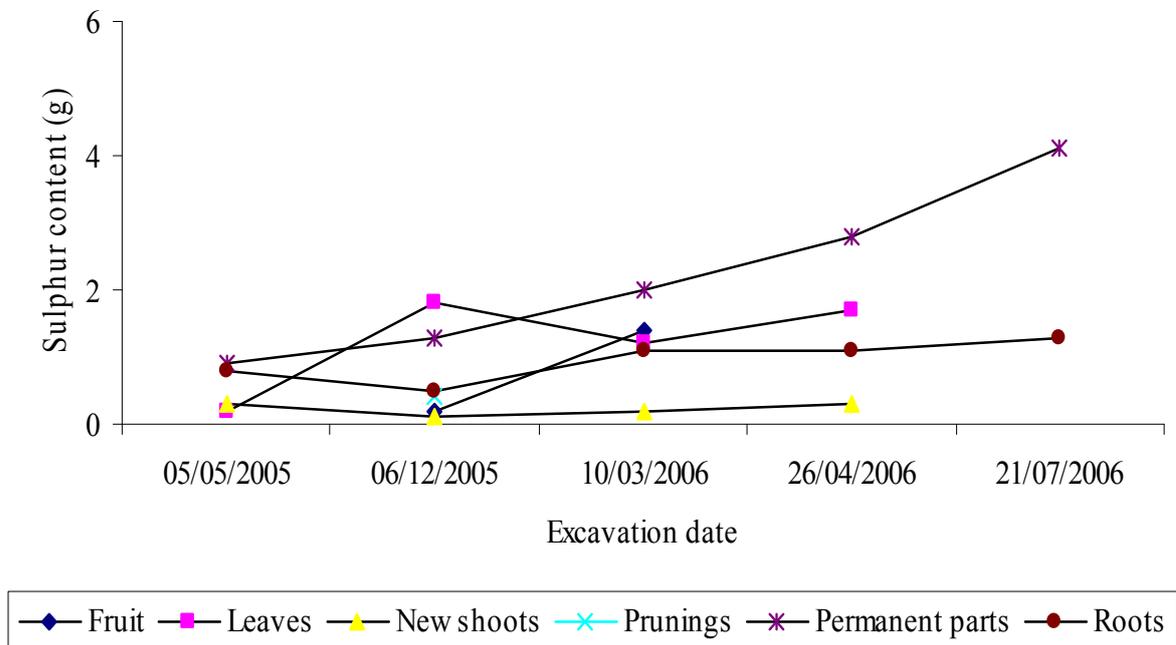
Appendix Figure 7: Average seasonal accumulation of sulphur in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
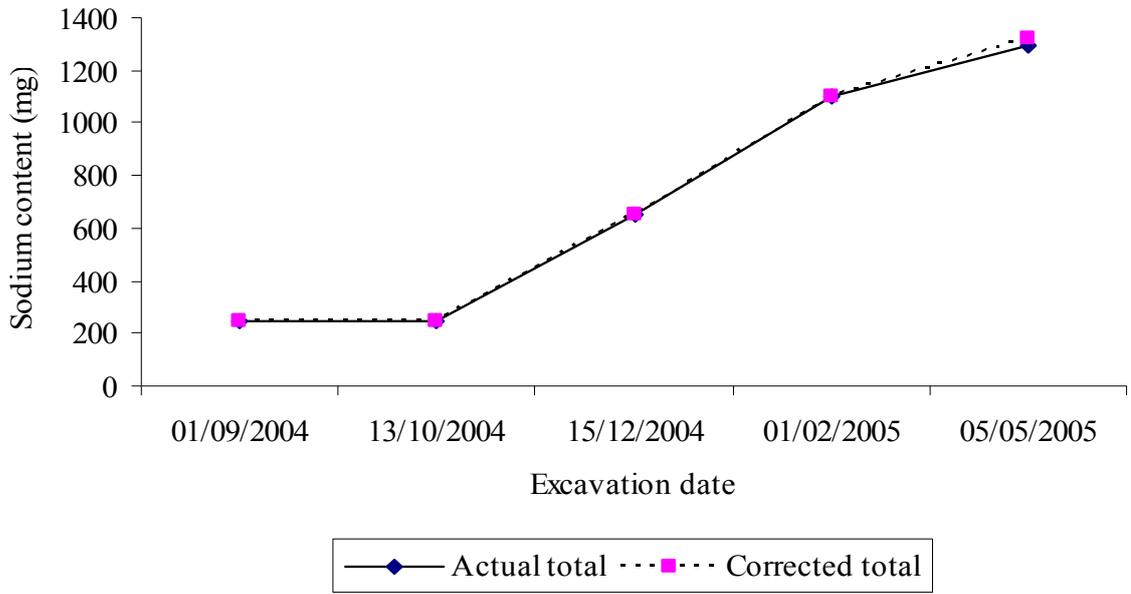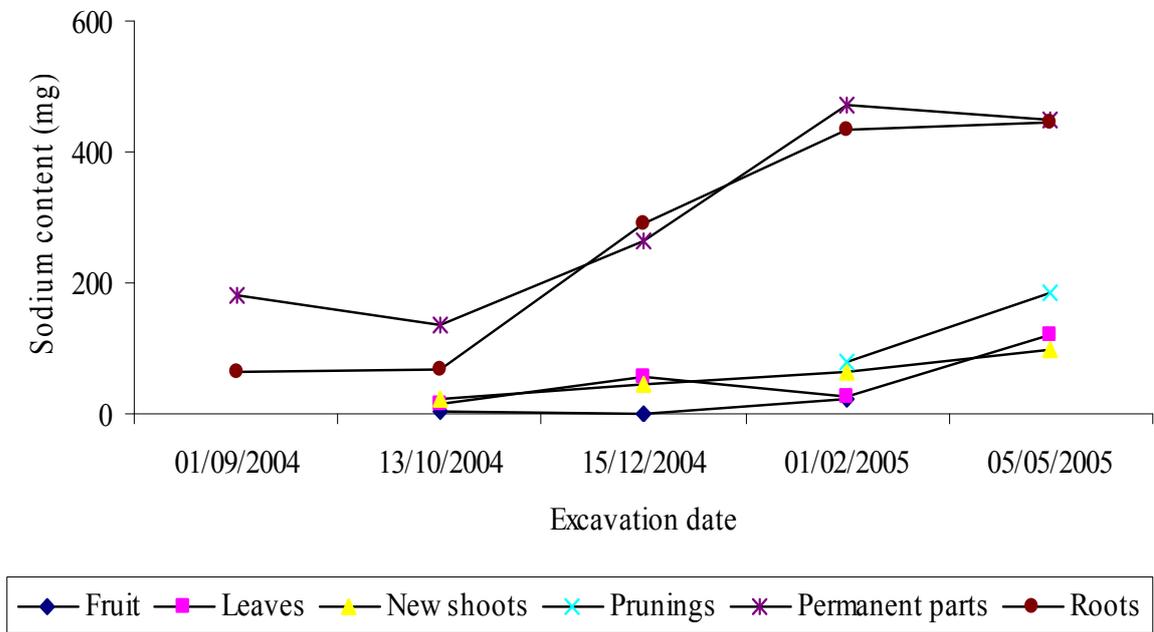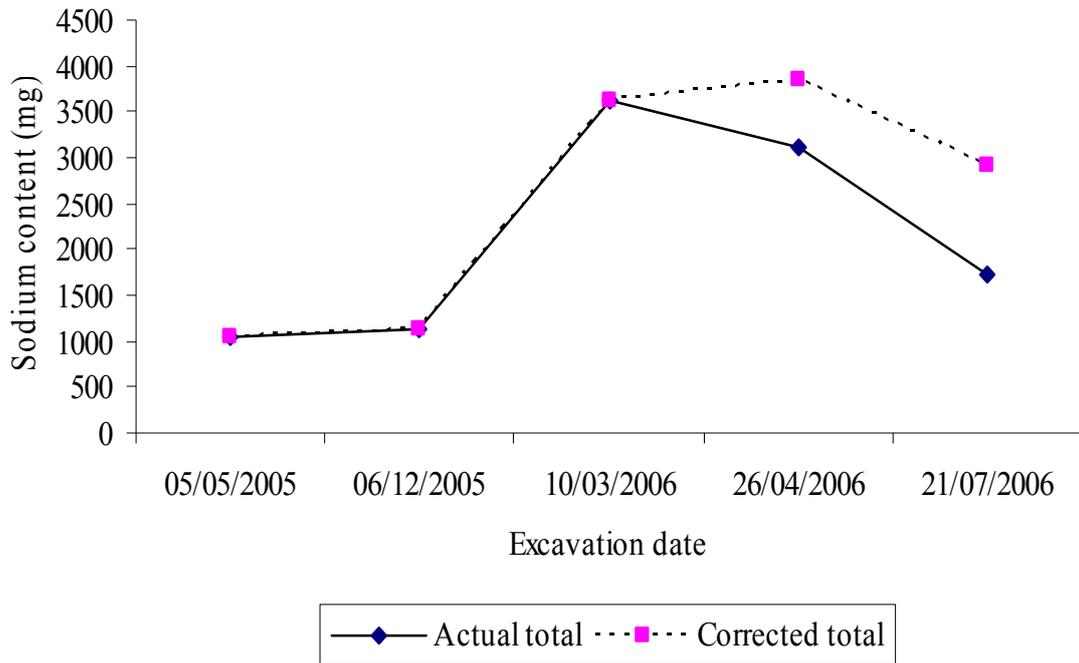
* Corrected total is corrected for fruit removed and leaves that dropped

d)
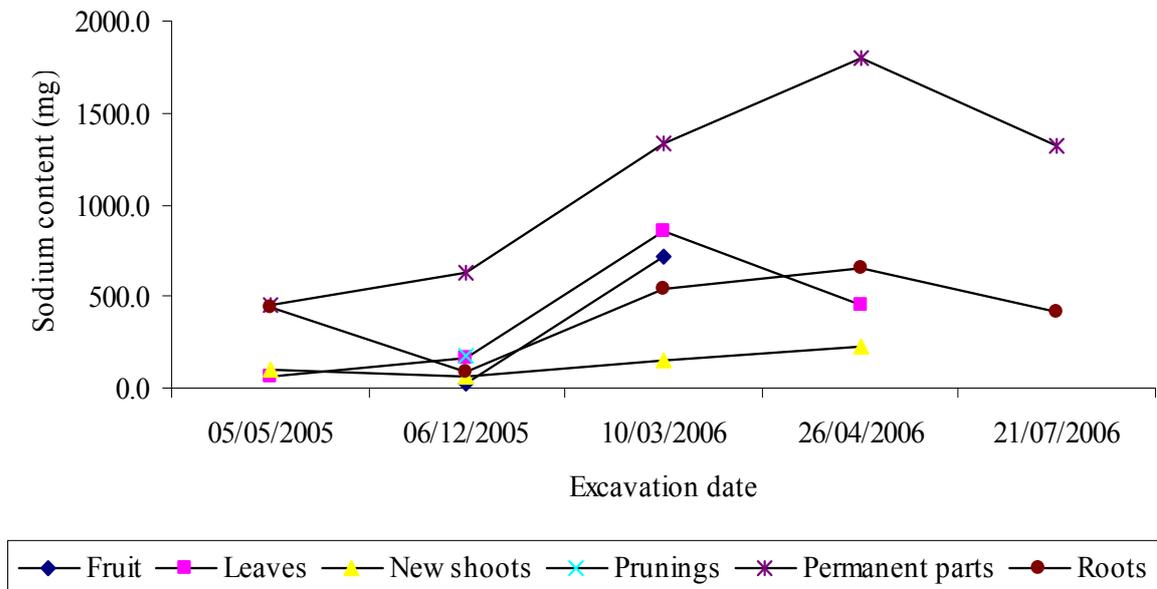
Appendix Figure 8: Average seasonal accumulation of sodium in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)
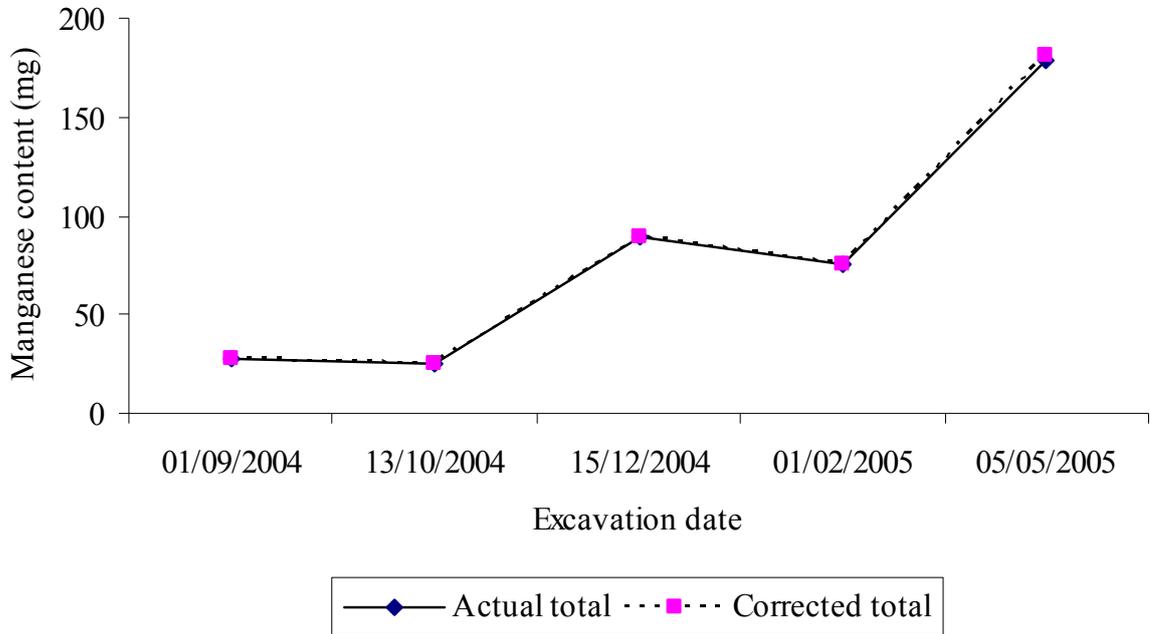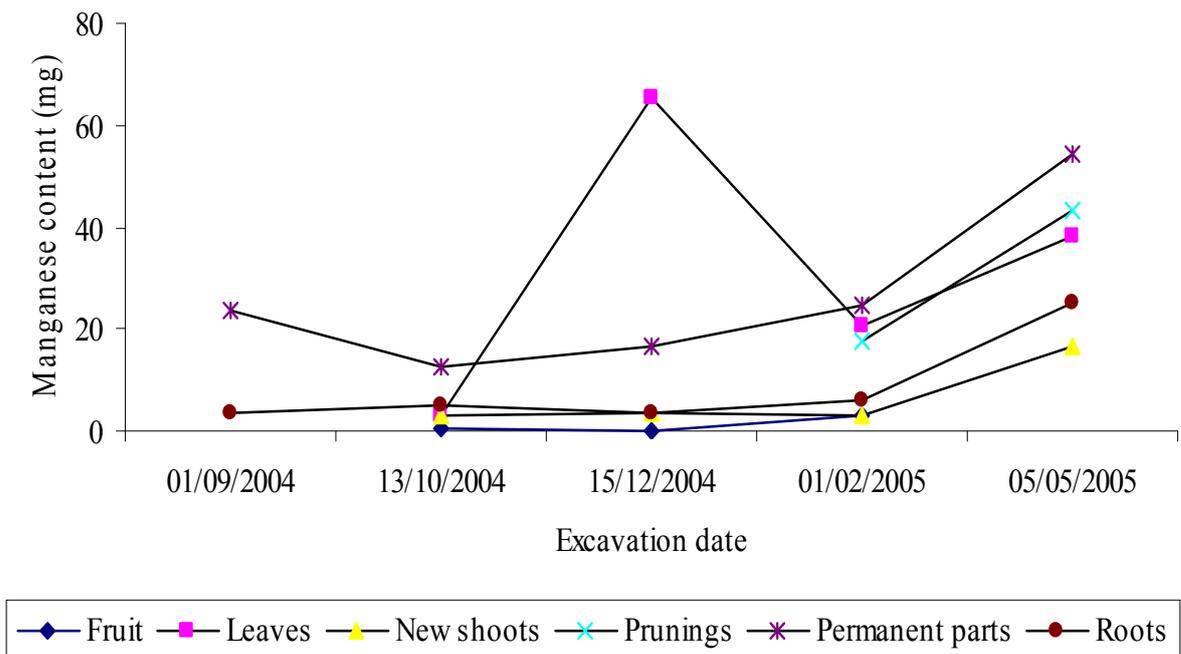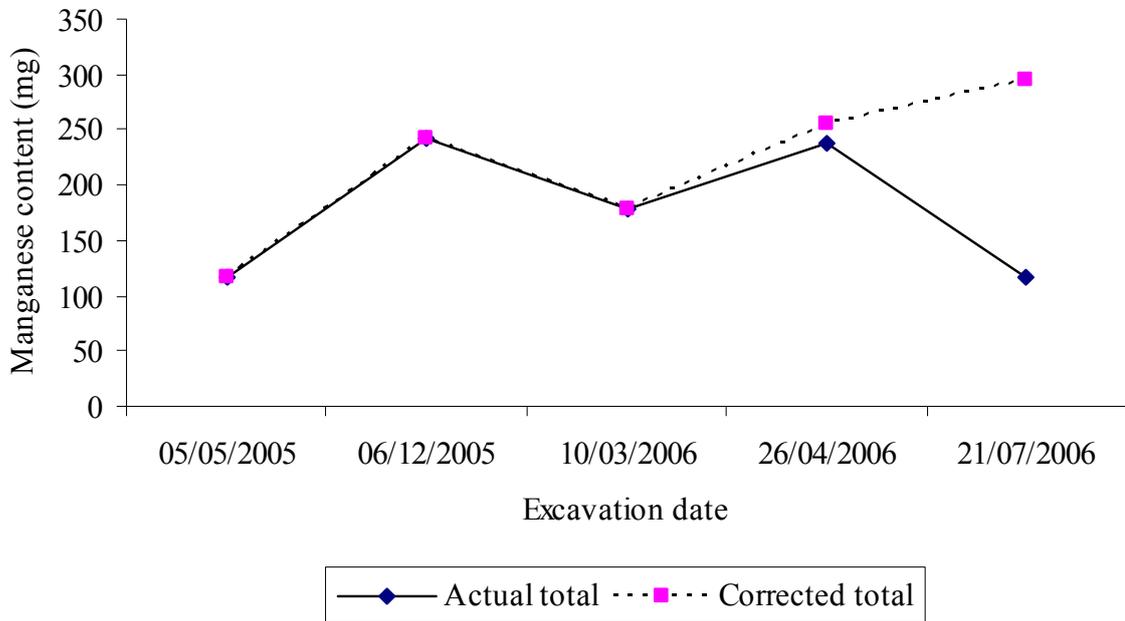
* Corrected total is corrected for fruit removed and leaves that dropped

d)
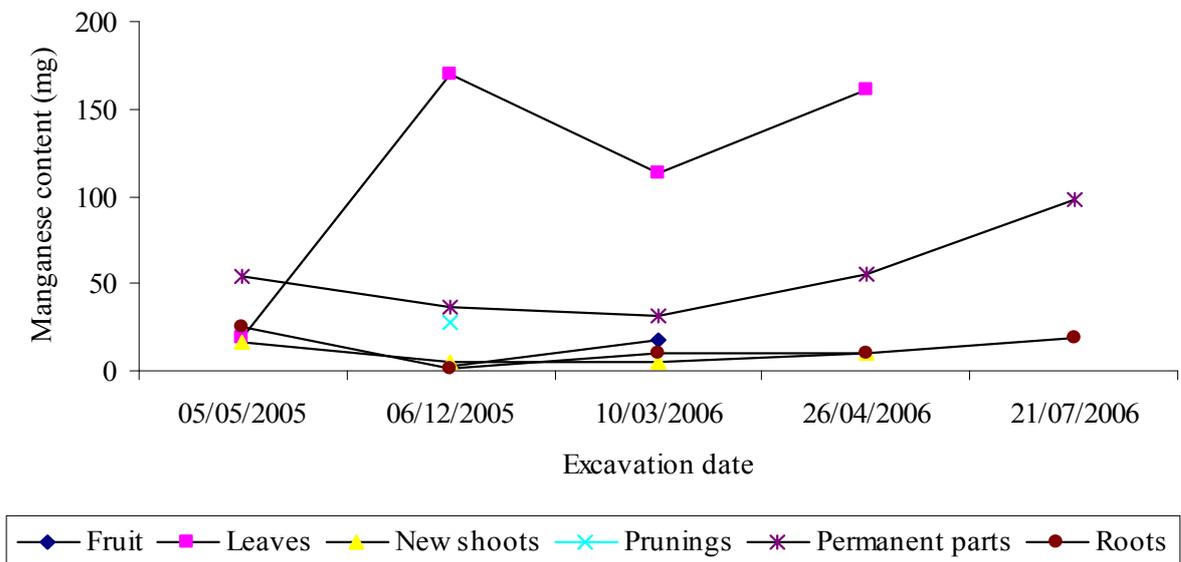
Appendix Figure 9: Average seasonal accumulation of manganese in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)

* Corrected total is corrected for fruit removed and leaves that dropped

d)
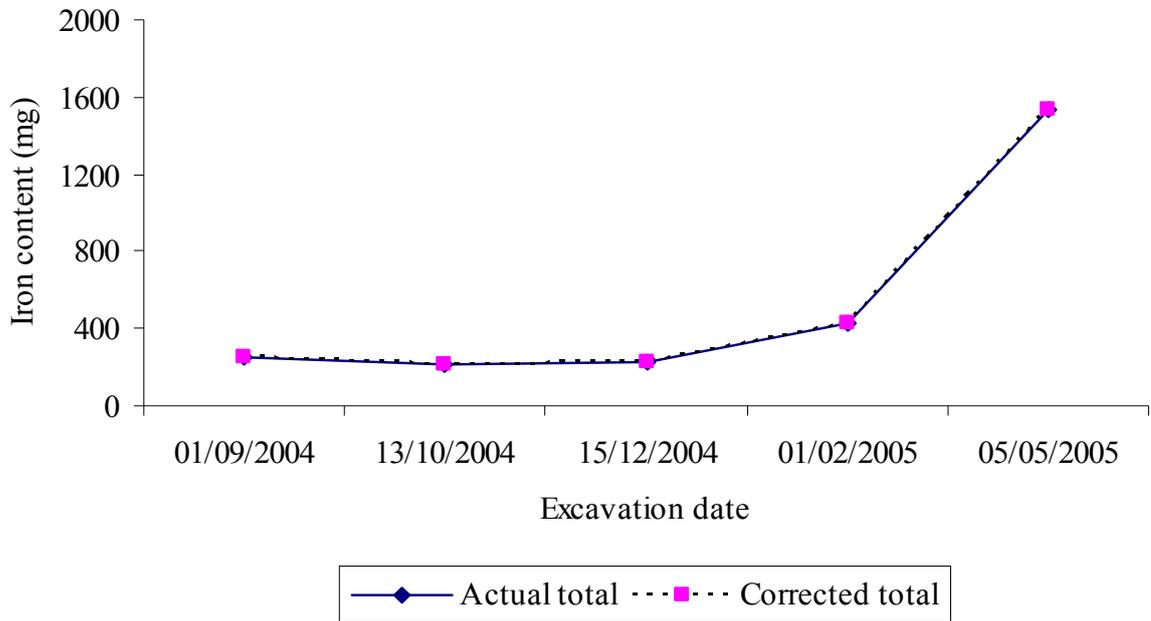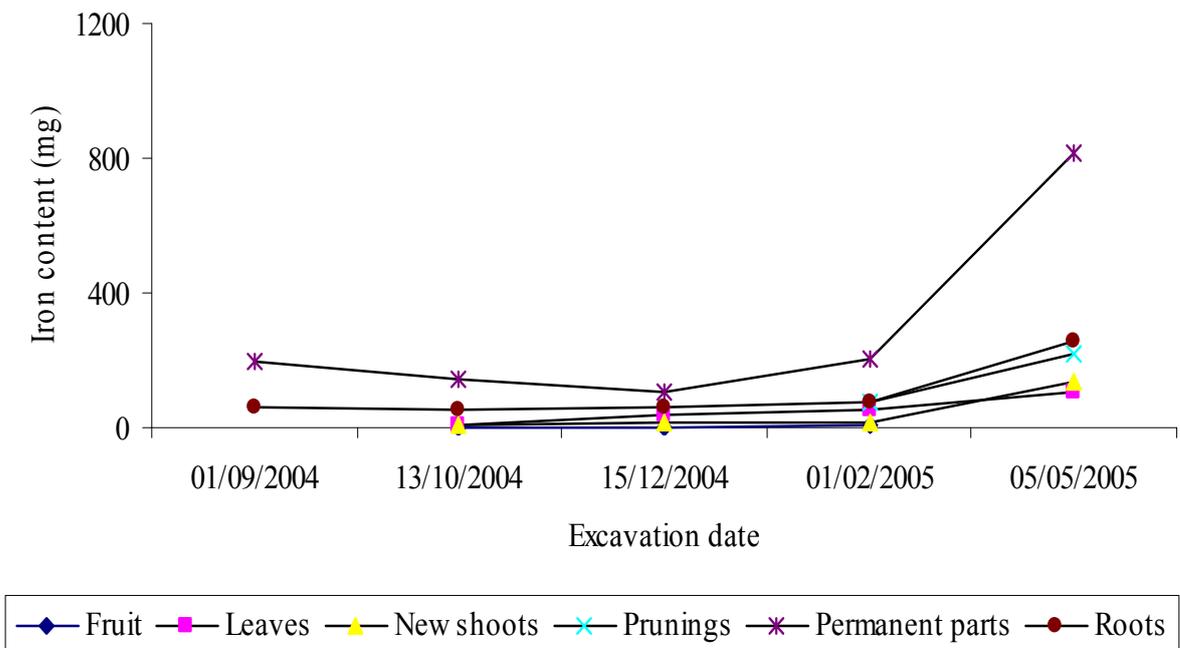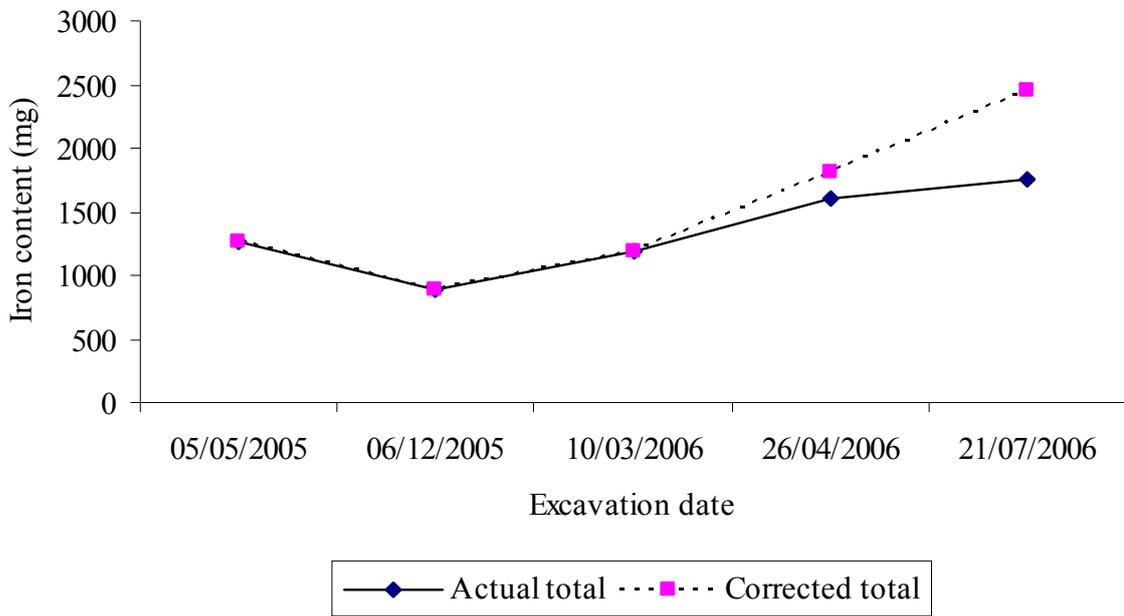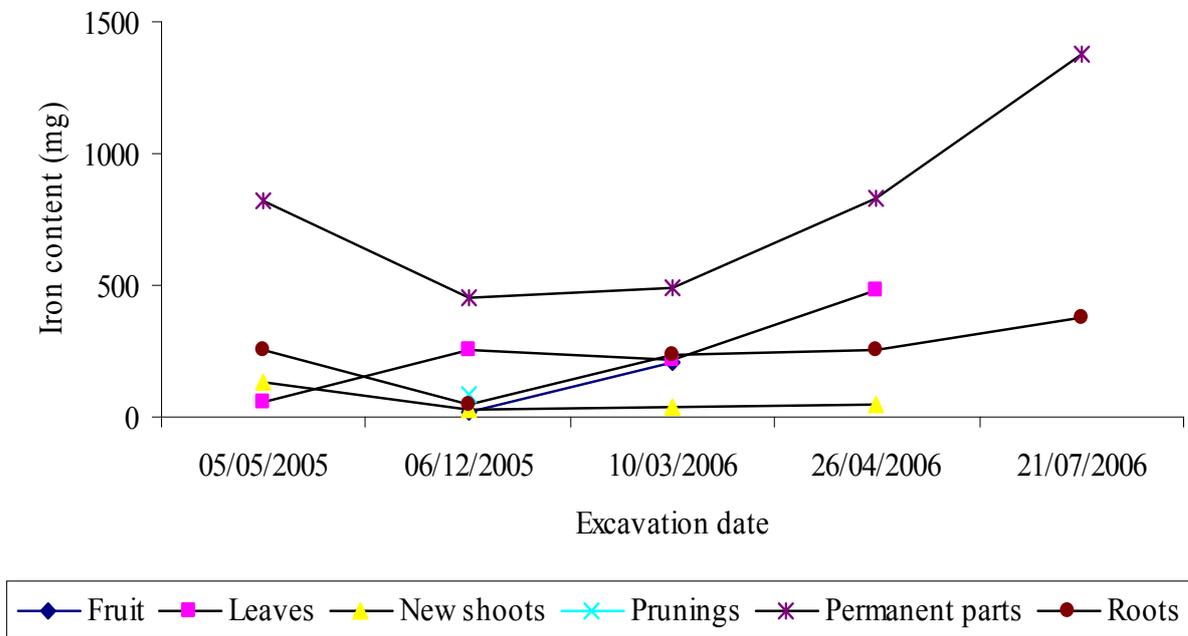
Appendix Figure 10: Average seasonal accumulation of iron in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)

* Corrected total is corrected for fruit removed and leaves that dropped

d)
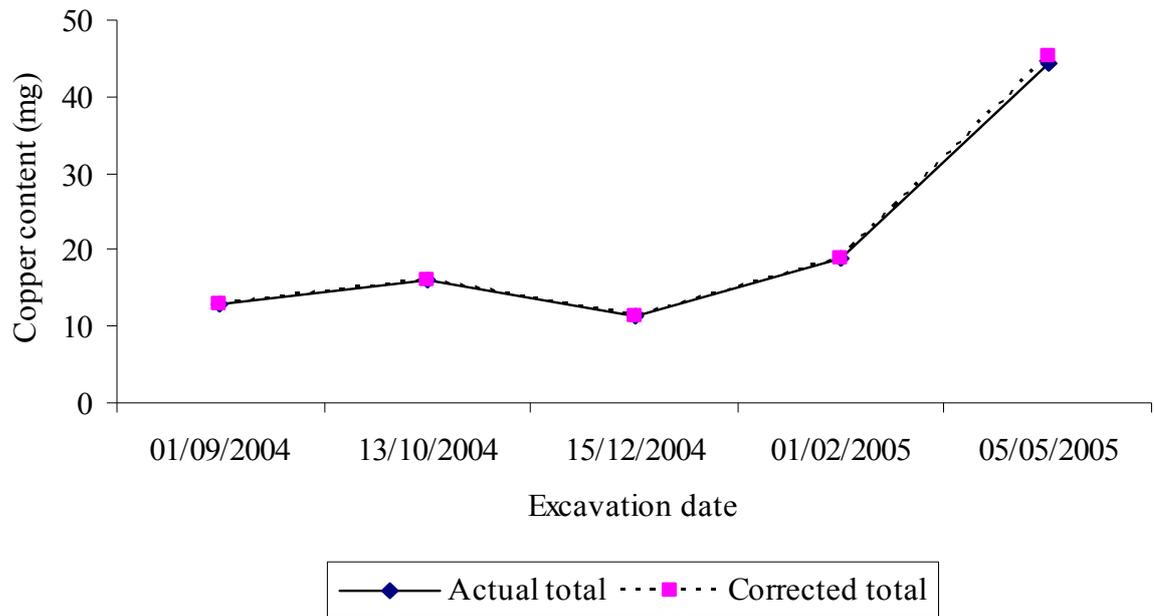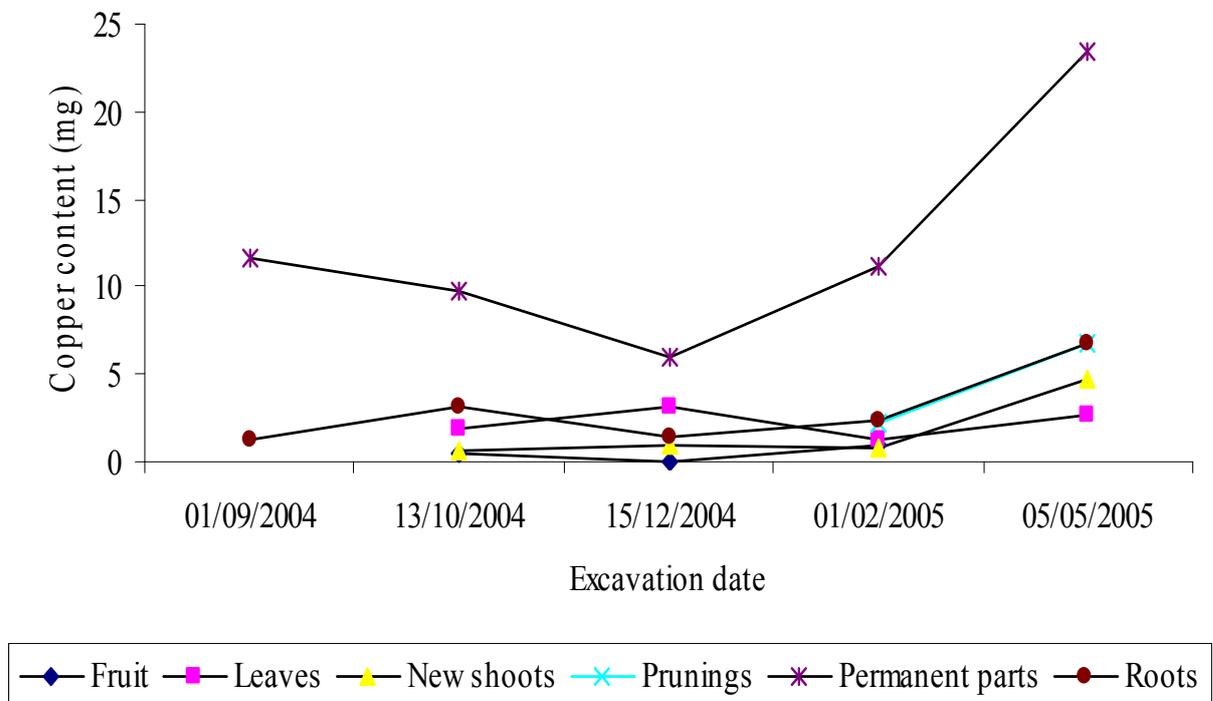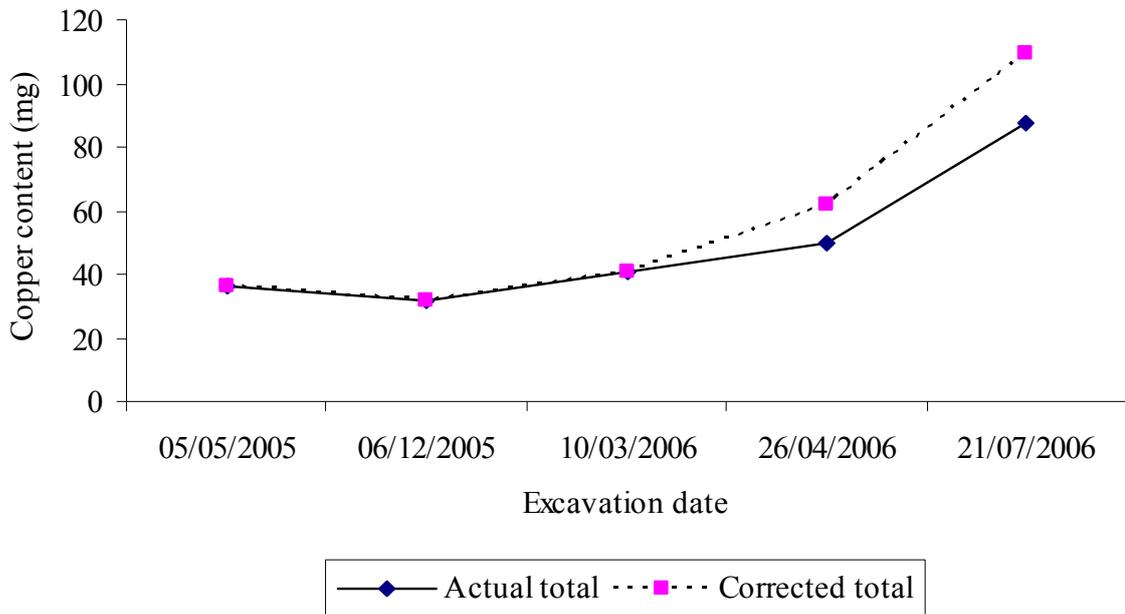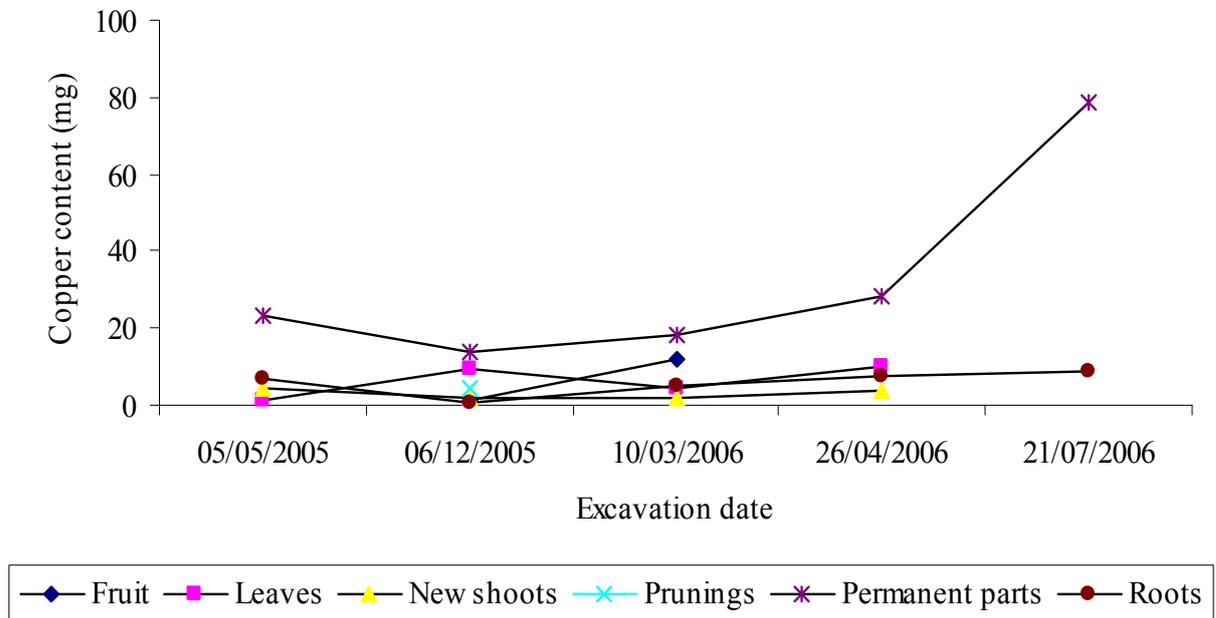
Appendix Figure 11: Average seasonal accumulation of copper in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)

* Corrected total is corrected for fruit removed and leaves that dropped

b)

c)

* Corrected total is corrected for fruit removed and leaves that dropped

d)
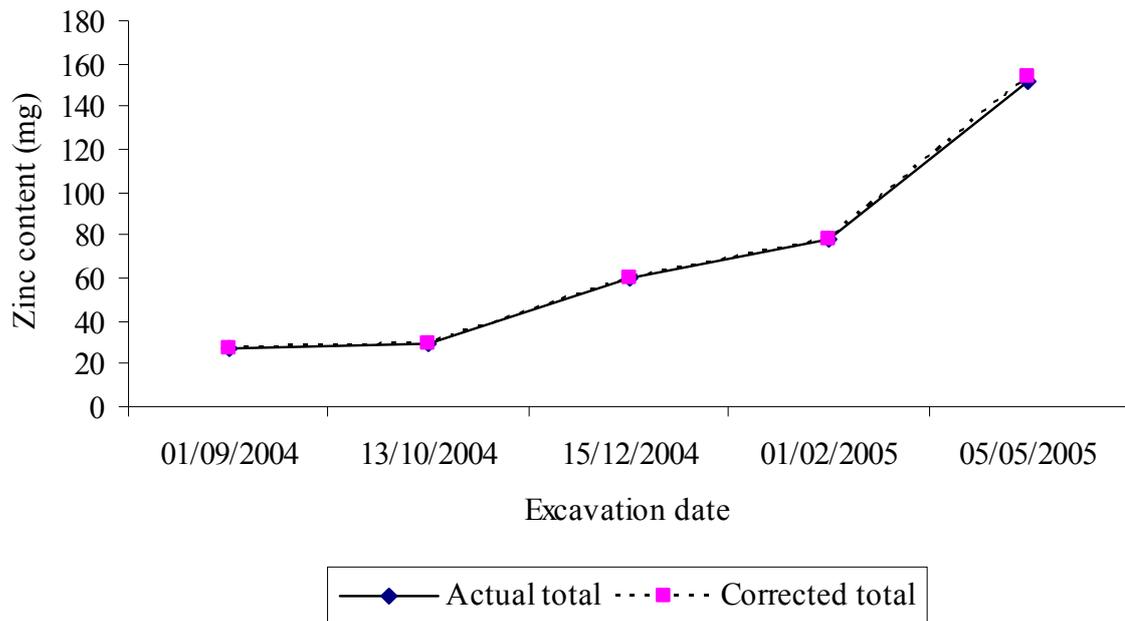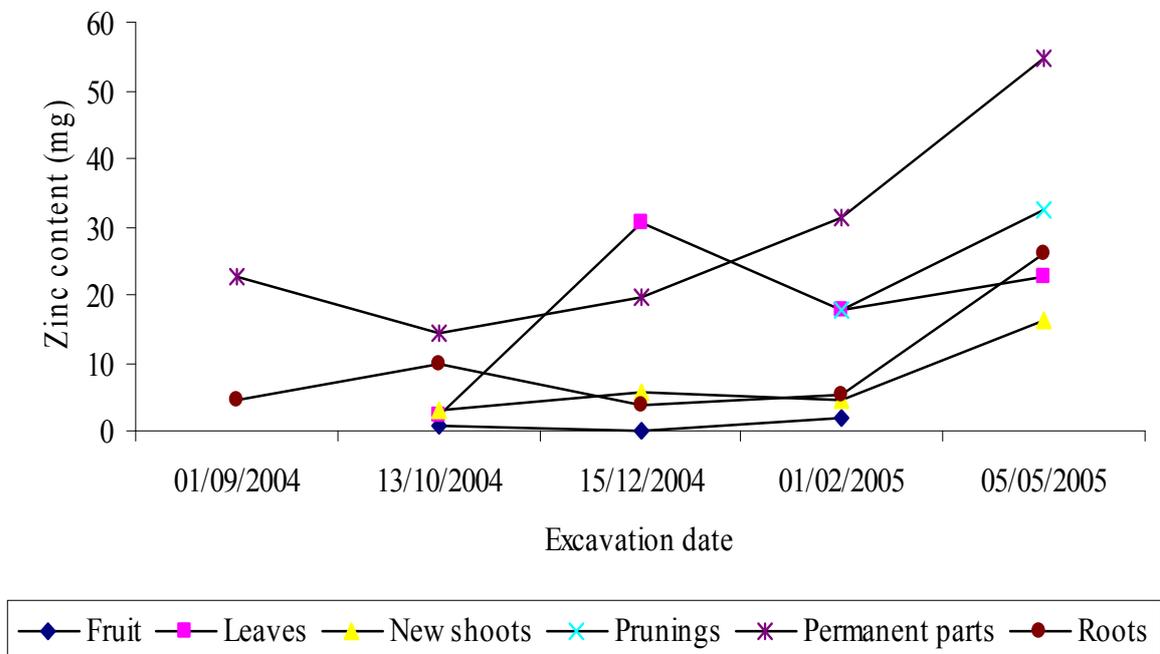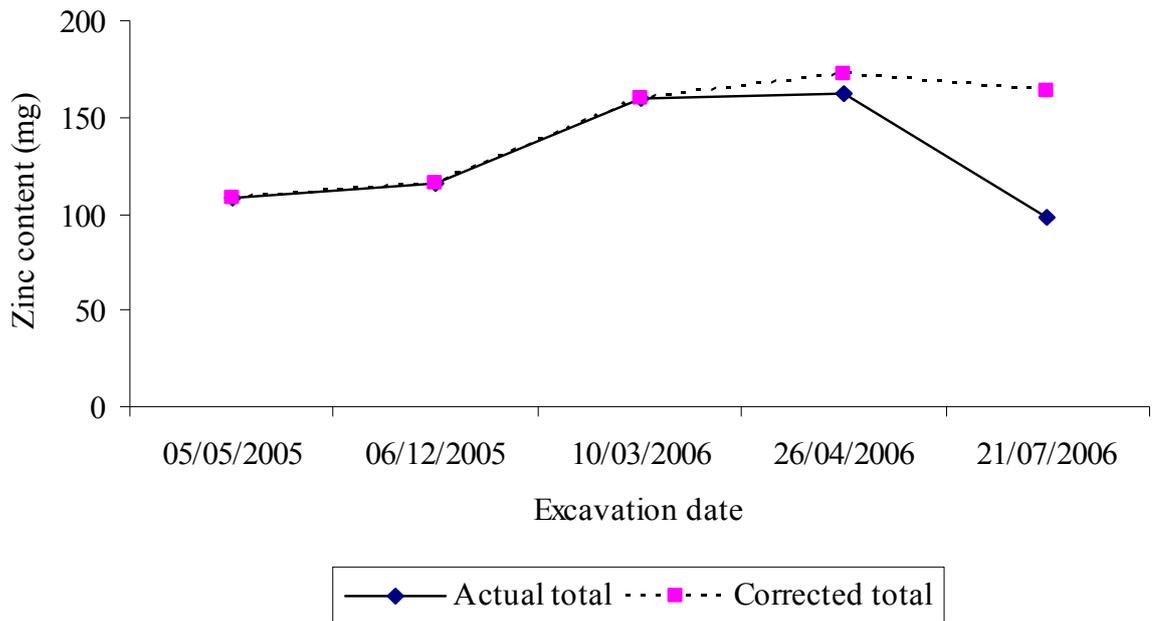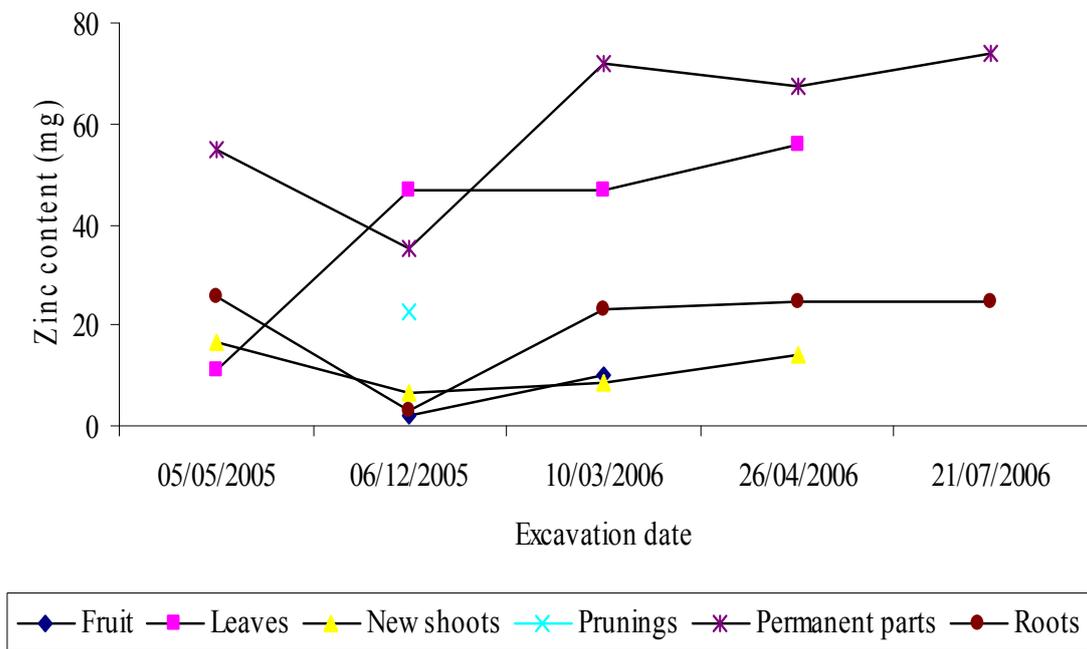
Appendix Figure 12: Average seasonal accumulation of zinc in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

a)
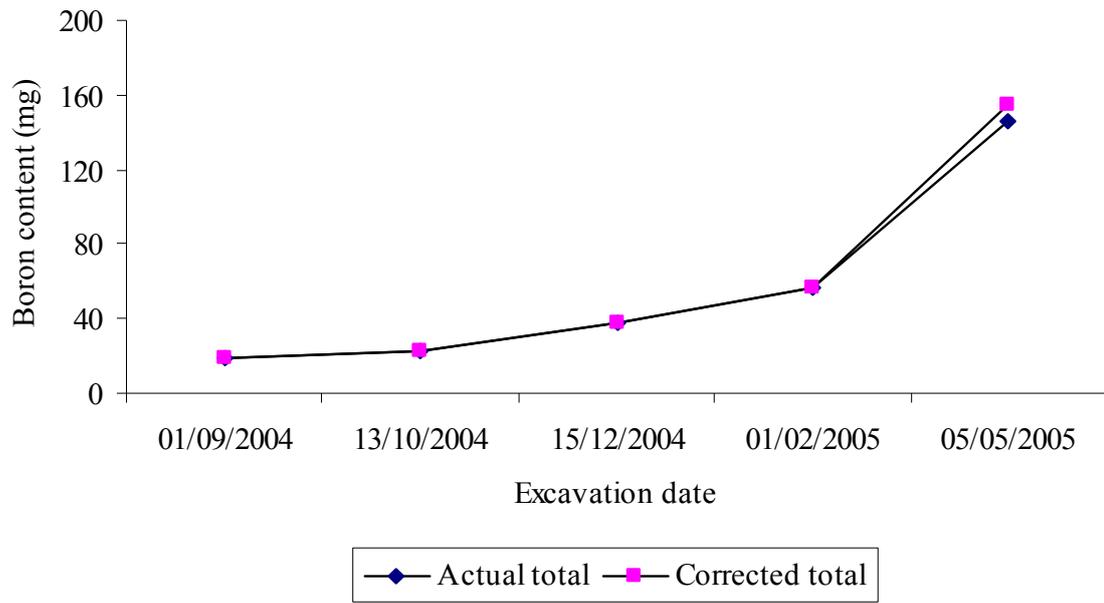
* Corrected total is corrected for fruit removed and leaves that dropped

b)
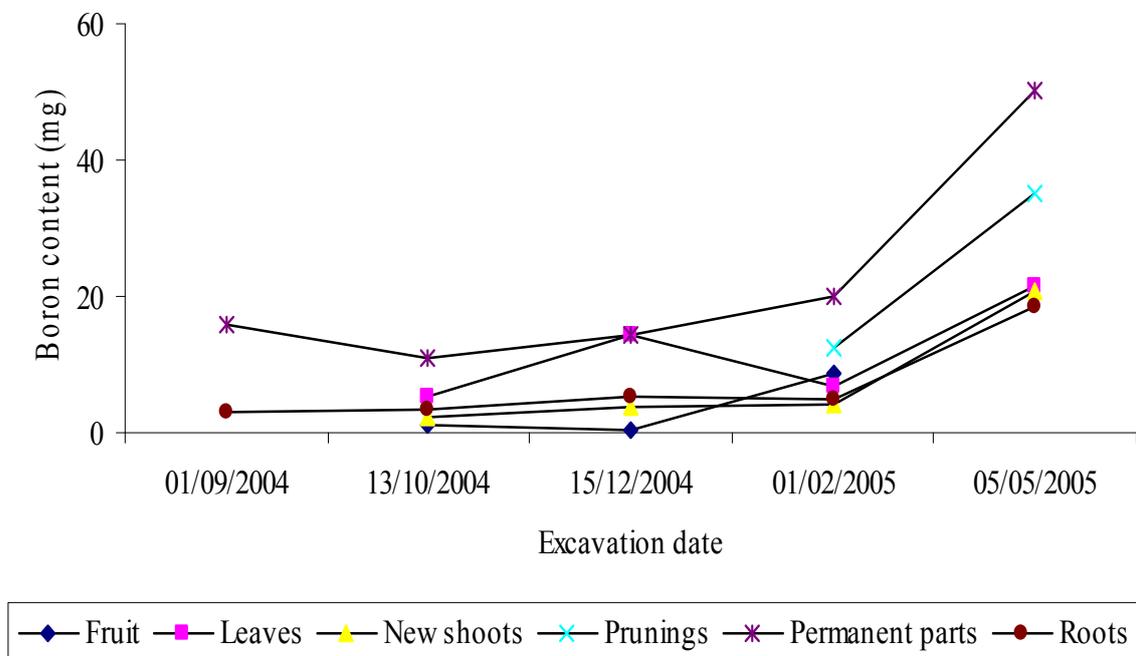
c)

d)
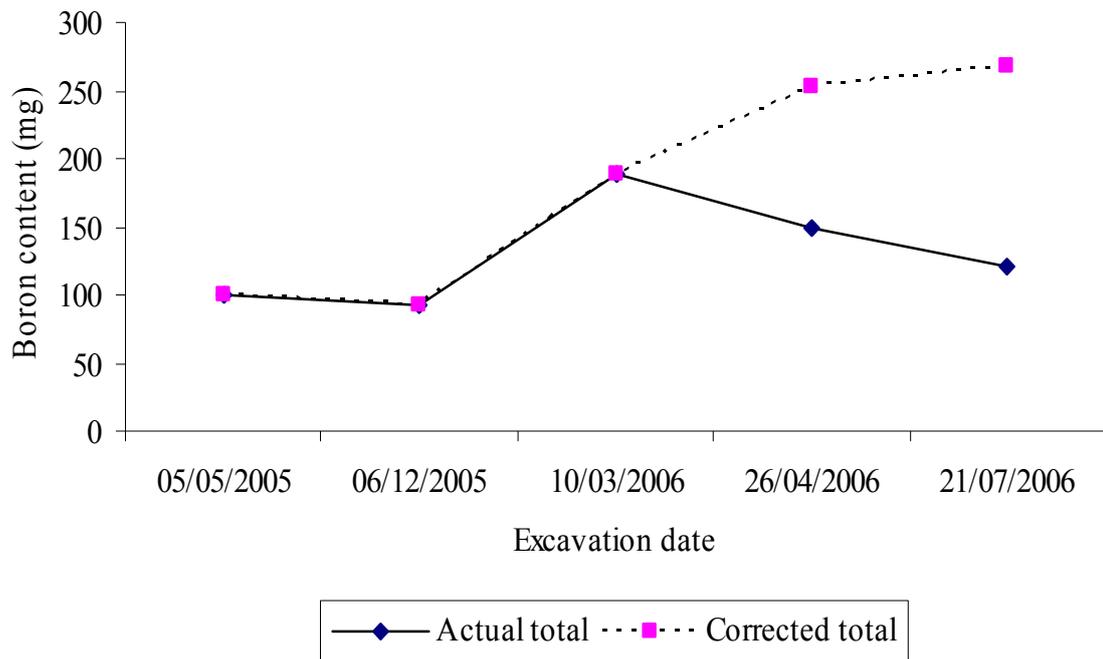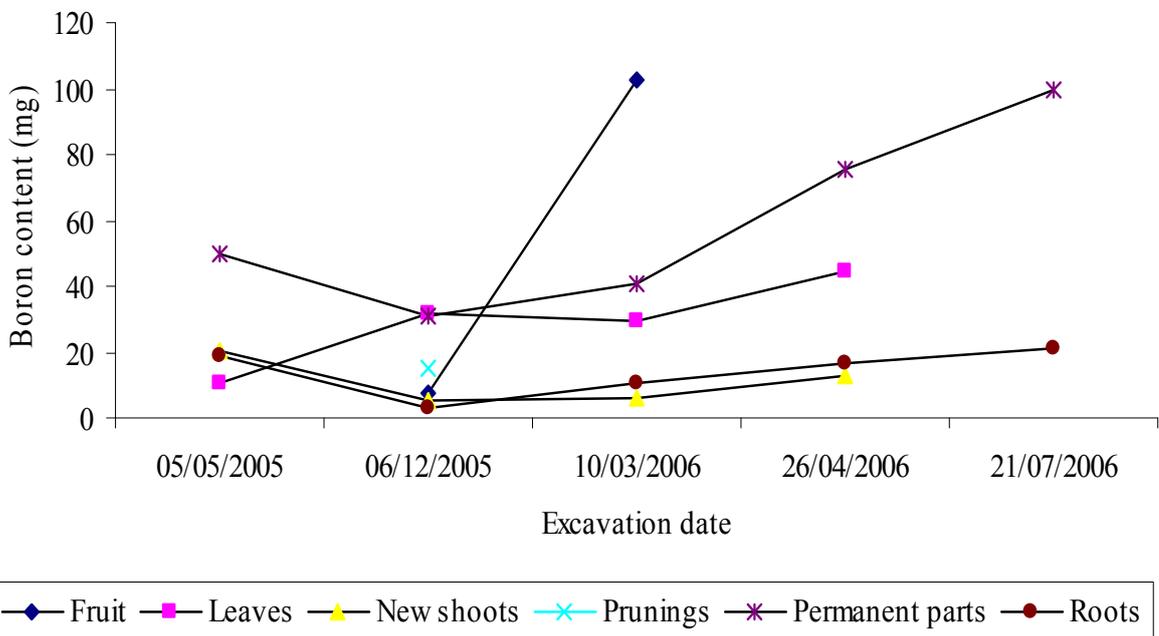
Appendix Figure 13: Average seasonal accumulation of boron in a 'Brookfield Gala' apple tree (a) 2nd leaf tree, (b) different parts of 2nd leaf tree, (c) 3rd leaf tree corrected for leaf fall and fruit yield, (d) different parts of 3rd leaf tree

Appendix Table 2: Average Dry weight (DW) in different tree parts of young 'Brookfield Gala' apple trees (2nd leaf) that received 6.15g of labeled nitrogen at different dates and excavation at different phenological stages

Application Date	16/09/2004		05/10/2004		05/12/2004		05/02/2005	
	Dry weight (g)		Dry weight (g)		Dry weight (g)		Dry weight (g)	
Excavation Date	13/10/2004[(1)*]	06/12/2005[(2)*]	15/12/2004[(2)*]	06/12/2005[(2)*]	01/02/2005 [(3)*]	06/12/2005[(2)*]	05/05/2005[(4)*]	06/12/2005[(2)*]
New growth								
Fruit	9.0 ±2.0	340.3±47.7	9.2±2.8	749.3±188.4	240.0±17.8	566.6±296.9	-	405.7±148.9
Leaves	31.2 ±3.7	976.3±121.7	326.4±17.4	913.6±69.1	207.6±33.2	964.2±105.3	468.4 ±61.3	968.9±160.1
New shoots	114.3±0.0	172.5±16.0	122.5±0.5	198.7±23.6	147.0±48.1	181.2±12.8	656.0 ±122.2	213.7±79.5
Total New growth	**154.5±5.7**	**1489.1±185.5**	**458.1±20.7**	**1861.6±281.1**	**594.6±99.1**	**1712.0±415.0**	**1124.4±183.5**	**1588.3±388.5**
Permanent part								
Trunk	651.8±26.6	1546.5±92.6	518.1±0.1	1502.2±42.6	733.1±4.4	1559.3±93.1	1357.6±35.4	1551.5±14.4
Canopy Branches		1346.0±117.4	297.6±53.5	1699.6±209.8	433.6±94.0	1350.7±211.6	672.7±94.1	1367.1±227.7
Rootstock	523.9±57.5	1055.4±137.3	299.0±19.4	1260.1±71.4	585.7±22.0	866.2±254.6	784.1±47.4	1054.3±161.0
Total	**1175.7±84.1**	**3947.8±347.3**	**1114.7±73.0**	**4461.9±323.8**	**1752.4±120.4**	**3776.2±559.3**	**2814.4±176.9**	**3972.9±403.1**
Roots								
Fine roots	229.9 ±49.8	32.4±11.5	192.6±4.9	36.9±6.3	94.1±20.7	56.8±12.7	360.6 ±142.8	39.3±12.7
Thick roots		176.3±65.1	126.5±22.0	383.3±86.1	236.8±0.5	349.9±67.5	575.2±141.0	186.9±26.3
Total	**229.9 ±49.8**	**208.8±76.6**	**319.1±26.9**	**420.2±92.4**	**330.9±21.2**	**406.7±80.2**	**935.8 ±283.8**	**226.2±39.0**
Pruning								
Shoots		255.2±106.2		**282.9±41.3**	178.3±27.3	196.4±76.3	688.5±260.5	277.7±102.9
Leaves		20.6 ±7.0		31.9±1.2	221.9±33.5	19.6±4.3	312.5±84.7	16.2±4.9
Total		**275.8 ±113.2**		**314.8 ±42.5**	**400.2±60.8**	**216.0±80.6**	**1001.1±345.2**	**293.9±107.8**
Total/tree	1560.1±139.6	5921.5±722.5	1891.9±120.6	7058.5±739.8	3078.1±301.5	6110.9±1135.1	5875.7±989.4	6081.3±938.4

1*- Six weeks after bud-break
2*- Mid-summer
3*- Harvest
4*- Early winter before normal leaf drop

Appendix Table 3: Average total N in different tree parts of young 'Brookfield Gala' apple trees that received 6.15g of labeled nitrogen at different dates and excavation at different phenological stages

	Total N (g/tree)				Total N (g/tree)			
Application Date	16/09/2004				05/10/2004			
Excavation date	13/10/2004		06/12/2005		15/12/2004		06/12/2005	
	%	absolute values	%	absolute values	%	absolute values	%	absolute values
New growth								
Fruit	3.9	0.3±0.1	0.6	2.1±0.3	0.9	0.1±0.0	1.1	8.5±2.1
Leaves	4.5	1.4±0.2	2.4	23.2±2.9	2.6	8.5±0.7	3.0	27.1±2.1
New shoots	1.5	1.7±0.2	1.1	1.9±0.2	1.2	1.5±0.0	1.1	2.1±0.3
Total New growth	**9.9**	**3.4±0.5**	**4.1**	**27.2±3.4**	**4.7**	**10.1±0.7**	**5.2**	**37.7±4.5**
Permanent part								
Trunk	0.9	5.9±0.8	0.3	4.5±0.3	0.3	1.6±0.1	0.2	3.5±0.1
Canopy Branches			0.6	7.5±0.7	0.6	1.8±0.3	0.4	7.3±0.9
Rootstock	0.8	3.9±1.2	0.4	3.8±0.5	0.7	2.1±0.1	0.6	7.1±0.4
Total	**1.7**	**9.8±2.0**	**1.2**	**15.8±1.5**	**1.6**	**5.5±0.5**	**1.2**	**17.9±1.4**
Roots								
Fine roots	2.6	6.0±1.8	1.2	0.4±0.1	1.3	2.5±0.1	1.4	0.5±0.1
Thick roots			1.1	2.0±0.7	1.2	1.5±0.3	1.3	4.9±1.1
Total	**2.6**	**6.0±1.8**	**2.3**	**2.4±0.8**	**2.5**	**4.0±0.5**	**2.7**	**5.4±1.2**
Pruning								
Shoots			1.2	3.0±1.2			1.2	3.4±0.5
Leaves			2.5	0.5±0.2			2.8	0.9±0.0
Total			**3.7**	**3.5±1.4**			**4.0**	**4.3±0.5**
Total/tree	14.2	19.2±4.3	11.3	48.9±7.1	8.8	19.6±1.7	13.1	65.3±7.6

	Total N (g/tree)				Total N (g/tree)			
Application Date	05/12/2004				05/02/2005			
Excavation date	01/02/2005		06/12/2005		05/05/2004		06/12/2005	
	%	absolute values	%	absolute values	%	absolute values	%	absolute values
New growth								
Fruit	0.6	1.5±0.5	0.9	5.1±2.7	-	-	0.9	3.8±1.4
Leaves	2.4	5.1±0.7	2.7	25.7±2.8	2.0	9.5±1.9	2.7	25.7±4.2
New shoots	1.1	1.7±0.5	1.1	1.9±0.1	1.0	6.6±1.3	1.0	2.2±0.8
Total New growth	**4.1**	**8.3±1.7**	**4.7**	**32.7±5.6**	**3.0**	**16.1±3.1**	**4.6**	**31.7±6.4**
Permanent part								
Trunk	0.3	2.4±0.2	0.3	3.9±0.2	0.4	5.6±0.8	0.2	3.7±0.0
Canopy Branches	0.7	3.2±1.0	0.5	7.2±1.1	1.0	6.6±0.6	0.6	8.2±1.4
Rootstock	0.5	3.0±0.9	0.5	3.9±1.2	0.6	5.0±0.2	0.4	4.4± 0.7
Total	**1.5**	**8.6±2.1**	**1.3**	**15.0±2.5**	**2.0**	**17.2±1.5**	**1.2**	**16.3±2.1**
Roots								
Fine roots	1.6	1.5±0.3	1.4	0.8±0.2	1.5	5.5±2.0	1.6	0.6±0.2
Thick roots	1.2	2.9±0.3	1.3	4.5±0.9	1.2	7.1±1.4	1.5	2.7±0.4
Total	**2.8**	**4.4±0.6**	**2.7**	**5.3±1.1**	**2.7**	**12.6±3.4**	**3.1**	**3.3±0.6**
Pruning								
Shoots	0.9	1.6±0.2	1.2	2.3±0.9	1.0	7.0±2.9	1.4	3.7±1.4
Leaves	2.5	5.4±1.1	2.8	0.6±0.1	2.0	6.3±2.1	2.5	0.4±0.1
Total	**3.4**	**7.0±1.3**	**4.0**	**2.9±1.0**	**3.0**	**13.3±5.0**	**3.9**	**4.1±1.5**
Total/tree	11.8	28.3±5.7	12.7	55.9±10.2	10.7	59.2±13.1	12.8	55.4±10.6

Appendix Table 4a: Total N (control treatment), percentage ^{15}N and excess ^{15}N in the different tree parts of young 'Brookfield Gala' apple trees that received 6.15g of labelled N on different dates and were excavated on different dates

Application Date	Control		2004/09/16				2004/10/05			
Excavation Date	2004/09/01		2004/10/13		2005/12/06		2004/12/15		2005/12/06	
	Total N	^{15}N	$^{(\%)}\,^{15}$N	Excess ^{15}N (%)	$^{(\%)}\,^{15}$N	Excess ^{15}N (%)	$^{(\%)}\,^{15}$N	Excess ^{15}N (%)	$^{(\%)}\,^{15}$N	Excess ^{15}N (%)
New growth										
Fruit			0.44597	0.07967	0.42310	0.05680	0.68370	0.31740	0.42998	0.06368
Leaves			0.49873	0.13243	0.42004	0.05374	0.59647	0.23017	0.42359	0.05729
New shoots			0.38221	0.01591	0.41589	0.04959	0.63804	0.27174	0.42116	0.05486
Permanet Structure										
1 yr wood	1.50	0.36611								
Trunk	0.93	0.36794	0.38911	0.02281	0.42759	0.06129	0.51278	0.14648	0.43687	0.07057
Canopy branches					0.42844	0.06214	0.55528	0.18898	0.44080	0.07450
Rootstock	0.93	0.36770	0.38551	0.01921	0.42207	0.05577	0.51287	0.14657	0.44371	0.07741
Average	**1.12**	**0.36725**	**0.38731**	**0.02101**	**0.42603**	**0.05973**	**0.52698**	**0.16068**	**0.44046**	**0.07416**
Roots										
Fine Roots	1.88	0.36635	0.48817	0.12187	0.41940	0.05310	0.51681	0.15051	0.46416	0.09786
Thick roots	1.30	0.36640			0.42423	0.05793	0.48274	0.11644	0.44186	0.07556
Average	**1.59**	**0.36638**	**0.48817**	**0.12187**	**0.42182**	**0.05552**	**0.49978**	**0.13348**	**0.45301**	**0.08671**
Prunning										
Shoots					0.43908	0.07278			0.45597	0.08967
Leaves					0.43325	0.06695			0.44333	0.07703
Average					**0.43617**	**0.06987**			**0.44965**	**0.08335**
Total	6.54	1.83450	2.58970	0.39190	4.25309	0.59009	4.49869	1.56829	4.40143	0.73843

Appendix Table 4b: Percentage ^{15}N and excess ^{15}N in the different tree parts of young 'Brookfield Gala' apple trees that received 6.15g of labelled N on different dates and were excavated on different dates

| Application Date	2004/12/05				2005/02/05			
Excavation Date	2005/02/01		2005/12/06		2005/05/05		2005/12/06	
	(%) ^{15}N	Excess ^{15}N (%)	(%) ^{15}N	Excess ^{15}N (%)	(%) ^{15}N	Excess ^{15}N (%)	(%) ^{15}N	Excess ^{15}N (%)
New growth								
Fruit	0.63310	0.26680	0.56328	0.19698			0.51293	0.14663
Leaves	0.48239	0.11609	0.57254	0.20624	0.41724	0.05094	0.51111	0.14481
New shoots	0.59456	0.22826	0.51637	0.15007	0.44646	0.08016	0.50013	0.13383
Permanet Structure								
1 yr wood								
Trunk	0.47561	0.10931	0.49182	0.12552	0.44334	0.07704	0.49087	0.12457
Canopy branches	0.50454	0.13824	0.51890	0.15260	0.49551	0.12921	0.52664	0.16034
Rootstock	0.45398	0.08768	0.49792	0.13162	0.45954	0.09324	0.52226	0.15596
Average	**0.47804**	**0.11174**	**0.50288**	**0.13658**	**0.46613**	**0.09983**	**0.51326**	**0.14696**
Roots								
Fine Roots	0.43767	0.07137	0.54351	0.17721	0.49466	0.12836	0.50997	0.14367
Thick roots	0.44634	0.08004	0.51686	0.15056	0.46153	0.09523	0.51794	0.15164
Average	**0.44201**	**0.44202**	**0.44203**	**0.44204**	**0.47810**	**0.11180**	**0.51794**	**0.14766**
Prunning								
Shoots	0.62787	0.26157	0.57289	0.20659			0.56014	0.19384
Leaves	0.52919	0.16289	0.57721	0.21091			0.56072	0.19442
Average	**0.57853**	**0.21223**	**0.57505**	**0.20875**			**0.56043**	**0.19413**
Total	4.30557	1.08023	4.92927	1.26626	3.21828	0.65418	4.70274	1.54971

a)

b)

c)

d)

e)

Appendix Figure 14: Root distribution and concentration of fine and thick roots of 'Brookfield Gala' apple trees a month before harvest in a) L80, b) S100, c) H120, d) H140 and e) H160

a)

Fruit growth (2005-2006 season)

b)

Percentage fruit growth increment (2005- 2006 season)

c)

Fruit growth (2006-2007)

d)

Percentage Fruit growth increment (2006- 2007)
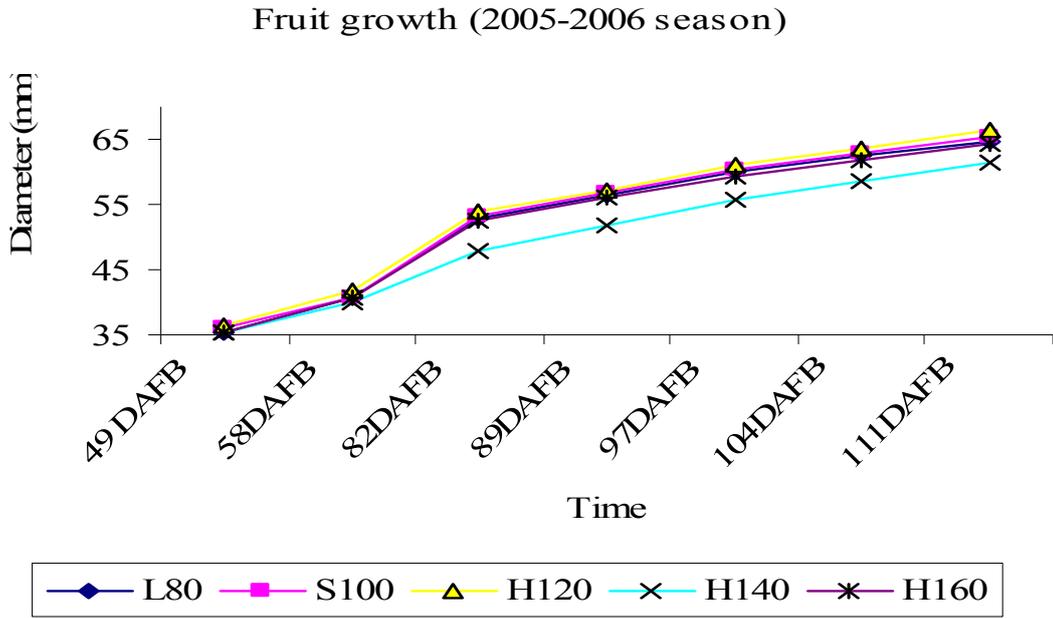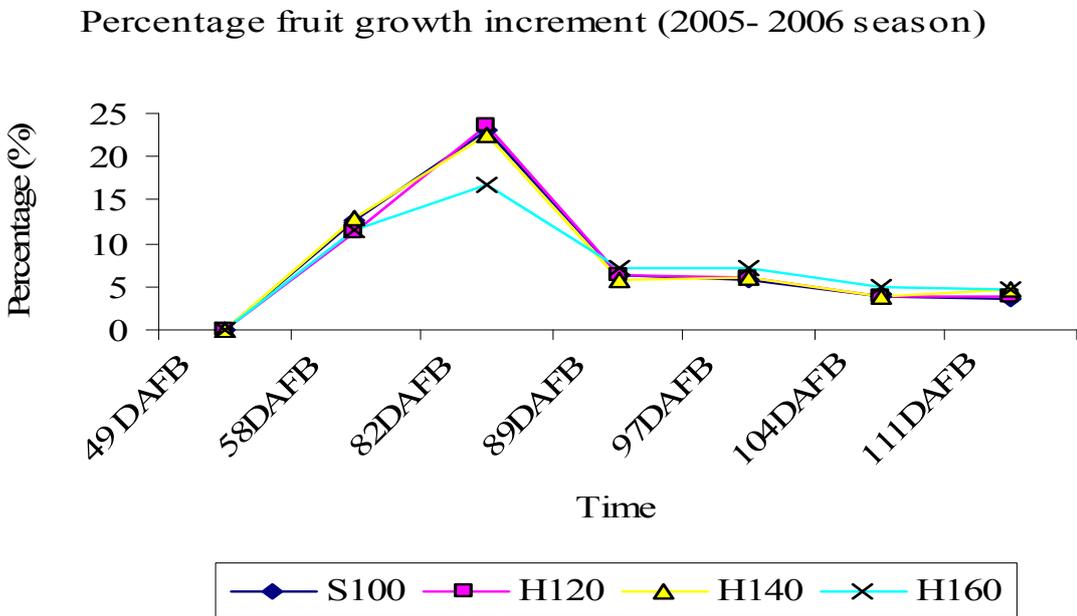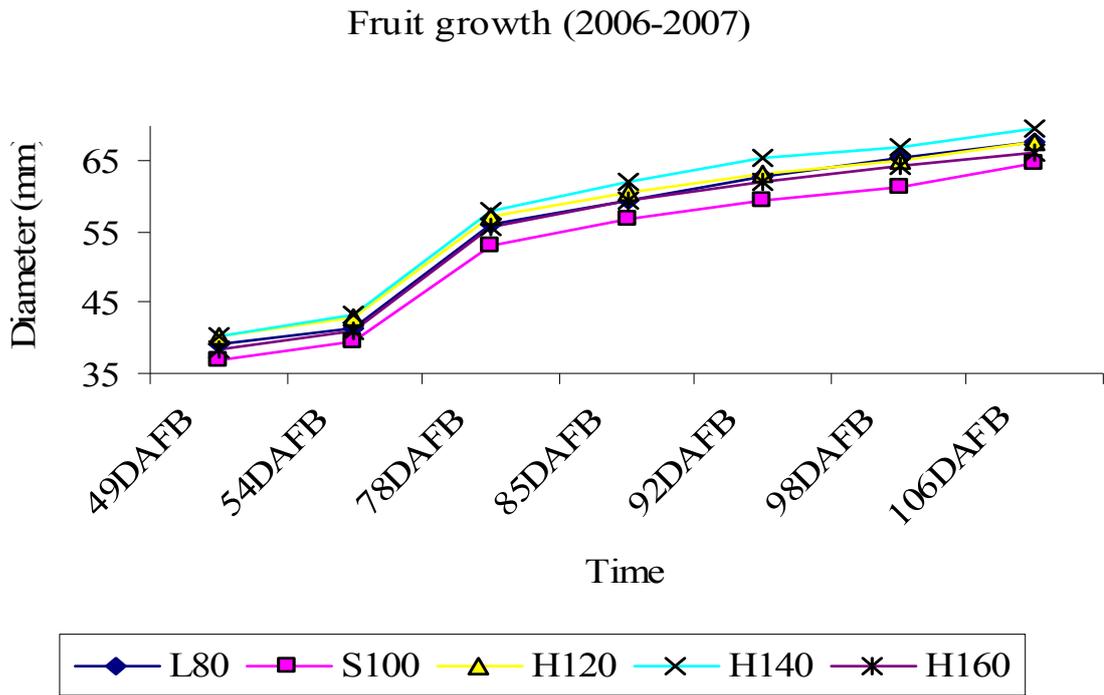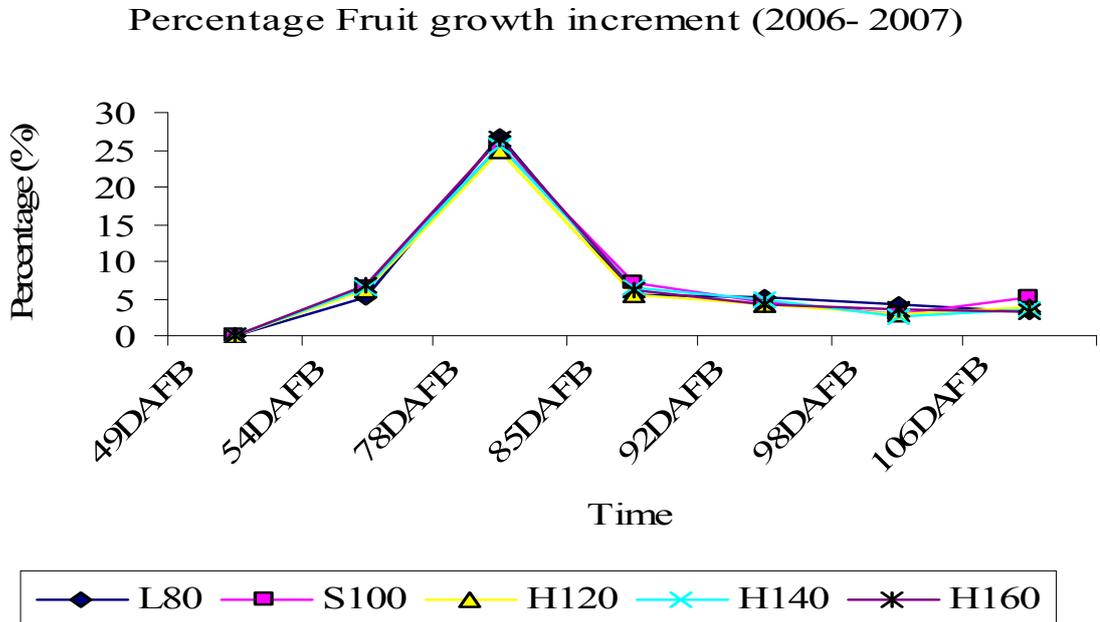
Appendix Figure 15: Fruit growth and the percentage increment of fruit growth in the different nutrient levels trial over two seasons, a) fruit growth in 2005/2006 season, b) percentage increment of fruit growth in 2005/2006 season, c) fruit growth in 2006/2007 season, d) percentage increment of fruit growth in 2006/2007 season

a)

Shoot growth (2005-2006 season)

b)

Percentage bi- weekly shoots increment (2005-2006 season)

c)

Shoot growth (2006-2007 season)

d)

Percentage bi-weekly shoot growth increment (2006-2007 season)
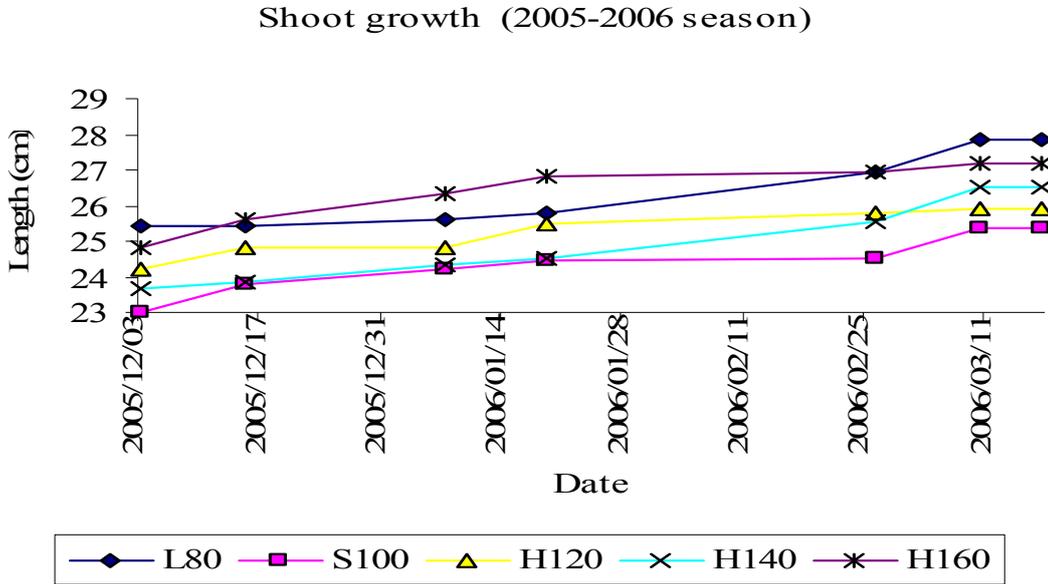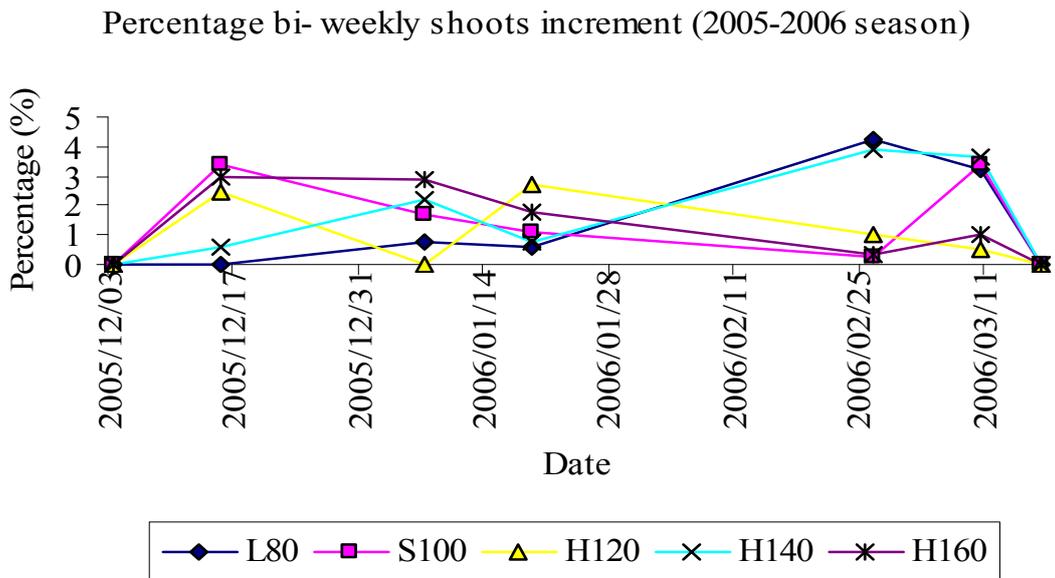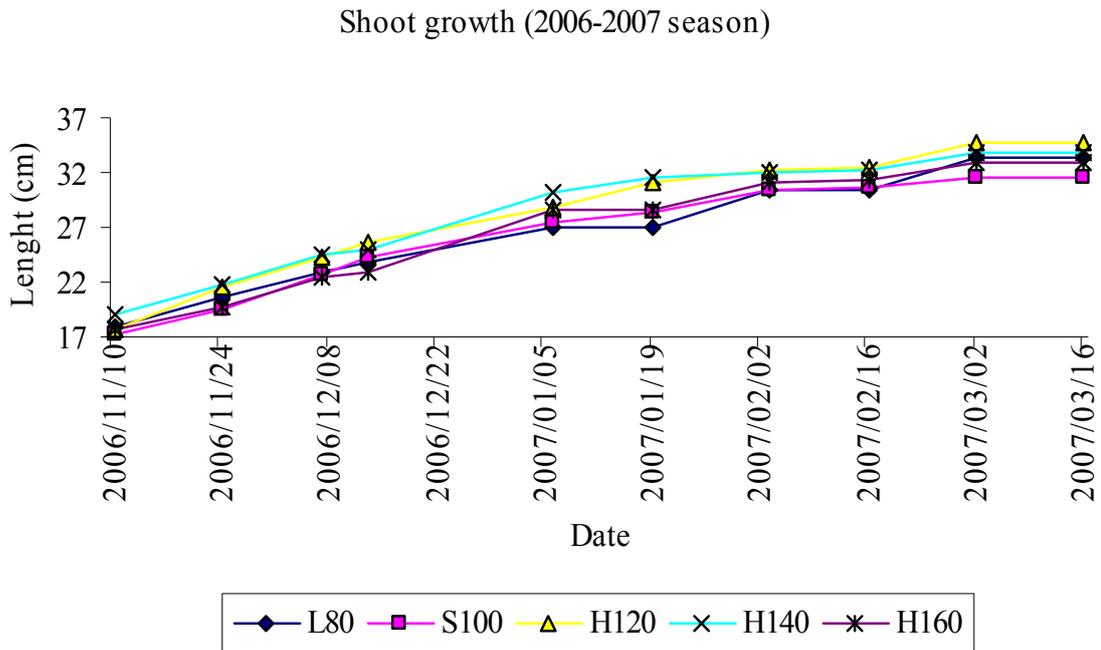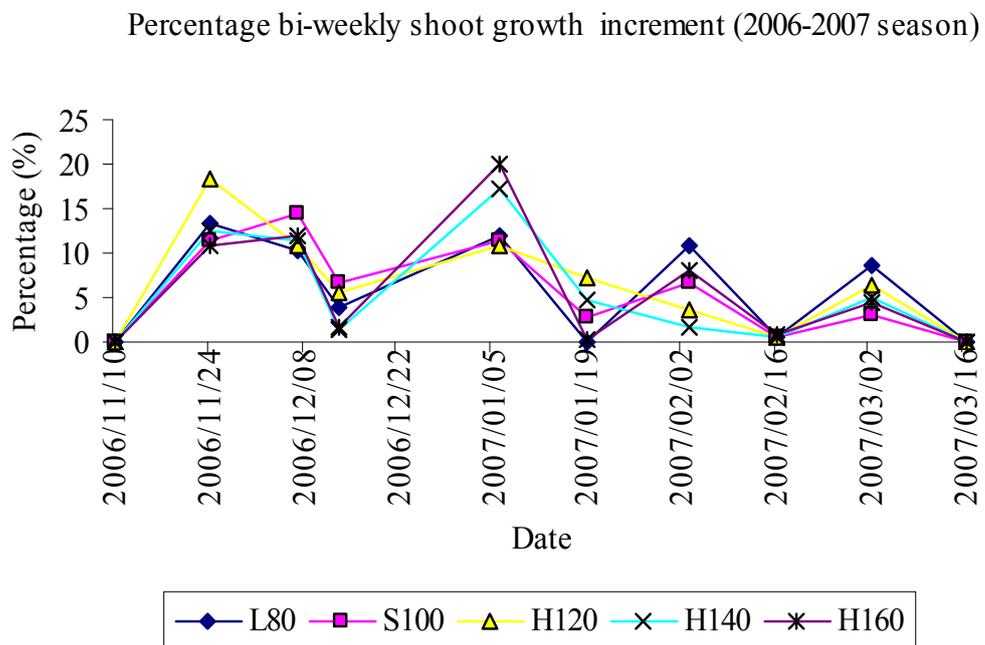
Appendix Figure 16: Shoot growth and the percentage bi-weekly increment in the shoot growth of the different nutrient levels trial over two seasons, a) shoot growth in 2005/2006 season, b) percentage increment of the shoot growth in 2005/2006 season, c) shoot growth in 2006/2007 season, d) percentage increment of the shoot growth in 2006/2007 season

a)

Fruit growth (2005-2006 season)

b)

Percentage fruit growth increment (2005-2006 season)

c)

**Fruit growth (2006-2007 season)**

d)

Percentage fruit growth increment (2006-2007 season)
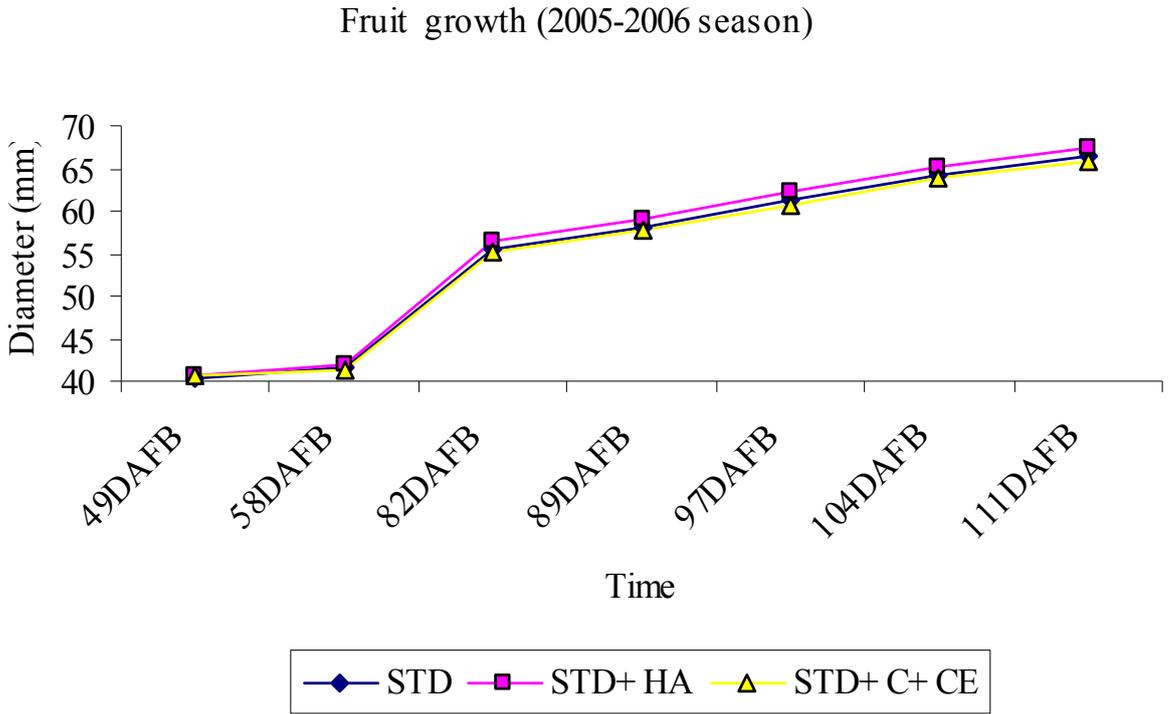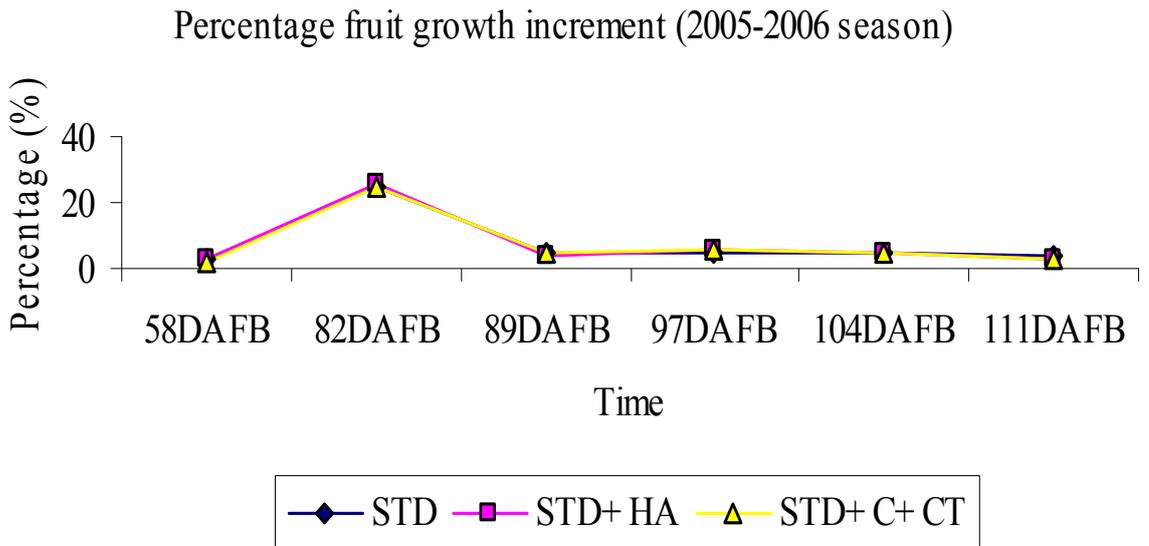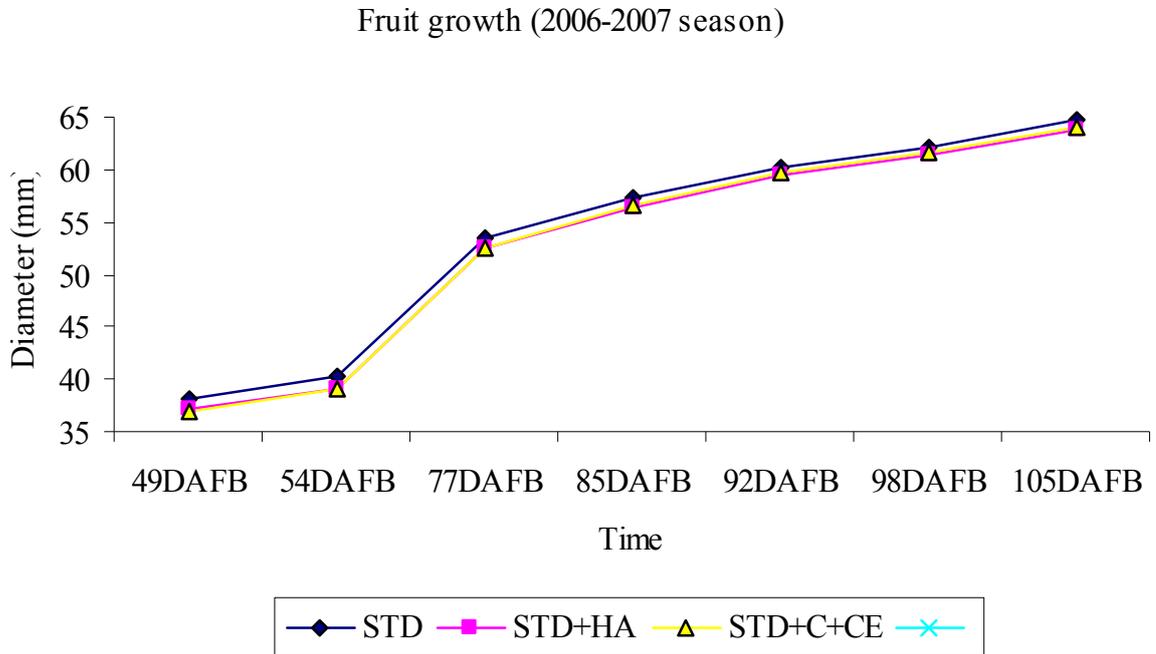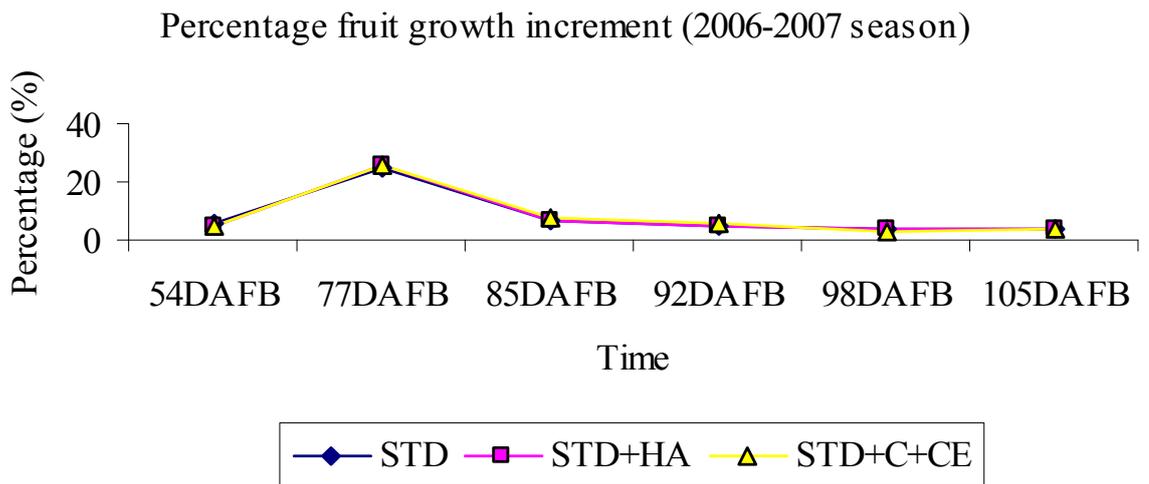

Appendix Figure 17: Fruit growth and the percentage increment of fruit growth in the biological ameliorant trial over two seasons, a) fruit growth in 2005/2006 season, b) percentage increment of fruit growth in 2005/2006 season, c) fruit growth in 2006/2007 season, d) percentage increment of fruit growth in 2006/2007 season

a)

Shoot growth (2005-2006 season)

b)

Percentage bi-weekly shoot growth increment (2005-2006 season)

c)

Shoot growth (2006-2007 season)

d)

Percentage bi-weekly shoot growth increment (2006-2007)
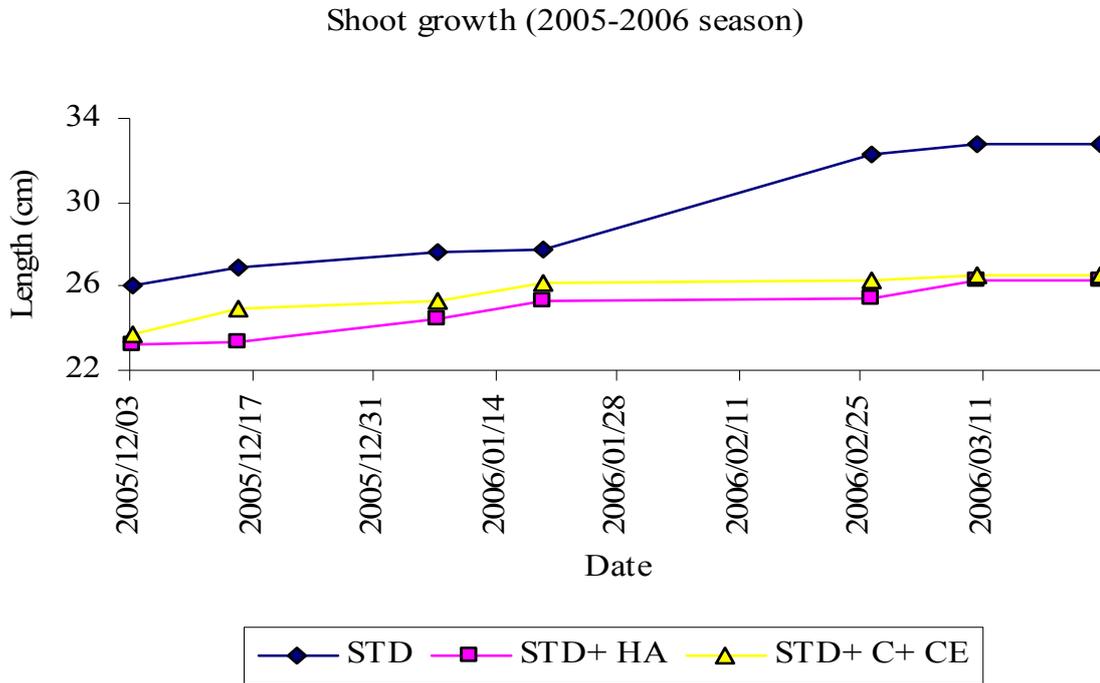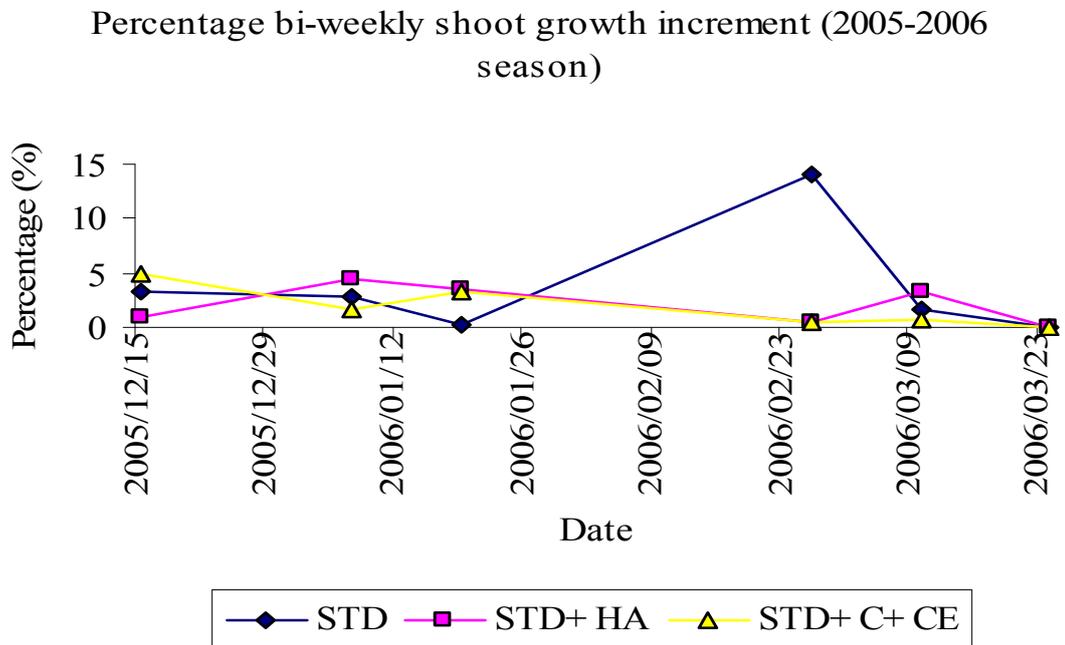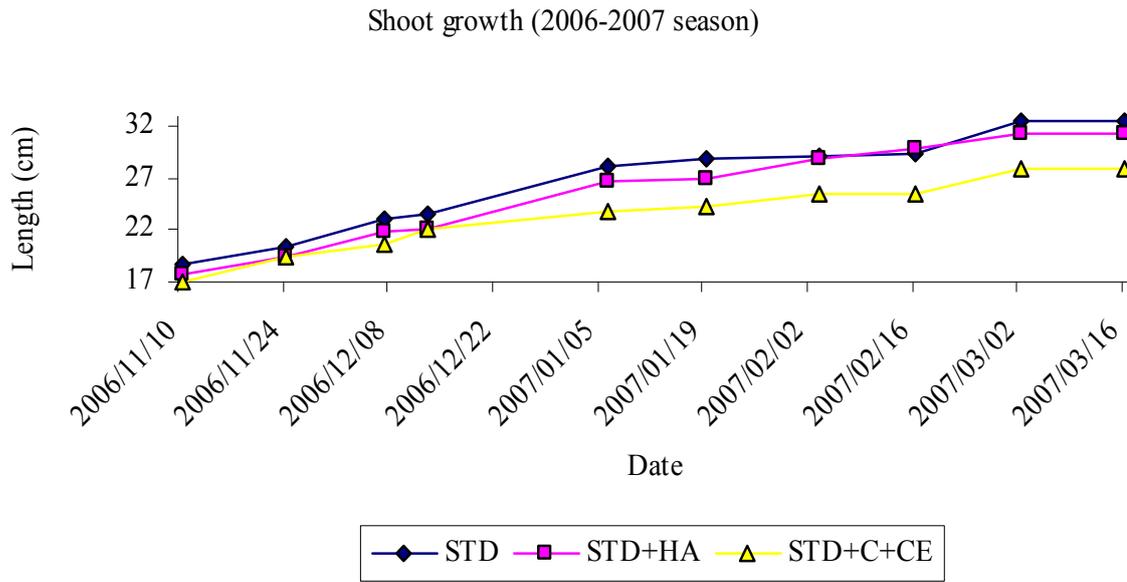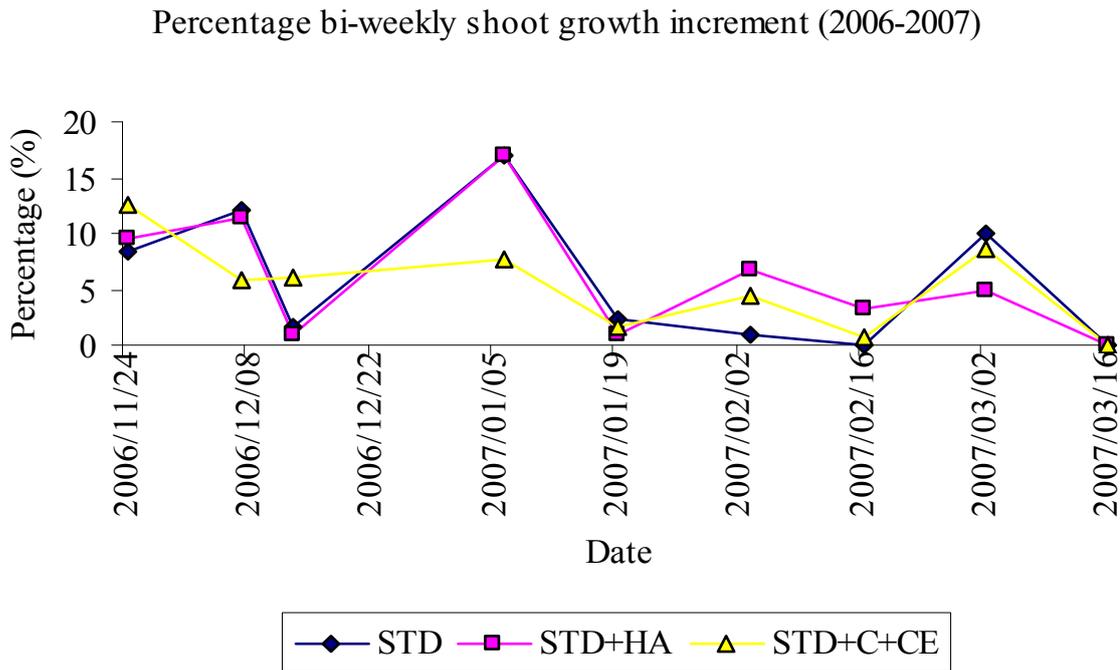
Appendix Figure 18: Shoot growth and the percentage increment in the shoot growth of the apple trees in the biological ameliorant trial over two seasons, a) shoot growth in 2005/2006 season, b) percentage increment of the shoot growth in 2005/2006 season, c) shoot growth in 2006/2007 season, d) percentage increment of the shoot growth in 2006/2007 season

a)

b)

c)

Appendix Figure 19: Root distribution and concentration of fine and thick roots of 'Brookfield Gala' apple trees a month before harvest in a) control, b) trees treated with humic acid and c) trees treated with compost plus compost extract

Appendix Table 5: The effect of different nutrient levels on fruit quality of 'Brookfield Gala' apple trees six weeks after harvest (2005-2006 season)

Treatment	Mass (g)	Background colour**		Firmness (kg)	TSS (% Brix)	Starch***	Malic acid	Citric acid
		Back	Blush					
L80	127.72	3.92a	4.50	8.12	14.33	73.27a	0.44	0.42
S100	126.34	3.93a	4.69	7.99	14.43	70.62a	0.44	0.42
H120	133.90	3.88a	4.67	7.85	14.20	73.93a	0.44	0.42
H140	119.71	3.68b	6.07	8.69	14.93	48.20b	0.46	0.44
H160	106.02	3.85a	5.21	8.19	14.07	68.04^a	0.42	0.40
Significance Level	*0.4205ns*	*0.0020*	*0.1301ns*	*0.0589ns*	*0.0577ns*	*0.0173*	*0.0748ns*	*0.0546ns*
Contrast Linear	0.1479	0.0084	0.0634	0.1916	0.9586	0.0693	0.8257	0.7152
Contrast Quadratic	0.2520	0.2911	0.6962	0.7574	0.2127	0.4415	0.0884	0.0915
Contrast Cubic	0.8021	0.0028	0.1647	0.0421	0.0598	0.0316	0.0522	0.0295
LSD (5%)	*31.0*	*0.12*	*1.33*	*0.57*	*0.59*	*15.99*	*0.03*	*0.03*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)
**Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark (0.5) and 5 light)
*** Percentage starch breakdown was determined by using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Appendix Table 6: The effect of different nutrient levels on fruit quality of 'Brookfield Gala' trees at shelf life (2005-2006 season)

Treatment	Mass (g)	Background colour**		Firmness (kg)	TSS (% Brix)	Starch***	Malic acid	Citric acid
		Back	Blush					
L80	127.08	4.12	5.57	7.00b	14.25b	92.51	0.38	0.37b
S100	124.67	4.17	4.82	7.02b	14.80b	93.84	0.41	0.40ab
H120	123.46	4.12	4.56	6.91b	14.45b	93.87	0.40	0.39ab
H140	109.22	3.92	6.26	7.89a	15.62a	82.11	0.43	0.41a
H160	119.81	4.05	5.63	7.21b	14.30b	88.58	0.39	0.37b
Significance Level	*0.1936ns*	*0.1847ns*	*0.1444ns*	*0.0220*	*0.0007*	*0.2488ns*	*0.0938ns*	*0.0379*
Contrast Linear	0.0947	0.1150	0.3291	0.0646	0.1730	0.1490	0.5837	0.6586
Contrast Quadratic	0.5281	0.9907	0.2446	0.7084	0.0091	0.9226	0.0336	0.0127
Contrast Cubic	0.1820	0.0823	0.0842	0.0299	0.0241	0.1502	0.3789	0.3803
LSD (5%)	*15.95*	*0.22*	*1.44*	*0.61*	*0.61*	*12.17*	*0.04*	*0.03*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)
**Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark (0.5) and 5 light)
*** Percentage starch breakdown was determined by using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Appendix Table 7: The effect of different nutrient levels on fruit quality of 'Brookfield Gala' apple trees six weeks after harvest (2006-2007 season)

Treatment	Mass (g)	Background colour** Back	Blush	Firmness (kg)	TSS (% Brix)	Starch***	Malic acid	Citric acid
L80	148.77ab	4.09	2.81	6.78bc	13.93b	95.10a	0.34b	0.33b
S100	128.30c	4.05	3.13	7.99a	14.67a	79.67b	0.38a	0.36a
H120	144.96 ab	4.10	2.87	6.82bc	13.82 b	94.23a	0.35b	0.33b
H140	153.34a	4.17	3.07	6.55c	13.88b	98.32a	0.35b	0.34b
H160	139.51bc	4.01	3.66	7.22 b	14.15 ab	91.68a	0.37ab	0.35ab
Significance Level	*0.0035*	*0.1549ns*	*0.4819ns*	*<. 0001*	*0.0224*	*0.0009*	*0.0417*	*0.0451*
Contrast Linear	0.6200	0.7990	0.1618	0.2937	0.5492	0.1765	0.4480	0.4588
Contrast Quadratic	0.7471	0.1889	0.4519	0.7713	0.9807	0.4849	0.8536	0.9613
Contrast Cubic	0.0002	0.0317	0.3942	<. 0001	0.0056	0.0001	0.0094	0.0100
LSD (5%)	*12.07*	*0.13*	*1.05*	*0.48*	*0.54*	*7.85*	*0.03*	*0.03*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)
*Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark (0.5) and 5 light)
* Percentage starch breakdown was determined by using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Appendix Table 8: The effect of biological ameliorants on fruit quality of 'Brookfield Gala' apple trees six weeks after harvest (2005-2006 season)

Treatment	Mass (g)	Background colour** Back	Blush	Firmness (kg)	TSS (% Brix)	Starch***	Malic acid	Citric acid
STD	124.52b	4.22	4.33	7.53	14.65	84.81	0.43	0.41
STD +HA	134.86a	4.13	4.74	7.52	14.74	85.27	0.45	0.43
STD+C+CE	128.58b	4.12	4.76	7.68	14.98	78.97	0.45	0.43
Significance Level	*0.0036*	*0.2878ns*	*0.6027ns*	*0.6593ns*	*0.3625ns*	*0.3919ns*	*0.2191ns*	*0.2840ns*
LSD (5%)	*5.38*	*0.14*	*1.00*	*0.41*	*0.49*	*10.64*	*0.03*	*0.03*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)
*Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark (0.5) and 5 light)
* Percentage starch breakdown was determined by using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Appendix Table 9: The effect of biological ameliorants on fruit quality of 'Brookfield Gala' trees at shelf life (2005-2006 season)

Treatment	Mass (g)	Background colour**		Firmness (kg)	TSS (% Brix)	Starch***	Malic acid	Citric acid
		Back	Blush					
STD	126.28	4.28	4.35	6.70	14.64	98.09	0.40	0.38
STD +HA	132.62	4.36	4.90	6.56	14.80	98.23	0.42	0.40
STD+C+CE	127.95	4.23	4.67	6.75	15.21	95.83	0.41	0.39
Significance Level	*0.0881ns*	*0.3609ns*	*0.6698ns*	*0.5782ns*	*0.1267ns*	*0.0836ns*	*0.3482ns*	*0.3180ns*
LSD (5%)	*5.85*	*0.19*	*1.30*	*0.39*	*0.58*	*2.36*	*0.03*	*0.03*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)
**Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark (0.5) and 5 light)
*** Percentage starch breakdown was determined by using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Appendix Table 10: The effect of biological ameliorants on fruit quality of 'Brookfield Gala' apple trees six weeks after harvest (2006-2007 season)

Treatment	Mass (g)	Background colour**		Firmness (kg)	TSS (% Brix)	Starch***	Malic acid	Citric acid
		Back	Blush					
STD	137.05	4.04	3.30	7.16	14.18b	93.77	0.36b	0.35b
STD +HA	131.02	3.99	4.04	7.54	14.91a	91.37	0.38ab	0.37ab
STD+C+CE	125.23	3.98	4.28	7.39	15.24a	93.24	0.40a	0.39a
Significance Level	*0.1394ns*	*0.7051ns*	*0.1521ns*	*0.4875ns*	*0.0193*	*0.8891ns*	*0.0165*	*0.0440*
LSD (5%)	*11.89*	*0.14*	*1.05*	*0.67*	*0.72*	*11.13*	*0.03*	*0.03*

* Means within a column, followed by different letters are significantly different (P =0.05; LSD)
**Background colour was assessed using the Deciduous Fruit Board chart for apples and pears (value 0.5-5; dark (0.5) and 5 light)
*** Percentage starch breakdown was determined by using the iodine test and corresponding starch conversion chart for pome fruit (Unifruco Research Services, Bellville, South Africa).

Appendix Table 11: Leaf nutrient analysis (2005/2006 and 2006/2007 seasons). Leaf analysis done by a commercial laboratory (Bemlabs, Strand, South Africa) a) Nutrient levels trial; b) Biological ameliorant trial

a)

Date	Treatment	Macro nutrients (%)						Micro nutrient (mg/kg)						
		N	P	K	Ca	Mg	S	Na	Mn	Fe	Cu)	Zn	B	Mo(µg/kg)
31/01/2006	L80	2.47	0.18	1.43	1.97	0.41	0.15	266	168	262	6	87	30	872
	S100	2.42	0.19	1.33	1.92	0.42	0.11	281	166	290	6	80	28	393
	H120	2.44	0.20	1.38	2.03	0.40	0.13	246	175	315	7	92	30	1053
	H140	2.40	0.18	1.34	2.07	0.40	0.16	297	197	290	6	103	30	871
	H160	2.42	0.18	1.31	1.99	0.42	0.16	239	172	270	6	88	28	504
31/01/2007	L80	2.46	0.18	1.51	1.17	0.37	0.16	123	434	314	5	81	34	1358
	S100	2.38	0.18	1.53	1.24	0.43	0.15	137	307	192	5	73	34	848
	H120	2.55	0.17	1.77	1.09	0.38	0.15	129	208	233	6	50	34	704
	H140	2.62	0.19	1.67	1.14	0.36	0.16	129	250	172	5	55	35	452
	H160	2.43	0.18	1.74	1.20	0.40	0.16	161	235	172	5	63	36	626

Norms: Kotzé (2001) N (2.1-2.6 %), P (0.14-0.19 %), K (1.2-1.4 %), Ca (1.45-1.60 %), Mg (0.30-0.40%), S (0.2-0.4 %), Na (>500mg/kg),

Mn (20-90 mg/kg), Fe (80-150 mg/kg), Cu (5-10 mg/kg), Zn (30-50 mg/kg) and B (30-35 mg/kg).

b)

Date	Treatment	Macro nutrients (%)						Micro nutrient (mg/kg)						
		N	P	K	Ca	Mg	S	Na	Mn	Fe	Cu)	Zn	B	Mo(µg/kg)
31/01/2006	STD	2.30	0.16	1.28	1.83	0.36	0.14	209	167	261	6	89	29	849
	STD+ HA	2.36	0.17	1.53	1.97	0.38	0.13	260	168	270	7	90	30	709
	STD + C+CE	2.48	0.18	1.37	1.99	0.41	0.15	262	186	235	7	96	30	250
31/01/2007	STD	2.46	0.17	1.50	1.28	0.42	0.17	162	315	158	4	62	32	644
	STD+ HA	2.30	0.17	1.74	1.22	0.37	0.14	170	241	143	4	58	33	595
	STD + C+CE	2.20	0.23	1.72	1.38	0.42	0.14	188	229	156	4	56	30	445

Appendix Table 12: Soil sample analysis over two season ((2005/2006 and 2006/2007 seasons) for 0-300 mm and 300-600 mm soil depths. Soil analysis done by a commercial laboratory (Bemlab, Strand, South Africa) a) analysis before treatment started, b) soil analysis for the different nutrient levels trial, c) soil analysis for the biological ameliorants trial

a)

Date	Profile	N (%)	K (mg/kg)	K (c mol(+)//kg)
2005/12/02	A (30 cm)	0.144	203	0.52
	B (60 cm)	0.115	108	0.28

b)

Date	Element	Treatment: Profile									
		L80: 30 cm	L80: 60 cm	S100: 30 cm	S100: 60 cm	H120: 30 cm	H120: 60 cm	H140: 30 cm	H140: 60 cm	H160: 30 cm	H160: 60 cm
2006/01/06	N (%)	0.099	0.082	0.081	0.078	0.101	0.077	0.077	0.065	0.077	0.084
	K (mg/kg)	0.354	0.366	0.335	0.208	0.552	0.345	0.248	0.130	0.242	0.215
2006/01/31	N (%)	0.075	0.069	0.066	0.037	0.087	0.067	0.092	0.071	0.105	0.088
	K (mg/kg)	0.364	0.195	0.671	0.281	0.499	0.275	0.578	0.448	0.707	0.745
2006/02/28	N (%)	0.100	0.096	0.085	0.059	0.107	0.075	0.068	0.094	0.114	0.093
	K (mg/kg)	0.218	0.087	0.245	0.232	0.456	0.181	0.262	0.196	0.554	0.285
2006/03/31	N (%)	0.057	0.058	0.043	0.047	0.085	0.086	0.064	0.068	0.054	0.068
	K (mg/kg)	115.35	70.38	62.95	52.79	152.50	125.13	66.47	117.70	19.55	68.43
	K (me/ 100g)	0.295	0.180	0.161	0.135	0.390	0.320	0.170	0.301	0.050	0.175
2006/11/24	N (%)	0.088	0.159	0.096	0.078	0.107	0.112	0.114	0.147	0.081	0.070
	K (cmol/kg)	0.149	0.083	0.325	0.213	0.390	0.211	0.148	0.110	0.242	0.103
2007/03/16	N (%)	0.038	0.023	0.071	0.022	0.061	0.087	0.054	0.021	0.052	0.027
	K (mg/kg)	79.990	9.996	117.662	30.427	118.652	73.687	102.329	33.350	59.807	36.466

c)

Date	Element	Treatment: Profile					
		Std: 30 cm	Std :60 cm	Std+HA: 30 cm	Std+HA: 60 cm	Std+C+CE: 30 cm	Std+C+CE: 60 cm
2006/01/06	N (%)	0.079	0.109	0.064	0.053	0.063	0.073
	K (mg/kg)	0.395	0.297	0.268	0.209	0.212	0.233
2006/01/31	N (%)	0.051	0.033	0.069	0.050	0.063	0.052
	K (mg/kg)	0.460	0.311	0.180	0.160	0.307	0.201
2006/02/28	N (%)	0.088	0.067	0.087	0.065	0.081	0.066
	K (mg/kg)	0.613	0.340	0.441	0.350	0.562	0.279
2006/03/31	N (%)	0.073	0.046	0.058	0.045	0.059	0.069
	K (mg/kg)	70.77	26.20	26.59	0.00	118.09	16.42
	K (me/ 100g)	0.181	0.067	0.068	0.200	0.302	0.042
2006/11/24	N (%)	0.108	0.089	0.077	0.107	0.084	0.106
	K (cmol/kg)	0.189	0.152	0.090	0.092	0.483	0.257
2007/03/16	N (%)	0.028	0.036	0.056	0.028	0.068	0.035
	K (mg/kg)	92.096	58.475	358.308	72.280	123.414	63.176

Appendix Table 13: Compost analysis done by a commercial laboratory (Bemlab, Strand, South Africa)

Date	pH (KCL)	Resistance ohm	Moisture %	Density kg/m3	Extractable nutrients (%)					Micro elements (mg/kg)					
					N	P	K	Ca	Mg	Na	Mn	Cu	Zn	B	C (%)
17/10/2005	7.7	80	33.1	607.7	0.76	0.07	0.67	1.06	0.12	974.29	34.86	3.56	33.41	5.62	11.10
26/01/2006/	6.3	90	36.9	596.1	1.29	0.10	0.26	0.62	0.15	1130.87	46.37	3.83	50.58	8.80	15.20