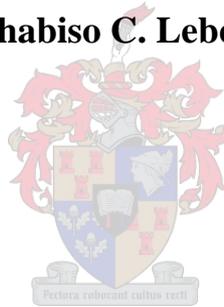


**Influence of crop based water and nutrient strategies on physiological
aspects of apple trees ‘Brookfield Gala’**

By

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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SUMMARY

It is a common practise in the Western Cape to use micro sprinklers as the standard irrigation system for apple trees. Over the past forty years much effort has been put into the optimisation of the tree canopy. Less attention has been given to root proliferation, and the question as to whether root stimulation and proliferation, through intensive water and nutrient management, can contribute towards improved tree efficiency and more efficient water use. This is addressed in this study.

‘Brookfield Gala’ apple trees were studied in the Genadendal area near Greyton, in the Western Cape Province, South Africa. The trees were planted in Dundee soil (well aerated sandy loam soil) during winter 2003. Both horticultural aspects (tree growth, shoot growth, fruit yield and quality, trunk circumference and root growth) and gas exchange were studied from 2004/5 until 2007/8 under three different water application strategies, namely micro sprinkler irrigation, daily drip and pulsing drip irrigation and using two different rootstocks: M793 and M7. Irrigation under micro sprinkler irrigation was applied once to three times weekly, daily drip irrigation once daily/twice daily, and pulsing drip irrigation one to six times daily.

Water use for bearing apple trees was calculated using long-term evaporation data (for Villiersdorp and Caledon) and existing crop factors for apples. Annual nutrient requirements were adapted from literature and divided percentage-wise into the requirements for five different phenological stages. Soil sensors were used to keep plant available soil water between 100% and 50%. A computer software program was used to incorporate all the above mentioned information and calculate the exact amounts of water and nutrients, and the application times. In general, drip irrigation systems used $\pm 26\%$ less water than micro sprinkler irrigation system.

Significantly higher fruit yields were obtained with trees under daily or pulsing drip irrigation than those under micro irrigation during 2005/6 and 2007/8. During 2006/7 the crop load was low due to unfavourable weather conditions during flowering, resulting in poor fruit set and no differences in yield. There was a significantly higher number of thin plus medium roots (3mm and less in diameter) in the 0–400mm rooting zone and total root mass at 0–800mm rooting zone under drip irrigation systems than under micro sprinkler irrigation.

'Brookfield Gala' apple trees grown under daily drip irrigation and pulsing drip irrigation performed better compared to those grown under micro sprinkler irrigation with respect to CO_2 assimilation rate (A), stomatal conductance (g_s), water use efficiency (WUE) and leaf water potential. None of the three irrigation systems affected the biochemical efficiency of the leaf significantly, except on a few occasions during the pre-harvest period. This implied that the changes in leaf biochemical efficiency were as a result of both stomatal and non-stomatal effects (temperature and vapour pressure deficit).

The removal of fruit at harvest had a great influence on leaf photosynthetic capacity under micro irrigation but less so under drip irrigation systems. Higher chlorophyll a and chlorophyll b concentrations were observed under drip irrigation systems than under micro sprinkler irrigation, implying efficient biochemical efficiency under these systems compared to micro sprinkler irrigation during the post-harvest period. Use of daily drip irrigation and pulsing drip irrigation delayed the process of leaf ageing.

This study demonstrated the benefits of more intensive water and nutrient application for apple trees. Improved root proliferation, increased fruit yield and photosynthetic efficiency have been found under drip irrigation system than under micro sprinkler irrigation.

OPSOMMING

Dit is 'n algemene praktyk in die Wes-Kaap om mikro as die standaard besproeiingsstelsel vir appelbome te gebruik. Oor die afgelope veertig jaar is baie moeite gedoen om die blaredak te optimaliseer. Minder aandag is aan wortelgroei geskenk en die vraag is of wortelstimulering en -vorming deur intensiewe water- en voedingsbeheer kan bydra tot verbeterde boomdoeltreffendheid en meer effektiewe waterverbruik. Dit word in hierdie studie ondersoek.

'Brookfield Gala'-appelbome is in die Genadendal-area naby Greyton in die Wes-Kaap, Suid-Afrika, bestudeer. Die bome is gedurende die winter van 2003 in Dundee-grond (goed deurlugte, sanderige leemgrond) geplant. Tuinboukundige aspekte (boomgroei, lootgroei, vrugopbrengs en -kwaliteit, stamontrek en wortelgroei) sowel as gaswisseling is bestudeer vanaf 2004/5 tot 2007/8 onder drie verskillende watertoedieningstrategieë, naamlik mikrobeprosing, daaglikse drup- en polsdrupbesproeiing en twee verskillende onderstamme: M793 en M7. Besproeiing onder mikrobeprosing is een tot drie keer per week toegedien, daaglikse drupbesproeiing een tot twee keer daaglik en polsdrupbesproeiing een tot ses keer daaglik.

Waterverbruik vir draende appelbome is bereken deur gegewens oor langtermyn-verdamping (vir Villiersdorp en Caledon) en bestaande dragfaktore vir appels te gebruik. Jaarlikse voedingsvereistes is uit literatuur aangepas en persentasiegewys in die vereistes vir vyf verskillende fenologiese stadiums ingedeel. Grondsensors is gebruik om plantbeskikbare grondwater tussen 100% en 50% te hou. 'n Rekenaarsagtewareprogram is gebruik om al die bogenoemde inligting te inkorporeer en die presiese hoeveelhede water en voedingstowwe asook die toedieningstye te bereken. Oor die algemeen het drupbesproeiingsstelsel $\pm 26\%$ minder water as die mikrobeprosingsstelsel gebruik.

Aansienlik hoër vrugopbrengste is verkry van bome onder daaglikse of polsdrupbesproeiing as dié onder mikrobeprosing gedurende 2005/6 en 2007/8. Gedurende 2006/7 was die draglading min as gevolg van ongunstige weersomstandighede tydens blomtyd, wat gelei het tot swak vrugset en geen verskille in opbrengs nie. Daar was 'n aansienlik hoër aantal dun tot medium wortels (3mm en minder in deursnee) in die 0–400 mm wortelsone en totale

wortelmasse in die 0–800 mm wortelzone onder drupbesproeiingsstelsse as onder mikrobeproeijing.

'Brookfield Gala' appelbome gekweek onder daaglikse drupbesproeiing en polsdrupbesproeiing het beter gevaar met betrekking tot CO₂ assimilasietympo (A), huidmondgeleiding (g_s), doeltreffendheid van waterverbruik (DWV) en blaarwaterpotensiaal in vergelyking met wanneer dit onder mikrobeproeijing was. Geeneen van die drie besproeiingsstelsse het die biochemiese doeltreffendheid van die blaar beduidend beïnvloed nie, behalwe by 'n paar geleenthede gedurende die tydperk voor die oes. Dit impliseer dat die veranderinge in biochemiese blaardoeltreffendheid die resultaat van huidmond- sowel as nie-huidmondeffekte (temperatuur en dampdruktekort) was.

Die verwydering van vrugte onder mikrobeproeijing tydens die oes het 'n groot invloed gehad op fotosintetiese blaarkapasiteit, maar minder onder drupbesproeiingsstelsse. Hoër chlorofil a- en chlorofil b-konsentrasies is opgemerk onder drupbesproeiingsstelsse as onder mikrobeproeijing, wat doeltreffende biochemiese doeltreffendheid onder hierdie stelsse impliseer in vergelyking met mikrobeproeijing gedurende die tydperk ná die oes. Die gebruik van daaglikse drupbesproeiing en polsdrupbesproeiing het die proses van blaarveroudering vertraag.

Hierdie studie het die voordele van meer intensiewe water- en voedingtoediening vir appelbome gedemonstreer. Verbeterde wortelgroei, verhoogde vrugopbrengs en doeltreffende fotosintese is gevind onder drupbesproeiingsstelsse teenoor dié onder mikrobeproeijing.

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Influence of crop based water and nutrient strategies on physiological aspects of apple trees ‘Brookfield Gala’

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1. Literature review: Influence of different water frequencies and nutrient solution applications on the physiological and horticultural performance of apple trees

1.1 Introduction

In South Africa, as in many other places worldwide, water resources are limited. A high demand for water by agriculture, industry and municipalities, and periodic droughts, has often led to water shortages. Apple fruit cultivation in the Western Cape is under some level of irrigation to increase production and improve fruit yield. Most of the orchards are under medium-density planting systems, although there has been a move to higher-density orchards in the Western Cape, with planting populations of 1900 to 2500 trees per hectare. With a projected increase in the number of trees per hectare in the future, good management practices, especially intensive water and nutrient management strategies, are needed. In the long run this will improve the fruit yield and quality, and increase the producers' returns whilst simultaneously minimising costs and utilising water more efficiently. Better irrigation strategies that require less water and result in increased fruit yield and quality are required.

Economic realities are putting increasing pressure on producers to limit inputs while requiring the returns and quality be increased. During the last three decades there has been much focus on high-density planting and sophisticated trellising (Robinson, 2003). In the next few years, however, there will be a need to increase tree productivity, by responding promptly and correctly to its requirements. New technologies, based on the integration of horticultural and physiological knowledge, could enhance the efficacy of root systems and increase nutrient absorption, in particular calcium. An effective root system stimulates many growth points (proliferation), it receives optimal oxygen, optimises absorption of nutrients and increases the synthesis of cytokinin. Cytokinin synthesis is strongly associated with the development of lateral shoots and increased shoot angles (Jones & Schreiber, 1997).

Many producers are currently using micro sprinkler irrigation (micro sprays) and hand fertilisation (fertilizer allocation according to requirements). There are also producers who are

using more intensive and controlled irrigation and fertilisation by means of drip systems (fertigation). During the current decade there has been a growing interest in the pulsing drip irrigation system in which enriched water is continuously supplied to the plant so that the roots are surrounded by a film of water and nutrients. Specific amounts and types of elements can be applied at specific phenological and physiological stages to manipulate plant processes beneficially (Stassen *et al.*, 1999). In this way crop optimisation can theoretically be reached. The relationship between irrigation strategies and their effects on physiological processes such as photosynthesis are poorly understood.

The primary objective of every fruit producer is to produce fruit of high quality (high packout percentage) whilst maintaining high yields and keeping costs within certain limits. A high percentage of apples produced in South Africa is destined for the export market. Fruit quality and fruit size are therefore of paramount importance. The challenge that faces most South African apple producers is to increase fruit quality and fruit size, and optimise yield, by good horticultural and management practices.

Use of different irrigation systems and irrigation scheduling are some of the important factors known to improve fruit size and quality (Naor, 2006b). Fruit trees explore a substantial soil volume during their lifetime and depend on the soil's water holding capacity for avoidance of water stress. Soil depth and water holding capacity were important factors in the selection of land for fruit tree cultivation until the use of high frequency irrigation made the soil water holding features less critical (Girona *et al.*, 2002).

Intensive planting of apple trees, e.g. 2000 trees per hectare on dwarfing rootstocks (e.g. M9), has become common practice in many of the world's apple production areas (Webster, 1997). In South Africa higher densities (more than 1667 trees/ha) have been hampered by the use of M793 as rootstock, however, efforts are now being made to implement newer generation rootstocks to overcome this (Costa & Stassen, 2007). For the new generation of rootstocks, with their smaller root systems, more sophisticated water and nutrient strategies need to be in place. The dwarfing rootstocks and limitation of shoot extension (Avery, 1970) are important to growth restrictions, allowing fruit yields to be maintained as the trees mature (Buwalda & Lenz, 1992). The final

dimensions of the apple tree depend largely on the growth and activity of the rootstock. The water and nutrient uptake capacities of the rootstock are also important, although as yet not well understood (Buwalda & Lenz, 1992).

Efficient tree management that ensures fruit quality and optimal yield will be increasingly important to fruit tree production in the future. Use of dwarfing rootstock leads to minimal pruning and training (because of less vigorous growth) hence a better fruit size and lower requirement for fruit thinning. Irrigation strategies that ensure that water is applied directly to the root zone (Assaf *et al.*, 1984) and the application of nutrients in times of maximum consumption are vital to future apple production (Terblanche, 1972; Stassen & North, 2005).

1.2 Soil water availability

A plant transports large volumes of water over its lifetime – in the range of 200–1000 times the dry mass of its body weight (Hsiao & Xu, 2000). This is the result of having to keep the interior of its leaves open to the atmosphere for the adequate absorption and assimilation of carbon dioxide, with the inevitable consequence that water vapour escapes from the leaves. Water transport is closely associated with the myriad of plant processes, including photosynthesis, translocation, mineral nutrition, hormonal regulation, and numerous molecular and genetic factors (Hsiao & Xu, 2000). Knowledge of the factors controlling soil water availability is essential to the understanding of fruit tree water use and irrigation requirements (Jackson, 2003). The amount of water available in the soil depends on the amount supplied (by rainfall or irrigation), the amount lost by evaporation and runoff from the surface or by drainage to below the rooting zone, and the amount retained in the rooting zone until taken up by the trees (Girona *et al.*, 2002). The water content, the rate of water movement in the soil and runoff depend on soil type and soil structure (Holbrook, 2002). Water flows more readily in coarse textured soils e.g., sandy soils (2000–200 μm in particle diameter) and less readily in fine textured soils e.g., clay soils (<2 μm particle diameter) (Holbrook, 2002; Tromp, 2005).

Drainage of water to below the rooting zone varies with soil type. Water is drained more easily under sandy type soils and the drainage is less under clay soils (Holbrook, 2002). Field capacity is the amount of soil moisture or water content held in soil after excess water has drained away

and the rate of downward movement has materially decreased, which usually takes place within 2–3 days after rain or irrigation in pervious soils of uniform structure and texture (Jackson, 2003). Drainage in soils is largely influenced by layering in the soil profile and by the presence of different pore size distributions (Miller, 1982). The higher the layering within the soil profile the more the resistance and the slower the water drainage (Miller, 1982). The wilting point is the soil water content below which plants growing in that soil remains wilted even when transpiration is nearly eliminated, and this varies with the soil type (Ahuja & Neilsen, 1990). Available water capacity is defined as the difference between the field capacity and the permanent wilting point (Holbrook, 2002), while the soil moisture deficit is the difference between the amount of water held at field capacity and the amount held at the time considered (Miller, 1982).

It has been postulated that soil water is readily available to plants throughout the entire range between field capacity and wilting point (Viehmeyer & Hendrickson, 1950). However, many researchers have questioned the validity of the term field capacity from the physical point of view and proposed that only part of the water between field capacity and wilting point is available to plants (Ahuja & Neilsen, 1990; Girona *et al.*, 2002). The major reason for this disagreement amongst researchers regarding the effect of water availability on plant performance appears to be an insufficient understanding of the interaction between physiological and physical soil water processes (Bravdo, 2000). Furthermore, the soil water availability data reported by various authors do not always relate the same dynamic aspects. Soil water availability is, however, regarded as a dynamic aspect rather than a static parameter because soil water potential at any given time is a function of the flow throughout the soil–plant atmosphere continuum (Bravdo, 2000).

1.3 Basics of water relations in apple trees

Water relations are important to the functioning of the apple tree, as water is the greatest component of the active tree (by mass) (excluding the wood consisting of dead tissue), and almost all critical processes can be limited by an inappropriate water status (Lakso, 2003).

1.3.1 The soil–plant–water–atmosphere continuum (SPAC)

An Ohm's law analog was proposed to describe and analyse the path of water flow from the soil, through plants, and into the atmosphere (Van den Honert, 1948). This water flow pathway running through a series of gradients and resistances is referred to as the soil–plant–water–atmosphere continuum (SPAC) (Landsberg & Jones 1981; Bravdo, 2000). The analogy equates water flux to an electrical current, the water phase to the electromotive force, the resistance to either liquid or gaseous diffusion, and water flux to an electrical resistance analog, e.g.,

$$E = \frac{\Delta\psi_{\text{soil} - \text{root surface}}}{R_{\text{soil}}} = \frac{\Delta\psi_{\text{root surface} - \text{xylem}}}{R_{\text{root}}} = \frac{\Delta\psi_{\text{xylem}}}{R_{\text{xylem}}} = \frac{\Delta\psi_{\text{leaf} - \text{atmosphere}}}{R_{\text{leaf}}}$$

(Bravdo, 2000) Eq 1

where: E = water flux, ψ = water potential, R = resistance to soil, root, xylem and leaf.

The SPAC pathway involves four major phases:

- a) water movement in the soil towards the roots
- b) water movement into the roots and through the conducting tissues to the stems
- c) water movement through the stems to the leaves
- d) water movement in the leaves to the evaporation sites in the intercellular spaces and through the stomata.

Leaf water potential, which is often used as a measure of water status, is dependent not only on the water status of other parts of the plant but also on the evaporative demand and stomatal aperture and on flow resistance in the transport pathway (Landsberg & Jones, 1981). The water flow through the soil–plant–water continuum is restricted by a number of resistances through the system. Most of these are hydraulic resistances, and are governed by resistances of the water potential in the bulk soil at the surface of the roots, at the base of the stem, at the base of the petiole, and in the bulk mesophyll cell of the leaf. The application of the Ohm's law analogy to the SPAC system is an oversimplification because it assumes steady-state isothermal flow and constant resistance conditions, which seldom prevail (Denmead & Millar, 1976; Landsberg and Jones, 1981; Bravdo, 2000, Tromp, 2005). It is important to note that the flux within the gaseous

phase is linearly related to the vapour pressure gradient between the sub-stomatal cavity within the intercellular spaces in the leaves and the external atmosphere, rather than to the potential difference (Kramer & Boyer, 1995).

1.3.2 Water potential concepts

Water potential is defined as the potential energy of water per unit mass of water in the system relative to the turgor required for enlargement and growth in plants. The total water potential (ψ_t) of a sample is the sum of four component potentials: osmotic (ψ_π), pressure (ψ_p), matric (ψ_m), and gravitational (ψ_g) (Holbrook, 2002; Tromp, 2005).

$$\psi_t = \psi_\pi + \psi_p + \psi_m + \psi_g \quad \text{Eq 2}$$

The matric potential is the reduction in potential due to interactions of water with surfaces and it is negligible in total leaf water potential measurements (Lakso, 2003). Gravitational potential depends on the height of the water above the reference state water, the density of water and the acceleration due to gravity. Gravity causes water to move downward unless the force of gravity is opposed by an equal and opposite force. Above the ground the gravitational potential changes by only 0.01 MPa m^{-1} . When dealing with water transport at the cellular level the gravitational component is negligible compared to the osmotic potential and pressure potential (Salisbury & Ross, 1993; Holbrook, 2002). The total water potential, for all practical purposes, is controlled by the balance of osmotic and pressure potentials (Lakso, 2003). Within the tree, the total water potential provides the gradients for water movement, with water moving from high to low water potentials. Thus the importance of total water potentials is to determine the direction of water movement and the strength of the gradient for that movement (Lakso, 2003).

Osmotic potential (ψ_π) is the lowering of water potential by the interaction of water with solutes in the cell (Lakso, 2003). Osmotic potential is independent of the specific nature of the solute (Holbrook, 2002). Adjustments in the osmotic potential of a cell or tissue modify the relationship between the total and pressure potentials (Lakso, 2003). At a constant total water potential a more negative osmotic potential, due to accumulation of solutes, increases the pressure potential. As the total water potential becomes more negative with, for example drought stress, the leaves of an apple tree can reduce their osmotic potential by accumulating sugars (glucose, fructose and the sugar-alcohol sorbitol) and other solutes (hydrolysis of starch to sugars) to maintain turgor

(Lakso *et al.*, 1984). Apple fruits also accumulate many solutes during their development which affect the fruit osmotic potential and fruit water relations (Lakso, 2003). Moreover, the hydrolysis of starch to sugars as the fruit matures reduces the osmotic potential without requiring imported carbohydrates (Lakso *et al.*, 1984).

The positive hydrostatic pressure within cells is the pressure referred to as turgor pressure (Salisbury & Ross, 1993; Holbrook, 2002). The value of the pressure potential can also be negative as in the case of the xylem and in the walls between cells where tension or a negative hydrostatic pressure can develop. Pressure potential is critical for expansive growth of cells and for tissue turgidity of all parts of the tree (Lakso, 2003). Many plant processes sense turgor, although the mechanisms of sensing are not well known (Holbrook, 2002).

Osmotic adjustment is a phenomenon in plants that are exposed to stress and for various fruit species adjustments varying from 0.5 to 3 MPa have been found (Wang & Stutte, 1992, Tromp, 2005). Osmotic adjustment has been mentioned to occur in apples and other fruit species during midday when water supply by the roots cannot keep pace with transpiration and the tissue water content decreases (Tromp, 2005). Different substances have been mentioned in active adjustment of 0.6 MPa in 3–5 days after stress in apples. These include glucose, fructose and the sugar-alcohol sorbitol. Osmotic adjustment is not restricted to long-term stresses and can cause losses in cell water and a decline in cell volume leading to increase in solute concentration, hence a lower ψ_{π} (Wang & Stutte, 1992). During cell growth increases in water stress results in loss of cell turgor, as a result of water movement from its high concentration to lower concentration out of the cell. This increases the solute concentration of the cell causing it to lose more water and lowering the pressure potential. As a result protoplasts pull away from the cell wall (cell plasmolysis) (Holbrook, 2002).

1.3.3 Soil resistance, root hydraulic conductance and tree water relations

The soil resistance to water uptake has been divided into ‘rhizosphere’ and ‘pararhizal’ components (Landsberg & Jones, 1981). The rhizosphere resistance is the resistance to water movement in the immediate vicinity of the root, whilst pararhizal resistance refers to the resistance to water movement from a zone of moist soil to the root zone (Newman, 1969). The

pararhizal resistance is determined by the depth of the root zone and by soil type and water content (Landsberg & Jones, 1981). The rhizosphere component is also affected by soil type and water content, but it is predominantly determined by root density (Cowan, 1965; Newman, 1969, Landsberg & Jones, 1981). Two of the key characteristics of the apple tree root system of relevance to water relations are (i) an extremely low root-length density in soil and (ii) a very non-uniform root distribution (Lakso, 2003). Apple root systems can explore all the space between the trees to a depth of at least 1.6 m (Hughes & Gandar, 1993) but in young trees they commonly explore only a small part of the available soil volume (Atkinson & Wilson, 1980). The low root density is likely to lead to local depletion of soil moisture and relatively high diverse effects of resistance to water flow in the soil, however, the mycorrhizal nature of the roots and the fact that they can proliferate in moisture-rich soil zones several meters below the surface compensates for this depletion (Lakso, 2003). Apple roots have been seen to concentrate near trickle irrigation drippers, and about three times as many roots per square metre at 100 to 300mm from the trickle line than at 400 to 600mm (Levin *et al.*, 1979). Atkinson & Wilson (1980) postulated that water and nutrient uptake is more rapid in young, white roots, especially in terms of phosphorus uptake, although older roots are still quite active. Results of recent studies carried out in New York State over many seasons showed that new root production generally did not occur until about one month after bloom and that most of the growth was completed within 60 to 80 days after bloom (Psarras & Merwin, 2000). Conversely, in a warm dry year, with heavy crop loads, new root production peaked at bloom and again postharvest, with little growth in midsummer. These patterns of growth have not been correlated with water status or nutrient uptake (Lakso, 2003).

Water movement in the soil is transported by bulk flow and when it comes in contact with the roots, it follows sequence of pathways (root hydraulic conductance). Water moves both apoplastically (movement of water through the cell wall without crossing any membranes) and symplastically (water movement from one cell to another via plasmodesmata) as well as within membranes (movement of water, involving entering at one side and exiting at a different end) (Holbrook, 2002; Tromp, 2005). Water uptake is limited within the exodermis, however, some water absorption has been recorded to take place through older roots through cortical cells. Again

water uptake decreases if roots are subjected to low temperatures or treated with inhibitors e.g., cyanide, which inhibit root respiration (Holbrook, 2002).

The effect of the rootstock on is important in apple water relations (Atkinson *et al.*, 2001), but there is no clear correlation between the use of different rootstocks and tree water use in apples (Atkinson, 2001; Lakso, 2003). Despite numerous studies directed at determining the mode of action of the dwarfing rootstock in influencing scion vegetative growth, a good understanding on scion rootstock interaction is lacking (Ranney *et al.*, 1991; Atkinson, 2001; Atkinson *et al.*, 2001). Rootstocks differ in their resistance to sap flow. This was deduced by Olien & Lakso (1986), who found that 'Empire' apples on dwarfing rootstocks (M9) were under greater water stress at midday, as measured by stem water potential, than those on more vigorous rootstocks (MM106), with no effect on transpiration, stomatal conductance or the ability of the scion stem to conduct water. Similar patterns have been reported for photosynthesis, with trees on vigorous rootstocks having higher rates of photosynthesis than those on dwarfing rootstocks (Schechter *et al.*, 1991; Fallahi *et al.*, 1994; Fallahi *et al.*, 2001; Chun *et al.*, 2002). Part of this effect can be attributed to the smaller root systems of dwarfing rootstocks and lower root/shoot ratios of trees budded on them (Jackson, 2003). Atkinson *et al.* (2001) showed the resistance between rootstock graft union and scion to be significantly different (lower) for vigorous rootstocks (M27) than for dwarfing (M9) rootstocks (higher). The more dwarfing rootstocks increase the resistance to sap flow of scions top worked on them, although the effect is less pronounced than the differences in rootstock resistance. Olien & Lakso (1986) found that the cultivar and the size of trees on the same rootstock are accompanied by variations in root resistance, with larger trees having higher root conductivity than smaller trees. The slope of this relationship is, however, less on M9 and M26 than on more vigorous rootstocks (Atkinson *et al.*, 2001; Fallahi *et al.*, 2001).

1.3.4 Stem water potentials

According to Landsberg & Jones (1981) the longitudinal resistance to water flow in stems is small; it is lower in the main trunk and increases towards the branch ends. At high levels of tension, with very negative leaf water potentials, embolisms (cavitation) develop which leads to the water columns in xylem vessels snapping (Jackson, 2003). Water stored in the tree trunk is withdrawn during the day and replenished at night. This has a buffering effect; it reduces the

impact of transpirational losses (Intrigliolo & Castel, 2005) and can be used as an indicator of transpiration flux, and thus water requirement. The tree growth has been found to affect variations in seasonal trunk diameter (Kozłowski & Winget, 1964), but diurnal shrinkage and swelling of stem tissues (Kozłowski, 1967) have been seen to occur as a result of thermal effects and changes in plant tissue hydration (MacCracken & Kozłowski, 1965; Simonneau *et al.*, 1993). Physiological indicators of plant water status have a good potential for use as water stress indicators, including stem water potential (Naor, 2001; Fereres & Goldhamer, 2003). Stem water potential measured at midday is considered as a standard parameter to determine the plant water status for irrigation scheduling in apples (Lakso, 2003) and in grapes (Sellés *et al.*, 2004). Furthermore, the continuous recording of trunk diameter variations has been shown to be a more sensitive parameter to water moisture availability under moderate water stress conditions than under stress conditions (Van Louwen *et al.*, 2000; Goldhamer & Fereres, 2001).

1.3.5 Leaf water potentials

The diurnal maximum water potential is largely dependent on soil water status and occurs at or near dawn (Powell, 1974). It is generally regarded that the diurnal minimum water potential occurs in the early afternoon, at the time of the maximum transpirational rate (Goode & Higgs, 1973; Landsberg *et al.*, 1975). It has also been reported that in well-irrigated trees the water potential values commonly fall to between -0.6 and -2.0 MPa (Goode *et al.*, 1979), whereas the leaves of drought stressed trees can reach -2.5 to -3.0 MPa (Jones & Higgs, 1979). However, it is generally regarded that stomatal closure and leaf fall tend to prevent more severe stresses developing in field grown trees.

1.4 Factors that affect water use in apple orchards

1.4.1 Atmospheric factors

Transpiration of plants is driven by energy from solar radiation, which heats the air and exposed surfaces, such as the soil, water and leaves (Lakso, 2003). Generally, the vapour pressure gradient of the air, or from leaf to air, is the driving variable, but transpiration is also based on the energy from solar radiation via VPD (Lakso, 2003). Effects of humidity on stomatal conductance (West & Gaff, 1976) and leaf temperature (Landsberg & Jones, 1981) are known to affect water use in apples.

1.4.2 Water supply in the soil

The physical characteristics of the soil determine the soil water content and the rate of water absorption by the roots (Tromp, 2005). Sandy soils have lower water holding capacity compared to clay soils. The difference lies within their differences in particle density. The total water potential in the soil is dependent on ψ_p . The value of ψ_p is 0 MPa in wet soils and is -1.5 MPa at permanent wilting point. Osmotic potential in soils is normally low, usually about -0.01 MPa and its negligible (Lakso, 2003; Tromp, 2005).

1.4.3 Leaf area

Defoliation in pears is known to be reduced by addition of irrigation (Hudina & Štampar, 2002). The larger the leaf assimilation area the greater is the net photosynthesis and in most cases the greater the concentration of carbohydrates in the leaves (Faust, 1989). The amount of leaf area on a tree is important to its water use since the leaves provide the most active transpiring surfaces and they also intercept the radiation that drives transpiration (Angelocci & Valancogne, 1993). As the leaves intercept radiation the energy warms the leaves and provides the energy for the evaporation of water within the stomatal cavities of the leaves and transpiration (Lakso, 2003). Water use rates vary over the season with the development and loss of the leaf canopy and the related radiation interception. A similar effect occurs over the canopies when they fill their space and intercept more radiation (Wibbe & Lenz, 1995).

1.4.4 Training systems

The canopy form and spacing of apple trees have a significant effect on water use by orchards, e.g. wider or larger tree forms use more water than thinner or more vertical forms (Palmer, 1989). It is commonly accepted that efficient orchard systems are those in which tree canopies achieve maximum light interception by the leaves (Jackson & Palmer, 1977; Warrington *et al.*, 1996). The tree form used should also allow adequate light distribution within each canopy. Once the maximum light interception by the leaves and optimal light distribution within the canopy have been attained, optimum rates of photosynthesis at all positions of the tree, maximum fruit growth rates, high fruit quality, and sufficient flower bud formation can be achieved (Jackson, 1980). Different training systems have been used in apples; commonly apple trees are trained to a central leader with closed or open vase (Jackson, 2003). Depending on the training system used, bending

of branches away from the vertical axis decreases shoot growth and leaf area index (Forshey & Elfving, 1989). Reduced leaf area index reduces the leaf area that is exposed to evaporation, resulting in less water loss through the leaves (Forshey & Elfving, 1989; Tromp, 2005).

1.5 Photosynthesis and transpiration

1.5.1 Photosynthesis and transpiration and response to water deficit

During photosynthesis the energy from solar radiation is converted into chemical energy, which enables the reduction of carbon dioxide to produce carbohydrate (Govindjee, 1975; Salisbury & Ross, 1993). This process involves both light and dark reactions in very close conjunction. During the light reactions, light energy is converted into chemical energy in the form of adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) (Blankenship, 2002). During the dark reaction, which is closely coupled to the light reactions, carbon dioxide is incorporated by the carboxylation of ribulose-1,5-bisphosphate by ribulose 1,5-bisphosphate carboxylase-oxygenase (Jackson, 2003). In properly managed orchards an increase in photosynthesis results in an increased yield of marketable apples, quality, colour and size (as a result of increased activity of rubisco and reduction of other stress factors). The most light effective orchard configurations have been reported as being capable of intercepting 60–70% of available radiation, which may translate into very high yields (Grappadelli, 2003). On the other hand, intercepted light must also penetrate and be distributed into all parts of the canopy to reach all the buds and leaves (Jackson, 2003).

Photosynthesis is driven by solar radiation, whereas transpiration is determined by the temperature and VPD of the air, i.e. the evaporative demand resulting from net radiation absorbed by leaves, and the drying power of the atmosphere, which is related to wind speed and relative humidity (Giuliani *et al.*, 1997). The processes of photosynthesis and transpiration have been thoroughly investigated in individual leaves, but the contributions of the environmental and physiological factors driving and controlling gas exchange at whole canopy level are not well defined (Giuliani *et al.*, 1997). It is difficult to make a generalisation of tree gas exchange based on one leaf's gas exchange because it may not reflect the complexity of the canopy. Furthermore, the control of single leaf and canopy responses involves several variables and it is reasonable to assume that some variables have somewhat different effects at the canopy state than at the leaf

level (Thornley & Johnson, 1990). However, apple canopies are well coupled to the atmosphere (Palmer, 1989). Atmospheric conditions such as VPD and temperature have been mentioned to affect leaf photosynthetic capacity (Giuliani *et al.*, 1997; Jackson, 2003), hence measurements at leaf level validate well into stomatal responses and changes within leaf boundary layer conductance (Jackson, 2003; Flore & Lakso, 1989).

Water stress is used as a descriptive term for an imbalance between the supply of and the demand for water (Jackson, 2003). It is accompanied by changes in plant water potential that may or may not have deleterious effects on plant processes. Souza *et al.* (2004) found that reductions in carbon dioxide assimilation rates in water-stressed cowpea plants are largely dependent on stomatal closure, which decreased available internal carbon dioxide and restricted water loss through transpiration. Lakso (1979) indicated that net photosynthesis in apple leaves can occur at very low water potential and that substantial reduction of photosynthesis may not occur until the water potential falls below -3.0 MPa. Photosynthesis in apple leaves can withstand much lower water potential than is the case in many tree crops and in grapes (Lakso, 1979), because of their adaptation and feedback control strategy. Apple leaf photosynthesis has been reported to be high in the mid-morning and declines from midday onwards, but some recoveries have been mentioned later in the afternoon as a result of stomatal aperture adjustment and cycling during high VPD and temperature (Cheng & Luo, 1997).

The rate of entry of carbon dioxide into the leaf is a major limiting factor to photosynthesis (Jackson, 2003). Effects of both environmental factors and factors within the plant on photosynthesis may therefore be mediated by effects on stomatal conductance. Palmer (1992) observed a close relationship between stomatal conductance and net photosynthesis of apple leaves. The pattern of interaction in this relationship may be complex (Lakso, 1994). 'Sun' leaves in exposed canopy positions have a high net photosynthesis per unit and a higher stomatal conductance (Campbell *et al.*, 1992), but also have a number of other adaptations that lead to higher photosynthetic potential. Humidity may control stomatal conductance directly, hence photosynthesis appears to control stomatal behaviour, rather than vice versa (Lakso, 1994).

1.5.2 Water use efficiency (WUE)

Water use efficiency (WUE) is defined as the ratio of carbon gained in dry matter over a given period, to water loss over the same period (Chaves, *et al.*, 2004). In C3 plants the actual rate of CO₂ assimilation that is dictated by CO₂ availability (stomatal conductance, g_s) corresponds to the C_i (internal carbon dioxide) partial pressure. If g_s increases above the operational point, leaf photosynthetic rate would only marginally increase and WUE would decrease (Schulze, 1986; Schulze, *et al.*, 1994, Chaves, *et al.*, 2004). Schulze *et al.* (1994) summarised the WUE as follows: stomata are able to balance CO₂ entry into the cellular space for photosynthesis to occur, and also control cell dehydration by minimising water loss, thus stomata will open to the extent required to provide sufficient CO₂ to meet the requirements for photosynthesis. During water stress periods, when the midday stomatal conductance is high, the daily net CO₂ assimilation decreases, leading to low CO₂ availability, which further leads to decline in carboxylation efficiency and lower intrinsic WUE (WUE_i) (Valladares & Pearcy, 2002; Chaves, *et al.*, 2004).

1.5.3 Plant growth regulators and water relations in apples: the role of abscisic acid (ABA) and cytokinins

The functioning of the plant depends upon specific levels of plant growth regulators, each in balance with the others. The achievement of specific agricultural objectives, however, may also depend upon the correct balance of natural and applied growth regulators (Westwood, 1978). Growth regulators, both natural and synthetic, may be divided into several groups, based on differences in their structures and the effects they have: auxins, gibberellins, cytokinins, abscisic acid and ethylene (Westwood, 1978). The effect of growth regulators on stomatal movement, which controls the flow of water vapour from the leaf, is well documented. While cytokinins (Luke & Freeman, 1968; Kaufman *et al.*, 1995) and possibly GA (Livne & Vaadia, 1965; Kaufman *et al.*, 1995) induce the opening of stomata, auxins (Mansfield, 1967) and ABA (Mittelheuser & Van Steveninck, 1969; Tardieu & Davies, 1992; Dodd *et al.*, 1996) cause them to close.

However, amongst all the plant growth regulators studied to date, it has been shown that auxin, ABA and cytokinin are more actively involved in water relations in plants than any others (Westwood, 1978). Auxins are known to be involved in the osmotic uptake of water across the

plasma membrane, which is driven by a water potential gradient. Cytokinins play a predominant role in the induction of cell division in callus cells in the presence of an auxin and if any environmental factor that interferes with root function, such as water stress, reduces the amount of cytokinin, then the content in the xylem also reduces (Itai & Vaadia, 1971). Water relations affect many physiological and biochemical processes in plants. This includes mechanisms that regulate root and shoot growth and also stomatal response to ABA (Ismail *et al.*, 2002). Two of the major resistances to water flow that govern water status in the plant are the resistance to water absorption in the root and the resistance to water loss in the leaf (Slatyer, 1967; Jackson, 2003). When the matric potential of the soil water around plant roots declines, stomatal closure will eventually occur. Drought is one of the most common stresses experienced by plants. The conventional view of this is that soil drying induces a restriction of the water supply and this results in a sequential reduction of the tissue water content, water potential and turgor, growth and stomatal conductance (Dodd *et al.*, 1996). Dodd *et al.* (1996) and Hartung & Jeschke (1999) reported that changes in soil moisture can change the root physiology and thereby enable plants to change the soil water status and adapt to decreasing soil moisture content by reducing growth, the transpiring leaf surface and size of stomatal aperture. It appears that, in some cases, changes in leaf physiology are more closely linked to changes in the soil water content than to the leaf water status. One of the best examples of this type of plant response is presented by Jones (1985), who found that over a period of up to 10 weeks the midday water potential values were higher in unwatered than in irrigated apple seedlings. The higher water potential values in plants exposed to drought were associated with lower stomatal conductance and a higher osmotic adjustment indicating that stomata controlled leaf water status rather than the converse, which is generally assumed to be the case (Dodd *et al.*, 1996). This kind of stomatal reaction requires that the plants have some mechanism for sensing the availability of the water in the soil and regulating stomatal behaviour accordingly. Jones (1980) and Cowan (1982) have suggested that this involves transfer of chemical signal (possibly ABA) from the roots to the shoots via the xylem. Such control has been termed non-hydraulic or chemical signalling. This distinguishes it from hydraulic signalling, which represents transmission of reduced soil water availability via changes in the xylem sap tension (Dodd *et al.*, 1996).

The root system communicates changes in soil water availability to the shoot via the xylem hydrostatic pressure (root water status) and hydraulic signals (chemical composition of the xylem sap) (Davies *et al.*, 1990; Tardieu & Davies, 1993; Davies *et al.*, 1994). A principal candidate for such a signal is the plant hormone ABA (Dodd *et al.*, 1996). Hydraulic signals arise from changes in the hydrostatic pressure and this may add to the control of the plant's physiological responses to the stress by modifying the stomatal sensitivity to ABA (Tardieu & Davies, 1992) or reducing shoot growth (Saab & Sharp, 1989) and plant gas exchange (Tardieu & Davies, 1993; Davies *et al.*, 1994). Stomatal closure without reduced leaf water potential (Graves *et al.*, 1991; Behboudian *et al.*, 1994) has been interpreted as evidence for root derived chemical signals moving via the xylem to the shoots to reduce stomatal conductance (Dodd *et al.*, 2000). Alkalisiation of the xylem sap, without increased xylem sap ABA concentration [X-ABA], can cause stomatal closure (Wilkinson *et al.*, 1998).

As with other plant hormones, cytokinins influence many aspects of a plant's response to changes in the environment. Environmental stress will depress the cytokinin levels in the xylem sap (Kieber, 2002). Such evidence suggests that cytokinins are very mobile in the plant, but this is not universally the case (Kieber, 2002). Cytokinins have effects on many physiological and developmental processes, including leaf senescence, nutrient metabolism, apical dominance, formation and activity of shoot apical meristems, breaking bud dormancy and seed germination. They mediate aspects of light-regulated development, including chloroplast differentiation. They also regulate cellular processes. Their control of cell division is of considerable significance for plant growth and development (Davies *et al.*, 1986).

The subject of hormonal control of water relations in plants has been dominated by ABA for a very long time, and much evidence has centred on linking ABA with the stomatal movements that are associated with water economy (Incoll & Jewer, 1987). However, the role of other growth regulators including cytokinins and auxins has not been overruled. Universally, ABA is considered to close stomata, while the effects of cytokinins and auxins on stomata have only been reported in a few plant species (Incoll & Jewer, 1987). The role of ABA as the only chemical messenger of soil water status has been questioned by several researchers (Munns & King, 1988; Fußeder *et al.*, 1992). The possibility of a multiple chemical signal with several variable

components, one of them being cytokinins has, however, been suggested (Davies *et al.*, 1986). The interactions observed between ABA and cytokinins and plant growth and development, especially antagonism with ABA, both in the roots and leaves of plants subjected to soil drying, can explain some of the effects of a single regulator on leaf conductance (Incoll & Jewer, 1987). The phenomenon of soil drying, which in turn results in reduced amounts of endogenous cytokinins in xylem exudates, has long been observed (Itai & Vaadia, 1965). Reduction of cytokinin transport from the roots to the leaves will result in a decrease in the size of stomatal aperture (Blackman & Davies, 1985). Confirmation of the existence of cytokinins in the xylem sap has been reported for certain woody species, e.g. in basket willow (*Salix viminalis*) (Alvim *et al.*, 1976), sweet cherry (*Prunus avium*) (Stevens & Westwood, 1984), and in apples *Malus domestica* (Tromp & Ovaas, 1990, Cutting *et al.*, 1991; Cook *et al.*, 2001). In most of these species xylem sap contains cytokinins of the Z (zeatin) type and of the iP [$N^6 - (\Delta^2$ -isopentenyl) adenine] type, both in the fraction containing free bases and ribosides and in the fraction of the nucleotide-derived cytokinins (Fußeder *et al.*, 1992). Evidence has been found for the role of cytokinins in regulating plant response to water stress applied to the roots (Itai & Vaadia, 1971). There are several reports in this regard which have shown a measurable reduction in cytokinin in root exudates when plant roots had undergone a period of water shortage (Itai & Vaadia, 1965), excess osmotica (Itai *et al.*, 1968) or water flooding (Burrows & Carr, 1969). Recent studies have shown that plant tissue exhibits high but transient levels of cytokinins (e.g. iP, [9R] iP, Z and [9R] Z) during specific periods of development (Jones & Schreiber, 1997). The decline in cytokinins has, however, been associated with the activity of cytokinin oxidase, an enzyme which irreversibly cleaves the side chains of such cytokinins, leading to a complete loss of activity. It is clear that cytokinin oxidase is the only plant enzyme that is known to catalyse the degradation of these specific cytokinins, and thus it becomes an important point of control of cytokinin levels in specific plant tissues (Jones & Schreiber, 1997).

1.5.4 Seasonal and daily changes of photosynthesis

The light environment influences leaf anatomy, morphology and physiology (Campbell *et al.*, 1992). Natural shading by a plant canopy results in anatomically distinct leaves with differing gas exchange characteristics compared to sun-exposed leaves. Apple leaf photosynthesis is of the C₃ type, with a hyperbolic light response that is typically saturated at 500 to 1500 $\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$

(Jackson, 2003; Pretorius & Wand, 2003). The light compensation point, i.e. the light level below which net carbon dioxide exchange is negative, with respiration exceeding photosynthesis, is 20 to 60 $\mu\text{mol quanta m}^{-2} \cdot \text{s}^{-1}$. Globally, good rates of photosynthesis per unit area for healthy exposed leaves are around 15 $\mu\text{mol. CO}_2 \text{ m}^{-2} \cdot \text{s}^{-1}$ (Lakso, 1994), however higher rates of 16 to 21 $\mu\text{mol. CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ have been reported in the Western Cape Province (Pretorius & Wand 2003; Gindaba & Wand, 2007a; 2007b). Although stomata are closed in the dark they open fully at light levels well below photosynthetic light saturation and the photosynthesis light response curve does not reflect changes in stomatal conductance, but reflects changes in the initial linear response of photosynthesis until saturation, when stomata completely close (Kriedemann & Ganterforty, 1971; Flore & Lakso, 1989).

Seasonal patterns of photosynthesis rates, which are slow at the beginning of the season and very rapid at the end of season due to decline in temperature, reflect the maturation and ageing of individual leaves (Jackson, 2003; Pretorius & Wand, 2003). The daily patterns of apple leaf photosynthesis have been established. Maximum photosynthesis generally occurs before noon (Cheng & Luo, 1997; Pretorius & Wand, 2003; Gindaba & Wand, 2007a; 2007b), and rates are lower in the afternoon at similar levels of irradiance. The decline in the afternoon may be partially due to the accumulation of assimilates, feedback inhibition and to the increase in VPD and temperature.

1.5.5 Photosynthetic light use, light stress and senescence

Energy utilisation by the leaf can be studied by *in situ* chlorophyll fluorescence, which is directly related to the photosynthetic potential of the leaves (Wünsche & Ferguson, 2005). Chlorophyll fluorescence measurements allow an assessment of the orderly dissipation of absorbed light energy through the photochemical pathway to photosynthesis or through the xanthophyll cycle-mediated photoprotective pathway (Demmig-Adams & Adams, 1996). The underlying physiology of photosynthesis is affected by internal stresses such as the accumulation of carbohydrates, changes associated with source-sink relations and redistribution of energy away from photosynthesis (Pammenter *et al.*, 1993; Chow, 1994). The leaves of apple trees are known to contain high amounts of chlorophyll and carotenoids (Jackson, 2003). The natural and artificially induced senescence of photosynthesising plant tissues are commonly considered to

represent a highly ordered process, involving changes in pigment content and composition (Spencer, 1972; Smart, 1994). During disassociation of the photosynthetic apparatus, Solovchenko *et al.* (2005) reported an extensive breakdown of chlorophylls, and further indicated that the chlorophyll decline is not accompanied by a similar decline in carotenoids. Studies of apples have shown a higher chlorophyll concentration and a lower chlorophyll a:b ratio, which is characteristic of shade leaves (Ghosh, 1973). Chlorophyll promoting substances such as hormones (cytokinins), amino acids, nitrogen and magnesium have been found to be high per total unit shoot dry matter in fruiting trees compared to non-fruiting trees (Ferree *et al.*, 1984). This is further illustrated by the fact that chlorophyll decreases in non-fruiting trees with an increase in leaf assimilates, which is associated with the lower photosynthetic capacity of non-fruiting trees.

1.6 Measurement of water relations and photosynthetic capacity in apple trees

1.6.1 Leaf water potential measurements

Trunk shrinkage, stem water potential, leaf water potential, stomatal conductance and the rate of apple fruit growth have been used with varying degrees of success as physiological parameters relevant to irrigation scheduling (Bravdo, 2000). The most common method of measuring tree water status has been to estimate exposed leaf total water potential with a Scholander pressure chamber ('pressure bomb') (Scholander *et al.*, 1965). A leaf is cut at the leaf petiole with a razor blade and inserted into the pressure chamber with the cut surface protruding from the rubber gasket. Compressed air is used to gradually increase the pressure in the chamber until xylem water first appears at the cut surface. The chamber pressure (recorded as a negative value) equals the apoplastic hydrostatic pressure in the leaf, and this in turn equals the symplastic value of water potential under most conditions (Koide *et al.*, 1989). However, many leaf processes, such as stomatal opening and photosynthesis, are correlated with water potential. The limitations of using water potential alone include significant osmotic adjustment in the apple, which can change critical levels of water potential (Lakso *et al.*, 1984) and variability due to individual leaf exposure and transpiration rates, so that exposed leaf water potential may not represent shaded leaves, fruit or shoot tips, which do not transpire as much as exposed leaves do (Higgs & Jones, 1990). This can, however, be avoided by bagging the leaf for 30 to 45 minutes with a black zip-lock bag to cut the solar radiation and photosynthesis. Jones *et al.* (1983) also established that

stomatal closure may reduce transpiration enough to stabilise exposed leaf water potential, so that the osmotic potential is not related to internal water status.

Factors that affect stomatal conductance are important since stomatal opening has an important role in regulating apple tree transpiration (Lakso, 2003). Stomatal aperture and its resistance to gas exchange are known to be affected by light, temperature, air humidity, carbon dioxide concentration, leaf water status, the presence or absence of fruits, and by the mineral nutrition status (Landsberg & Jones, 1981). In apple trees the stomata have been found to be coupled with photosynthesis: they usually do not open more than needed to maintain a constant internal carbon dioxide concentration (Lakso, 1994). Most of the factors that affect photosynthesis, such as crop load, have been shown to affect gas exchange and water use in many ways (Lakso, 2003). Stomatal conductance and leaf photosynthesis have also been reported to decrease as very low or zero crop loads are reached (Palmer *et al.*, 1997), hence non-cropping trees are likely to use less water per unit of leaf area (Masarovicova & Navara, 1994; Blanke, 1997). Apple trees are hypostomatous, having between 2×10^4 and 6×10^6 stomata per cm^2 on the abaxial surfaces (West & Gaff, 1976). The variation from leaf to leaf and from point to point within a leaf has also been noted (Landsberg & Jones, 1981). The number of functional stomata is reported to increase from emergence and reaches maximum when the leaves are 4 to 6 weeks old (Slack, 1974). Apple stomata are known to respond to light in the same way as those of most mesophytic plants, and stomatal conductance is known to be reduced by low relative humidity. Large increases in carbon dioxide concentrations have also been implicated in causing stomatal opening (Landsberg & Jones, 1981).

Predawn leaf water potential is an important measurement of water availability in plants since it integrates soil water potential over the root zone of the plant and decreases with a decrease in soil water potential (Tardieu & Simonneau, 1998). Predawn water potential is generally regarded to represent soil water potential by equilibrating soil and plant water potential through the night when there is little or no transpirational water losses (Naor *et al.*, 1995). Midday leaf water potential gives an indication of the extent of the plant water condition and it is the combination of soil water supply and atmospheric demand (Tardieu & Simonneau, 1998).

Total transpiration by a fruit tree is the sum of the transpiration of the individual leaves plus a much smaller amount of transpiration from the fruits, stems and sepals (Jackson, 2003). Apple leaves have thick, waxy cuticles, with very low vapour conductance, so most transpiration takes place via the stomata (Boyer, 1985). The rate of transpiration per unit leaf area depends on physical factors that control evaporation and on the degree of opening of the stomatal pores. Stomatal opening and closing results from changes in the turgor of the two guard cells surrounding the pores (Holbrook, 2002). Stomatal conductance is influenced by plant growth hormones (particularly ABA), atmospheric carbon dioxide concentration, crop load, irradiance, vapour pressure deficit (VPD), wind speed and water availability. Changes in guard cell turgor are generally driven by fluxes of cations and anions, notably K^+ balanced by either Cl^- or malate, across the plasma membrane and tonoplast.

Stomatal opening has been found to reflect a net accumulation of K^+ (Holbrook, 2002). Generally, stomata are insensitive to a reduction in water potential until a threshold is exceeded, and then they close rapidly and almost completely. West and Gaff (1976) found that in apples this threshold is usually between -1.9 and -2.5 MPa. The relationship between stomatal conductance (g_s) and leaf water potential (ψ_1) varies between different genotypes (rootstock/cultivar) of apple and also with leaf age (Atkinson *et al.*, 2000). Mature leaves on the branch have relatively lower leaf water potential compared to young growing leaves at the tip of the shoot (Atkinson *et al.*, 2000). The intercellular concentration of carbon dioxide in the leaf is a major factor controlling stomatal apertures (Jackson, 2003). Studies done on 'Golden Delicious' apples by Warrit *et al.* (1980) revealed that a fairly steady increase in stomatal conductance in 'Golden Delicious' leaves existed as the ambient carbon dioxide concentration was reduced from about $750 \mu\text{mol. mol}^{-1}$ to about $50 \mu\text{mol. mol}^{-1}$.

The effects of light on stomatal opening have been extensively studied. West & Gaff (1976) found that the effect of light on stomatal opening may operate at least in large part, through its effect on internal carbon dioxide concentration. There have also been some studies done to correlate apple crop load to stomatal opening. Hansen (1971) observed that the uptake of water by fruiting trees of 'Golden Delicious' apples was about 80% more than that of non-bearing fruit trees. Buwalda & Lenz (1992) found that the water uptake per unit root weight was more than

twice as high in fruiting trees than in non-fruiting trees of apple cultivars ‘Golden Delicious’, ‘Cox’s Orange’ and ‘Gloster’. These crop load effects may involve effects on internal carbon dioxide concentration and the lower abscisic acid (ABA) concentration found in leaves of fruiting trees compared with non-fruiting trees (Giuliani *et al.*, 1997).

1.6.2 Integrated water potential measurements

Sap flow measurements have been used in apples to measure the water transport in the stem (Smith & Allen, 1996; Tromp, 2005). Sap flow is a measure of transpiration rate in whole branches and whole plants and can be determined by measuring the xylem sap ascension rate in the stem (Smith & Allen, 1996). In xylem sap most mineral elements are present as ions but complex organic compounds may occur (Tromp, 2005). Most xylem sap is contained in the xylem vessels (Holbrook, 2002).

The shrinking and swelling of apple tree trunks and fruit in relation to soil moisture deficits and evaporative demands have been recognised for many years (Taerum, 1964; Jackson, 2003). This method (measurements of shrinkage and swelling) has some advantages over water potential measurements in that the measurement can be performed continuously and the trunk and fruit better integrate the whole tree water status than single leaves (Jones, 1985). The stable isotope discrimination method has also been used with some success to determine leaf water potential. It is based on the discrimination against stable isotopes of different molecular weight (^{13}C , ^{16}O and ^2H) during diffusion and exchange process in the soil and in the plant and ^{13}C and ^{12}C relates better to intrinsic water use efficiency (Ehleringer *et al.*, 1993).

1.6.3 Stomatal conductance and gas exchange measurements

Different techniques for measuring photosynthesis on the basis of carbon dioxide exchange or oxygen exchange have been developed (Field *et al.*, 1989). Carbon dioxide exchange systems using infrared gas analysers (IRGAs) have been found to be useful in field experimentation. Field *et al.* (1989) have reviewed some of the techniques used to measure photosynthesis. They found that photosynthesis cannot be measured by a single instrument, but rather by a system. This is because there is no photosynthesis discrete sensor, and photosynthesis is a calculated parameter determined from measurements of carbon dioxide concentrations, gas flows and other

parameters. Rates of gas exchange (using differential systems) are determined using a mass balance and photosynthesis is calculated based on the rate of exchange of carbon dioxide using absolute rather than relative differential infrared gas analysers. A differential system calculates photosynthesis from the carbon dioxide depletion that occurs as air flows at a known rate past a photosynthesising leaf, whilst in a compensating system the carbon dioxide depletion by photosynthesis is compensated for by carbon dioxide injection, so that the carbon dioxide concentration in the air exiting the chamber is the same as that in the air stream entering the chamber. Stomatal conductance is a proportional constant between transpiration and vapour concentration gradient between the leaf interior and the surface. It is obtained from the total conductance by removing the contribution from the boundary layer, and transpiration is the difference between flow rate of sample air and reference air to the surface area of the leaf (Von Caemmerer & Farquhar, 1981).

1.6.4 Photosynthetic response curves (light and CO₂)

Response curves between the rate of photosynthesis and the level of radiation generally reflects rectangular hyperbole that is characterised by a steep increase at low levels that gradually slows down and flattens at light saturation, which is between 1200 and 1500 $\mu\text{mol. m}^{-2}. \text{s}^{-1}$ photosynthetic photon flux density (PPFD) in apples (Lakso, 2003; Gindaba & Wand, 2007a, 2007b). Flore and Lakso (1989) indicated that a small change in PPFD can have a profound change in photosynthesis level, while at levels higher than saturation it may have very little effect. Powles (1984) reported that higher levels of PPFD beyond saturation point on shaded leaves can also result in photosynthesis decreasing as a result of photoinhibition. Carbon dioxide response curve (A/C_i) involves assimilation rates plotted against intercellular CO₂ (C_i) and provide useful information on the maximum rate of carboxylation ($V_{c_{\max}}$) and the light-saturated rate of electron transport (J_{\max}). Initially the rate of assimilation increases with increase in C_i until a saturation point. The initial slope provides an *in vivo* measure of the activity of rubisco in the leaf or mesophyll conductance and the compensation point is regarded as the value of C_i where photosynthesis and respiration are in balance. Within the mesophyll, carboxylation limitations can be separated from electron transport limitations (Farquhar & Sharkey, 1982).

1.6.5 Chlorophyll fluorescence measurements

Radiation reaching a leaf can be transmitted, reflected or absorbed. The chlorophyll molecules absorb light energy for use during the light-dependent stages of photosynthesis (Salisbury & Ross, 1993). Fluorescence constitutes a 1–2% fraction of the dissipated energy but is coupled to other dissipating pathways (Massacci & Jones, 1990; Maxwell & Johnson, 2000). Chlorophyll fluorescence is a non-destructive measurement technique that can be performed relatively rapidly and with great precision using portable fluorimeters (DeEll *et al.*, 1999). A recent review by Maxwell & Johnson (2000) described the use of modulated fluorescence techniques in plant stress physiology and the following definitions were suggested: Maximum quantum efficiency of photosynthesis is measured as the ratio F_v/F_m , where F_v is defined as the difference in fluorescence yield between the maximum (F_m) and the minimum (F_o) fluorescence levels. It is measured on dark adapted leaves using modulated fluorescence measuring system (Schreiber, 1986). The value of F_v/F_m is generally between 0.75 and 0.85, and relates approximately linearly to the quantum yield of photosynthesis. A reduction in photochemical efficiency in apple leaves indicates a higher percentage of photosystem II reaction centre pool closure and a greater capacity for non-photochemical quenching (thermal dissipation) (Osmond, 1994; Wüschel *et al.* 2000). Chlorophyll fluorescence measurements have been found to have the following advantages: the measurement is made directly on the living plant, the method is non-destructive, each variable takes only seconds to determine, cellular injury is detected well in advance, and finally, measurements can be taken during treatment and can be continued afterwards to follow recovery or deterioration (Smillie *et al.*, 1987; Massacci & Jones, 1990).

1.7 Irrigation and water requirement of apple trees

1.7.1 Frequency of irrigation

Irrigation provides supplementary water that is not provided by rainfall or soil water reserves. As a result, efficient irrigation management requires knowledge of the water loss of the apple orchard (trees, soil, evaporation and cover crops/weeds), the soil water reserves and rainfall (Lakso, 2003). The amount and frequency of water application is based on an assessment of crop needs, adjusted to take into account insufficiencies in the irrigation system (e.g. evaporation from open water channels and surface runoff) and effective natural precipitation, i.e. rain-fed adjustment for losses from surface runoff and drainage (Jackson, 2003).

Irrigation has long been known to affect the growth and production of deciduous trees. There are two main mechanisms by which this occurs: effects of irrigation on stomatal conductance and assimilation rate, and irrigation effects on turgor and expansive growth (Naor, 2006b). The amount of water applied is intended to return to the soil profile the amount of water transpired by the tree and the cover crop, in addition to the amount evaporated from the soil surface. The sum of these components is called evapotranspiration. Transpiration further requires that the water is converted from liquid form to gas and diffuses through stomatal cavities (Landsberg & Jones 1981; Lakso, 2003; Naor, 2006b). This process is controlled by the vapour pressure deficit. Resistance to this process is primarily due to stomatal resistance and the boundary layer resistance, which is determined by wind speed, leaf size and shape and canopy structure (Naor, 2006b).

1.7.2 Irrigation systems

Water use under different irrigation systems in apples has been studied (Chapman & Krew, 1978; Rumayor-Rotriguez & Bravo-Lozano, 1991; Fallahi *et al.*, 2006). Traditional maintenance irrigation may be provided by surface systems or sprinklers. Surface irrigation applies water into basins around each individual tree. This is a very efficient way of supplying water to young, widely spaced trees (Jackson, 2003). Furrow irrigation is also used but has been largely replaced by micro sprinkler irrigation because of its ease of management and flexibility of use (Rumayor-Rotriguez & Baravo-Lozano, 1991). Micro sprinklers apply water over most of, or the entire orchard surface (both intra and inter row) and can be wasteful. Micro sprinklers are most valuable when multipurpose approaches are put in place e.g. when they are also used for frost protection or orchard cooling (Jackson, 2003).

Drip irrigation is the most efficient method of irrigating. While micro sprinkler systems are around 75–85% efficient, drip systems are typically 85% or higher (Elfving, 1982). For this reason drip irrigation is the preferred method of irrigation in arid to semi-arid regions. Drip irrigation also has other benefits that make it useful almost anywhere. Drip irrigation works by applying water slowly, and directly, to the soil. The high efficiency of drip irrigation results from two primary factors. The first is that the water soaks into the soil before it can evaporate or run

off. The second is that the water is only applied where it is needed (at the plant's roots), rather than sprayed between the rows. Drip irrigation differs from conventional bulk water application in that only smaller volumes of water are applied to the plant at more frequent intervals and the application is to only a limited part of the soil surface area (Elfving, 1982; Pijl, 2001; Wang *et al.*, 2006). Water is piped through plastic tubing and is released only at selected points through the emitters (drippers). The tubing runs on the soil of a hedgerow, or to either side of it, with emitters at regular intervals (Jackson, 2003). The more frequent the emitters, the less water is applied through each emitter, and the less the risk there is of water loss through drainage (Elfving, 1982). Drip irrigation has very high water use efficiency. This is because of the enclosed nature of the water delivery system and the restriction of the water supply to the soil zone with the highest density of fruit tree roots (Jackson, 2003). Drip irrigation has been noted for its many benefits (Assaf *et al.*, 1984). A restricted volume of wetted soil is maintained with small fluctuations in water tension and with the development of a dense root system with minimum loss of water and fertilizers by leaching (Black, 1976; Assaf *et al.*, 1984). Typically, a higher irrigation frequency is associated with a smaller wetted soil volume during the period when irrigation water has reached saturation point in the soil (Wang *et al.*, 2006). Richards & Rowe (1977) and Salomon (1978) reported some of the beneficial aspects of drip irrigation to be (a) irrigating according to consumptive water; (b) maintaining soil water tension close to the optimum available water for the plants; (c) keeping the desired concentration of nutrients around the root, and (d) thus restricting root volume and allowing a higher tree density per hectare; and finally, (e) affecting a balance of physiological processes such as fruiting and vegetative growth.

1.7.3 Fertigation and open hydroponics

Fertigation is the application of nutrients through an irrigation system, thus a combination of fertilization and irrigation (Follet, 2002). The most common nutrient applied by fertigation is nitrogen, but other elements such as phosphorus, potassium, sulphur, zinc and iron are also applied. Fertigation allows the application of nutrients exactly and uniformly, and only to the wetted root volume where the active roots are concentrated. This increases the efficiency of the application of the fertilizer, which results in a reduction of the amount required (Bar-Yosef & Sagiv, 1982; Imas, 1999) and thus leaching into the soil. Studies by Goldberg *et al.* (1971) have shown that high irrigation frequency reduces evaporation and deep percolation and establishes a

favourable soil moisture and oxygen condition in the root zone. Fertigation also allows the tree to adapt to the amount and concentration of the applied nutrients in order to meet the actual nutritional requirement of the crop throughout the growing season. In order to correctly plan the supply of nutrients to the crop according to its physiological stage the optimal daily nutrient consumption rate during the growing cycle that results in maximum yield and production has to be determined (Imas, 1999). Since in pulsing drip fertigation the applications are given more frequently (several pulses per day), it is thought that crop manipulations can be adapted to the advantage of yield and quality (Stassen *et al.*, 1999).

There are two fundamental types of hydroponic systems: the closed system and the open system (Donnan, 1994). In total or closed hydroponics systems the plants are totally controlled without interference from soil and environmental influences, as in a greenhouse. In hydroponics systems the plants roots are supplied by pulsing or continuous application of water. Sand, vermiculite and peat can be used as anchoring structures for the plant roots and the nutrients may be recirculated (Stassen *et al.*, 1999). In the greenhouse it is easy to use the closed system because there is no additional, unlike in the field where soil is involved resulting in both water and nutrients that are not taken up by the plant being leached into the soil and out of the rooting system.

The open hydroponics system operates where the plant is established outside in a soil medium and nutrients are not recirculated (Rossen, 1998). As a result the contribution of other variables, such as soil fertility, is not completely eliminated in this system. Water and nutrients are applied continuously because they cannot be circulated, hence nitrogen management, in particular, can be better controlled (Stassen *et al.*, 1999). The open hydroponics system principle is different from fertigation in that in the case of the former the plant is fed water and nutrients several times a day to keep a film of water and nutrients around the roots. It therefore tends to be a more intensive management system than conventional fertilisation and irrigation or fertigation (Rossen, 1998).

1.7.4 Plant nutrient solutions and the nutrient film technique

Nutrient solutions for hydroponics contain the necessary minerals for each crop in appropriate concentrations and ratios and as a result plants grow under suitable and adequate water and nutrient conditions. Plants grown using hydroponics have more mineral salts than those of

conventional systems but less heavy metals since these can be monitored in hydroponics systems (Karimaei *et al.*, 2004). Hydroponics applications and the use of nutrient solutions have been used more extensively in vegetable production than in trees. When applied in vegetables, the technique is commonly referred to as the nutrient film technique (NFT) (Graves, 1983). NFT is a specialised form of soilless culture, developed at the Glass House Crops Research Institute in England in the late 1960s. The basic principle of NFT is to recirculate a shallow stream of the nutrient solution over the base of growing roots to provide them with adequate water, nutrients and aeration (Graves, 1983). NFT has been found to have the following advantages: the root environment can be controlled more easily, watering is simplified, uniformity in nutrient supply is ensured, and nutrient concentration can be matched to the varying needs of the crop throughout its growth (Winsor *et al.*, 1979). Plant nutrition scientists have developed nutrient recipes for optimum plant growth. This includes Hoagland solution, Hoagland and Arnon solution (the water culture method for growing plants without soil), Robbins solution and Knop's solution. Hoagland's solution has become well known and in the market today it is referred to as a modified Hoagland's solution (Winsor *et al.*, 1979). A modified Hoagland solution contains all of the known mineral elements needed for rapid plant growth, without any risk of toxicity or salinity stress. Different concentrations have been adapted for different crops with great success. A further important aspect of the Hoagland solution is that nitrogen is supplied both as ammonium and nitrate (Bloom, 2002).

1.7.5 Irrigation scheduling for fruit trees

Irrigation scheduling involves the application of water to plants at the most appropriate time and in adequate rates (Reginato, 1990; Naor, 2006b). Irrigation scheduling in tree orchards is universally based on three approaches involving the soil, the plants and the atmosphere. The most common procedure for soil irrigation scheduling to date has been to monitor how much water is in the soil and to irrigate when the soil water content has reached a certain value. This method is based on the empirical relationship between the amount of water in the soil and some measure of crop response, such as crop yield (Naor, 2006a).

For decades, models using weather parameters to calculate evapotranspiration have been used to schedule irrigation, and most of the parameters have been estimated by a water budgeting process

(Reginato, 1990; Arca *et al.*, 2004). The first method involves the use of potential evapotranspiration, which is calculated from empirical methods such as the Penman method (Penman, 1948), the Penman and Monteith method (Allen *et al.*, 1998), the FAO corrected Penman method (Allen and Pruitt, 1991) and the Hargreaves method (Hargreaves & Samani, 1985; Allen *et al.*, 1998) determined from crop factors. A crop factor is defined as the percentage of ground covered by the crop canopy and it varies depending on the crop stage ($K_c = ET_c / E_{To}$), where ET_c is evapotranspiration of reference crop and E_{To} is the potential evapotranspiration (Allen *et al.*, 1998). The second method is based on statistical analysis of past evapotranspiration rates, and involves the use of E and K_c to compute E_{To} (Arca *et al.*, 2004). The daily amount of water used (actual ET) is calculated and when this value reaches a certain depletion figure the crop is irrigated (Reginato, 1990).

Plant water stress indicators are considered to be more direct and provide values closer to the real values than both the soil and atmospheric indicators for scheduling irrigation in orchards (Naor, 2006a). These indicators can either be direct (associated with certain horticultural attributes such as fruit yield) or indirect correlations, involving physiological parameters such as stomatal conductance, assimilation rates and shoot growth (Naor, 2006b). Some of the plant indicators include measuring the xylem water potential with a pressure chamber, in order to schedule irrigation. The pressure-chamber technique measures the apoplastic value (Scholander *et al.*, 1965). Recent methods also include infrared thermometry, which measures canopy temperature (Naor, 2006b). Infrared thermometry is based on the principle that, as water becomes less available in the soil, the evaporation decreases and the canopy temperature increases, hence there will be less evaporative cooling. However, other environmental factors such as air temperature, vapour pressure deficit (VPD), wind speed and net radiation affect canopy temperature and need to be considered (Reginato, 1990; Naor, 2006a; 2006b). The daily trunk shrinkage has also been proposed as an indicator of irrigation scheduling in deciduous trees (Cohen *et al.*, 2001; Fereres & Goldhamer, 2003; Naor & Cohen, 2003). Results of most studies with respect to daily trunk shrinkage have, however, been found to be very variable and measurements less stable than the midday stem water potential (Goldhamer & Fereres, 2001; Naor, 2006b). Nevertheless, the relationships between midday stem water potential and daily VPD and potential

evapotranspiration, together with the advantages of continuous electronic data recording, have been found to be of great potential in almonds (Feres & Goldhamer, 2003).

1.7.6 Critical phenological stages of water application in apples

Various stages of fruit growth in apples have been found to be affected differently by deficit irrigation. Deficit irrigation is defined as a system of managing soil water supply to impose periods of predetermined plant and soil water deficit that can result in some economic benefit (Behboudian & Mills, 1997). Some of the important phenological stages for fruit and tree development in apples are the following: (1) reproductive cell division (which lasts ± 30 –40 days after full bloom), (2) fruit drop (40 days after full bloom), (3) canopy growth (from the beginning of the season) and (4) flower bud differentiation and development (which starts midsummer and continues throughout the growing season), (5) reserve carbohydrate accumulation (starts from end of harvest until leaf senescence), (6) shoot growth (begins in the period just after full bloom throughout the growing season) and (7) root growth (begins at budburst until full bloom and again after harvest) (Forshey & Elfving, 1989; Naor, 2006b).

Water stress during fruitlet cell division has been reported to decrease vegetative growth in pears (Marsal *et al.*, 2000) and in peaches (Marsal *et al.*, 2002), and coupled with decreases in midday leaf and stem water potentials. Reductions in fruit size occur with decreases in midday stem water potential during fruitlet cell division in apples and pears (Marsal *et al.*, 2000; Naor *et al.*, 2000). Fruit patterns in apples and pears follow an exponential-increase during reproductive cell division, followed by a linear growth pattern thereafter (Lakso *et al.*, 1995; Naor *et al.*, 2000). Behboudian *et al.* (1998) reported that moderate water stress up to 102 days after full bloom reduced canopy growth in apples, whereas water stress after this period did not have any effect. Early water deficit (for about two months post reproductive cell division) reduced apple fruit size (Kilili *et al.*, 1996).

1.7.7 Effects of irrigation on apple tree performance and fruit quality

Woody tissues, including canopy branches, water shoots and bearing wood competes with fruits for leaf photosynthates (Forshey & Elfving, 1989). Practices such as pruning, the training systems, nutrient strategies that discourage vegetative growth are all aimed at the vegetative-

fruiting relationship (Jackson, 2003; Tromp, 2005). The choice of cultivar and rootstock and selection of management system all affect this relationship (Forshey & Elfving, 1989).

Interactions between irrigation and crop load, and the effects on yield, fruit size and tree water relations have been mentioned in many studies of fruit trees (Naor, 2001). Climate and tree water relations during the growing season have been implicated in aspects of harvest quality and the susceptibility of apples to storage disorders (Landsberg & Jones, 1981). The most researched aspect has been the effect of water status of fruit trees on fruit size. Many authors have reported that fruit size decreases during dry years and is increased by irrigation (Hewett, 1976; Powell, 1976; Naor, 2001). However, the effects of water status on fruit size have also been found to be difficult to interpret because of size and fruit load interactions (Landsberg & Jones, 1981; Naor, 2001). Many other aspects of fruit quality are considered to be related to fruit size, and hence indirectly influenced by tree–water relations. Assaf *et al.* (1976) observed that larger fruit tend to have lower acidity and are more susceptible to storage rot, bitter pit, breakdown and other storage disorders. Plant water status has also been shown to affect fruit firmness: Behboudian & Mills (1997) have reported higher firmness as a result of deficit irrigation. However, results of studies on pears (Ramos *et al.*, 1994) and peaches (Gelly *et al.*, 2003) show no increases in firmness as a result of reduced tree water status. Results of studies on the dynamics of fruit firmness suggest that firmness increases in response to cell-division water stress but that these increases are often temporary (Kilili *et al.*, 1996; Mpelasoka *et al.*, 2001). Other studies on apples have shown that increased water supply resulted in fruit growth increases; however a non-proportional increase in water consumption was also noted (Goode, 1975). In contrast, a reduced water supply in conjunction with increased nutrition was shown to reduce fruit set, fruit number, and individual fruit weights. However, a low water supply to bearing trees increased flowering the following year, and reduced water uptake and vegetative growth (Goode, 1975). Effects of deficit irrigation on ethylene concentration in apples postharvest (Ebel *et al.*, 1993; Kilili *et al.*, 1996; Mpelasoka *et al.*, 2000; 2001), aroma volatiles (Behboudian, *et al.*, 1998), and total soluble solids (TSS) (Mills *et al.*, 1994) have been reported. There is a general increase in ethylene and TSS as a result of deficit irrigation.

1.8 Methods for measuring soil moisture in fruit orchards

Many methods have been used to estimate soil moisture. These methods vary from simple and low-cost feel methods to more accurate and expensive neutron probe units.

1.8.1 Feel method

This is an old, traditional method that involves manual feeling of the soil. It comprises the use of a chart to judge the relative moisture levels. The disadvantages of this method are that it lacks scientific data to back it up and therefore requires repetitive use to master it, and it only estimates soil moisture, hence accurate measurements are not possible (Reginato, 1990). The advantage, however, is that the feel method requires no financial investment.

1.8.2 Watermark sensors 200SS

This method involves the use of porous blocks installed in the ground. Water moves in and out of the block in equilibrium with the soil, and soil moisture tension is measured (by the use of conversion meter supplied by the manufacturer) (Scanlon *et al.*, 2002). A meter is used to read the electrical resistance of moisture blocks. Meter resistance readings change as moisture in the block changes with the amount of water in the soil (Thompson *et al.*, 2006). The wetter the soil the lower the electrical resistance and the better the block conductance to electricity. These sensors are usually more sensitive in the 0–80 kPa range, which is suitable in sandy textured soils (Shock *et al.*, 1998). Watermark sensors can either be used for spot measurements using a hand held reader or measurements can be automatically and continuously logged using data loggers (Thompson *et al.*, 2006). Since the meter is portable, an advantage of the hand held Watermark is that soil moisture can be checked at an unlimited number of sites, wherever soil moisture blocks are buried. A disadvantage of hand held meters is that each monitoring site must be marked clearly in order to be able to find the electrodes in the field before they can be connected to the meter. The sensors can be used with ease in most soils.

1.8.3 Tensiometers

Tensiometers are sealed water-filled tubes with a vacuum gauge on the upper end and a porous ceramic tip at the lower end (Cassel & Klute, 1986). They measure soil water potential or tension in the soil. Water in the tensiometer normally comes into equilibrium with water in the soil

(Reginato, 1990). Readings are an indication of the availability of water in the soil. Tensiometers work best in fine textured soils because the vacuum gauge is only effective up to 80 kPa, which is equivalent to 50–70% soil water depletion from the soil (Thompson *et al.*, 2006). Tensiometers require more preparation time prior to use and more maintenance than electrical sensors.

1.8.4 Neutron probes

A neutron probe is an electronic instrument with a radioactive source that is lowered into the soil through an access tube (Gaze *et al.*, 2002). The neutron probe indicates volumetric soil moisture by detecting hydrogen ions in the soil water. Neutron probes use the neutron thermalisation principle; this states that during operation high energy neutrons are emitted from the radioactive source. Elastic collisions of the fast neutrons with elements in the soil produce slow electrons (thermalised) and the process is most rapid when neutrons collide with hydrogen nuclei because of the similar masses. The number of neutrons detected is a measure of the concentration of the hydrogen nuclei and hence the water content in the soil around the probe (Hignett & Evett, 2002). Due to the requirement for radioactive material, neutron probes are not widely used and also the probes are less effective for determining changes in soil moisture in the top 20 cm of the profile (which is critical in apple trees), hence the value of neutron probes as an irrigation scheduling tool has been doubted (Gaze *et al.*, 2002). Furthermore, neutron probes require special licensing, training is required and the equipment is expensive. Installation of access tubes in the soil can also be labour intensive without a power soil probe (Hignett & Evett, 2002).

1.8.5 Capacitance probes (C-probes)

C-probes are similar to neutron probes except that they do not use radioactive material. An electronic meter measures volumetric soil moisture based on its electrical properties. The sensor depths are chosen relative to the crop's root system and the soil structure. Permanent systems, such as EnvironScan™, C-probe, Aquaterr, etc., can be linked to a central processing system, allowing evaluation of soil moisture status at any time. The C-probe does not have the safety and legal limitations of neutron probes and can be effectively used at or near the soil surface (Hess & Knox, 2003). The sensors utilise a capacitance technique for repetitive continuous readings that involves use of the high dielectric constant of water compared to that of the soil and air to determine the water content of the soil. A pair of electrodes or electrical plates is used as a

capacitor. When activated, the soil–water–air matrix around the PVC tube forms the dielectric around the capacitor and completes an oscillating circuit. Changes in the resonance frequency of the circuit depend on changes in the capacitance of the soil access tube system (Dean *et al.*, 1987; Fares & Alva, 2000). The cost of the equipment (including radio transmitters, tree sensors as well as temperature sensor) is about the same as a neutron probe, but special licensing is not required.

1.8.6 Dendrometers

A dendrometer is a measuring instrument that encircles the tree, attached to some kind of manual or automatic recording device. Dendrometers are very sensitive to climatic conditions such as high temperatures. They have long been used to monitor and record the growth of trees on time scales from hours to years. The working thereof is based on the interactions between physiological and environmental mechanisms (e.g. cold spells during growing period, edaphic soil conditions, rainfall amounts, etc.), so that a better understanding can be reached relating to environmental factors and tree responses (Cohen *et al.*, 2001).

1.9 Nutritional requirements of apple trees and other deciduous fruit trees

1.9.1 General requirements

Apple trees require 16 elements for growth and development during their lifecycle. Among these elements are carbon, hydrogen and oxygen, which are important non-material elements and major constituents of organic materials (Neilsen & Neilsen, 2003). They are combined in photosynthesis, a process exclusive to green plants, to manufacture carbohydrates (Mills & Jones, 1996). They form an essential part of the protoplasm and cell walls and comprise the principal energy materials such as carbohydrates, fats and oils (Bloom, 2002). Along with nitrogen and some other elements they are components of proteins. Hydrogen and oxygen constitute water and water functions as a building material for numerous other compounds and as a transport medium (Winkler *et al.*, 1974). Mineral elements found in abundance in plants include nitrogen, phosphorus, sulphur, potassium, calcium and magnesium, and minor elements include iron, manganese, copper, zinc, boron, molybdenum and chlorine (Klein & Weinbaum, 2000).

Approximation of the necessary supply of major elements for apple and pear tree growth is obtained by measurement of the mineral content of well-grown and productive trees (Jackson,

2003). Most of the nutrients removed from the soil and not returned to it are in the fruits, so the need to replace nutrients is largely a function of crop yield (Haynes & Goh, 1980). Where yields are high, e.g. in South Africa and especially in New Zealand, the replacement needs will be greater (Jackson, 2003). Losses by leaching can be appreciable under conditions of high rainfall or irrigation on certain soil types (Jackson, 2003). Leaf and fruit nutrient concentrations have, however, been found to reflect nutrient status and requirements (Nielsen & Nielsen, 2003). Stassen (1987) and Stassen & North (2005) determined the nutrient requirement in young and full-bearing peach and pear trees by analysing the tree parts. Calculations of nutrient requirements were based on mineral analysis of different nutrients and losses due to fruit removal, pruning and leaf drop (although certain nutrients are redistributed back into the tree before leaf drop).

The annual requirement for added mineral nutrients has been reported to depend on a number of factors such as total requirement and the natural supply from the soil (Klein & Weinbaum, 2000). Several practices and indices have been developed for fertilizer guidelines in many fruit producing areas. These include fixed fertilization rates, applications according to tree response, leaf analysis, extrapolation from small trees, crop nutrient removal, ¹⁵N isotope studies and sequential tree excavations (Weinbaum *et al.*, 2001). Different nutrients are given at different concentrations according to a plant's needs and the phenological stage of plant growth. The nutrient requirements can only be estimated if the periods of nutrient element uptake in the tree are known (Stassen *et al.*, 1981a; 1981b; Stassen & Stadler, 1988). Apple trees are divided into the following phenological stages according to their growth pattern during the season: bud-break, shoot and leaf extension, cell division and growth, fruit harvest and leaf fall. In apples, Ca, Mg and K have been found to be readily absorbed early in the season during shoot elongation (Mason & Whitefield, 1960; Terblanche, 1972). Nitrogen is responsible for tree growth vigour and can be used to manipulate tree growth. In South African orchards nitrogen is usually applied in three instalments: at full bloom, 6–8 weeks after full bloom and during the postharvest period (Terblanche, 1985).

1.9.2 Soil nutrient analysis

Soil nutrient analysis plays an important role in determining potential needs and problems, however soil mineral analysis cannot be used alone because of difficulties in determining the effective tree rooting zones, the importance of carry over of nutrient reserves in the tree from one year to the next and the importance of the supply of nutrients to specific organs rather than cross uptake (Jackson, 2003). Determination of mineral nutrient requirements based on tree response incorporates tree nutrient demand, soil nutrient availability, and biotic and abiotic variables in the orchard system (Worley, 1990). However, use of the tree response is of limited value to perennial crops because the necessary field experiments are time consuming, expensive and yield-site specific (Buwalda & Smith, 1988). The use of extrapolation from pot-grown trees to small trees has been used in the past (Stassen *et al.*, 1981a; Muñoz *et al.*, 1993). However, differences have been found to exist in terms of size of the tree, seasonal duration of vegetation, and reproductive and storage sinks (Weinbaum *et al.*, 2001). Crop nutrient removal (from the crop and pruning) has been used as an alternative way to determine mineral nutrient needs (Haynes & Goh, 1980). This determination works on the principle that the heavier the crop the better the crop nutrient removal approximates the annual nutrient uptake, especially with respect to K (Rosecrance *et al.*, 1996). Assessment of nutrient usage on the basis of crop nutrient removal alone may hold when cropping is heavy, but it is said to ignore the growth and nutrient demands of alternative vegetative sinks, and it tends to be site-specific (Weinbaum *et al.*, 2001). Isotope studies have been used effectively to quantify the timing of N application (Weinbaum *et al.*, 1978; Muñoz *et al.*, 1993). Stable N isotopes permit discrimination between ambient nitrogen in the orchard system and tree uptake of isotopically labelled fertilizer (Weinbaum *et al.*, 2001). The use of ^{15}N isotope studies, as an indicator of annual N uptake by deciduous fruit trees, is limited to short-term studies because it leads to underestimation and is site specific (Powlson & Barraclough, 1993). Sequential tree excavation is a widely used method of fertilizer determination in woody species because this method covers both the amounts and seasonal patterns of nutrient uptake (Weinbaum *et al.*, 2001). Stassen (1987, peaches (*Prunus persica*)), Rosecrance *et al.* (1996 pistachio (*Pistachia vera*)) and Stassen & North (2005 pears (*Pyrus communis*)) found that sequential excavations and nutrient determinations over a specific chronological or phenological time interval permit calculation of tree nutrient accumulation or loss. However, the reliability of biomass estimations for mature trees has not been demonstrated and therefore the seasonal

changes in concentrations of mineral nutrients in leaves, fruit and other organs may not reflect whole tree nutrient uptake patterns (Picchioni *et al.*, 1997; Weinbaum *et al.*, 2001). Biomass estimation for whole trees has, nonetheless, been done in South Africa (Stassen *et al.* 1983; Stassen, 1987).

1.9.3 Leaf nutrient analysis

Leaf nutrient analysis is a reliable method for diagnosing tree nutritional status and it is an important tool for determining future fertilizer requirements in fruit trees (Benton Jones, 1985). Leaf nutrient concentration reflects the factors that influence nutrient availability, including those affecting nutrient supply from the soil and year-to-year variation in climate and crop load (Nielsen & Nielsen, 2003). There are fluctuations in the season as a result of changes in nutrient supply and internal tree cycling throughout the period of annual leaf and shoot development. Some nutrient concentrations such as nitrogen, phosphorus, potassium and zinc decrease over the growing season, while others such as calcium and manganese increase (Nielsen & Nielsen, 2003). In order to accommodate the variations in leaf nutrient concentrations, sampling procedures need to be carried out in a consistent and representative manner (Jackson, 2003). Usually samples comprise 25 to 50 leaves collected from 20 to 25 randomly selected trees from the same cultivar or rootstock combination, with leaves collected around the tree from the mid-shoot portion of the current season's extension growth on shoots of representative vigour (Nielsen & Nielsen, 2003). Leaf age significantly affects leaf nutrient concentration and nutrient content per leaf, further supporting the importance of standardised leaf sampling for nutrient determination (Fernández-Escobar *et al.*, 1999). Leaf nutrient concentration is normally regarded as a useful tool in diagnosing nutrient disorders that occur during the growing season, and can also be used efficiently to fine-tune the fertilizer programme in apple orchards. The leaf nutrient status involves determining the elemental composition of plant tissue during the growing season and then comparing these values with those already established (Jones, 1985). Nutrient deficiencies or excesses can be determined from this comparison (Rossen, 1998).

1.9.4 Fruit nutrient analysis

Fruit mineral analysis, especially for calcium, is used as an aid in post-harvest management decisions (Nielsen & Nielsen, 2003) to determine quality indices such as firmness, crispness, lack

of mealiness, bitter pit, freedom from defects, etc. (Perring, 1984). Fruit nitrogen and calcium concentrations also vary considerably between cultivars and within seasons, and within and between individual trees, which further necessitates large sampling sizes (of about 25–50 fruits) in order to obtain values that are representative of the crop (Nielsen & Nielsen, 2003). During analysis of fruit nutrient concentration it is important to separate different portions of the fruit, such as seeds, cortical plugs, opposite sectors, skin, etc., as these vary considerably in terms of nutrient concentration (Jackson, 2003). As in the case of leaf nutrient concentration, fruit nutrient concentration involves a comparison of the fruit nutrient concentration under observation with established standard figures (Jones, 1985), and making suggestions accordingly.

1.9.5 Influence of root characteristics on nutrient uptake

The root system plays a major role in the absorption and translocation of water and nutrients from the soil (Nielsen & Nielsen, 2003). Apple cultivars are grafted on clonal rootstocks that have been selected primarily on the basis of traits such as precocity, ability to reduce scion vigour and resistance to pests, and little on the basis of ability to take up water and nutrients (Atkinson *et al.*, 2003). Apple root systems have several characteristics that affect their nutritional status and response to soil conditions (Jackson, 2003). In apples the roots are often non-uniformly distributed within the exploitable soil volume, and can penetrate depths exceeding 1–2 meters. However, without competition from other trees, apple trees can achieve a lateral spread exceeding that of the top branches (Lakso, 2003). Despite the potential for extending to great distances and depths, apple root density is low, and frequently lower than those of *Graminaceae* species with which apple is often inter-planted (Atkinson *et al.*, 2003).

1.9.6 Role of roots in nutrient absorption and ion transport

Minerals absorbed by the roots are carried to the shoots by a transpiration stream moving through the xylem (Poole, 2002). Ion transport through the roots is predominantly through both symplastic and apoplastic translocation. An ion entering the root enters the symplast by crossing the plasma membrane of an epidermal cell, or alternatively the ion may enter the apoplast and diffuse between the epidermal cells through the cell walls (Salisbury & Ross, 1993; Marschner, 2002; Poole, 2002). From the apoplast of the cortex an ion either crosses the plasma membrane of a cortical cell and enters the symplast, or diffuses radially all the way to the endodermis through

the apoplast. Irrespective of the avenue followed, the ions must first enter the symplast before they can enter the stele because of the presence of the Casparian strip (Poole, 2002). Growing roots vary both anatomically and physiologically along their longitudinal axes. There is generally a tendency for the rate of ion uptake per unit of root length to decline as the distance from the apex increases (Marschner, 2002), although this tendency is dependent on the type of mineral element and the nutritional status of the plant. Nutrient uptake by roots occurs by direct root interception, by mass flow of dissolved nutrients in water absorbed by the plant, and by diffusion down a concentration gradient from the specific ion developing around the absorbing root (Nielsen & Nielsen, 2003). Apple trees are likely to access fewer nutrients by direct interception due to their low root density and also because they are commonly grown in low fertile soils (Jackson, 2003). Factors such as root density have been implicated in influencing the rate of nutrient uptake. Both the long roots and high root density affect diffusion of the mineral elements into the roots but their relationship is non-linear. When the root density is high the uptake rate levels off because of overlapping of the depletion zones of individual roots. This reflects inter-root competition of nutrients by the roots (Marschner, 2002).

1.10 Nutrition in apple trees

Macronutrients

1.10.1 Nitrogen (N)

The nitrogen (N) available to fruit trees can come from the mineralisation of soil organic matter (although many soils are poor in minerals) and a small percentage from atmospheric deposition in the form of rain, but the bulk of nitrogen comes from nitrogen applications (Stassen & North, 2005). Most of the soils in the Southern Hemisphere are poor in soil organic matter and hence there is a need for additional applications of N. Nitrogen is necessary for many tree functions including growth, fruit bud formation, fruit set and fruit size (Salcedo *et al.*, 2000). Photosynthesis has been reported to increase linearly when sunlit leaves (receiving greater PPFD) have greater N content per unit area (N_{area}) compared to shaded leaves (Field, 1991). Fertilizer practice is often governed by the need to compensate for N removed by the orchard surface cover crops, usually grass, and the requirement for additional N by the tree at flowering time (Terblanche, 1972). Cultivars differ in their N requirements, e.g. a cultivar grown for processing requires more N than one for the fresh market (Salcedo *et al.*, 2000). Some of the important

considerations in N application include the rootstock used, the tree spacing, the rate of tree growth, the foliage colour, nutrient balance in the leaves, and soil and fruit quality (Scalcedo *et al.*, 2000). Klein & Weinbaum (2000) further state that proper timing, i.e. application of nitrogen fertilizer when the sink demand is high, ensures better interception and less leaching; hence less N is required to achieve optimal yield and fruit quality. Nielsen *et al.* (1995) reported lower leaf N under drip irrigated trees compared to micro sprinkler irrigation on ‘Gala’ apples following NP-fertigation, and this was attributed to availability of a smaller volume of soil for nutrient absorption.

1.10.2 Phosphorus (P)

The absolute phosphorus (P) requirement in apple trees is small relative to other nutrients (Scalcedo *et al.*, 2000; Jackson, 2003; Neilsen & Neilsen, 2003). The deficiency of P in apple orchards has been attributed to soil fixation and the inability to increase the P level at the root surface (Klein & Weinbaum, 2000). This explanation is not valid under drip irrigation since the P concentration in the soil solution can be suitably increased around a significant portion of the root system (Klein & Weinbaum, 2000). Plant phosphorus plays a significant role in energy transfer involving ATP and many enzymatic processes (Jackson, 2003), and it is a constituent of phthalitic acid and nucleic acids (Neilsen & Neilsen, 2000). It is an important component in the DNA and RNA macromolecules (Klein & Weinbaum, 2000). During CO₂ assimilation orthophosphate (Pi) derived from ATP is consumed in the chloroplast stroma to form triphosphate (Salisbury & Ross, 1993). Concentrations of P in the soil are usually very much lower than those of nitrogen, potassium, magnesium and calcium (Robson & Pitman, 1983). Hansen (1980) reported that the concentration of P in the bark, roots, and the previous year’s extension wood increases in October (Southern Hemisphere) when P is exported from the leaves. During summer the xylem sap contains appreciable amounts of P and it seems that both xylem and phloem transport are involved in the supply of P to the fruits. Accumulation of P in the leaves reaches a maximum in summer whilst accumulation in the fruit continues until harvest.

1.10.3 Potassium (K)

Apple trees have high potassium (K) requirements in terms of both gross and net uptake (Jackson, 2003). Large quantities of K are removed in fleshy fruits, resulting in low leaf K

concentrations during years of heavy fruit load (Klein & Weinbaum, 2000). Potassium is important in apple trees for maintenance of the internal vacuole, and providing the electrical balance for organic and inorganic anions (Rossen, 1998). It also maintains the structure of the non-woody parts through its effect on cell turgor (Jackson, 2003), and is involved in enzyme activation, in translocation of sugars and starch synthesis (Salisbury & Ross, 1993; Stassen *et al.*, 1999). The main solutes involved in the osmoregulation process are sucrose, K^+ , and accompanying anions (malate and chloride) depending on the environmental conditions. Stomatal opening mainly results from K^+ salt accumulation in the morning whilst in the afternoon it would mainly rely on sucrose accumulation (Salisbury & Ross, 1993). Potassium movement through the soil to the root surface is primarily by diffusion. The soil water content is a dominating factor for this diffusion, hence K uptake can be severely limited by drought (Jackson, 2003). Passive as well as active processes play a role in the movement of K within plants, however, the overall uptake of K in apple trees appears to be under metabolic control (Tromp, 1980). Fruit K responds readily to potassium application, with measurable effects on composition, taste and storage properties, related to the K/Ca ratio of the fruit (Klein & Weinbaum, 2000).

1.10.4 Calcium (Ca)

Apple wood contains more calcium (Ca) than any other mineral element, with the result that orchard requirements to maintain above-ground and root structures are higher than for all other nutrients (Neilsen & Neilsen, 2003). Calcium transport to the root surface within the soil is usually high but within the plant calcium movement is slowed by ion exchange in the xylem (Jackson, 2003). Translocation of Ca to the fruit is severely diminished after completion of cell division, as the supply of both water and nutrients to the fruit gradually becomes phloem dependent (Klein & Weinbaum, 2000). Calcium is important in fruit trees because of its pronounced effect on cell wall strengthening, which is increased upon Ca application (Jackson, 2003). Calcium also forms a critical part of the cell wall that generates strong structural rigidity by forming crosslinks within the pectin polysaccharide matrix. With rapid plant growth, the structural integrity of stems that hold the fruit is strongly coupled to calcium availability (Vang-Petersen, 1980).

1.10.5 Magnesium (Mg)

Apple trees have a greater demand for magnesium (Mg) than many other types of fruit trees and they readily show Mg deficiency symptoms (Mills & Jones, 1996). These can arise because of Mg deficiency in the soil. Magnesium, unlike Ca, is considered to be phloem mobile and will not accumulate to high levels as the leaf ages when its supply is limited (Klein & Weinbaum, 2000). Magnesium plays a major role as an enzyme activator (Mengel & Kirkby, 1987; Stassen *et al.*, 1999), and it forms an integral component of chlorophyll (Mengel & Kirkby, 1987). It is also involved in nucleic acid synthesis and electrostatic functioning. Efficient catalysis by Mg, related to enzymic reactions, is a consequence of the ability of Mg to form a stabilizing complex with an enolate-like transition state and to reduce repulsive electrostatic interactions of the substrate and a catalytic base (Mills & Jones, 1996, Klein & Weinbaum, 2000).

1.10.6 Sulphur (S)

Apple requirements for sulphur (S) are similar to those of P (Neilsen & Neilsen, 2003). Sulphur is present in many of the organic compounds present in apples, including cystine, methionine and proteins. It is also a component of lipoic acid, coenzyme A, thiamine pyrophosphate, glutathione, biotin, adenosine-5'-phosphosulfate and 3-phosphoadenosine (Mengel & Kirkby, 1987). Lack of sulphur is most likely to occur in orchards with leached soils, low in organic matter content and receiving limited sulphur (Neilsen & Neilsen, 2003). Sulphur has little residual action in the soil as it is rapidly leached (Mengel & Kirkby, 1987).

Micronutrients

Some of the important micronutrients required by apples include iron, manganese, copper, zinc, boron, molybdenum and chlorine (Neilsen & Neilsen, 2003). Although the role of these nutrients in apple tree nutrition is minimal, their important role in cell division, fruit set and fruit quality cannot be underestimated (Brown & Hu, 1996). The majority of micronutrients appear to be phloem immobile and most of their deficiency symptoms appear on new leaves, near the shoot tips (Neilsen & Neilsen, 2003).

1.10.7 Boron (B)

In apple trees boron (B) is required at low concentrations in leaves and fruits. Its main role is to maintain plant meristematic activity and cell wall stability. It functions as a coenzyme in the formation and transport of sucrose (Jackson, 2003; Neilsen & Neilsen, 2003). Boron forms complexes with mannitol, mannun, polymannuronate acid and other constituents of cell walls. It is also involved in cell elongation, pollen tube growth and nucleic acid metabolism (Bloom, 2002). Boron deficiency leads to abnormal fruit development, with a gnarled misshapen appearance, causing depressions on the fruit skins (Shear & Faust, 1980). Boron is present in phloem and is retranslocated in phloem, often in sufficient amounts to satisfy the demands of developing sink regions that do not readily transpire. In the soil it is highly mobile and often lost through leaching. Rapid B uptake is at budburst and during the post-harvest period.

1.10.8 Zinc (Zn)

Apples and pears have a low demand for zinc (Zn) and unless deficiency symptoms are visible additional Zn applications have no effect (Shear & Faust, 1980; Jackson, 2003; Neilsen & Neilsen, 2003). Zinc plays a role in several plant enzyme systems and plant biochemical functions, including pH regulation in plant cells, protein synthesis of RNA and tryptophan, as a precursor of indoleacetic acid, and in shoot elongation (Swietlik, 1999; Neilsen & Neilsen, 2003). Zinc uptake in fruit trees, including apple trees, is during bud burst, and applications during dormancy, such as in the form of soil applications, dormant-spray applications and trunk injection have been shown to be effective (Jackson, 2003).

1.10.9 Manganese (Mn)

Absolute manganese (Mn) requirements are very small in fruit trees and they only slightly exceed the trees' demand for Zn. Manganese is required in enzyme functions, for photosynthesis and carbon assimilation and it acts as a catalyst in photosynthetic O₂ evolution (Marschner, 2002; Neilsen & Neilsen, 2003). Manganese deficiency often occurs together with Zn deficiency. Deficiency manifests itself on the leaves, as irregular shaped light green spots in the margins and between veins of basal shoots in summer. Further, in cases of severe deficiencies, the leaf size and shoot growth may be decreased (Shear & Faust, 1980). Higher leaf Mn levels have been

reported under micro sprinkler irrigation compared to drip irrigation, as a result of restricted soil volume for absorption under drip irrigation compared to micro sprinklers (Neilsen, *et al.*, 1995).

1.10.10 Copper (Cu)

The copper requirements of apple trees are among the lowest of all the nutrients. Copper is required for chlorophyll synthesis and in several copper-containing enzymes involved in the reduction of molecular oxygen (Neilsen & Neilsen, 2003). Copper also forms a component of ascorbic acid oxidase, tyrosinase, monoamine oxidase, uricase, cytochrome oxidase, phenolase, laccase and plastocyanin (Bloom, 2002). Copper deficiency in apples is rare, but has been recorded in orchards in Australia, England, South Africa and the USA (Neilsen & Neilsen, 2003).

1.10.11 Iron (Fe)

Iron is an important constituent of the Fe-haem complex, a naturally occurring plant chelate involved in electron transfer in a number of important plant enzyme processes (Mengel & Kirkby, 1987). It is part of the cytochromes and non-heme iron proteins are involved in photosynthesis, nitrogen fixation and respiration (Bloom, 2002). In green leaves the iron supply is closely associated with the chlorophyll content (Neilsen & Neilsen, 2003).

1.10.12 Molybdenum (Mo)

Molybdenum (Mo) assists in the formation of plant proteins, starch, amino acids and vitamins. Molybdenum is considered as a catalyst that aids the conversion of gaseous N to usable forms by nitrogen-fixing microorganisms, and it forms a constituent of the plant enzyme that converts nitrate to ammonia (Bloom, 2002).

1.11 Conclusions and future research possibilities

The movement of water through the plant, until it is lost to the atmosphere through the leaf stomata, has long been investigated. However, little knowledge exists on how different irrigation strategies and the timing of water applications (e.g. the frequencies per week or per day) affect some of the important physiological processes, such as photosynthesis, stomatal regulation, transpiration and water use efficiency. The use of dwarfing rootstocks to control growth and increase planting densities is currently being investigated to better understand some of the

relationships between water and the physiological processes. Use of drip irrigation systems compared to use of micro sprinklers is a strong alternative to regulate growth, maintain physiological processes and water regulation within the tree. The results will eventually increase fruit yield and quality at minimum water usage. In the long run the overall running costs would be reduced, irrigation water would be saved and the producer's returns per hectare would increase.

Deciduous fruit producers are faced with a major challenge in maintaining high fruit yields per hectare and fruit quality while simultaneously achieving sustainable and viable returns. Lower producer returns can be attributed to a number of factors, such as poor fruit quality and size, lower yield per hectare, unfavourable exchange rates, high running costs (such as costs of labour and water), and unreliable weather conditions. One of the major problems identified in the Western Cape Province is the recurring drought, associated with below average rainfall and high temperatures, which often leads to intensive water usage to optimise plant growth and maintain high fruit yield and quality.

In the past, numerous methods of irrigation have been used by apple producers. The most widely used is the conventional micro sprinklers, which are currently used by many producers. The micro sprinklers are used to supply water to the trees but may also involve manual application of nutrients by hand according to the plant needs. The use of daily drip irrigation is also gaining popularity and it involves application of water and nutrients through drip emitters once daily. However, there are also a number of producers currently using pulsing drip irrigation, which involves continuous application of water several times daily.

1.12 Research objectives and hypotheses

Overall objective

To study the effect of the frequency of water and nutrient applications on 'Brookfield Gala' apple trees, grafted on two rootstocks and planted on a sandy loam soil with 80% or more sand fraction, using commercially available irrigation systems to study certain physiological processes and horticultural aspects.

Overall hypothesis

More frequent water and nutrient application on a sandy loam soil will stimulate the development of a more efficient root system, enhance rapid water and nutrient absorption and translocation, increase photosynthetic ability and water use efficiency, thus increasing the synthesis of carbohydrates and ultimately improving yield and fruit quality. Increased gas exchange activity and tree water use efficiency could lead to better manipulation between the reproductive and vegetative balance.

Specific objectives of the study were the following:

1. To calculate predetermined theoretical water use and determine actual water requirements in young and bearing 'Brookfield Gala' apple trees.
 - 1(a). To predetermine theoretical calculated water use on a daily, monthly and annual basis using long-term weather data and apple crop factors (K_c).
 - 1(b). To use these predetermined values as a basis for supplying apple trees with their actual water requirements, then using water sensors, climate data, dendrometer indications and results of soil profile studies to manage the plant available soil water at optimum levels.
 - 1(c). To use available annual nutrient requirement information (kg.t^{-1} macronutrients per unit yield and g.t^{-1} microelements per unit yield) based on nutrient losses, nutrient fixation and redistribution, and determine the amounts of nutrients necessary per application and per phenological stage.

- 1(d). To feed the above information into a software program to determine compositions of the correct nutrient solutions per application.

It was hypothesised that long-term evaporation data and apple crop factors can be used as a good basis from which actual water usage can be determined using different methods. Annual macro element and micro-element requirements can be predetermined and fitted into the program, which can then be refined according to needs, based on actual day-to-day weather forecasts from the South African weather bureau, soil moisture sensors, soil profile studies soil and leaf analysis studies and tree performance. More directed water application into the root area can also save water.

2. To study different horticultural aspects in ‘Brookfield Gala’ apple trees in relation to use of different water and nutrient application frequencies using three irrigation systems and two rootstocks.

- To compare the three irrigation systems (micro sprinkler irrigation, daily drip irrigation and pulsing drip irrigation) in combination with two rootstocks (M7 and M793) with respect to tree performance based on fruit yield, fruit quality, shoot and root growth.

It was hypothesised that a more refined and controlled water and nutrient management system can play a significant role in the improvement of horticultural tree performance by limiting excessive vegetative growth, promoting root proliferation and improving fruit yield and quality.

3. To study gas exchange measurements and water relations in ‘Brookfield Gala’ apple trees in relation to use of different irrigation systems and two rootstocks.

- To study the influence of different irrigation systems in commercial use, namely micro sprinkler irrigation, daily drip irrigation and pulsing drip irrigation, in combination with two rootstocks (M7 and M793) on physiological parameters such as leaf photosynthesis rate, stomatal regulation, transpiration, instantaneous and intrinsic water use efficiency, and leaf water potential in ‘Brookfield Gala’ apples, with emphasis on daily and seasonal changes.

It was hypothesised that water and nutrient management systems can play a significant role in the improvement of leaf photosynthetic capacity and increase tree water use efficiency. This could be achieved by mitigating the reduction in midday leaf water potential and maintaining higher leaf photosynthesis thus reducing stomatal closure at midday as well as increasing biochemical photosynthetic capacity.

1.13 Layout of dissertation

This dissertation is made up of seven chapters. Chapter one gives the detailed literature review of the study and the study objectives. Chapter two explains the methodology followed in this study. Chapter three comprises of the horticultural aspects in 'Brookfield Gala' as affected by different water and nutrient strategies. Chapters four, five and six, detail how different water and nutrient strategies affect the photosynthesis, stomata conductance, carboxylation efficiency, electron transport and water use efficiency in 'Brookfield Gala' apple trees. Lastly chapter seven is the concluding remarks of the study.

1.14 References

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2. Methodology used for the determination of water and nutrient management strategies on ‘Brookfield Gala’ apple trees

Abstract. An experimental ‘Brookfield Gala’ apple orchard was planted in a sandy loam soil during June 2003. Soil analysis indicated that the soil was ideally prepared and should provide an excellent medium for root development. Data from two nearby weather stations, mean long-term evaporation and the existing crop factors for apples were used to predict the water use of bearing trees. Soil water sensors and on-site weather data were used to manage plant available soil water, actual application time and length of irrigation. Literature on the nutrient analysis of tree parts provided information for the calculation of the annual nutrient requirements for apple trees. These annual requirements were divided into specific phenological stages according to the needs of the plant. Use was made of two commercially-used irrigation systems to create three water and nutrient application frequencies, namely micro sprinkler irrigation (standard system used by the fruit producers of the Western Cape Province), daily drip and pulsing drip irrigation (used to distribute the water and nutrients to trees at different shorter frequency levels). Micro sprinklers, which involved the wetting of a continuous strip, applied water once to three times a week (depending on the rate of evapotranspiration and temperature). This system was used to represent a longer cycle water application. Daily drip fertigation applied water within a limited drip area once to twice a day whilst pulsing drip applied water in one to six pulses a day. These drip systems were used to represent shorter cycles of water application. All trees received the same amount of water in the root zone, however the micro sprinkler system used more water because of transpiration and the larger area of wetting. All the trees received the same amount of annual macro and micro elements. In the case of the micro system the nutrients were manually applied under the drippers spread over the continuous area, or applied using leaf sprays. Results showed that the predicted water requirements for mature trees provide a good basis for establishing correct water requirements and correspond well to the actual water usage that was measured accurately for the last three seasons (2005/6, 2006/7 and 2007/8). Various soil sensors (C-probe, Watermark and Decagon sensor) were used to accurately manage plant available water between 50% and 100%. Leaf area was determined and used to predict water use for trees of different ages. Determination of tree performance and leaf analysis showed that the nutrient solutions that were used were adequate.

Key words: Evapotranspiration, crop factors, theoretical water use, actual water use, nutrient solution

2.1 Introduction

Irrigation is intensively practised in apple orchards worldwide, including South Africa, especially in the Western Cape Province. Irrigation is important as it replenishes water that has evaporated from the soil and from the plants. Irrigation greatly depends on climatic data, and this dependency becomes even more important with the progression from temperate to semi-arid and arid zones (Rackham, 1996; Naor, 2006). The performance of deciduous trees, especially apples and pears, is dependent on irrigation in drier regions (Assaf *et al.*, 1982; Naor *et al.*, 1997). A reduction in available water for agricultural use is becoming a worldwide phenomenon (Naor, 2006). It has therefore become a primary objective to both growers and plant breeders to increase water use efficiency either by improving the genetic performance of the trees, improving horticultural practices or by improving irrigation strategies (Naor, 2006). The aim is thus to increase the efficiency of fruit trees by means of more intensive water management, using water more suitably and sparingly, in order to achieve better yield and quality.

Irrigation water applied to plants is intended to return to the soil the amount of water transpired by the tree and the cover crop (T), in addition to the amount evaporated from the soil surface (E). The sum of these components is referred to as evapotranspiration (ET) (Wright, 1982; Allen *et al.*, 1998; Naor, 2006). The ET of any specific crop (including apples) under maximum moisture availability is defined as $E_{Tr} \times K_c$, where E_{Tr} is the evapotranspiration of a reference crop (well-watered alfalfa or grass) (Wang *et al.*, 2007), which covers the whole surface area and which can be replaced by evaporation from a free water surface in a standard evaporation pan (Allen *et al.*, 1998). K_c , the crop coefficient, is a proportional factor that depends on the fraction of the soil surface covered by a crop, the canopy conductance and canopy roughness, and this factor varies throughout the season (Kang *et al.*, 2003). Canopy conductance of deciduous trees during the dormant season (June–August) in the Southern Hemisphere is zero and hence the trees are usually not irrigated, however the soil evaporation from actual evapotranspiration (E_{Ta}) is not zero (Van Zyl & De Jager, 1997; Arca *et al.*, 2004). Crop factors of deciduous trees, e.g. of apples, increase with increasing foliage coverage, tree age and tree spacing (Wang *et al.*, 2007), and vary according to seasonal changes in canopy conductance, which results from changes in tree water relations

according to crop level (Arca *et al.*, 2004). Sets of different crop factors have been developed in South Africa (Green, 1985; Kotzé *et al.*, 1988).

There are two methods that can be used to predict reference ET (Arca *et al.*, 2004). The first method involves using weather forecast variables from numerical weather forecasting models and then calculating ET using empirical or analytical models (Arca *et al.*, 2004). These include the Penman method (Penman, 1948), the Penman and Monteith method (Allen *et al.*, 1998), the FAO corrected Penman method (Allen & Pruitt, 1991) and the Hargreaves method (Hargreaves & Samani, 1985; Allen *et al.*, 1998). The second method is based on statistical analysis of past evapotranspiration rates, and involves the use of E and K_c to compute potential evapotranspiration (ET_o) (Arca *et al.*, 2004). The role of temperature has an effect on all the above models because increases in temperature increase the rate of evapotranspiration. The relationship between temperature and irrigation frequency and rate to refill point becomes steeper with increases in temperature during heat waves or on hot days (Allen & Pruitt, 1991).

Apple trees are known to use large volumes of water daily (60–70 l. day⁻¹. tree⁻¹ for mature apple trees) during mid-summer (Green *et al.*, 2003). Water consumption varies from season to season and from month to month within a season. Dependency on irrigation decreases with the inception of autumn and the start of the rainy season. Planting of higher-density apple orchards is increasing in the Western Cape Province, and some producers are changing to drip irrigation systems as opposed to using micro sprinkler irrigation in order to save water and to optimise production and quality. The water resources for agricultural use are known to be diminishing and agriculture also faces a very strong competition from industry and urban human requirements, with the result that there is an urgent need to use water optimally. The amount and the frequency of water to be applied to trees are dependent on the age of the tree, the existing climatic conditions, especially the rate of evapotranspiration, and the mean daily temperature.

Nutrient requirements play a significant role in fertigation systems, to ensure that the correct amounts of nutrients are given at the correct phenological stages. This is because nutrients have important functions in plant processes (Mengel & Kirby, 1982; Faust, 1989; Bloom, 2002). The requirements are usually based on well-grown and productive trees (Jackson, 2003). Calculations of nutrient requirements include nutrients that have been lost through fruit

removal, pruning, leaf loss and leaching, and nutrients that have been fixed and held in the permanent parts (Terblanche, 1972; Stassen, 1987; Stassen & Stadler, 1988; Stassen *et al.*, 1999; Neilsen & Neilsen, 2003; Stassen & North, 2005, Krige, 2007; Kanguuehi, 2008).

The objectives of this methodology chapter were:

- 1) To select a suitable site for the establishment of an apple orchard for irrigation and nutrient studies.
- 2) To select uniform planting material, and to prune and train trees according to their growth and development, in order to ensure that the allocated spaces are filled as soon as possible, with correctly balanced and well positioned side branches bent horizontally. This was to be followed by fruit thinning according to the bearing ability of the spurs, to prevent the levelling out of the yield, by using ridged thinning programmes.
- 3) To ensure that adequate and correct nutrient requirements of both macro and micro elements, from tree establishment to full bearing capacity, are applied. To ensure rapid tree establishment in the initial phase and a correct balance between vegetative and reproductive growth during the full bearing phase. To ensure that nutrients are given in the correct amounts during specific phenological stages.
- 4) To ensure that all the experimental trees receive optimal water, by predicting the annual, monthly and daily amount of water needed from long-term weather data and apple crop factors. To adjust the predicted water requirements to accurate actual values, using soil water sensors to manage the plant available water in the soil at optimal levels for the trees.
- 5) To use a specifically developed software program to calculate the correct, balanced solution from commercially available fertilisers and mix it in correct proportions based on the tree's phenological stages, yield performance and water requirements.
- 6) To use two commercially known irrigation systems to create three water and nutrient application frequency strategies, namely:
 - i) A long cycle application frequency (one to three times weekly, according to available water in the soil) using a micro sprinkler system.
 - ii) A medium short cycle application frequency (one to two times daily, according to available water in the soil) using a drip irrigation system (daily drip).

- iii) An even shorter application frequency (one to six times/day, according to available water in the soil) using a drip irrigation system (pulsing drip).
- 7) To measure the leaf and trunk area increase for adaptation of water requirement for trees at different ages.

It is hypothesised that long-term evaporation data and appropriate crop factors can provide the foundation for determining optimal daily, monthly and annual water requirements of a full-bearing apple tree. Complimentary to this, accurate soil water measurements, using soil water sensors, can be used to maintain soil water at a level of between field water capacity and 50% of plant available water. Nutrient requirements based on the analysis of full-bearing trees can be divided into phenological stages to reflect and support important tree processes. Leaf area increase can be used to reflect tree canopy development and to predict the water requirements at different ages.

2.2 Materials and methods

2.2.1 Orchard cultural practices (soil preparation, tree planting, training and fruit thinning)

‘Brookfield Gala’ apple trees (*Malus domestica* Borkh) were budded on M793 and M7 and planted out during June 2003 at a spacing of 4m × 1.25m in a sandy loam soil (sand (85%), silt (9.6%) and clay (5.2%)) classified as a Dundee soil form, at Genadendal, near Greyton, Western Cape Province, South Africa. Soil samples were taken during 2003 prior to planting and soil analysis tests were done by Bemlab® (Bemlab Pty. Ltd, Strand, South Africa). The soil has a water holding capacity of 130 mm.m⁻¹ and pH range of 5.7 to 6.1 (Table 1a and b), and is well aerated and well drained. Preplant soil preparation included cross-ripping the soil to a depth of 800 mm, adjustment of soil pH to approximately 5.5 (KCl) and phosphorus to 30 mg.kg⁻¹ (Bray II, as extraction method) by amelioration with lime and phosphorus. Trees were planted in a NE–SW row orientation and trained to a central leader spindle, using a four-wire support system with lateral branches bent horizontally according to the French solaxe principle. Pruning was done during summer and winter. During summer pruning, upright water shoots were removed to open the trees for light penetration and improve spur development and fruit bearing positions. Later in the season this was followed by removal of limbs that were either too low, too thick, too close or on top of one another. The aim was to fill the allocated space and have 20–24 bearing lateral branches at the end of year four. Fruit thinning was done immediately after fruit drop and a maximum of two fruits were left per spur cluster for the first proximal 50% of the bearing branch and three fruits/cluster for the

other distal 50% of the bearing branch, leaving ± 10 to 20 fruits per branch (2005/6 and 2007/8). No fruit thinning was done during 2006/7 (when less fruit was available) due to low fruit set as a result of cold and misty weather and wet soil conditions during flowering.

2.2.2 Study site

The site lies at the foot of the Riviersonderend mountains, six kilometers east of Genadendal (34°03'S, 19°37'E). The experimental site was situated at the lower terrain, SW of a ± 40 m high hill, ideal for gravitational irrigation, with a river running below to the NE of the hill. The site is moderately cold with ± 800 Richardson cold units (RCU), which provide adequate chill units for 'Brookfield Gala' cultivation.

2.2.3 Irrigation layout

Three irrigation treatments, namely micro sprinkler, daily drip and pulsing drip irrigation systems, were randomly laid out in eight rows. A split-plot design was applied using each system as a main plot and the two rootstocks (M7 or M793) as sub-plots. Each experimental unit consisted of five trees. The three irrigation systems were installed in 2003, however for the first year all the trees were only irrigated using daily drip. The two drip-based irrigation systems discharged water from the emitter (dripper) according to frequency, with two drippers per tree. The micro sprinklers delivered water one to three times a week (depending on the maximum daily temperatures). The rows were separated by a 1.2m \times 0.5m deep trench lined with double-layer, black gunplast plastic (150 μ m) and filled with soil in between to prevent any lateral movement of water between the treatments.

2.2.4 Irrigation strategies

Two commercially used irrigation systems were used to create three application frequency strategies. The first strategy was to apply water and nutrients at longer frequency intervals i.e. every three to four days. The micro sprinklers with a delivery capacity of 30l.h⁻¹ and standing time of ± 120 min are considered the standard irrigation system for fruit producers in the Western Cape area. This system applies water once to twice (sometimes three times) a week and uses sprinklers that spray water in a circle (1.5m diameter) resulting in wetting a continuous strip within the drip row (drip area of the trees). Micro sprinkler irrigation is generally considered to have a longer irrigation cycle from the last day of irrigation to the next, which ranges from once fortnightly (winter) to once to three times weekly (warmer months). As a result of wide coverage and spreading in the air, micro irrigation leads to

increased rates of evaporation and drift and hence uses more water compared to drip irrigation systems. Nutrients are applied manually within the drip area e.g. nitrogen was given manually in five instalments through the year, potassium in three and all other nutrients in two instalments, according to standard commercial strategies based on seasonal nutrient uptake in apples. This strategy will be referred to as a micro sprinkler system. The second strategy (daily drip system) is to apply water on a daily basis creating a shorter cycle compared to the micro sprinkler system. Drip systems used in this study had a lower delivery rate of $2.3\text{l}\cdot\text{h}^{-1}$ and shorter continuous cycles ranging from twice daily (daily drip) (with irrigation lasting for $\pm 120\text{min}$) to six times daily in a pulsing drip system (with each pulse lasting for $\pm 20\text{min}$). The objective of daily drip is to wet the area around the tree directly onto the soil and is characterised by low evaporation rates, thus uses less water compared to a micro irrigation system. In this strategy nutrients are given in a solution with water every time irrigation is administered. The third strategy (pulsing drip system) is to apply water several times during the day creating an even shorter frequency cycle than the second strategy. Nutrients are applied in solution with water every time irrigation is administered.

2.2.5 Trunk and leaf area as indicators of water use

Trunk circumference was measured every winter and used in calculating the trunk circumference area during the course of the trial. For this purpose five trees were used per treatment. Leaf area measurements were taken after harvest. The trees were stripped of all the leaves followed by counting of leaves and determining their total leaf area using a portable leaf area meter (LI-3000C, Li-Cor, Lincoln, Nebraska, USA). Stripping of trees took place after fruit harvest and the trees used were not included for data collection in other subsequent years.

2.2.6 Predicted water use in apples

Evaporation figures were obtained by considering E-pan evaporation from class A standard evaporation pan for the past 25 years from official weather stations at Villiersdorp ($\pm 43\text{km}$ from experimental site) and Caledon ($\pm 35\text{km}$ from experimental site) (Tables 2a, 2b, and Appendix, Table 1). These values were replaced into E_{Tr} to calculate reference crop evapotranspiration for each season (Allen *et al.*, 1998). $ET = E_{Tr} \times K_c$, where E_{Tr} is reference evapotranspiration and K_c is the crop coefficient for apples. Varying values of crop coefficients were used during the season, ranging from 0.2 in July to 0.5 in February (for full bearing trees) (Kotzé *et al.*, 1988) (Table 2a). The total predicted amount of water needed for

full-grown apple trees was calculated from the above equation for two closely situated areas (Villiersdorp and Caledon) (the experimental site was situated between these two areas) (Table 3).

2.2.7 Water management

2.2.7.1 Soil moisture and trunk diameter measurements

During the first year (July 2003 to September 2004), young trees were given water only to wet the root zone according to soil profiles made daily and using daily drip irrigation. From October 2004 onwards the three irrigation strategies as described were in place and irrigation scheduling (between field capacity and 50% plant available water) was based on data from soil sensors. Accurate soil water measurements were achieved using different soil moisture sensors, complimented with weather data from the weather station (CR10X, Campbell Scientific, Inc., Logan, Utah, USA) in the orchard. One A723® C-probe soil moisture device (Adcon International Inc., Davies, CA, USA) was installed at one replicate each of the three irrigation systems to monitor soil moisture (%) and was designed to read at 20cm, 40cm, 60cm and 80cm soil depths. The data were communicated to a data logger, attached to a PC, at 10-min intervals. Twelve Watermark sensors (Irrometer Co., Riverside, CA, USA) were installed in the orchard; four at each irrigation system at depths of 20cm, 40cm, 60cm and 80cm, and readings were taken at 07h00 daily before irrigation. Neutron probe sensors (CPN Neutron probe, ICT International Pty Ltd, Armidale, Australia) were used during 2007/8 season to establish the refill point (wilting point) and full point (field capacity) (based on available water between field capacity and 50% plant available water) for the soil used at Genadendal and also to calibrate the readings obtained from C-probes and Watermark sensors (Appendix, Figs 1 and 2). Three 1.5m depth holes were dug for neutron probe sensors for each system in three different rows, the holes were fitted with aluminium access tubes sealed at the bottom (50mm wide ×1.5m long), fitted with tube drive and tube extractor. The tube extractor was calibrated to read soil moisture at soil depths of 20cm, 40cm, 60cm 80cm and 100cm. Measurements (of both refill and full points) were taken at each hole on Wednesday (for one week) and Monday and Friday for the following week starting December 2007 to February 2008 (Appendix, Fig 2). ECH₂O soil moisture sensors (Decagon Devices, Inc. Pullman, WA), were installed at 10cm, 30cm, 50cm and 70cm soil depths for the pulsing irrigation system only. Unlike the other three sensors the ECH₂O sensors read the soil moisture in terms of percentage at different soil depths. Two wetting front detectors (Agriplas, Pty Ltd., Pretoria, South Africa) were installed for each system at depths of 20cm and 80cm to

monitor any possible excessive irrigation during the season. Three dendrometers (Model DF $\pm 2.5\text{mm}$, accuracy $\pm 10\mu\text{m}$, Solartron Metrology, Bognor Regis, UK) were attached to the tree stems where the C-probe sensor was mounted to monitor trunk diameter fluctuations (TDF) and water stress was monitored using C-probe logger. Measurements were taken every 15 seconds and the data logger (Model CR10 \times with AM 416 multiplexer, Campbell Scientific Ltd., Logan, Utah, USA) was programmed to report 10 minute means. Maximum trunk shrinkage (MDS) was calculated by subtracting the minimum radius (afternoon readings) from the maximum radius (morning readings). All the water sensors were placed at the given depths within the root zone and tightly sealed with soil to avoid any air pores between the sensor and the soil. At regular intervals (at the beginning of each new phenological stage), soil profiles were compiled to observe the soil water movement both laterally and horizontally in the profile. Wetting front detectors were used to indicate over irrigation, usually popping up once the soil has reached saturation point (after irrigation) and stayed low if the water is below field capacity. The irrigation systems were flushed every month with water (for six to eight hours) to avoid any clogging of the system and accumulation of nutrients in the soil profile.

2.2.7.2 Irrigation scheduling

For micro sprinkler irrigation the system was scheduled as done on a commercial basis with 50-60% available volumetric soil water (according to C-probes and Neutron probe) (Fig. 1A and Appendix, Fig. 2A). Micro irrigation had the field capacity of $\pm 107\text{mm}$ and wilting point at 44mm (Appendix, Fig. 2A). For daily drip the field capacity was $\pm 108\text{ mm}$ and wilting point at 83mm (Appendix, Fig. 2B), The daily drip system was scheduled as done on commercial basis with 50–60% plant available volumetric soil water was used (according to C-probes and Neutron probe) (Fig 1B and Appendix, Fig. 2B), whilst pulsing drip used 60–75% volumetric soil water (according to C-probes and Neutron probe) (Fig 1C and Appendix, Fig 2C). For pulsing drip irrigation the field capacity was $\pm 120\text{mm}$ and wilting point 88mm (Appendix, Fig. 2C). However, the micro irrigation is usually scheduled twice during summer, but during the hot spells, when the rate of evapotranspiration is high as a result of high temperatures the time taken to the wilting point is shortened hence the frequency of irrigation increases from two to three times a week to keep the system running at optimal available water.

2.2.8 Nutrient management

Annual nutrient requirements were adapted from Stassen and North (2005) (for pears) and again amended with 'Royal Gala' studies at Villiersdorp (Table 4a) and divided percentage-wise into five phenological stages, according to the programme described by Stassen *et al.* (1999) (1. dormancy, 2. bud burst, 3. stage of rapid growth and cell division, 4. flower induction, completion of flower differentiation, cell enlargement, fruit development, and harvest, and 5. postharvest period) throughout the year (Table 4c and Appendix, Table 2). This was evaluated for two years on 'Royal Gala' apple trees near Villiersdorp (P.J.C. Stassen, 2003, personal communication) before implementing in this experiment. Macronutrient and micronutrient concentrations expressed in kg element/ton fruit and g element/ton fruit, respectively, used in this study did not differ significantly compared to concentrations found in 'Brookfield Gala' studies in the same orchard (Kangueehi, 2008) and for nectarines, where nitrogen was higher but other elements were similar to those used in this study (Krige, 2007) (Table 4b). Small changes were made, as necessary, according to tree performance as well as soil and leaf nutrient analysis during the season (Appendix, Tables 3–4).

A computer software program was developed by P.G. Mostert (personal communication, 2004) to integrate the above mentioned information (annual nutrient requirements at different phenological stages and predicted water use in apples) and to calculate the exact amount of water and nutrients in the solution (in balanced proportions, using available commercial fertilisers, ammonium sulphate (NH_4SO_4 , 109 kg/ha/yr), potassium chloride (KCl, 36 kg/ha/yr), mono-potassium phosphate (KH_2PO_4 , 33 kg/ha/yr), calcium nitrate (CaNO_3 , 75 kg/ha/yr), magnesium sulphate (MgSO_4 , 75 kg/ha/yr), copper sulphate (CuSO_4 , 0.4 kg/ha/yr), zinc sulphate (ZnSO_4 , 1 kg/ha/yr), borate (B(OR)_3 , 0.5 kg/ha/yr), sodium molybdate (NaMO_4 , 0.1 kg/ha/yr), manganese sulphate (MnSO_4 , 1 kg/ha/yr) and iron sulphate (FeSO_4 , 10 kg/ha/yr), and the standing time for each application according to the information obtained from soil sensors. The computer program was also used to keep an accurate computer record of the exact amount of water and nutrients delivered daily, weekly, monthly and annually. Using this program any adaptation made to any aspect was taken into account. In both drip irrigated systems nutrients were supplied by fertigation, whilst with micro irrigation the macro and micro nutrients were applied manually within the drip area. Nitrogen in the form of (NH_4SO_4), was given manually in five instalments (three in spring and two during post-harvest), potassium (KCl), in three and all other nutrients in two instalments, according to

standard commercial strategies based on seasonal nutrient uptake in deciduous fruit trees (Hill-Cottingham, 1963; Stassen, 1980; Stassen *et al.*, 1981; Terblanche, 1986; Stassen & Stadler, 1988). During the first year (2003/4, June 2003 to September 2004) all the trees received the same nutrient solution for young trees (solution prepared by Omnia fertilizers, Epsom Downs Park, Bryanston, South Africa) daily, using a drip irrigation system. During the second year (from October 2004 to September 2005) the nutrient solutions were prepared (as described above) on an estimated yield of 10t.ha⁻¹ and increased by 30% to allow for vegetative growth. During the third year (from October 2005 to September 2006) nutrients were based on 25t.ha⁻¹ yield estimations, and for the fourth year (2006/7) on 15t.ha⁻¹ (yield was calculated at full bloom to be 45t.ha⁻¹ but, due to cold and misty weather and wet soil conditions during the flowering period, yield had to be adapted to 15t.ha⁻¹). For the fifth year (2007/8) nutrients were based on 60t.ha⁻¹.

2.2.9 Water and nutrient application

Water and nutrients for both daily drip irrigation and pulsing drip irrigation systems were mixed in a 10 000 l tank according to computed calculations based on the tree's phenological stages and plant needs (adjusted according to soil moisture measurements and weekly weather forecasts) (P.G. Mostert, 2004, personal communication). The water and nutrients ran gravitationally down the hill to the bottom of the orchard at ± 2.2 bar pressure. An Aquarius applicator (AQ 516 Aquarius, Davies, CA, USA), using a smart card that was programmed in the morning after sensor readings were taken, using the information calculated from the software program (P.G. Mostert, 2004, personal communication), was used to control the opening and closing of the valves for all three systems (Aqua Pro DC solenoid) that regulated the time and duration of applications. Three municipal water meters (WM series, multi-jet water meters, Reliance worldwide, Chapman place, Australia) were installed for each system to monitor the amount of water applied per irrigation. An Arkal filter system (120 and 130 micron mesh) was placed within the tree rows to filter any debris before water and nutrients were applied. In the case of the micro irrigation system, water was pumped directly from the river, filtered, and then applied to the row of trees according to computed information described above. The exact time required for the pump to run was determined automatically as per programmed installations. All irrigation systems were designed by Netafim® (Bellville, South Africa), commercial suppliers of irrigation equipment.

2.2.10 Leaf mineral nutrition analysis

Leaf mineral analysis was carried out every month to determine the toxicity or deficiency levels and the figures were compared to the known leaf nutrient standards in apples (Faust, 1989; Kotzé, 2001) (Appendix, Tables 3 and 4). Leaf samples consisting of 60 leaves per sample were randomly collected from each treatment in eight blocks, from October 2005 to April 2006 and again from October 2006 to April 2007. The leaves were collected from the mid-third portion of extension shoots of current year's growth from each of the five trees. Mineral leaf concentration analysis was performed using a commercial analytical laboratory Bemlab® (Bemlab Pty. Ltd, Strand, South Africa). The leaf samples were first washed in 1% v/v HCl solution and then rinsed twice, first with tap water and then with deionised water, and then dried in a forced-air oven at 80°C overnight. Nitrogen was analyzed using a nitrogen analyzer (LECO FP528 Nitrogen analyzer, LECO Cooperation, St. Joseph, Michigan, USA). All other nutrients were analysed on inductively coupled plasma-optical emission spectrometer (Varian MPX-OEX, Varian, Inc. Co., Palo Alto, California, USA).

2.2.11 Meteorological data

Meteorological data were obtained from the municipal weather stations of Villiersdorp and Caledon (Appendix, Figs. 2 and 3). On the farm meteorological data were recorded by a custom-assembled automated weather station connected to a data logger (CR10X, Campbell Scientific, Inc., Logan, Utah, USA) located 50m from the orchard. Parameters which were averaged hourly and daily included visible solar radiation (photosynthetically active radiation), air temperature and relative humidity. Rainfall was totalled hourly and daily (Appendix, Figs. 4 and 5). Weather forecasts were taken into account during the summer months to adapt the irrigation strategies for heat wave conditions.

2.2.12 Diurnal gas exchange measurements

Diurnal gas exchange measurements were taken two-hourly between 06h00 and 18h00 under ambient sunlight and temperature conditions during 10/01/2008, using the LI-6400 infra-red gas analyzer (Li-Cor, Lincoln, Nebraska, USA). The daily solar radiation was tracked using a Li-190SA quantum sensor (Li-Cor, Lincoln, Nebraska, USA). Two leaves per plot were measured from six blocks.

2.3 Discussion on methodologies adapted for the experimental site

2.3.1 Soil conditions

Soil analysis showed that the prevailing soil should provide a good medium for apple tree performance and root development (Tables 1a and 1b). Although this soil (Dundee soil series) was highly sandy, a silt percentage of 9.6 and a clay percentage of 5.2 gave it good holding capacity for minerals and water. The cation-exchange capacity for K was between 3.2 and 4.1%, for Ca it was between 76.1 and 79.2% and for Mg it was between 11.3 and 13.5% (Table 1b), which is close to the 4:75:16 ratios recommended by Kotzé (2001). The soil was deep, well drained and well aerated.

2.3.2 Management of water use

Long-term (25 years) data from Villiersdorp and Caledon and using crop factors described by Kotzé *et al.* (1988), indicated a theoretical water usage per annum of 5428 and 5796m³/ha/yr respectively, for mature apple trees under micro irrigation (Tables 2a and 2b). These long-term data showed that about 82% of the annual requirement is needed from October to March of each year, with a peak of 20% needed in January. This is also reflected in the crop factors of Kotzé *et al.* (1988), which vary from 0.35 in October, 0.50 in January to 0.45 in March (Tables 2a and 2b). According to Volschenk *et al.* (2002) (unpublished progress report, ARC Infruitec–Nietvoorbij) the measured ET of a full-bearing ‘Golden Delicious’ orchard was about 5991m³. ha⁻¹ from October to May for the Villiersdorp area which is in agreement with the theoretical water needed. The actual amount of water given to the trees is summarised in Table 3. Three systems of water application were used as commercially practised. With micro irrigation the objective is to apply water to a continuous area (drip area) of the orchard at a high application rate. For daily drip irrigation water is applied more frequently (daily), wetting a specific soil volume at both sides of the tree in the rows. The water distribution creates a ‘pot’ at both sides of the tree, with the middle of the ‘pot’ being wetter and the perimeter drier. In pulsing drip irrigation water is applied up to six times per day to wet a specific volume at both sides of the tree. The objective behind this was to create a situation where roots are continuously surrounded by water and nutrients. From Table 3 it is clear that the theoretical water determination from the two nearby weather stations (average 5612m³/ha/yr) is in line with the actual water supplied by micro irrigation during 2005/6 (5661m³/ha/yr), when the trees were three years old. During 2006/7 the yield was low due to poor fruit set and water applied was less than expected. During 2007/8 rainfall was high during October, November and December. Macro and micro nutrients were applied in more

concentrated solutions during this time. For comparison purposes the same amount of water for these months (October, November and December) as during 2005/6 were adapted. The total adapted amount of water applied for 2007/8 was 5755.44m³/ha/yr.

During 2003/4 less water (2450m³/ha/yr) was required for the one-year-old trees (Table 3). This was 43.7% of the theoretical amount (5612m³/ha/yr), due to the fact that the trees were still small, as measured from their trunk cross sectional area (TCA) (Appendix, Tables 5a). During year one (2003/4) the soil water sensors were not yet installed and water was applied by monitoring the soil moisture content by making soil profiles. This method did not prove to be that accurate and might have led to over irrigation at times. From the third year onwards the monitoring system was in place and the actual water usage was regarded as accurate. During the three years that actual water applied was measured by means of water meters and scheduling of available water was managed accurately, the mean amount of water applied with both drip systems was $\pm 74\%$ of that of the micro system. This suggests that $\pm 26\%$ less water needs to be applied with the drip systems to manage the plant available soil water between 50% and 100%.

During late winter (August/September 2005, 2006 and 2007) the water table was at about 1000 mm. The water front detectors and soil profile studies showed over-irrigation during the monthly flushing when several hours of irrigation were given. During the spring of 2006 at flowering time the adjacent river over-flowed its banks for several days resulting in wet soil conditions. Cold and misty conditions also occurred. During 2007/8 the river over-flowed for two days in November, however this time the fruit had already set and this was not accompanied by cold and misty conditions. The Western Cape Province, particularly the Genadendal area where the study was conducted, experiences hot, dry summers and cold, wet winters. From the long-term rainfall data, there has been little variation from year to year since 1996 (Appendix, Fig. 3A). However, monthly rainfall (in this study) decreased more during the summer and autumn months while high rainfall was still recorded for the winter months (Appendix Fig. 4A), however more data is required to make concise conclusions. Overall, the Genadendal area, based on the averages between Villiersdorp and Caledon long-term weather data, received anomalously high rainfall in Oct-Nov 2007/8, (Appendix, Fig. 5A). However more or less similar rainfall patterns have been recorded compared to long-term mean averages and generally less water was applied through irrigation in the winter

months and early spring months (June to September) as a result of high rainfall during this time.

During the summer months the temperatures usually reach 29°C; the steady temperature increases were recorded in 1999 (22°C), and increased until 2006 (25°C) (Appendix, Fig 4B). There were consistent higher daily temperatures, with mean monthly average temperatures above 22°C during the second week of January to end of February during 2005/6, 2006/7 and during 2007/8 at the experimental site, compared to the long-term mean temperatures of $\pm 18^\circ\text{C}$ (Appendix, Fig. 4B). Higher temperatures were recorded in January, February, September and October compared to the long-term averages (Appendix, Fig. 5B). Monthly and daily mean temperatures from on-site weather station also showed some variations between years with 2007 being the warmer year compared to 2005 and 2006 (Appendix, Fig. 5B and 6B). For the past three seasons, there has been a steady increase in average temperatures over the long-term averages. Daily maximum soil temperature in temperate regions usually ranges from 2°C (during winter) to 22°C (during summer months) (Tromp, 1996), however, in this study monthly mean soil temperatures during hot summer months (January and February) reached 20°C (Appendix. Fig 7B). Low temperatures are known to increase number of lateral shoots along the main axis and affect the distance between graft union and the nodes (Tromp, 1996).

During high temperatures (heat waves) trees coped better with early application of water and regular frequency applications under daily drip and pulsing drip irrigation systems compared to micro sprinkler irrigation (Appendix, Figs. 8A, B and C). This was monitored during 2007/8, where stomata were shown to possibly remain open for relatively longer periods of time, maintaining higher rates of photosynthetic efficiency for the rest of the morning, however declining significantly later in the afternoon, irrespective of the frequency of water application (Appendix, Figs. 8A, B and C). Less difference were observed for stomatal conductance than for photosynthesis, possibly due to low stomatal adjustment and recycling as influenced by VPD and temperature.

Use of a pulsing drip irrigation system and a daily drip irrigation system, together with water determination, based on past ET rates and Kc factors play an important role water management at orchard level. The use of ETr and ETc to estimate water needs in apples is regarded to be more reliable in determining water requirements (Fallahi *et al.*, 2006). Earlier

studies by Goldberg *et al.* (1971) on vines (*Vitis vinifera*), Bar-Yosef and Sagiv (1982) on tomatoes (*Lycopersicon esculentum*), Wan & Kang (2006) on radish (*Raphanus sativus*) and Fallahi *et al.* (2006) on apples (*Malus domestica*) have shown that a better crop performance (in terms of both productivity and growth) can be obtained under drip irrigation systems than under micro sprinkler irrigation systems. The Kc factors used, as recommended by Kotzé *et al.* (2001) possibly overestimated the evaporation values in winter, thus there is a need to remodel winter Kc values if actual water use is to be taken into consideration. The April and May crop factors should double from the currently recommended 0.2 to 0.4. The winter months from June to September should be lower than the 0.2 recommended (± 0.07) and for October a little lower than 0.35 (± 0.3) (Table 2a).

For the past three seasons the soil moisture content was maintained within 40–60% volumetric moisture content (VMC) of available water at 0–800mm depth according to C-probe sensors. These data were used on a daily basis to monitor any stress level in the soil and adjust the irrigation accordingly (Figs. 1A, B and C). The soil moisture tension (force required by roots to extract a water molecule from the soil) was maintained between 10 to 35 kPa at 0–400mm and 40–60kPa at 400–800mm soil depth under micro irrigation (Figs. 2A and 3A), according to Watermark soil sensors. In the two drip-based irrigation systems, soil moisture tension was maintained at <20kPa at 0–200mm, <40kPa at 200–400mm and at ± 60 kPa at 400–800mm (Figs. 2B, 2C, 3B and 3C). The wetting profile pattern was well distributed from 200 mm soil depth, with a decrease towards 600 and 800mm soil depths under drip-based systems. Under the micro irrigation, the top 200mm to 400mm soil depth was wetter compared to the 600 to 800 mm soil depth. The soil moisture content was managed between 60–70% available water for 0–400mm and at 40–55% at lower soil depths, according to the Decagon ECH₂O sensor (Appendix, Fig 9A).

The maximum daily shrinkage (difference between maximum and minimum diameter) of the stem measured by the dendrometers showed low rates in February 2006, which increased until April 2006 (2–6%) and then remained constant until November 2006 (4–6%), followed by a drop in December 2006, and an increase again in January and February 2007 under daily drip irrigation (Appendix, Fig 9B). This clearly demonstrates that daily stem shrinkage is likely active after fruit harvest. Pulsing drip irrigation showed fluctuations in maximum daily shrinkages during this period (Appendix, Fig 9B). In micro sprinkler irrigation maximum shrinkage stayed lower than the other two irrigation systems and increased steadily from

October 2006 until February 2007 (Appendix, Fig 9B). Daily trunk shrinkage showed little changes in the months of November ($\pm 2.5\text{--}4\text{mm}$), December ($\pm 4.8\text{--}6.2\text{ mm}$) and January ($\pm 4.8\text{--}6.2\text{mm}$) for the years 2004, 2005, 2006 and 2007 (Appendix, Figs. 10–12). Smaller trunk diameter fluctuation (TDF) was observed in micro sprinkler irrigated trees (November 2005 and 2006, but not during November 2004) compared to daily drip and pulsing drip irrigation (Appendix, Figs. 10A, B and C). Generally maximum shrinkage was higher when yield was low (2004/5) (Appendix, Figs. 11A and C) and higher when yield was comparatively higher during 2005/6 (Appendix, Fig 11B). Maximum shrinkage indicates the relative loss of water reserve in tissue of the plant and it is dependent on environmental factors influencing the plant transpiration rate. The higher the soil water loss the greater the maximum daily shrinkage and the more the plant stress, which ultimately leads to poor growth and low fruit yield and poor fruit quality (Garnier & Berger, 1986). Similar TDF measurements have been mentioned by Taerum (1964), in ‘Rome Beauty’ apples, and this method has been shown to be a useful way to measure integrated above-ground water potential since it can be monitored continuously. TDF measurements are dependent on the environmental factors such as soil moisture status, rate of evaporation, etc. and also the trunk at times, which makes them easy to detect any stressful water potential. Neutron probes showed that for the sandy loam soil at Genadendal the field capacity is $\pm 108\text{mm}$ and wilting point is $\pm 44\text{mm}$. However the systems were scheduled to run between 60–70% of plant available water and irrigated once the soil moisture fell below 50% of the available water (Appendix, Figs. 13 A–C).

Soil water measurements have been found to be important tools that can aid in irrigation scheduling (Sellés & Berger, 1990, Ortuño *et al.*, 2006), more precisely, when used in conjunction with long-term weather data. Daily variation of trunk diameter (maximum daily growth and maximum daily shrinkage) has been found to be the most responsive feature to water stress in peaches (*Prunus persica*) (Sellés & Berger, 1990; Cohen *et al.*, 2001), in apples (*Malus domestica*) (Naor & Cohen, 2003), in plums (*Prunus domestica* L.) (Intrigliolo & Castel, 2005), and in oranges (*Citrus aurantium*) (Ortuño *et al.*, 2006). Use of Watermark sensors and C-probes is a reliable and efficient way to determine soil moisture accurately and can assist in precise irrigation scheduling, if calibrated with a neutron probe (Heng *et al.*, 2002; Thompson *et al.*, 2006). Studies by Thompson *et al.* (2006) in peppers and melons found that Watermark provided an accurate indication of soil metric potential and showed wide adaptability to different growing conditions.

The role of played by water and nutrient strategies at the orchard level is very important. For any sound water and nutrient management practice, there is a need to first determine as basis, the theoretical water use. This can depend on past experiences, tree canopy/volume and leaf area development, and can be scheduled by using soil water sensors and tree performance based on tree growth, fruit growth curves and fruit: leaf ratios. In this study the trees were planted out in June 2003 and water and nutrients were given by a conventional drip irrigation system once a day, and nutrients were based on Omnia nutrient solution for non-bearing young tree (to stimulate growth) during the 2003/4 season. All the sensors were put in place in January 2004, but became operational in October 2004. Soil profile studies were used to determine irrigation application during June 2003 to September 2004.

2.3.3 Trunk and leaf area

Figures 4a and b both give an indication of the development of the trees over time until reaching the optimal size and filling the allocated space in the orchard. According to Wang *et al.* (2007) crop factors of deciduous trees increase with increasing foliage coverage. The crop factors adapted according to leaf area increase can be used to predict the water requirement for young and full bearing apple trees. For example, at full bearing the trees for Villiersdorp/Caledon area need 5612m³/ha/yr thus their predicted water use will be 1122, 2806, 4209 and 5050m³/ha/yr for the first, second, third and fourth years, respectively using micro sprinkler irrigation. The cross-sectional area increased from 1.2 cm² to 47.4 cm² (Appendix, Table 5a and Fig 4b) during first, second, third and fourth years, respectively. However the leaf area and trunk circumference (representing tree volume) give similar trends to predict the way that trees might fill their allocated space from planting to the point of optimum leaf area or tree volume. TCA was significantly higher with M793 rootstock than with M7 (Appendix, Table 5C). These trends can be used to predict the amount of water needed by trees during their development until maturity. For practical reasons the use of leaf area to determine amount of water needed for irrigation is proposed as also discussed by Fallahi *et al.* (2006). Stem circumference has been correlated to dry mass in mango (*Mangifera indica*) (Van der Walt *et al.*, 1996) and with tree volume in apples (*Malus domestica*) (Behboudian & Mills, 1997).

2.3.4 Nutrient management

The important function fulfilled by macro and micro elements is well documented (Clarkson & Hanson, 1980; Mengel & Kirby, 1982; Tisdale *et al.*, 1985; Nielsen & Nielsen, 2003). Accurate water and nutrient management are essential in highly intensive orchard systems to enable the manipulation of both reproductive and vegetative development to ensure the possibility of higher quality fruit with longer storage potential and to reduce pollution and costs (Tagliavine & Marangon, 2000). Various studies have been conducted to determine this requirement (Batjer *et al.*, 1952 for apples; Conradie, 1980; 1981 for vines; Haynes and Goh, 1980 for apples; Stassen, 1987 for peaches; Stassen *et al.*, 1997a; 1997b for mangoes; 1997c for avocados; Stassen and North, 2005 for pears; Krige, 2007 for nectarines and Kanguuehi, 2008 for apples). From these studies it is clear that a balanced nutrient requirement for apples and other fruit trees can be calculated and administered.

Nutrients were given to the trees based on the tree phenological stages and plant needs, and determined based on estimated yield (Tables 4a and 4c, and Appendix, Table 2). Monthly leaf mineral nutrient concentrations (Appendix, Tables 3 and 4) did not show any nutrient deficiency or toxicity and nutrients were within published guidelines (Faust, 1989; Kotzé, 2001). The following are the macro and micro leaf nutrient norms for South African apple orchards (31 January, reference date) according to 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 (500 mg/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). The above figures were found to be consistent with the leaf nutrient analysis data recorded in the present study (Appendix, Tables 3 and 4).

2.4 Conclusions

This study clearly indicated that the water requirements of a mature apple orchard can be predicted with a great deal of accuracy when compared to actual water applied. Long-term evaporation (mm) from nearby weather stations and locally determined apple crop factors (Kc) can be used to achieve this on an annual and monthly basis. The average water requirement for mature apple trees in this area is 5612m³/yr/ha, while the actual water given using micro sprinkler irrigation over the last three seasons was 5661m³/yr/ha, 4964m³/yr/ha and 5755m³/yr/ha. Results showed that available crop factors need some downward adjustments for winter months (June, July and August and even September) when winter rains occur in this area. The months of April and May need some upward adjustment to the crop

factors because of moderate conditions that induce thickening growth of roots and shoots and well developed bud differentiation and longer leaf functioning) in the area.

Predicted water requirements provide a useful tool for planning. This prediction includes temperature and transpiration rates over a period of many years, but it is an average and within and between seasons it can change and therefore it must be adapted for what is actually happening in the orchard. To ensure optimal irrigation scheduling, it is necessary to maintain plant available soil water between field capacity and 50% available water for optimal plant performance. This can be achieved with several soil water sensors calibrated against the Neutron probe as it is more reliable compared to other types of sensors. The choice between these sensors will depend on affordability and management system, on the farm, as Neutron probes need licensing for operation, whilst C-probes are more expensive than the Watermark sensors.

This study clearly showed that drip irrigation is more water efficient ($\pm 26\%$) than micro sprinklers in delivering the same amount of water to the root zone. This can be because of inefficient placement and drifting of water applied with the micro sprinklers. An increase in leaf area provides a good indication of canopy development in this higher density orchard. This can be used to predict the water requirements for different ages of apple orchards. Nutrient requirements were based on many studies that included the analysis of tree parts including use of leaf analysis to determine the minimum amounts of each macro and micro element that were lost or fixed and had to be replenished. The nutrient solution used in this study was adequate according to leaf analysis and observations made from general tree performance. Furthermore there was no difference in mineral nutrient content between the two rootstocks used in this study.

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Table 2a: Monthly evapotranspiration and theoretical water usage based on long-term evaporation data (1978–2003) and crop factors (Kc) for apples. (Kc apples according to Kotzé, (1988)).

Data from Villiersdorp

Month	Evaporation (mm)	Crop factors (apples) Kc	Evapotranspiration (ET _o) (mm)	Theoretical water use/month (m ³ /ha)
October	132.40	0.35	46.34	463.40
November	155.90	0.40	62.36	623.60
December	179.90	0.45	90.96	909.60
January	199.70	0.50	99.85	998.50
February	162.20	0.50	81.10	811.00
March	143.20	0.45	64.44	644.40
April	91.30	0.20	18.26	182.60
May	63.90	0.20	12.78	127.80
June	58.80	0.20	11.76	117.60
July	65.60	0.20	13.12	131.20
August	78.90	0.20	15.78	157.80
September	96.60	0.27	26.08	260.80
Total			542.83 mm.ha ⁻¹ .yr ⁻¹	5428 m ³ ha ⁻¹ .yr ⁻¹

Table 2b: Monthly evapotranspiration and theoretical water usage based on long-term evaporation data (1978–2003) and crop factors (Kc) for apples. (Kc apples according to Kotzé, (1988)).

Data from Caledon

Month	Evaporation (mm)	Crop factors (apples) Kc	Evapotranspiration (ET _o) (mm)	Theoretical water use/month (m ³ /ha)
October	161.10	0.35	56.39	563.90
November	151.00	0.40	60.4	604.00
December	133.50	0.45	60.08	600.80
January	248.90	0.50	124.45	1244.50
February	180.00	0.50	90.00	900.00
March	174.50	0.45	78.53	785.30
April	106.90	0.20	21.38	213.80
May	100.20	0.20	20.04	200.40
June	67.40	0.20	13.48	134.80
July	58.00	0.20	11.6	116.00
August	77.20	0.20	15.44	154.40
September	103.10	0.27	27.84	278.40
Total			579.63 mm ha ⁻¹ .yr ⁻¹	5796 m ³ ha ⁻¹ .yr ⁻¹

Table 3: Theoretical monthly water usage of an apple orchard at Genadendal compared to actual water applied with three irrigation systems over four seasons. During 2003 only daily drip system was used.

Month	Theoretical water use (m ³ /ha) Villiersdorp and Caledon (average)	Actual water applied (m ³ /ha)				
		2003/4	2004/5	2005/6	2006/7	2007/8
Micro sprinkler irrigation						
October	513.7	113.00	244.84	669.25	366.58	669.25
November	613.8	233.00	331.01	632.75	571.50	632.75
December	755.2	303.30	505.18	690.55	550.78	690.55
January	1121.5	512.90	938.83	937.68	938.42	1007.69
February	855.5	491.58	974.30	784.00	812.00	1200.90
March	714.9	308.95	844.05	716.88	714.85	700.34
April	198.2	93.80	720.00	555.00	336.00	300.34
May	164.1	65.65	521.23	489.03	389.23	368.00
June	126.2	64.91	43.00	45.75	44.62	44.62
July	123.6	67.40	44.10	47.28	47.00	47.00*
August	156.1	81.06	44.10	47.28	47.00	47.00*
September	269.6	114.13	43.00	45.75	47.00	47.00*
Total	5612 m ³ ha ⁻¹ .yr ⁻¹	2450 m ³ ha ⁻¹ .yr ⁻¹	5254 m ³ ha ⁻¹ .yr ⁻¹	5661 m ³ ha ⁻¹ .yr ⁻¹	4964 m ³ ha ⁻¹ .yr ⁻¹	5756 m ³ ha ⁻¹ .yr ⁻¹
Daily drip irrigation						
October	513.7	113.00	183.63	268.11	292.02	268.11
November	613.8	233.00	248.26	362.47	455.40	362.47
December	755.2	303.30	378.89	553.19	631.24	553.19
January	1121.5	512.90	748.88	743.38	744.42	954.63
February	855.5	491.58	717.74	638.88	609.00	705.59
March	714.9	308.95	451.08	574.12	589.35	600.23
April	198.2	93.80	136.95	346.40	252.32	258.59
May	164.1	65.65	95.85	290.60	366.56	259.89
June	126.2	64.91	88.20	36.60	35.85	35.85
July	123.6	67.40	98.40	37.82	37.00	37.00*
August	156.1	81.06	114.60	37.82	37.00	37.00*
September	269.6	114.13	166.64	36.60	37.00	37.00*
Total	5612 m ³ ha ⁻¹ .yr ⁻¹	2450 m ³ ha ⁻¹ .yr ⁻¹	3429 m ³ ha ⁻¹ .yr ⁻¹	3926 m ³ ha ⁻¹ .yr ⁻¹	4087 m ³ ha ⁻¹ .yr ⁻¹	4110 m ³ ha ⁻¹ .yr ⁻¹
Pulsing drip irrigation						
October	513.7	113.00	183.63	268.11	296.36	268.11
November	613.8	233.00	248.26	362.47	455.40	362.47
December	755.2	303.30	378.89	553.19	525.58	553.19
January	1121.5	512.90	748.88	752.68	744.42	895.63
February	855.5	491.58	717.74	546.24	609.00	785.23
March	714.9	308.95	451.08	564.82	589.35	520.36
April	198.2	93.80	136.95	455.40	252.32	258.69
May	164.1	65.65	95.85	395.56	366.56	369.26
June	126.2	64.91	88.20	36.60	35.80	35.85
July	123.6	67.40	98.40	37.82	37.00	37.00*
August	156.1	81.06	114.60	37.82	37.00	37.00*
September	269.6	114.13	166.64	36.60	37.00	37.00*
Total	5612 m ³ ha ⁻¹ .yr ⁻¹	2450 m ³ ha ⁻¹ .yr ⁻¹	3429 m ³ ha ⁻¹ .yr ⁻¹	4047 m ³ ha ⁻¹ .yr ⁻¹	3985 m ³ ha ⁻¹ .yr ⁻¹	4159 m ³ ha ⁻¹ .yr ⁻¹

N/A-The Western Cape experienced heavy rainfall during October, November and December 2007. Only enough water was applied to get the required nutrients in the soil in a more concentrated solution (in daily drip systems). To compare data with the previous years, the same amount of water was used for October, November and December 2005. * (estimations from previous years).

Table 4a: Predetermined macro and micro nutrient requirements of apples based on one ton fruit yield (adapted from Stassen and North, 2005).

Macro nutrients (kg element/ton fruit)					
N	P	K	Ca	Mg	S
2.3	0.5	1.8	1.8	0.5	1.0
Micro nutrients (g element/ton fruit)					
Mn	Fe	Cu	Zn	B	Mo
20	130	7.0	20	10	0.3

Table 4b: Minimum amount of macro and micro elements that must be replaced for full bearing nectarines (Krige, 2007) and apples (Kangueehi, 2008).

Fruit	Macro nutrients (kg element/ton fruit)					
	N	P	K	Ca	Mg	S
Nectarines	3.8	0.4	4.4	1.5	0.5	-
Apples	1.7	0.3	2.3	0.5	0.2	0.2
	Micro nutrients (g element/ton fruit)					
	Mn	Fe	Cu	Zn	B	Mo
Nectarines	10	40	3	14	10	-
Apples	1	30	1	3	6	0.3

Table 4c: Seasonal macro and micro nutrient requirement. Nutrients were distributed percentage-wise for 2004/5, 2005/6, 2006/7 and 2007/8. Nutrients were based on previous calculations on 'Royal Gala' on a commercial farm at Villiersdorp (P.J.C. Stassen 2003, personal communication).

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

*Phenological stages in apples: Stage 1, dormancy; Stage 2, bud burst; Stage 3, rapid growth and cell division; Stage 4, flower induction, completion of flower differentiation, cell enlargement, fruit development and harvest; Stage 5, postharvest period.

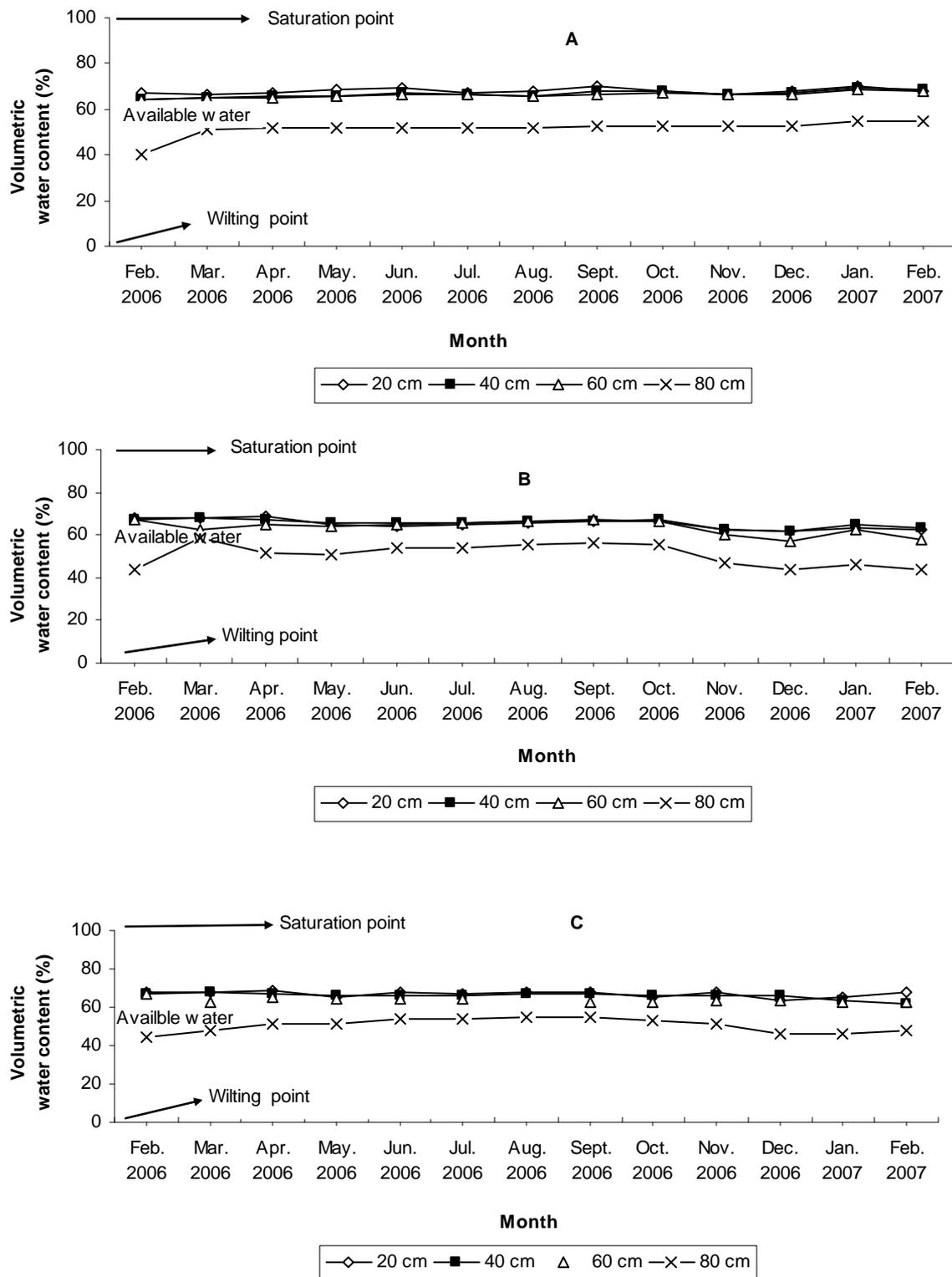


Fig. 1: Mean monthly volumetric soil moisture content recorded using C-probes at 20 cm, 40 cm, 60 cm and 80 cm soil depths. A (micro sprinkler irrigation system), B (daily drip irrigation system) and C (pulsing drip irrigation system).

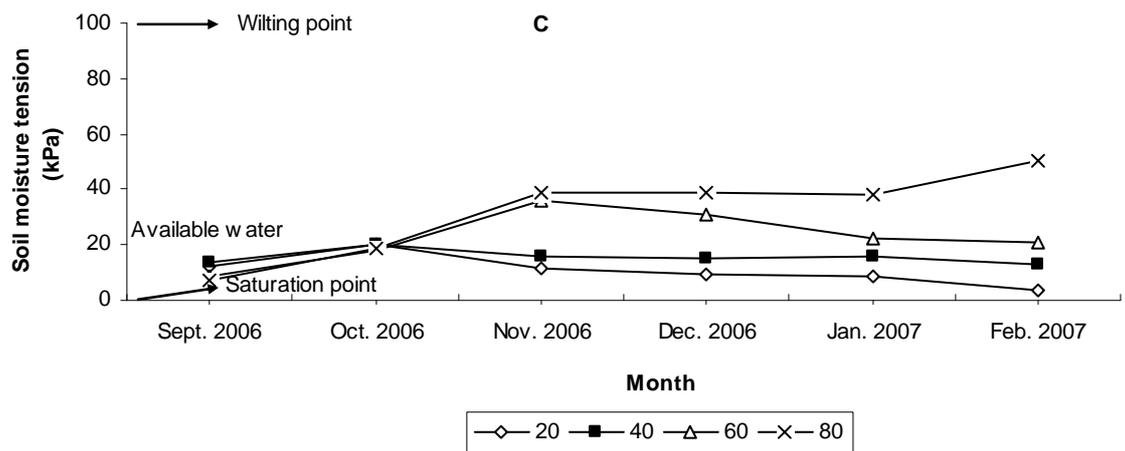
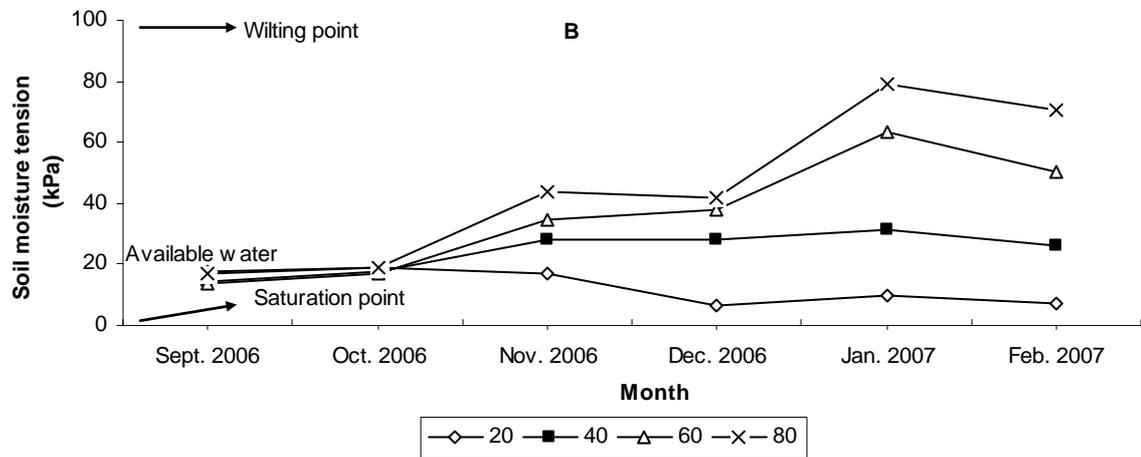
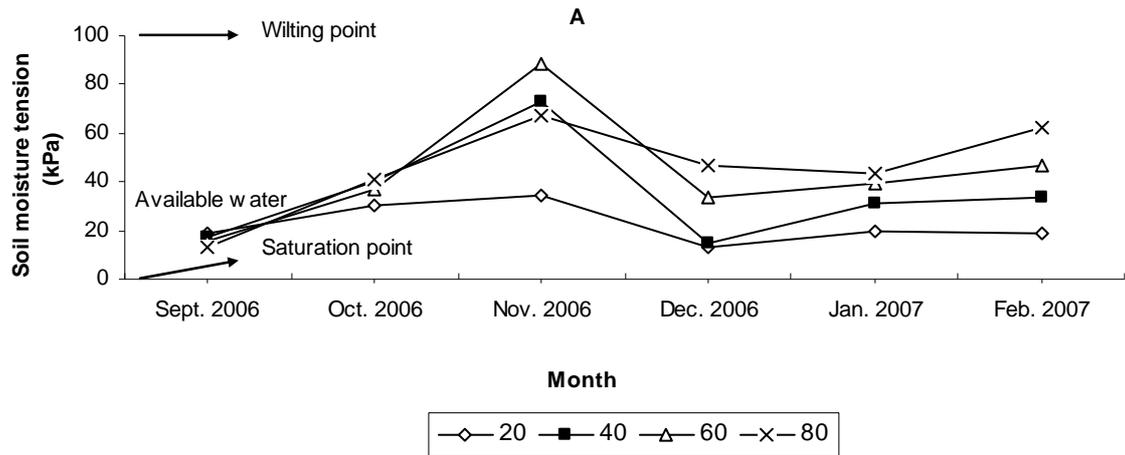


Fig. 2: Mean monthly soil moisture tension in kPa (where 0 is saturated and 100 is dry) recorded using a Watermark sensor at 20, 40, 60 and 80 cm soil depths. A (micro sprinkler irrigation system), B (daily drip irrigation system) and C (pulsing drip irrigation system).

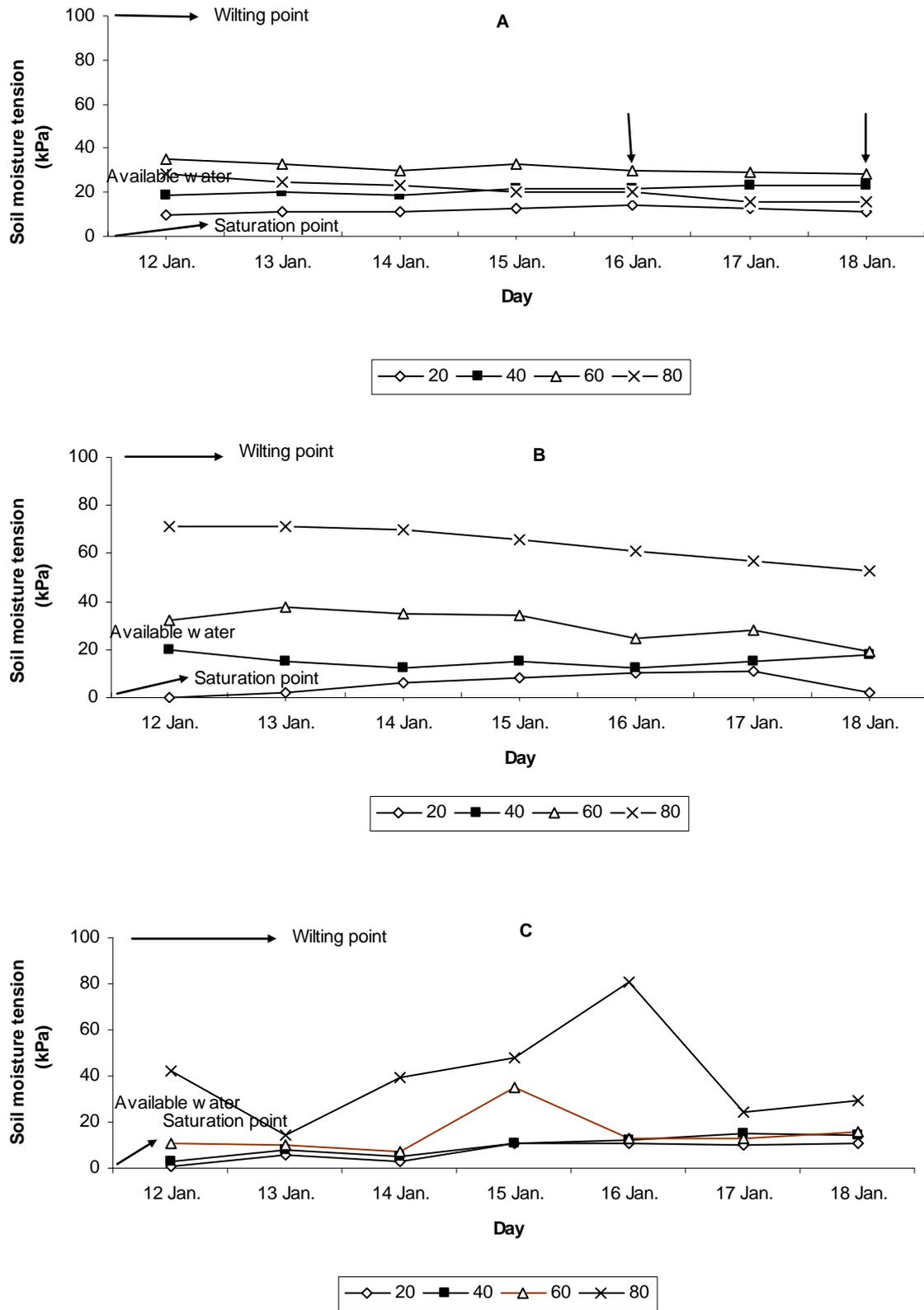


Fig. 3: Mean daily soil moisture tension in kPa (where 0 is saturated and 100 is dry) during January 2007 recorded using a Watermark sensor at 20, 40, 60 and 80 cm soil depths. A (micro sprinkler irrigation system), B (daily drip irrigation system) and C (pulsing drip irrigation system). Arrows indicate dates of irrigation under micro irrigation. No rainfall recorded at the experimental site during 12–18 January 2007).

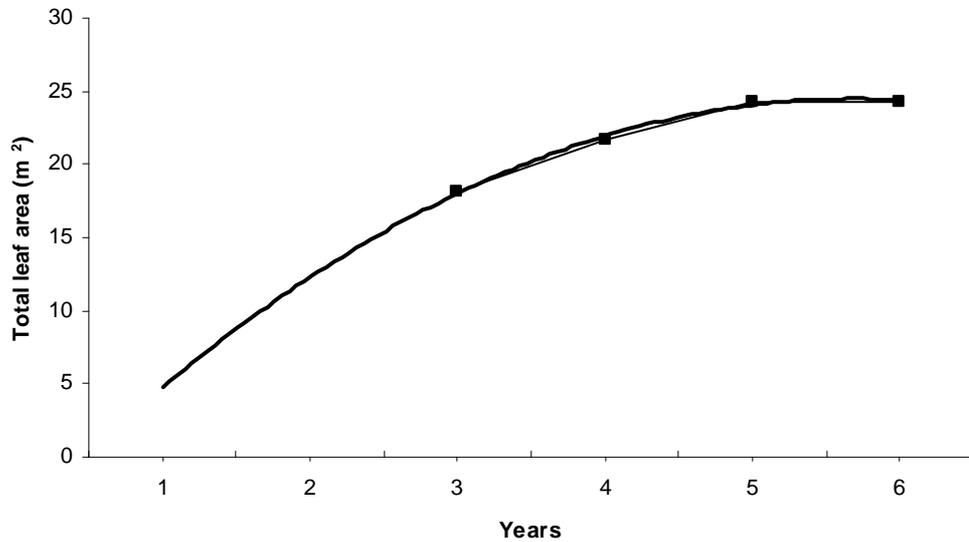


Fig. 4a: Leaf area from one year after planting (2003/4) to the sixth harvest season (2007/8) for 'Brookfield Gala' apple trees at the experimental site. The leaf area was included for all the three systems and two rootstocks. Year six was included as 100% since by then the trees had filled their allocated spaces.

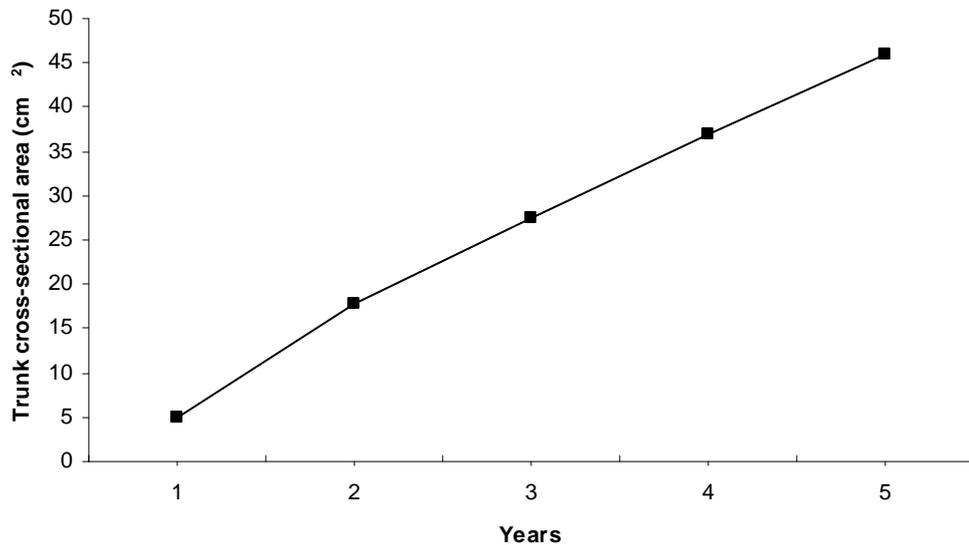


Fig. 4b. Trunk cross-sectional area development of 'Brookfield Gala' apples at the experimental site over five years (from 2003/4 to 2007/8). The TCA was included for all the three systems and the two rootstocks.

Appendix: Additional data

Appendix, Table 1: Monthly mean long-term and 2004, 2005 and 2006 evaporation (mm) from Villiersdorp and Caledon municipal weather stations.

Month	Evaporation (mm)			
	Villiersdorp weather station			
	1978-2003	2004	2005	2006
January	199.70	216.10	239.50	219.50
February	162.20	166.60	239.00	190.00
March	143.20	128.30	200.50	174.50
April	91.30	113.00	195.60	86.30
May	63.90	45.80	106.90	97.00
June	58.80	52.40	100.20	69.80
July	65.60	74.10	67.40	72.00
August	78.90	74.30	58.00	69.80
September	96.60	104.70	77.20	95.00
October	132.40	131.50	103.10	125.10
November	155.90	146.20	151.10	186.50
December	179.90	186.90	161.00	171.50
Total	1428.40	1439.90	1699.50	1557.00
	Caledon weather station			
January	248.90	196.3	202.30	218.50
February	180.00	159.00	283.50	180.70
March	174.50	138.40	116.00	144.70
April	106.90	89.50	112.50	94.40
May	100.20	62.90	70.20	70.00
June	67.40	58.70	59.00	53.00
July	58.00	69.10	63.00	75.50
August	77.20	79.90	82.90	59.50
September	103.10	101.00	85.20	87.80
October	161.10	132.60	158.60	106.50
November	151.00	226.20	202.80	91.40
December	133.50	179.20	218.50	161.90
Total	1561.80	1492.80	1654.50	1343.90
Total average	1495.10	1466.35	1677.00	1450.45

Appendix, Table 2: Annual nutrient requirements based on estimated yield for four seasons (2004/5, 2005/6, 2006/7 and 2007/8) in 'Brookfield Gala' trees.

Estimated fruit yield (ton/ha)	Nutrient concentrations (kg.ha ⁻¹ .yr ⁻¹)											
	N	P	K	Ca	Mg	S	Mn	Fe	Cu	Zn	B	Mo
1 st leaf	Young tree nutrient solution high in nitrogen, as provided by Omnia®											
10 + 30% (2 nd leaf)	29.9	6.5	23.4	23.4	6.5	13.0	0.26	1.69	0.09	0.26	0.13	0.01
25 (3 rd leaf)	57.5	12.5	45.0	45.0	12.5	25.0	0.50	3.25	0.18	0.50	0.03	0.03
15 (4 th leaf)	34.5	7.5	27.0	16.2	7.5	15.0	0.30	1.95	0.11	0.30	0.00	0.02
60 (5 th leaf)	138.0	30.0	108.0	64.8	30.0	60.0	1.2	7.8	0.44	1.2	0.6	0.08

Appendix, Table 3: Seasonal leaf nutrient analysis (2005/6) for different irrigation systems. Results expressed as g.kg⁻¹ DW for N, P, K, Ca, and Mg, and as mg.g⁻¹ DW for the micro nutrients.

Month	Irrigation system	Macro nutrients (g.kg ⁻¹)					Micro nutrients (mg.kg ⁻¹)					
		N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
Oct	Micro	2.98	0.37	1.94	0.61	0.25	257.50	39.00	194	9.50	16.50	65.00
	Drip	3.15	0.37	2.64	0.71	0.29	165.00	51.50	204	10.00	17.00	50.00
	Puls	3.16	0.38	1.87	0.62	0.27	155.00	49.00	187	9.50	16.00	52.00
Nov	Micro	2.79	0.26	1.88	1.13	0.32	99.50	172.00	188	9.50	53.50	41.00
	Drip	2.76	0.24	1.85	1.10	0.34	85.50	158.50	184	9.00	45.00	35.50
	Puls	2.88	0.24	1.78	0.99	0.34	68.50	179.00	178	10.50	47.00	37.00
Dec	Micro	2.76	0.22	1.50	1.34	0.30	185.50	164.50	150	6.50	71.00	36.50
	Drip	2.70	0.17	1.32	1.31	0.34	220.00	185.00	132	6.50	75.00	32.00
	Puls	2.76	0.18	1.33	1.24	0.34	171.50	179.00	133	5.50	73.00	31.50
Jan	Micro	2.76	0.25	1.47	1.86	0.34	199.50	164.00	147	5.50	70.00	35.00
	Drip	2.66	0.19	1.83	1.85	0.39	230.00	196.00	119	6.50	73.00	31.50
	Puls	2.60	0.19	1.27	1.77	0.40	232.50	179.00	127	5.50	68.50	32.50
Feb	Micro	2.33	0.29	1.51	1.77	0.31	189.00	128.50	151	6.00	67.00	34.00
	Drip	2.55	0.24	1.32	1.94	0.42	218.00	142.00	132	6.50	50.00	35.00
	Puls	2.35	0.21	1.39	1.85	0.40	249.50	149.50	139	7.00	72.00	36.00
March	Micro	2.12	0.21	1.75	1.94	0.35	254.00	119.00	175	5.50	55.50	30.50
	Drip	2.08	0.22	1.47	2.16	0.41	324.00	140.00	147	6.50	54.00	29.50
	Puls	2.15	0.20	1.48	2.09	0.42	291.00	140.50	148	6.00	60.50	30.50
April	Micro	1.69	0.19	1.46	2.00	0.27	297.00	161.00	146	5.00	63.00	30.50
	Drip	2.35	0.21	1.33	1.78	0.33	244.50	136.50	133	10.50	41.00	31.00
	Puls	2.34	0.25	1.17	1.77	0.38	259.00	155.00	117	8.00	43.50	30.50

Footnotes: Kotzé (2001) norms: 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 (500 mg/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). Leaf analysis done by a commercial laboratory (Bemlab®, Strand, South Africa). Each leaf sample consisted of 60 leaves and n=8. The leaf samples were first washed in 1% v/v HCl solution and then rinsed twice, first with tap water and later with deionized water, and then dried in a forced-air oven at 80 °C overnight. Nitrogen was analysed using a nitrogen analyzer (LECO FP528 Nitrogen analyzer, LECO Cooperation, St. Joseph, Michigan, USA). All other nutrients were analysed using an inductively coupled plasma-optical emission spectrometer (Varian MPX-OEX, Varian, Inc. Co., Palo Alto, California, USA).

Appendix, Table 4: Seasonal leaf nutrient analysis (2006/7 season) for different irrigation systems. Results expressed as g.kg⁻¹ DW for N, P, K, Ca, and Mg, and as mg.g⁻¹ DW for the micro nutrients.

Month	Irrigation system	Macro nutrients (g.kg ⁻¹)					Micro nutrients (mg.kg ⁻¹)					
		N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
Oct	Micro	2.87	0.23	1.30	0.66	0.28	116.50	143.50	90.50	6.50	32.00	31.00
	Drip	3.18	0.22	1.03	0.67	0.30	111.00	189.00	95.50	6.50	35.50	26.50
	Puls	3.13	0.23	1.35	0.68	0.26	134.50	163.00	141.50	7.00	32.00	29.00
Nov	Micro	2.61	0.26	1.51	1.04	0.39	129.50	175.50	131.00	7.00	48.00	31.50
	Drip	2.91	0.26	1.71	1.14	0.39	126.50	196.50	147.00	5.50	41.50	30.50
	Puls	2.73	0.23	1.69	0.99	0.34	122.00	206.00	122.00	5.00	46.00	31.50
Dec	Micro	2.45	0.21	1.57	1.19	0.29	153.50	191.50	149.50	6.00	73.00	28.00
	Drip	2.79	0.19	1.51	0.93	0.31	128.00	156.00	121.50	7.50	53.00	30.00
	Puls	2.74	0.18	1.34	0.82	0.33	97.50	171.50	121.50	6.50	59.00	32.00
Jan	Micro	2.24	0.24	1.85	1.20	0.32	169.00	222.00	347.00	5.50	63.00	37.00
	Drip	2.44	0.19	1.77	1.09	0.32	184.00	191.50	165.00	8.00	51.00	45.00
	Puls	2.52	0.21	1.87	1.02	0.35	136.50	191.50	232.50	6.00	54.00	31.00
Feb	Micro	2.35	0.28	1.51	1.88	0.30	191.00	135.00	125.00	5.00	66.00	36.00
	Drip	2.13	0.22	1.34	1.19	0.39	228.00	139.00	133.00	7.00	45.00	32.00
	Puls	2.05	0.20	1.85	1.78	0.44	239.50	151.00	141.00	8.00	68.00	33.00
March	Micro	2.22	0.22	1.75	1.92	0.40	223.00	125.00	185.00	6.00	56.00	29.00
	Drip	2.18	0.21	1.58	2.10	0.41	289.00	148.00	159.00	5.00	55.00	31.00
	Puls	2.22	0.22	1.65	2.05	0.38	205.00	138.00	151.00	4.00	66.00	26.00
April	Micro	2.00	0.17	1.44	2.05	0.29	259.00	144.00	142.00	5.00	56.00	30.00
	Drip	2.08	0.20	1.40	1.54	0.30	245.50	139.00	136.00	9.00	42.00	28.00
	Puls	2.33	0.26	1.10	1.59	0.36	274.00	133.00	118.00	8.00	48.00	29.00

Footnotes: Kotzé (2001) norms: 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 (500 mg/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). Leaf analysis done by a commercial laboratory (Bemlab®, Strand, South Africa). Each leaf sample consisted of 60 leaves and n=8. The leaf samples were first washed in 1% v/v HCl solution and then rinsed twice, first with tap water and later with deionized water, and then dried in a forced-air oven at 80 °C overnight. Nitrogen was analysed using a nitrogen analyzer (LECO FP528 Nitrogen analyzer, LECO Cooperation, St. Joseph, Michigan, USA). All other nutrients were analysed on inductively coupled plasma-optical emission spectrometer (Varian MPX-OEX, Varian, Inc. Co., Palo Alto, California, USA).

Appendix, Table 5a: Influence of different irrigation and nutrient strategies (micro sprinkler irrigation, daily drip and pulsing drip irrigation) on either semi-vigorous M793 or dwarfing M7 rootstock on 'Brookfield Gala' trunk cross-sectional area during 2004/5 to 2006/7. Data pooled across main effects and presented as system effect.

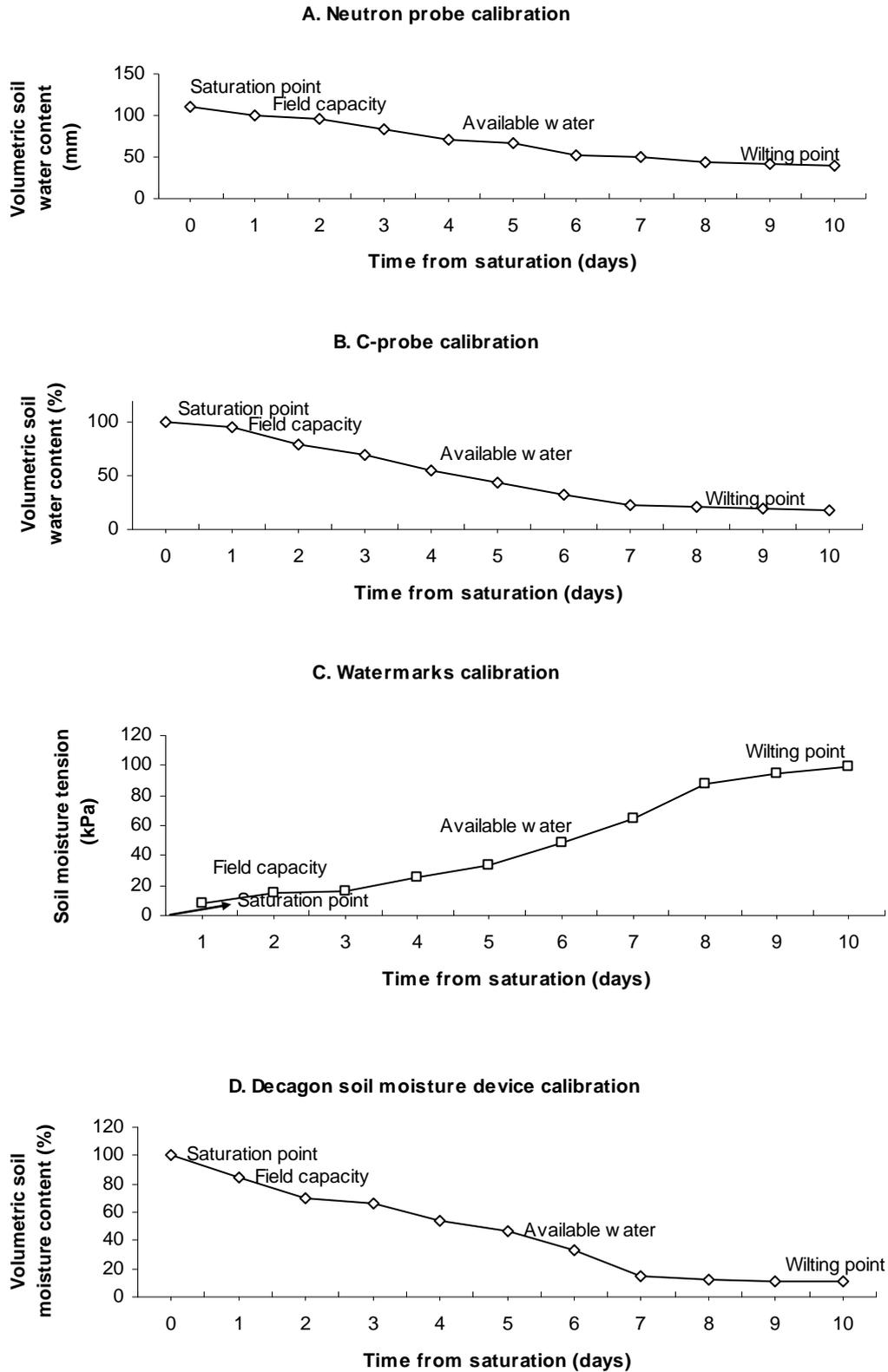
Treatment	Trunk cross-sectional area (cm ²)					
	Winter 2003 (nursery trees)	Winter 2004	Winter 2005	Winter 2006	Winter 2007	Winter 2008
Micro	1.2	5.024*	17.28 a	29.74 a	38.63 a	47.4 a
Drip	-	-	18.20 a	25.97 b	35.42 b	44.8 b
Puls	-	-	17.92 a	26.72 b	36.85 b	45.5 b
SE±	-	-	0.805	1.244	1.635	0.915
P-value						
System	-	-	0.1133	0.0510	0.0422	0.00356
Rootstock	-	-	0.0222	0.0002	0.0465	0.5896
System×rootstock	-	-	0.4680	0.8627	0.9688	0.8567

Appendix, Table 5b: Average total leaf area, total leaf weight and mean leaf number for nine trees (three under micro sprinkler, three under daily drip and three under pulsing drip irrigation) and two rootstocks during 2005/6, 2006/7 and 2007/8.

System	Total leaf area (m ²)			Total leaf weight (g)			Total leaf number		
	2005/6	2006/7	2007/8	2005/6	2006/7	2007/8	2005/6	2006/7	2007/8
Micro	19.90	24.12	28.12	2637	2885	3036	4054	4256	4447
Drip	15.84	17.76	20.56	2179	2501	2615	2753	3299	3656
Puls	18.57	23.14	24.25	2235	2889	2945	2570	4230	4361
±SE	3.19	1.98	2.56	430.30	160.92	140.25	431.50	397.19	258.25
P-value									
System	0.4761	0.2065	0.0856	0.1925	0.6991	0.5689	0.0895	0.3277	0.8956
Rootstock	0.2396	0.4163	0.4569	0.1265	0.0594	0.2568	0.1321	0.6986	0.2659
System×rootstock	0.5815	0.3736	0.4648	0.7190	0.7664	0.7858	0.4590	0.4393	0.4589

Appendix, Table 5c: Influence of the rootstock (M793 or M7) on trunk cross-sectional area on 'Brookfield Gala' tree trunks cross-sectional area during 2004/5 to 2006/7. Probability values are according to split-plot ANOVA, followed by Tukey's multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=8$.

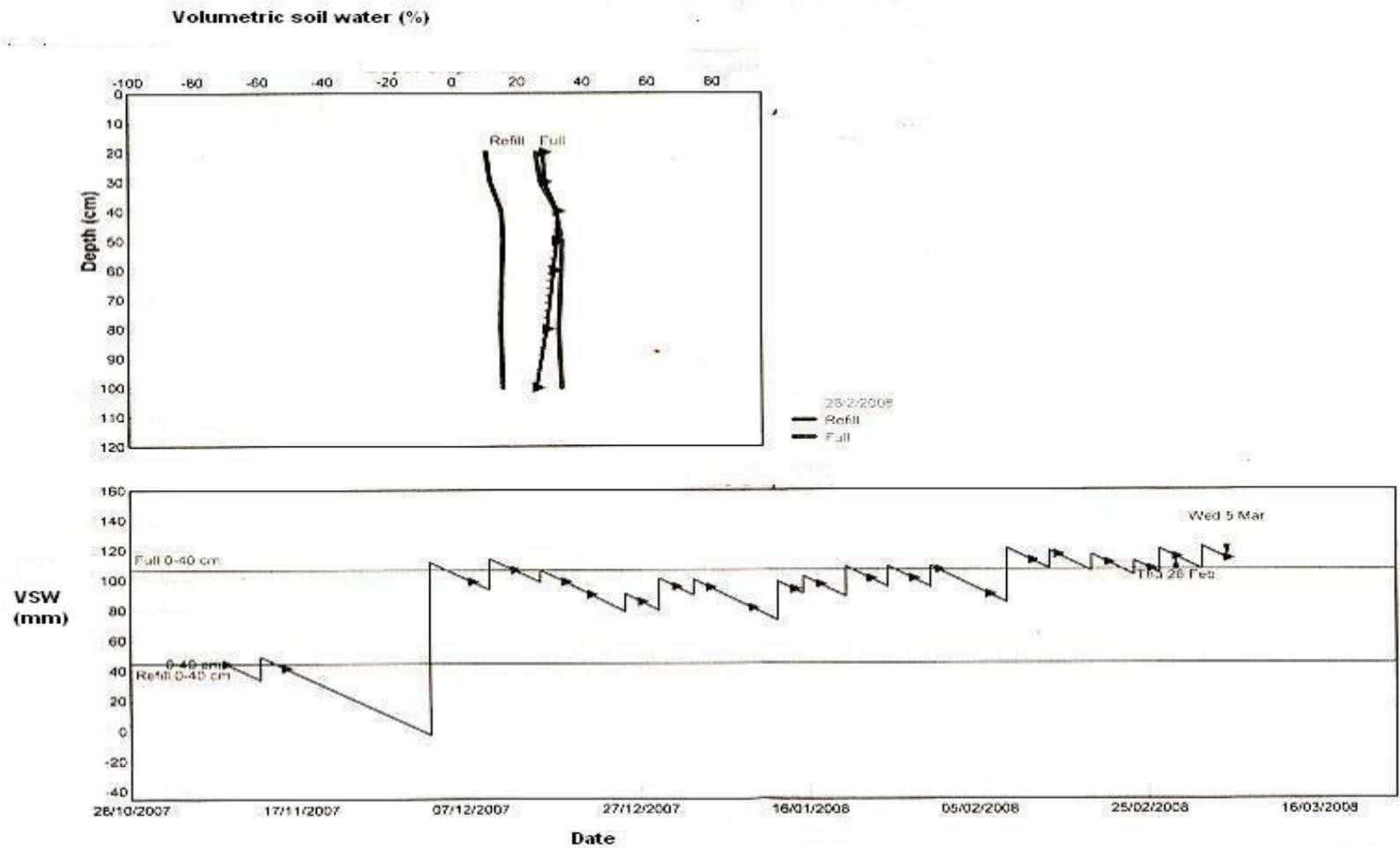
Treatment	Trunk cross-sectional area (cm ²)		
	Winter 2005	Winter 2006	Winter 2007
M793	18.99 a	30.99 a	39.36 a
M7	16.62 b	23.96 b	33.68 b
SE±	0.66	1.01	1.06
P-value			
Rootstock	0.0222	0.0002	0.0465



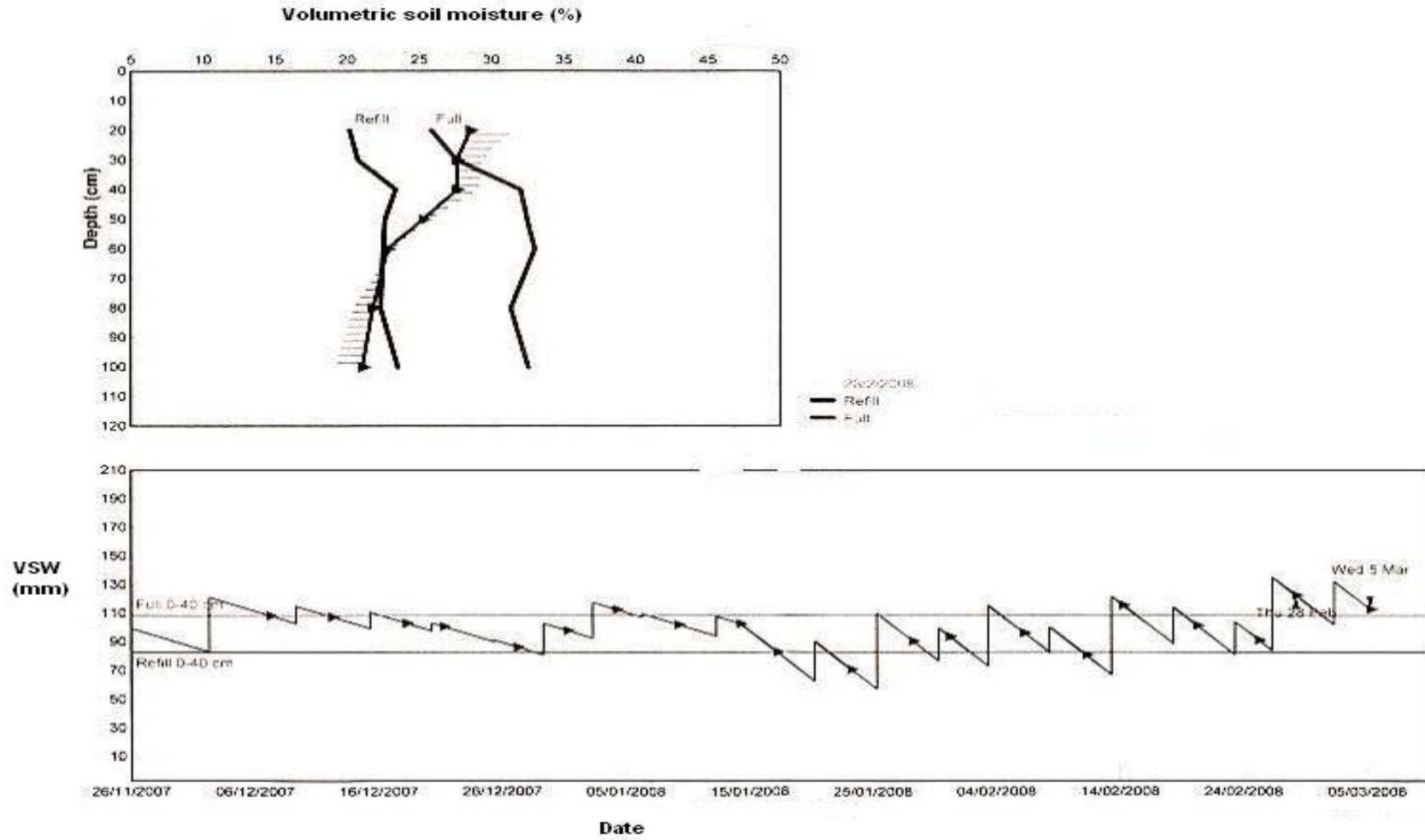
Appendix, Fig 1: A. Neutron probe soil water depletion curve. B. C-probe soil water depletion curve. C. Watermarks soil water depletion curve and D. Decagon soil moisture device soil water depletion curve. All curves show saturation point, field capacity, available water and wilting point for a sandy loam soil at Genadendal during January 2008

Appendix, Fig 2. Soil moisture in volumetric moisture content (%) measured by Neutron probe under A. Micro sprinkler irrigation, B. Daily drip irrigation and C. Pulsing drip irrigation

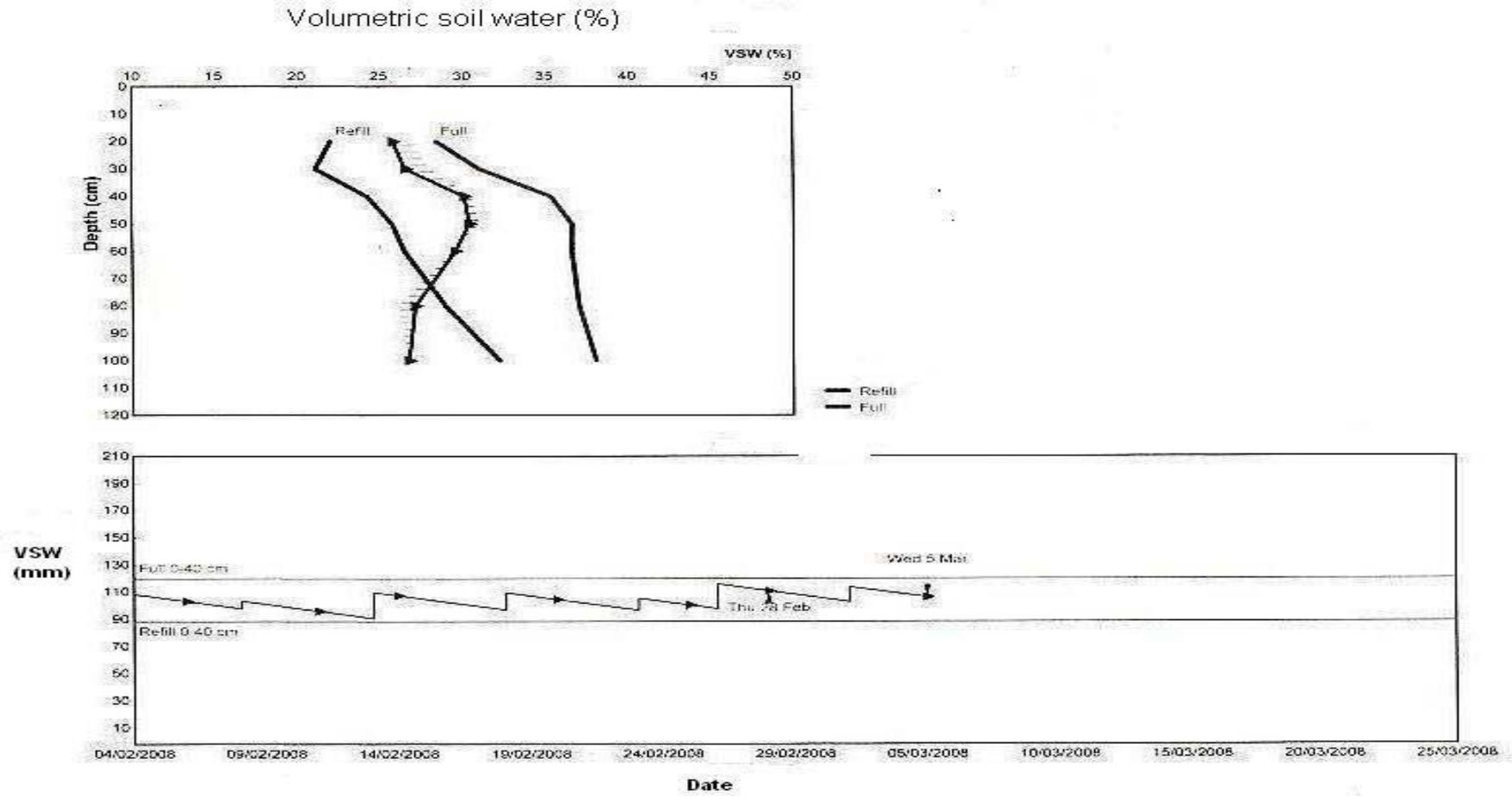
A.

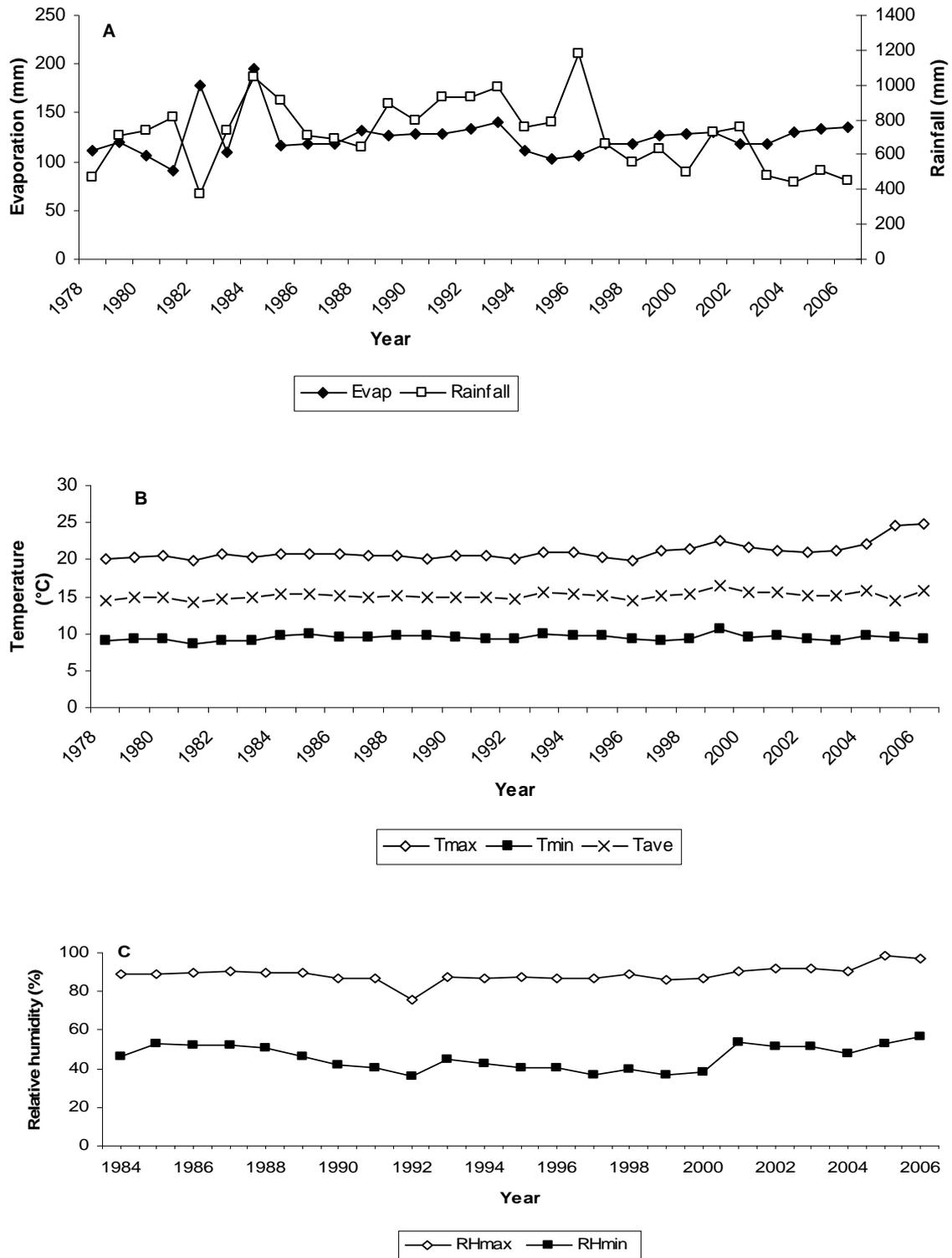


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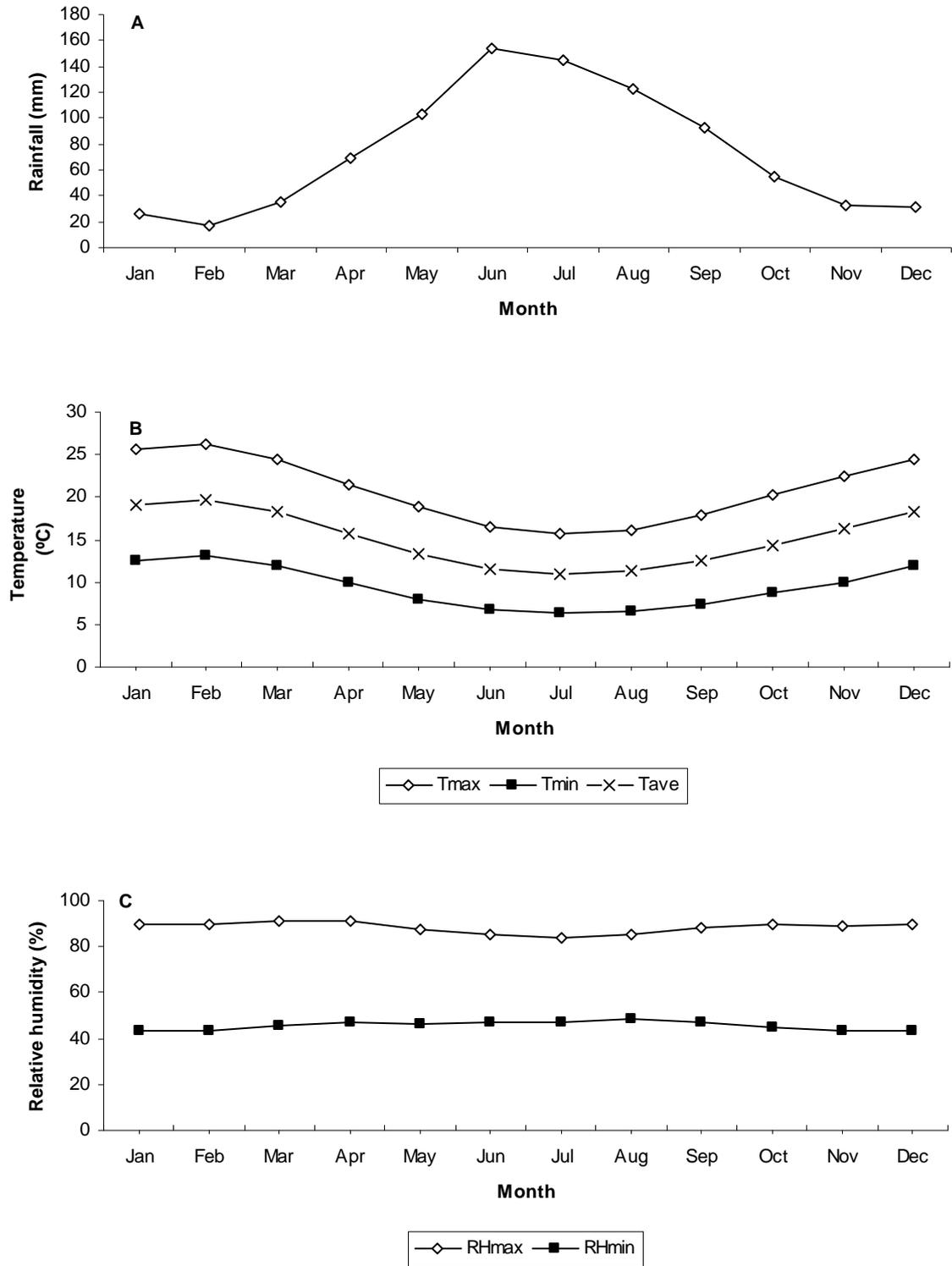


C.

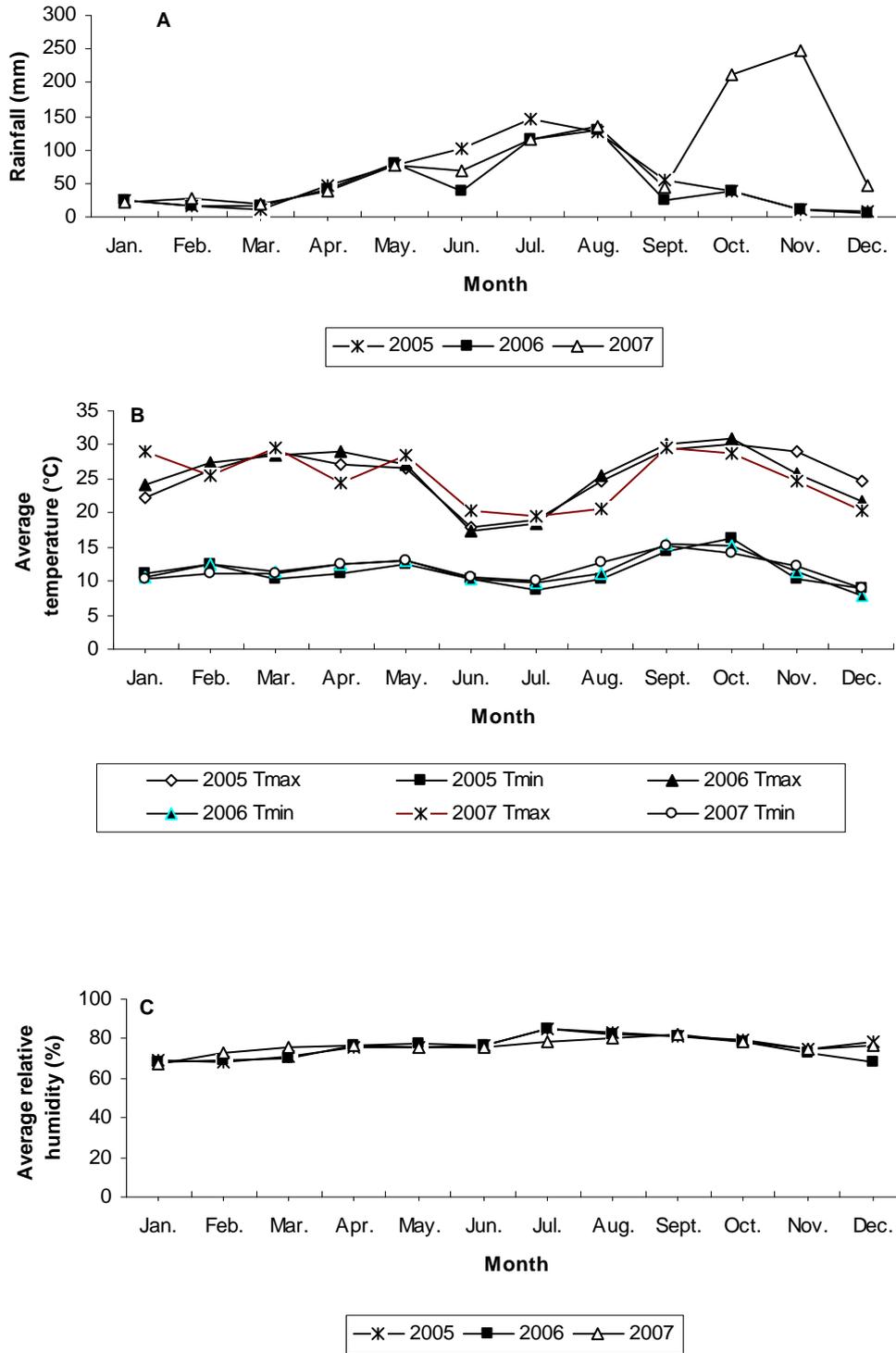




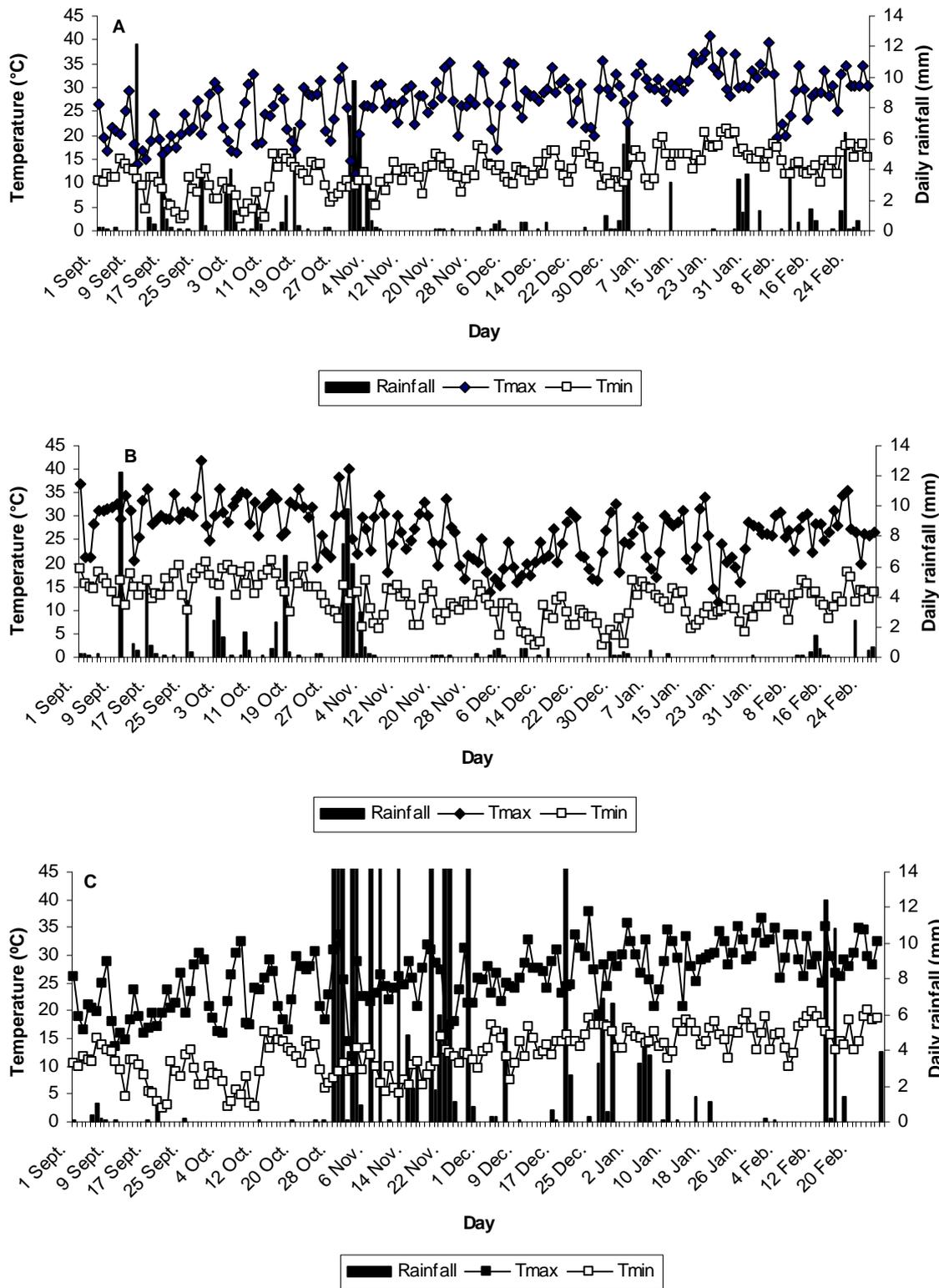
Appendix, Fig. 3: Long-term (25yr average) annual weather data from Caledon municipal weather station: A (rainfall, mm and evaporation, mm), B (air temperature, °C, Tmax, annual mean of maximum daily temperature, Tmin, annual mean of minimum daily temperature and Tave, annual mean of average daily temperature), C (air relative humidity %, RHmax – annual mean of maximum relative humidity and RHmin – annual mean of minimum relative humidity).



Appendix, Fig. 4: Long-term monthly data (25yr average) from Caledon municipal weather station: A (rainfall, mm), B (air temperature, °C, Tmax, monthly means of maximum daily temperature, Tmin, monthly means of minimum daily temperature and Tave, monthly means of average daily temperature), C (air relative humidity %, RHmax - monthly means of maximum relative humidity and RHmin - monthly means of minimum relative humidity).

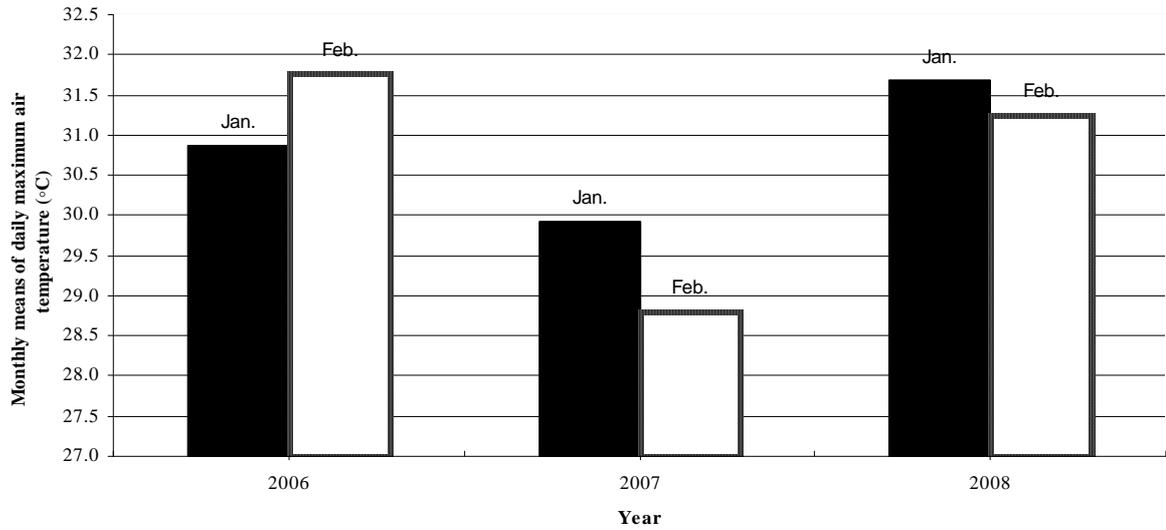


Appendix, Fig. 5: Monthly rainfall (A), monthly mean of maximum and minimum daily temperature (B) and monthly mean of average daily relative humidity from the on-site automated weather station at the experimental site during 2005, 2006 and 2007.

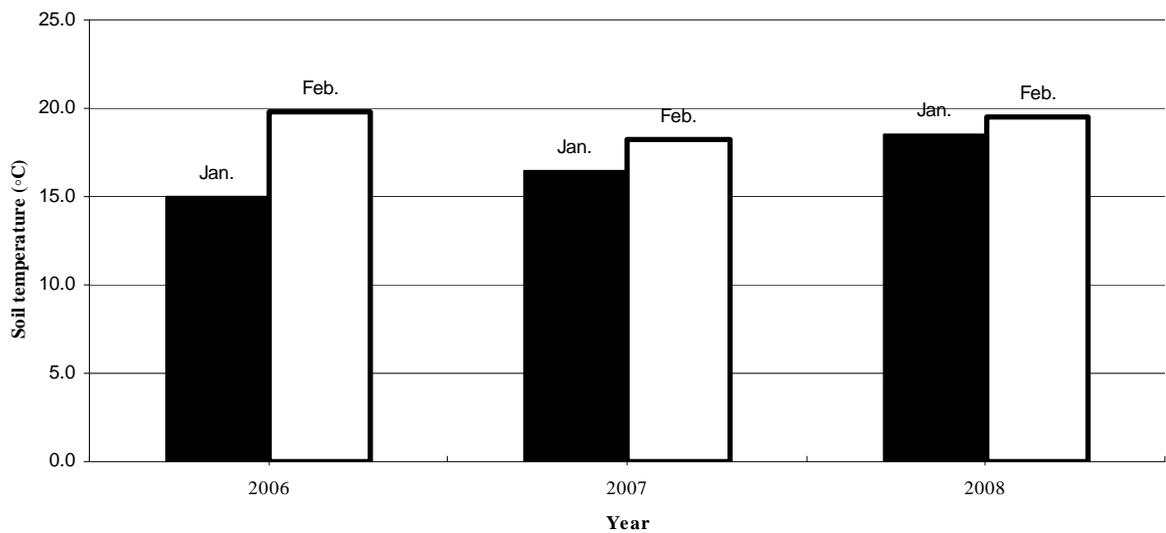


Appendix, Fig. 6: Daily weather data for the fruit growth season from the on-site automated weather station at the experimental site showing mean of daily minimum (Tmin) and mean of daily maximum temperature (Tmax) and daily rainfall (mm) during A: 2005/6, B: 2006/7 and C: 2007/8 seasons. For Fig. 6C, occasionally from 28/10 to 27/11 high daily rainfall (100.2 to 135.5mm) exceeding 14mm was recorded.

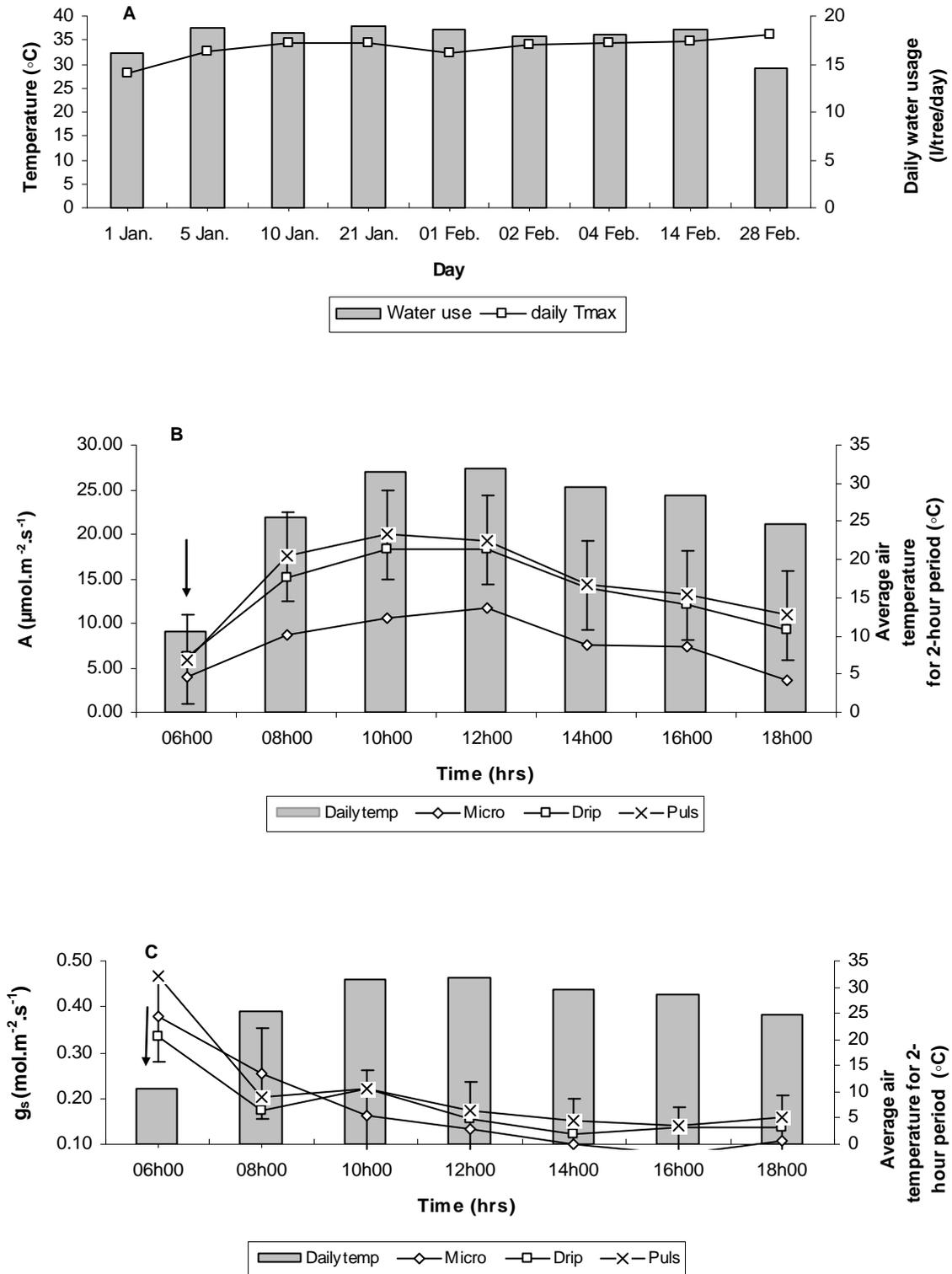
A. Monthly means of daily maximum air temperature for January and February



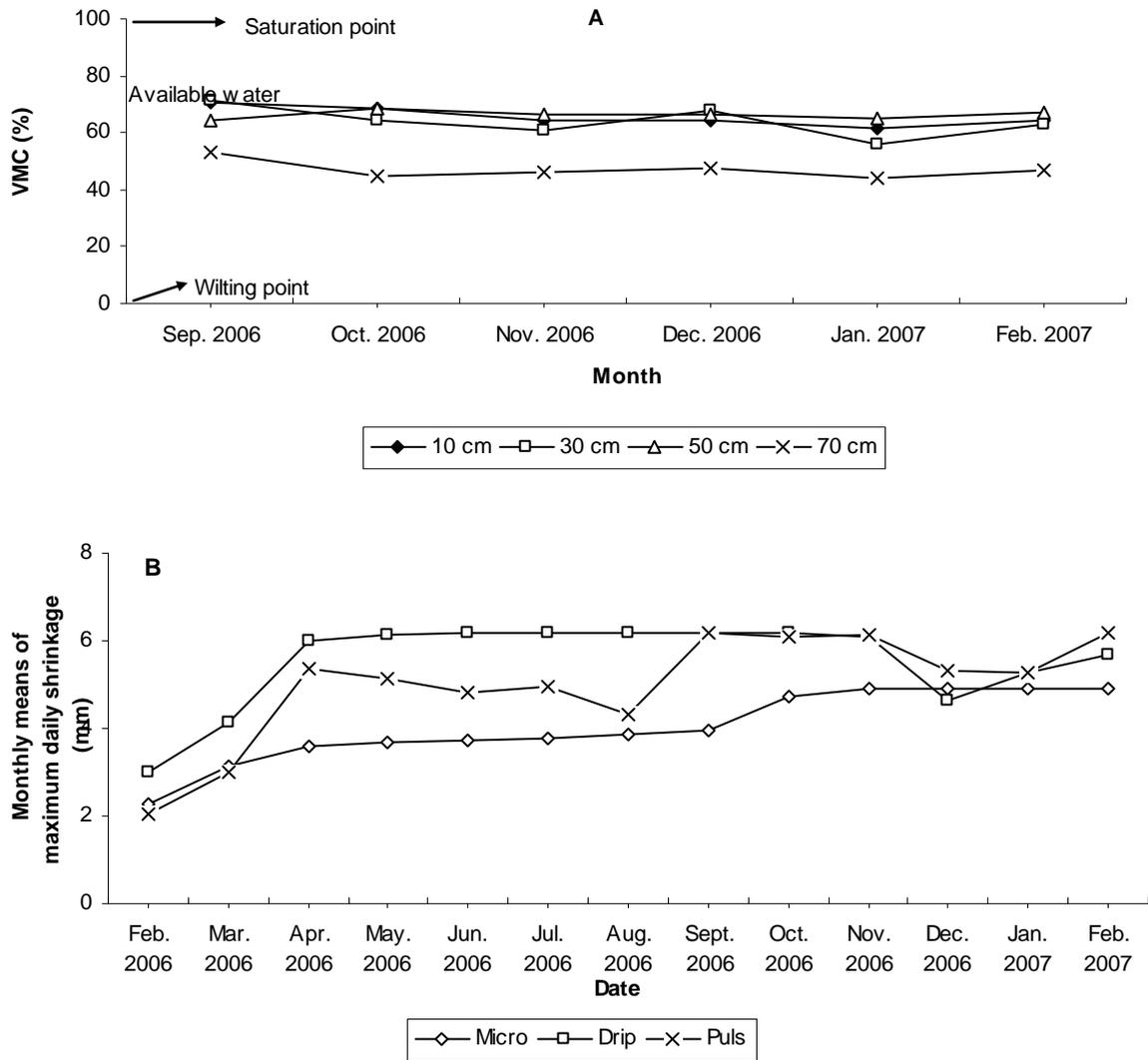
B. Monthly means of daily maximum soil temperature for January and February



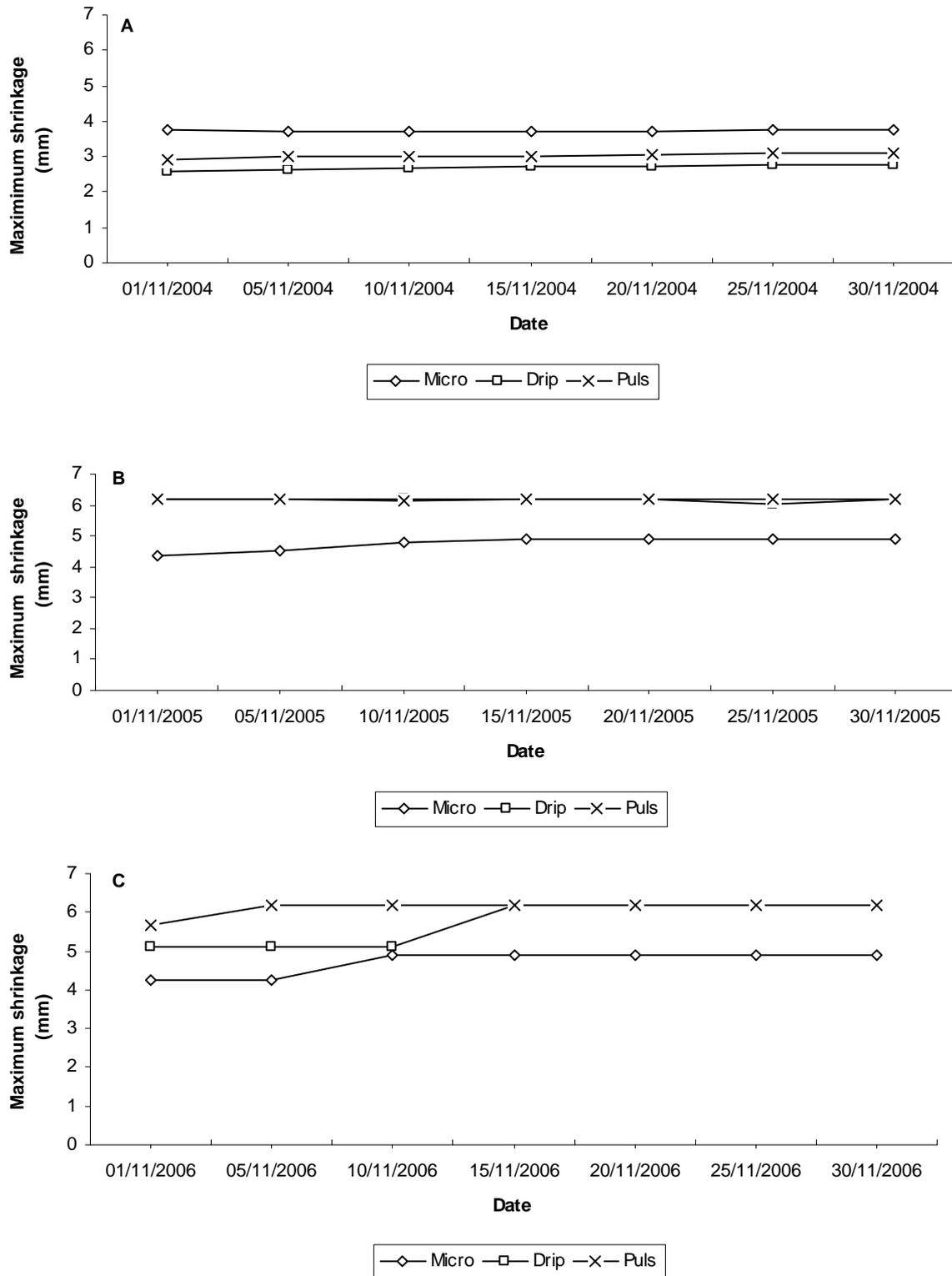
Appendix, Fig. 7: A. Monthly means of daily maximum air temperatures during January and February 2006, 2007 and 2008 from the on-site automated weather station and B. Monthly means of daily maximum soil temperature during January and February 2006, 2007 and 2008 (measured with C-probe sensor, temperature sensor attached at 40cm soil depth).



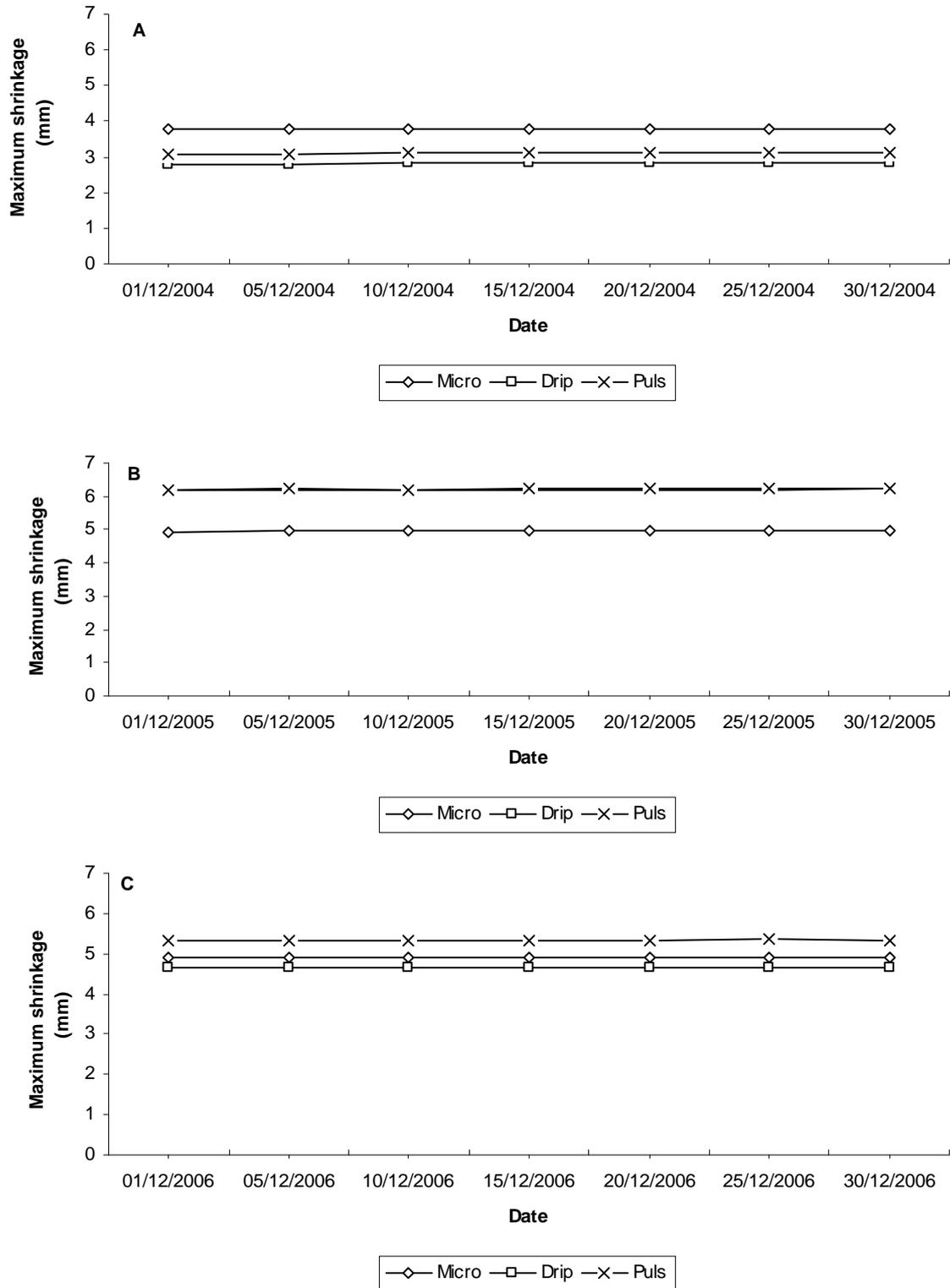
Appendix, Fig. 8: Daily weather data (2007/8 season) from on site automated weather station: A. Maximum daily temperature and daily water usage (l/tree/day) during hot days (heat waves) in January and February 2008, B. diurnal photosynthetic rate under three irrigation strategies during a hot summer day (10/01/2008), and C. diurnal stomatal conductance under three irrigation strategies during a hot summer day (10/01/2008). Arrows indicate start of irrigation.



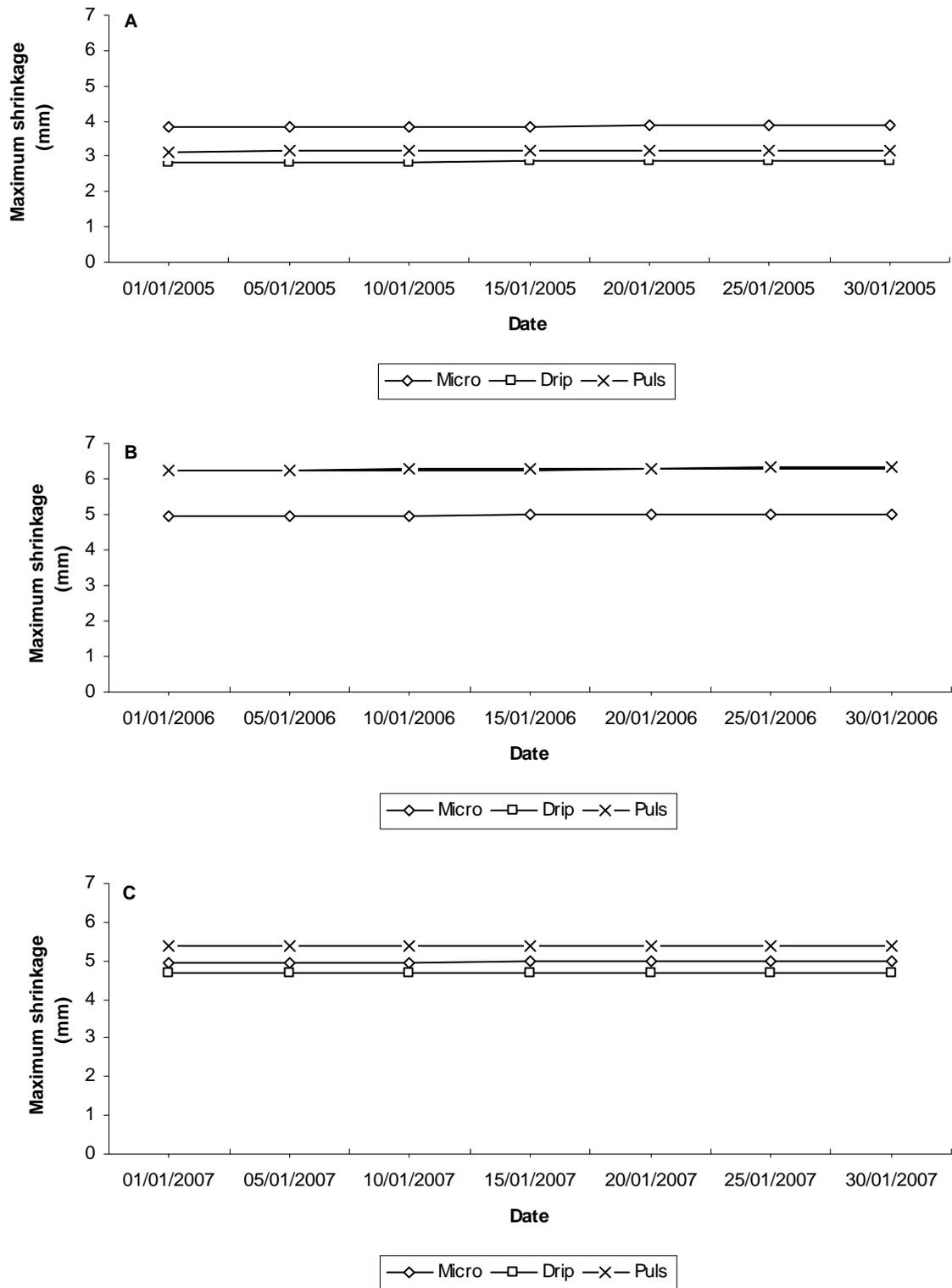
Appendix, Fig. 9: A. Volumetric soil moisture content (VMC, %) during 2006/7 recorded by a Decagon ECH₂O soil moisture device at 10, 30, 50 and 70cm soil depths (device installed in the pulsing drip irrigation system, B monthly means of maximum daily tree trunk shrinkage (mm) for different irrigation systems over the season (2006/7).



Appendix, Fig. 10: Maximum tree trunk shrinkage (mm) (presented after every five days) under ‘Micro’ (micro sprinkler irrigation), ‘Drip’ (daily drip irrigation) and ‘Puls’ (pulsing drip irrigation): A. November 2004, B. November 2005, C. November 2006. Maximum trunk shrinkage (MDS) was calculated by subtracting the minimum diameter (afternoon readings) from the maximum diameter (morning readings).



Appendix, Fig. 11: Maximum tree trunk shrinkage (mm) (presented after every five days) under ‘Micro’ (micro sprinkler irrigation), ‘Drip’ (daily drip irrigation) and ‘Puls’ (pulsing drip irrigation): A. December 2004, B. December 2005, C. December, 2006. Maximum trunk shrinkage (MDS) was calculated by subtracting the minimum diameter (afternoon readings) from the maximum diameter (morning readings).



Appendix, Fig. 12: Maximum tree trunk shrinkage (mm) (presented after every five days) under ‘Micro’ (micro sprinkler irrigation), ‘Drip’ (daily drip irrigation) and ‘Puls’ (pulsing drip irrigation): A. January 2005, B. January, 2006, C. January, 2007. Maximum trunk shrinkage (MDS) was calculated by subtracting the minimum diameter (afternoon readings) from the maximum diameter (morning readings).

3. Effects of different water and nutrient application frequency on 'Brookfield Gala' apple trees

Abstract. The effects of the frequency of water and nutrient application and the choice of rootstock on fruit yield, fruit quality, shoot growth and root development were studied in 'Brookfield Gala' trees during 2005/6, 2006/7 and 2007/8 in an area near Greyton (Genadendal), South Africa (34°03'S, 19°37'E). Three irrigation and fertilisation strategies were used: (i) micro sprinkler irrigation (water applied once to three times a week, depending on the daily maximum temperature and nutrients applied manually), (ii) daily drip (water and nutrients applied once to twice daily), and (iii) pulsing drip (water and nutrients applied once to several times a day, depending on the daily maximum temperature). Long-term evaporation data and apple crop factors were used to predict the amount of water required at different periods. More accurate water scheduling was determined using soil water sensors to maintain plant available soil water at optimum for tree performance. Trees were budded on M793 and on M7 rootstocks and planted in blocks using a split-plot experimental design, with irrigation systems as main plots and rootstocks as sub-plots. Fruit yield and quality were evaluated at harvest of the 2005/6, 2006/7 and fruit yield only for 2007/8. Shoot and fruit growth were measured bi-weekly from November to February/March. Root studies were carried out four weeks prior to the 2006/7 harvest and after harvest at the end of 2007/8. More frequent water and nutrient applications, applied via daily and pulsing drip systems, resulted in significantly higher fruit yields as well as increased numbers and masses of thin and medium roots, compared to lesser frequent application using a micro irrigation system. There were no significant differences between the two rootstocks, although use of M7 resulted in a better yield efficiency than M793. Fruit load had an overriding effect on fruit mass and diameter, as well as on shoot and tree growth, as reflected by the trunk cross-sectional area under all different frequencies of application.

Key words: Micro sprinkler irrigation, daily drip, pulsing drip, fruit yield, fruit quality, root development, shoot growth, trunk cross-sectional area.

3.1 Introduction

In South Africa, particularly in the Western Cape, micro sprinkler irrigation is the standard system for fruit trees. This involves the application of water using micro sprinklers and the manual application of nutrients. In the light of ever-increasing pressure on already limited water resources in the Western Cape, producers are currently interested in drip irrigation, where water and nutrients are applied in solution once or twice daily, as well as in pulsing drip irrigation, which involves the application of water and nutrients in solution several times a day. It is reported that the use of drip irrigation improves the yield and fruit size of many fruit types, such as apples (*Malus domestica*) (Naor *et al.*, 1997, 2000), oranges (*Citrus aurantium*) (Petillo *et al.*, 2004) and strawberries (*Fragaria ananassa*) (Sharma *et al.*, 2005).

The performance (crop yield and fruit size) of deciduous fruit trees, including apples, is known to be highly dependent on irrigation (Naor *et al.*, 1997, 2000; Naor, 2006). Shoot growth and trunk circumference growth have been reported to be greater under drip irrigation systems than under micro irrigation systems (Goode & Ingram, 1971; Bhardwaj *et al.*, 1995; Chauhan *et al.*, 2005). Shoot growth is closely related to apple tree water relations. Adequate water is required to promote expansive growth in apples (Lakso, 2003). Although shoot growth is reduced by declining midday stem water potential, again growth is rapid in the afternoon and evening when the moisture levels are adequate (Berman & DeJong, 1996; Lakso, 2003).

Apple roots have been reported to concentrate near irrigation drippers (in drip irrigation systems) About three times as many roots per square metre are found at 100–300mm from the trickle line compared to fewer roots found at >400mm from the trickle line (Levin *et al.*, 1979). The effect of rootstocks on the uptake of water and nutrients has been studied (Tukey *et al.*, 1962; Fallahi *et al.*, 2002). Rootstocks differ in their xylem sap nutrient concentration, suggesting significant differences in their genetic potential, for the absorption and translocation of nutrients from the soil (Jones, 1971).

Fertigation (application of fertilizer with irrigation water) is used worldwide, with relative success. Fertigation allows the application of nutrients exactly and uniformly to only the wetted root volume, where the active roots are concentrated (Imas, 1999). The use of fertigation as opposed to other irrigation systems, such as micro sprinklers, has several advantages, which

include a reduction in fertilizer application (amount) and water requirements, thus reducing production costs; a reduction of potential ground water pollution caused by fertilizer leaching; it is easy to adapt the amount and concentration of applied nutrients in order to meet the actual nutritional requirements of the crop throughout the growing season; and it provides more timely and accurate crop nutrition, resulting in higher crop yield and quality (Raina, 2002; Rana *et al.*, 2005).

The majority of total apple cultivation (approximately, 18 062ha) in South Africa is in the Western Cape (88% of the planted area), and a high percentage of the produce (42%) is destined for the export market (OABS, 2008). High production volumes and exportable fruit size are required in order for fruit producers to remain profitable. Numerous cultivation and management practices have been implemented in order to achieve this (e.g. pruning, thinning, girdling, use of growth regulators, etc.). However, it is the use of irrigation that has been found to be critical for the achievement of desired yields, and, in irrigation, it is the volume of water used and the volume of soil to be wetted that are most important (Petillo *et al.*, 2004).

The objective of this study was to compare the use of three different irrigation and nutrient strategies, namely micro sprinkler irrigation (where more water is applied less frequently over the drip area and nutrients are not given in solution), and daily drip irrigation and pulsing drip irrigation (where less water is applied more frequently to a specific area, with nutrients in solution), and the two rootstocks M793 and M7, on fruit yield, fruit quality and general growth characteristics in 'Brookfield Gala' apple trees. The objective behind all these systems is that water and nutrients must reach the root zone.

It was hypothesised that the application of water and nutrients at short cycle intervals (daily or shorter) would result in optimum tree performance. This would be achieved as a result of the proliferation of feeder roots, thus creating a more efficient root system. The benefit would be more fruitful bearing wood with adequate spurs. Furthermore, readily available water and nutrients would optimise carbohydrate usage and benefit fruit quality. In addition, it was expected that multiple daily applications would yield better results than a conventional single daily application under a drip system, especially on the semi-dwarfing rootstock and under high temperature conditions. This could subsequently increase the trees photosynthetic capacity,

carbohydrate synthesis, mineral uptake and allocation to the fruit, resulting in better fruit yield and quality.

3.2 Materials and methods

3.2.1 Study site and experimental layout

'Brookfield Gala' apple trees (*Malus domestica* Borkh.) were planted on a farm in the Genadendal area (34°03'S, 19°37'E), Western Cape Province, during June 2003. The trees were spaced at 4m × 1.25m, giving a total of 2000 trees/ha. Trees were trained to a central leader by implementing both summer and winter pruning. Fruit thinning was done immediately after fruit drop. A maximum of two fruits were left per spur cluster for the basal 50% and three for the rest of the bearing branch (2005/6 and 2007/8). Owing to poor weather conditions during flowering in 2006/7 the fruit set was low and no thinning was necessary. The trial layout was a split-plot design with three irrigation and fertilization strategies (micro sprinkler irrigation, daily drip irrigation and pulsing drip irrigation) as main plots and two rootstocks (M7 and M793) as sub-plots. Each experimental unit was replicated eight times in randomised blocks, and consisted of five trees per replication. The rows were separated by a 1.2m × 0.5m deep trench lined with double layer of black gunplast plastic (150µm) and filled with soil to prevent any lateral movement of water between the treatments. The micro sprinklers (spaced 1.25m apart) had a discharge rate of 30l.h⁻¹ and were used to apply water once to three times per week depending on requirements. Nutrients were applied manually. Drippers for the drip irrigation systems (drippers spaced 600mm apart) had a discharge rate of 2.3l.h⁻¹ and were used to apply water and nutrients on a daily basis. In the daily drip irrigation treatment one to two applications per day were given while in pulsing drip it can be up to six applications per day. For all three systems the same amount of water reached the rooting zone (Chapter 2) although the micro sprinklers needed more water applications because of high evapotranspiration and drift losses. The annual nutrient (macro and micro elements) requirements (see Chapter 2) were based on studies carried out by Stassen and North (2005) and on experience gained with 'Royal Gala' apple trees. This nutrient requirement was divided into five phenological periods.

Water requirements of full-grown apple trees were calculated using long-term (25 years) evaporation data of two nearby weather stations and locally developed apple crop factors (Kotze, 2001). This was adapted for younger trees according to leaf area development. Two types of soil water sensors (C-probes and Watermark sensors) were used for each of the three systems in order

to adapt the predicted water requirement into actual requirements according to soil water plant availability. Soil water was kept above 50% available water and below the field capacity for this specific soil. The C-probe and Watermark sensors were calibrated against a neutron probe because of its reliability and its ability to be recalibrated after each use, though it has different units to the other sensors.

In order to accurately mix and balance the nutrients according to specifications, and to apply the correct amount of nutrients during each irrigation, a computer software program developed by Mostert (P.G. Mostert, 2004, personal communication) and an Aquarius applicator (AQ 516 Aquarius, Davies, CA, USA) were used. In the case of the micro irrigation system, the macro and micro elements were applied manually within the drip area. Nitrogen was given in five instalments, potassium in three, and all other nutrients in two instalments, according to standard commercial strategies.

3.2.2 Fruit and shoot growth measurements

A total of 25 fruits on opposite sides of the tree per replicate were tagged after fruit thinning (in 2005/6 and 2006/7) and their diameters measured bi-weekly with an electronic-type Cranston calliper (Cranston Machinery Co., Oregon, USA). Days after full bloom (DAFB) were used instead of calendar days in order to relate fruit growth to the phenological stages of growth, which varies between seasons. Ten extension shoots per replicate were tagged at the beginning of the season (early November). Shoot length was measured bi-weekly. Trunk cross-sectional area was calculated from the tree stem circumference measured every winter (2004–2008). Fruit yield was based on fruit weight from all eight blocks consisting of three irrigation strategies and two rootstocks after each harvest. Fruit yield efficiency was calculated as the ratio of current season's yield to TCA of the previous winter.

3.2.3 Fruit quality

At harvest, 75 fruits (2005/6) or 50 fruits (2006/7) per replicate were sampled. Fruits were assessed for fruit weight, size (equatorial diameter), firmness, starch conversion, total soluble solids (TSS), malic acid, citric acid and background colour. Harvest quality evaluations were done on a 25-fruit sub-sample whilst the rest of the fruit was kept for eight weeks at $-0.5\text{ }^{\circ}\text{C}$ in regular atmosphere cold storage, after which quality evaluations were carried out on a 25-fruit sub-sample. The last sub-sample of 25 fruit was held at room temperature for a further 10 days

for shelf-life quality evaluation (done only for 2005/6). Firmness was measured on fruit flesh with the peel removed, on opposite cheeks of the fruit, using an automated penetrometer (Southtrade, FT327, Alphonsine, Italy) fitted with a convex 11-mm probe, penetrating at 90° to the surface and to a depth of 8mm. Starch conversion was determined by means of the iodine test and using the corresponding starch conversion chart for pome fruits (Unifruco Research Services, Bellville, South Africa). Soluble solids (TSS) were measured with a hand-held refractometer (PR-100 9501, Atago Co. Ltd., Tokyo, Japan), while the percentage acid (malic acid and citric acid) was analysed using a Metrohm 760 sample changer titrator (Swiss Labs Pty Ltd., Rivonia, RSA). Acid titration was done to end point pH 7.2 (citric acid) and 8.2 (malic acid) with 0.1 NaOH. Background colour was determined using a colour chart for apples and pears (values 0.5–5; dark green (0.5) and light green (5) (Unifruco Research Services, Bellville, South Africa).

3.2.4 Soil profiles and root studies

Eighteen soil profiles (800mm × 800mm × 800mm) were dug in January 2007, a month before harvest. Under each irrigation system and for each rootstock combination, three holes were dug (n=3). A frame measuring 800mm × 800mm with 200mm × 200mm square grids was used to count the roots and determine their distribution, expressed as the total number of roots per 20cm³ soil. Holes were opened 600mm from the stem of the tree, using a spade. The soil around the roots was carefully removed to 400mm from the stem, using a hand fork. The root number was determined for both the M793 and M7 rootstocks and all three systems. On 14/02/2008, 18 trees (three from each rootstock in three rows) were excavated and the total roots were weighed and divided into two fractions (thin to medium roots and thick roots). All roots plus soil were passed through a 2mm sieve to separate the soil from the roots. Thin to medium roots were categorised as all roots <3mm in diameter and thick roots as all roots >3mm in diameter, irrespective of their origin. Both fresh weight and dry weight (after oven drying at 60°C for 24h) were taken.

3.2.5 Statistical analysis

Data were analysed using a split-plot analysis of variance (ANOVA) with irrigation treatments as the main factor and rootstocks as a sub-factor (SAS GLM procedure, Enterprise Guide 6, release 1.3 SAS Institute, Cary, NC, USA, 2001). Means separation was done using Tukey's studentized range test (P≤0.05). Regression analysis was done on shoot and fruit growth.

3.3 Results and discussion

Table 1 shows that yield parameters (yield/tree, yield/ha and yield efficiency) followed the same trends during 2005/6 and 2007/8. During these two seasons, when yields were high, the two drip systems performed significantly better ($P \leq 0.05$) than the micro sprinkler system. The difference between the two drip systems was not significant. These results confirmed the hypothesis that more frequent water and nutrient application by means of drip irrigation increases yield performance. During 2006/7 no significant differences were found between the three systems for the yield/tree and yield/ha. Cold and misty weather was experienced during the flowering period (in 2006). This resulted in poor fruit set and low yields, which were similar under all three irrigation systems. The difference (in t/ha over two seasons) between the daily drip and pulsing drip systems was 11% in both good years (2005/6 and 2007/8). Although this difference was not significant it indicated a tendency towards the requirement for more frequent drip than once or twice daily. Since the soil on the experimental site contained 14.8% clay plus silt it was able to provide a good water-holding capacity over a one-day period. However, in soils with lower clay plus silt content differences between daily and pulsing drip might be more significant, especially during the warmer months. Furthermore, there was main effects interaction (rootstocks and systems) observed during 2007/8 (Table 3), with M793 rootstock showing significantly higher yield than M7.

Higher fruit yield efficiency (kg/cm^2) was obtained under the two drip irrigation systems than with the micro irrigation system during 2005/6 and 2007/8, irrespective of the lower crop load during 2006/7 (Table 1). Similar fruit yield increase under drip irrigation systems than under micro sprinkler irrigation have also been confirmed in other species. Studies on grapes (*Vitis vinifera*) (Gal *et al.*, 1996), peaches (*Prunus persica*) (Mitchell & Chalmers, 1983) and apples (*Malus domestica*) (Assaf *et al.*, 1984; Bussakorn *et al.*, 2000) revealed better yield and fruit quality under drip irrigation systems than under micro irrigation systems. Improved results have been associated with the repetitive water trickling that usually develops around the emitter as a result of frequent water application, which improves soil properties, root development and nutrient uptake (Assouline, 2002). Earlier studies by Goldberg *et al.* (1971) indicated that frequent irrigation reduces evaporation and percolation, and establishes a favourable soil moisture and oxygen condition in the root zone throughout the entire crop period.

According to Naor (2006) fruit size is dependent on the number of cells in the fruit pericarp and the fulfilment of the potential fruit size is dependent on irrigation and the crop load. Fruit size is known to be affected by crop load and water deficit in many fruit crops (Berman & DeJong, 1996; Naor *et al.*, 1999), hence it has become necessary that crop load and water availability are optimised in order to maximise the number of class I marketable fruit (Naor *et al.*, 1999). Comparative studies on fruiting and non-fruiting trees have been carried out for many fruit trees. It is generally accepted that crop load affects fruit size in apples (Forshey & Elfving, 1989; Naor *et al.*, 1997). Bearing fruit trees are reported to have greater stomatal aperture and conductance (Chalmers *et al.*, 1983; Schechter *et al.*, 1994, Wünsche & Ferguson, 2005), higher assimilation rates (Monselise & Lenz, 1980; DeJong, 1986), lower leaf water potential, and higher water consumption (Chalmers & Wilson, 1978; Erf & Proctor, 1987). These factors are discussed in Chapters 4 and 5.

The fruits during 2006/7 were less firm at harvest (Table 2). The percentage starch conversion also confirmed that these less-firm fruits were more mature. There were significant differences between the irrigation systems during 2005/6. Malic acid and citric acid content were both higher under micro sprinkler irrigation compared to daily drip irrigation and pulsing drip irrigation in 2006/7, but no differences were observed during 2005/6 (Table 2). The background colour that developed in fruits under the two drip irrigation systems was similar to those under the micro irrigation system in 2005/6, but not in 2006/7 (Appendix 1, Table 1a). After storage fruit analysis showed more total soluble solids under drip systems in 2005/6 but not during 2006/7 (Appendix 1, Table 1b). Analysis of fruit after 10 days of shelf life showed higher TSS and citric acid under both drip irrigation systems than micro irrigation during 2005/6, but no difference in malic acid, firmness and starch conversion (Appendix 1, Table 1c). There were some rootstock effects observed for colour (chart) and for starch conversion during 2005/6 but not during 2006/7 (Appendix 1, Table 1a).

During 2005/6 the fruit weight and diameter were significantly higher for trees under micro irrigation than for trees under pulsing drip, while for trees under daily drip they were intermediate (Table 2). During 2006/7 trees under both drip systems gave significantly higher fruit weight and fruit diameter than those under micro irrigation. During both seasons all fruit weight and diameter were always higher than required for export ($\pm 105\text{g}$ and 55mm for export of 'Brookfield Gala', according to guidelines provided by the Two-a-Day Group Ltd., Elgin, South Africa). Data in

Table 1 show significant differences in yield between trees under micro and pulsing drip, which can explain the differences in fruit weight and size seen in Table 2. During 2006/7, when yield was low and similar between the treatments, trees under both drip systems gave better fruit mass and size. It was, therefore, concluded that high yield has a greater influence on fruit size than the irrigation and nutrient strategy used when fruit size has already reached exportable size.

Fruit firmness and starch conversion are important variables that define physiological maturity in fruit. The balance between TSS, malic acid and citric acid plays a role in the apple taste. Higher soluble solids (in 2005/6, but not in 2006/7, only in drip not in puls) and less acid (during 2006/7, but not during 2005/6) were observed under pulsing drip irrigation and daily drip irrigation systems compared to micro irrigation. The observed differences between irrigation systems in malic acid and citric acid during 2006/7 could be due different systems because there were no crop load effects (sink/source relationships) and carbohydrate allocation effects. M793 rootstock had a better fruit weight and higher malic acid but less starch conversion and lower citric acid during 2005/6 and 2006/7 than M7 rootstock (Table 3). There were system, rootstock interactions for malic acid and citric acid (2006/7). The semi-vigorous M793 had a higher yield ($\text{kg}\cdot\text{tree}^{-1}$), yield ($\text{t}\cdot\text{ha}^{-1}$) and fruit weight (g) than semi-dwarfing M7. Higher photosynthetic rates reported for M793 in Chapters 4, 5 and 6 could imply more carbohydrates available for fruit and increased activity to sustain such a high fruit load. Similar results of higher photosynthesis rates in semi-vigorous rootstocks have been mentioned (Atkinson, 2001) and difference in rates of photosynthesis are known to be high in bearing trees than under non bearing trees (Fallahi *et al.*, 2002).

The trunk cross-sectional area, trunk cross-sectional area increment and total shoot growth from 2004/5 to 2007/8 are summarised in Table 4. The trunk cross-sectional area for trees under micro irrigation was significantly larger than that of trees under the two drip systems during 2005/6, 2006/7 and 2007/8. However, the difference in trunk cross-sectional area increment was only significant during 2005/6. The higher yield on trees under the drip strategies during 2005/6 (Table 1) probably had an influence on tree growth during that young stage (third year). The same suggestion can be put forward for shoot length. During 2005/6, the shoot length of trees under micro sprinkler irrigation was significantly higher than the shoot length under both drip systems. During 2006/7, when yield was low and similar for trees under all three systems, there was no significant difference in shoot length. Table 5 shows that the trunk cross-sectional area of

trees on M793 was significantly larger than on M7 during all three seasons, and there was a higher TCA increment during 2005/6, but M793 showed lower yield efficiency than M7.

The results of this study are in agreement with the findings of Cohen *et al.* (2001), who reported that a higher increment in trunk growth under micro irrigation relative to the growth obtained under the two drip systems may be due to the redistribution of water, which is modified by both the water potential gradients and the various resistances to water transport within the plant. An increased trunk cross-sectional area was measured under micro irrigation compared to under the drip irrigation systems, but the two drip irrigation systems had a better yield efficiency than the micro system. Factors such as nitrogen fertilization (Chapman, 1973), soil moisture (Forshey & Elfving, 1989) and climatic conditions (Simonneau *et al.*, 1993) have all been said to affect trunk growth. Trunk cross-sectional area has been found to be linearly related to tree volume (Behboudian & Mills, 1997). Diurnal fluctuations in trunk growth (Landsberg & Jones, 1981; Li & Huguet, 1990) can be used to measure stress and help in irrigation scheduling.

The semi-vigorous rootstock (M793) showed more vigorous growth and attained the highest canopy growth compared to the more dwarfing M7 rootstock. Influences of different rootstocks on canopy development and growth have been studied (Atkinson, 2001). Rootstocks are known to influence the rate and amount of vegetative growth of the grafted/budded shoot/bud, but the mechanism by which rootstocks affect vegetative growth is not fully understood (Ranney *et al.*, 1991). Other studies have, however, mentioned the role of root-induced cytokinins in xylem sap (Cutting *et al.*, 1991; Cook *et al.*, 2001) and the role of hydraulic conductivity (Dodd *et al.*, 1996) in apples.

Fruit growth measurements showed a logarithmic type of growth for all three irrigation strategies (Appendix 1, Figs. 1A–F). Other researchers, such as Lakso *et al.* (1995) and Naor *et al.* (2000), have made similar observations. Better fruit growth development was observed in the second season under the two drip irrigation systems than under the micro sprinkler irrigation system (Appendix 1, Figs. 1B, D and F). During 2006/7 a reduction in growth rate was observed 55 DAFB under all the irrigation systems, due to wet and cold weather that limited normal fruit growth and, eventually yield. Seasonal shoot growth (length) was higher under micro sprinkler irrigation compared to daily drip irrigation and pulsing drip irrigation during 2005/6 (Appendix 1, Fig. 2A), but not during 2006/7 when yield was lower (Appendix 1, Fig. 2B). Shoot growth was

significantly longer, especially during the period after harvest, for trees under micro sprinkler irrigation, when yield was lower, and the least for trees under daily drip irrigation, when yield was higher. During 2005/6 the following R^2 -values for final shoot length were observed under different irrigation systems: Similar R^2 values under micro sprinkler irrigation $R^2 = 0.86$, and daily drip irrigation, $R^2 = 0.87$ were observed whilst, a higher R^2 value under pulsing drip irrigation $R^2 = 0.95$. The system P-value was 0.0005. Higher final shoot growth was indicative of a better growth as evident from photosynthetic assimilative rates under drip based system than under the micro sprinklers. During 2006/7 the final shoot length under micro sprinkler irrigation was $R^2 = 0.94$ under daily drip irrigation $R^2 = 0.96$, and under pulsing drip irrigation $R^2 = 0.95$. The system P-value was 0.4556. There were no apparent differences observed under all the three systems, possibly due to even crop load during 2006/7. Shoot growth increased slowly during the early season and then increased more rapidly in January, before levelling off in March, with no further growth (Appendix 1, Figs. 2A and 2B).

Table 6 summarises the number of thin plus medium roots within a 0–800 mm soil profile. There were significantly more roots (3mm and less in diameter) (36–47%) for trees under drip irrigation systems than for trees under micro sprinkler irrigation during 2006/7. Of these roots, 66–71% were in the 0–400mm soil area. Micro sprinkler irrigation resulted in $\pm 44\%$ of the total number of roots (thin plus medium) within 0–400mm of the soil profile (Appendix 2, Plates 1 and 2). During the 2007/8 season whole trees were excavated and roots were divided into two classes and weighed. Data are summarised in Table 7. Roots of three mm and less in diameter had a significantly higher dry mass for trees under drip systems than for trees under micro sprinkler irrigation. If the pulsing drip system was assumed to have developed 100% (fine roots 3mm and less), daily drip would be 89% and micro sprinklers would be 49%. This result is similar to the result obtained for the yield parameters between the trees under these three irrigation systems. No significant differences occurred between the two strategies using drip systems, although there was a tendency towards more fine roots (3mm and less) for trees under the pulsing drip system. This soil contained 14.8% clay and silt. It is possible that in soils with a lower clay and silt percentage the pulsing drip could be more advantageous. Again, there was some rootstock main effect observed at 400–800mm soil depth for number of thin plus medium roots (Table 6).

The results of earlier studies on root efficiency, patterns of distribution and dynamics have been published for grapes (*Vitis vinifera*) and apples (*Malus domestica*) (Fallahi, 1994; Eissenstat *et*

al., 2001, 2006). Studies by Barber (1984), Fallahi (1994) and Eissenstat *et al.* (2006) showed that the most important factor influencing nutrient uptake by the roots and the total length of the root system is the root absorptive surface area. Thus trees with a greater root length distribution will also have a greater capacity for nutrient acquisition and fruit production (Eissenstat *et al.*, 2001). Root efficiency relates to the ratio of nutrient gained per unit of carbon expended and root longevity is shortest for roots of low efficiency and longest for roots of high efficiency (Eissenstat *et al.*, 2001). The uptake of water and nutrients has been reported to be more efficient in young, white roots, although older roots can still be active (Atkinson & Wilson, 1980). New root production occurs until about one month after bloom (from mid-October to mid-November) and most of the growth is completed within 60–80 DAFB (Psarras & Merwin, 2000). However, in warm dry years, with heavy crop loads, new root production peaks at bloom and again postharvest, with little growth taking place in midsummer. These patterns of growth have not been correlated with irrigation type or nutrient uptake (Lakso, 2003). From this, it is clear that the different irrigation and nutrient applications have a great influence on root development. Higher total root mass from both fresh and dry root samples further suggests a better root development and proliferation under pulsing drip and drip irrigation than under micro sprinkler irrigation.

3.4 Conclusions

Frequent water and nutrient applications significantly stimulated the development of more efficient thinner roots. Yield increase followed a similar trend to increase in thinner roots. Trees under daily drip and pulsing drip had significantly higher yields than trees under micro sprinkler irrigation, over two seasons. It is suggested that an increase in a more efficient root system with more root-growing tips for cytokinin synthesis and element uptake can have a positive influence on the fruitfulness of bearing wood. The drip systems used less water ($\pm 26\%$) than micro sprinkler irrigation (Chapter 2) because of the more efficient application of water to the root zone. In the sandy loam soil of the area under investigation no significant differences were found between one or two applications (daily drip) compared with one to six applications (pulsing drip). However, a lower percentage silt and clay, together with high summer temperatures, may give better results with pulsating drip. The confounding effects of different nutrient application under different systems in this study played a very important role. Under daily drip systems nutrients are supplied with water on a more regular basis and are readily available, whereas under micro sprinkler system they are applied manually, early in the season and later at post harvest which may pose danger of deficiencies during the season. However such deficiencies were not observed

in this study (Chapter 2) possibly due to the soil conditions under which the study was done, which did not have any apparent textural properties that could encourage nutrient adsorption and retention.

The fruit weight and fruit diameter were within acceptable export ranges, under all the systems. Fruit load had an overriding effect on fruit mass and fruit diameter, as well as shoot growth and tree growth, as reflected by the trunk cross-sectional area, under all frequencies of application studied. Again, no significant differences were observed between the two rootstocks studied in terms of yield during (2006/7), but during 2007/8 M793 were significantly better than M7; furthermore M7 rootstock had a better yield efficiency than M793.

These results clearly indicate that optimum water and nutrient management strategies can be achieved, to the benefit of commercial fruit farming in Western Cape. This can best be achieved using systems that involve more frequent application (drip systems), which can further increase yield and be beneficial to fruit producers, in terms of increasing their production and assisting them to cope with ever-increasing costs of production, whilst saving valuable irrigation water.

3.5 References

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Table 1: Fruit yield parameters of ‘Brookfield Gala’ apples (at harvest) grown under different water and nutrient strategies (‘Micro’: micro sprinkler irrigation, ‘Drip’: daily drip irrigation, and ‘Puls’: pulsing drip irrigation) on semi-vigorous M793 or semi-dwarfing M7 rootstock in 2005/6 to 2007/8. Probability values are according to split-plot ANOVA, followed by Tukey’s multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=8$.

Treatment	Harvest parameters		
	2005/6		
	Yield. (kg.tree ⁻¹)	Yield (t.ha ⁻¹)	Yield efficiency (kg/cm ²)
Micro	9.82 b	19.6 b	0.565 b
Drip	14.97 a	29.9 a	0.866 a
Puls	17.10 a	33.6 a	1.028 a
SE (±)	1.05	1.93	0.068
P-value			
System	<0.0001	<0.0001	0.0005
Rootstock	0.1064	0.1087	0.0013
System × rootstock	0.9480	0.9464	0.1982
		2006/7	
Micro	5.50 a	11.0 a	0.196 b
Drip	6.21 a	12.4 a	0.259 ab
Puls	7.18 a	14.4 a	0.328 a
SE (±)	0.51	1.02	0.027
P-value			
System	0.1821	0.1823	0.0137
Rootstock	0.1788	0.1793	0.0033
System × rootstock	0.5533	0.5535	0.2053
		2007/8	
Micro	19.74 b	39.48 b	0.521 b
Drip	24.85 a	49.70 a	0.701 a
Puls	27.96 a	55.93 a	0.750 a
SE (±)	1.25	2.51	0.030
P-value			
System	0.0193	0.0010	0.0040
Rootstock	0.0935	0.0937	0.0065
System × rootstock	0.0309	0.0309	0.2986

Table 2: Fruit quality parameters of ‘Brookfield Gala’ apples (at harvest) grown under different water and nutrient strategies (‘Micro’: micro sprinkler irrigation, ‘Drip’: daily drip irrigation, and ‘Puls’: pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstock in 2005/6 and 2006/7. Probability values are according to split-plot ANOVA, followed by Tukey’s multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n = 8$.

Treatment	Quality parameters						
	2005/6						
	Mean fruit weight (g)	Diameter (mm)	Firmness (kg/cm^2)	Starch conversion (%)	TSS (% Brix)	Malic acid (%)	Citric acid (%)
Micro	147.8 a	70.0 a	8.13 b	55.0 a	12.84 b	0.43 a	0.41 a
Drip	139.2 ab	67.2 ab	8.57 a	41.1 b	13.62 a	0.45 a	0.43 a
Puls	135.7 b	66.7 b	8.56 a	42.1 b	13.34 ab	0.43 a	0.42 a
SE (\pm)	2.99	1.17	0.01	3.08	0.18	0.01	0.01
P-value							
System	0.0656	0.0042	0.0528	0.0289	0.0072	0.3709	0.3022
Rootstock	0.0007	0.1067	0.7625	0.0104	0.5103	0.0321	0.0294
System \times rootstock	0.1857	0.4088	0.6170	0.7805	0.8261	0.4437	0.4709
	2006/7						
Micro	129.8 b	65.5 b	9.28 a	48.4 b	13.23 b	0.47 a	0.45 a
Drip	145.8 a	68.7 a	7.99 b	71.8 a	14.01 a	0.42 b	0.40 b
Puls	147.1 a	68.5 a	8.04 b	71.9 a	13.74 a	0.42 b	0.41 b
SE (\pm)	2.30	0.41	0.13	2.57	0.13	0.01	
P-value							
System	0.0013	0.0026	<0.0001	<0.0001	0.0296	0.0491	0.0482
Rootstock	0.0390	0.3187	0.2655	0.1036	0.3627	0.3189	0.3179
System \times rootstock	0.6229	0.5660	0.5930	0.6520	0.1193	0.0258	0.0352

Table 3: Influence of the rootstock (M793 or M7) on yield (kg.tree⁻¹), yield (t.ha⁻¹), mean fruit weight (g), starch conversion (%), malic acid (%) and citric acid (%) in 2005/6, 2006/7 and 2007/8 in 'Brookfield Gala' apples grown under different water and nutrient strategies (micro sprinkler, daily drip, and pulsing drip irrigation). Probability values are according to split-plot ANOVA, followed by Tukey's multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different (P<0.05), n=8.

Treatment	Yield	Yield	Mean fruit weight		Starch	Malic acid		Citric acid	
	(kg.tree ⁻¹)	(t.ha ⁻¹)	(g)	(g)	conversion (%)	(%)	(%)	(%)	(%)
	2007/8	2005/6	2005/6	2006/7	2005/6	2005/6	2006/7	2005/6	2006/7
M793	25.48 a	51.0 a	145.3 a	146.2 a	40.3 b	0.45 a	0.46 a	0.41 b	0.41 b
M7	22.89 b	46.8 b	136.4 b	130.4 b	54.0 a	0.43 b	0.42 b	0.42 a	0.44 a
SE±	1.0234	2.0465	1.0256	2.5630	1.9652	0.5236	0.2563	0.1258	0.5262
P-value									
System	0.0193	0.0010					0.0491		0.0482
Rootstock	0.0935	0.0937	0.0007	0.0390	0.0104	0.0321	0.3189	0.0294	0.3179
System× rootstock	0.0309	0.0309					0.0258		0.0352

Table 4: Influence of different water and nutrient strategies ('Micro': micro sprinkler irrigation, 'Drip': daily drip irrigation, and 'Puls': pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstock on 'Brookfield Gala' growth parameters from 2004/5 to 2007/8. Data pooled across main effects and presented as system effect. Probability values are according to split-plot ANOVA, followed by Tukey's multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=8$.

Treatment	Trunk cross-sectional area (cm ²)				Trunk cross-sectional area increment (cm ²)			Total shoot length (cm)	
	2004/5	2005/6	2006/7	2007/8	2005/2006	2006/2007	2007/8	2005/6	2006/7
Micro	17.3 a	29.7 a	38.6 a	47.4 a	12.5 a	8.1 a	8.7 a	38.8 a	31.9 a
Drip	18.2 a	26.0 b	35.4 b	44.8 b	7.8 b	9.9 a	9.5 a	27.7 b	34.6 a
Puls	17.9 a	26.7 b	36.9 b	45.5 b	8.8 b	10.1 a	8.4 a	31.4 b	33.7 a
SE±	0.805	1.244	1.635	0.915	0.729	0.892	1.841	1.22	1.40
P-value									
System	0.1133	0.0510	0.0422	0.0356	0.0138	0.1245	0.5691	0.0005	0.4552
Rootstock	0.0222	0.0002	0.0465	0.0058	<0.0001	0.4526	0.2564	0.2064	0.1654
System × rootstock	0.4680	0.8627	0.9688	0.8567	0.2744	0.2845	0.2368	0.9758	0.8095

Table 5: Influence of the rootstock (M793 or M7) on trunk cross-sectional area and yield efficiency in 2004/5, 2005/6 and 2006/7 in ‘Brookfield Gala’ apples grown under different water and nutrient strategies (micro sprinkler, daily drip, and pulsing drip). Probability values are according to split-plot ANOVA, followed by Tukey’s multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=8$.

Treatment	Trunk cross-sectional area (cm ²)				Trunk cross- sectional area increment (cm ²)	Yield efficiency (kg/cm ²)		
	2004/5	2005/6	2006/7	2007/8		2005/6	2006/7	2007/8
M793	19.0 a	31.0 a	37.4 a	46.3 a	12.0 a	0.666 b	0.206 b	0.415 b
M7	16.6 b	24.0 b	27.5 b	32.7 b	7.3 b	0.974 a	0.316 a	0.689 a
SE±	0.657	1.016	0.965	0.145	0.729	0.055	0.022	0.045
P-value								
Rootstock	0.0222	0.0002	0.0465	0.0058	≤0.0001	0.0013	0.0033	0.0065

Table 6: Number of thin plus medium roots* of 'Brookfield Gala' apple trees grown under three water and nutrient management systems ('Micro': micro sprinkler irrigation, 'Drip': daily drip irrigation and 'Puls': pulsing drip irrigation). Data pooled over rootstocks to represent main effects of the different systems. Analysis done in January 2007. Probability values are according to split-plot ANOVA followed by Tukey's multiple range test at 5% level of significance. Root number is the average per 20cm³ soil. Mean values within a column followed by different letters are significantly different (P<0.05), n=3.

System	Thin plus medium roots*		Total number#
	Number of roots		
	0–400 (mm)	400–800 (mm)	
Micro	9.3 b	4.8 a	14.1 b
Drip	17.7 a	9.0 a	26.7 a
Puls	16.7 a	6.8 a	23.5 a
SE(±)	1.47	0.39	1.31
P-value			
System	0.0307	0.0946	0.0241
Rootstock	0.8477	0.0043	0.1721
System × rootstock	0.3740	0.8360	0.3289

*Thin plus medium roots comprise all roots less than 3mm in diameter, irrespective of the origin of the roots.

#Total number of roots from 0–800mm soil depth per 20cm³ soil.

Table 7: Weight of excavated thin plus medium roots* and thicker roots* of 'Brookfield Gala' apple trees growing under three water and nutrient management systems ('Micro': micro sprinkler irrigation, 'Drip': daily drip irrigation and 'Puls': pulsing drip irrigation). Data pooled to represent main effects of different systems. Harvest date 07/02/2008. Probability values are according to split-plot ANOVA followed by Tukey's multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=3$.

Treatment	Thin plus medium roots*		Thick roots#	
	Fresh weight	Dry weight	Fresh weight	Dry weight
	(g)	(g)	(g)	(g)
Micro	184.17 b	113.83 b	1096.67 a	679.00 a
Drip	331.67 a	205.60 a	983.17 a	668.33 a
Puls	371.67 a	230.33 a	950.00 a	619.33 a
SE(\pm)	19.83	19.05	145.82	82.59
P-value				
System	0.0493	0.0122	0.8132	0.8608
Rootstock	0.9074	0.8598	0.8873	0.4635
System \times rootstock	0.5854	0.2885	0.6423	0.979

*Thin plus medium roots comprise all roots less than 3mm in diameter, irrespective of the origin of the roots.

#Thicker roots include all roots greater than 3mm in diameter, irrespective of the origin of the roots.

Appendix: Additional data

Appendix 1, Table 1a: Fruit quality indices (after storage) of ‘Brookfield Gala’ apples grown under different water and nutrient strategies (‘Micro’: micro sprinkler irrigation, ‘Drip’: daily drip irrigation, and ‘Puls’: pulsing drip irrigation) on semi-vigorous M793 or semi-dwarfing M7 rootstock in 2005/6 and 2006/7. Samples were analysed after eight weeks of cold storage at -0.5°C in 2005/6 and 2006/7. Probability values are according to split-plot ANOVA, followed by Tukey’s multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=8$.

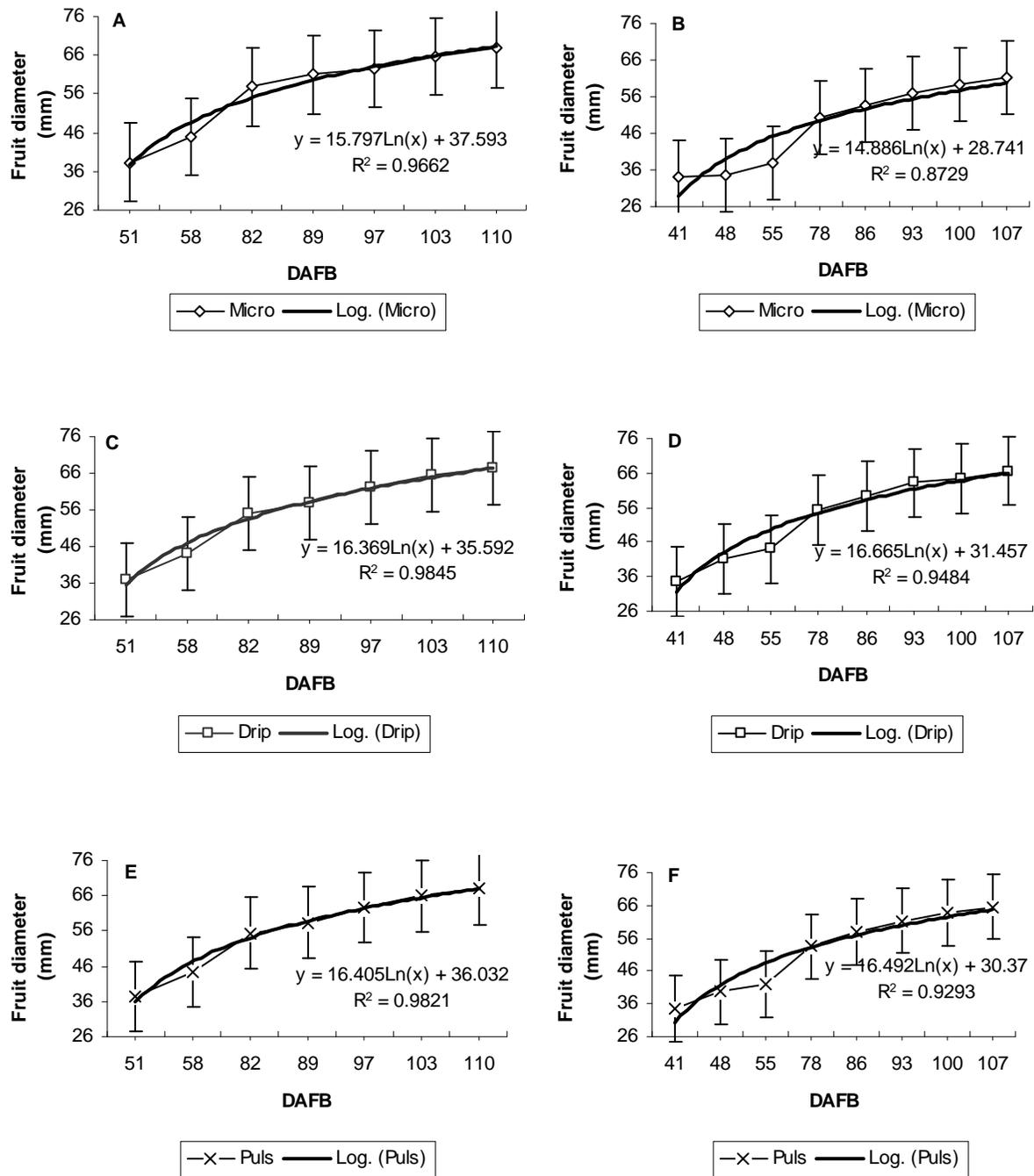
Treatment	Colour (chart)		Firmness (kg/cm^2)		Starch conversion (%)	
	2005/6	2006/7	2005/6	2006/7	2005/6	2006/7
Micro	3.85 a	3.66 b	7.58 b	8.53 a	83.5 a	64.1 b
Drip	3.94 a	3.90 a	7.94 a	7.45 b	71.2 b	77.9 a
Puls	3.89 a	3.77 ab	7.86 ab	7.39 b	74.5 ab	78.4 a
SE (\pm)	0.03	0.05	0.09	0.11	2.59	1.89
P-value						
System	0.3314	0.0216	0.0318	0.0019	0.0561	0.0026
Rootstock	0.0152	0.1106	0.1120	0.6252	0.0001	0.3891
System \times rootstock	0.8583	0.7055	0.2500	0.1111	0.2877	0.1857

Appendix 1, Table 1b: Fruit quality indices (after storage) of ‘Brookfield Gala’ apples (samples were analysed after eight weeks of cold storage at -0.5°C in 2005/6 and 2006/7), grown under different water and nutrient strategies (‘Micro’: micro sprinkler irrigation, ‘Drip’: daily drip irrigation, and ‘Puls’: pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstock in 2005/6 and 2006/7. Probability values are according to split-plot ANOVA, followed by Tukey’s multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n = 8$.

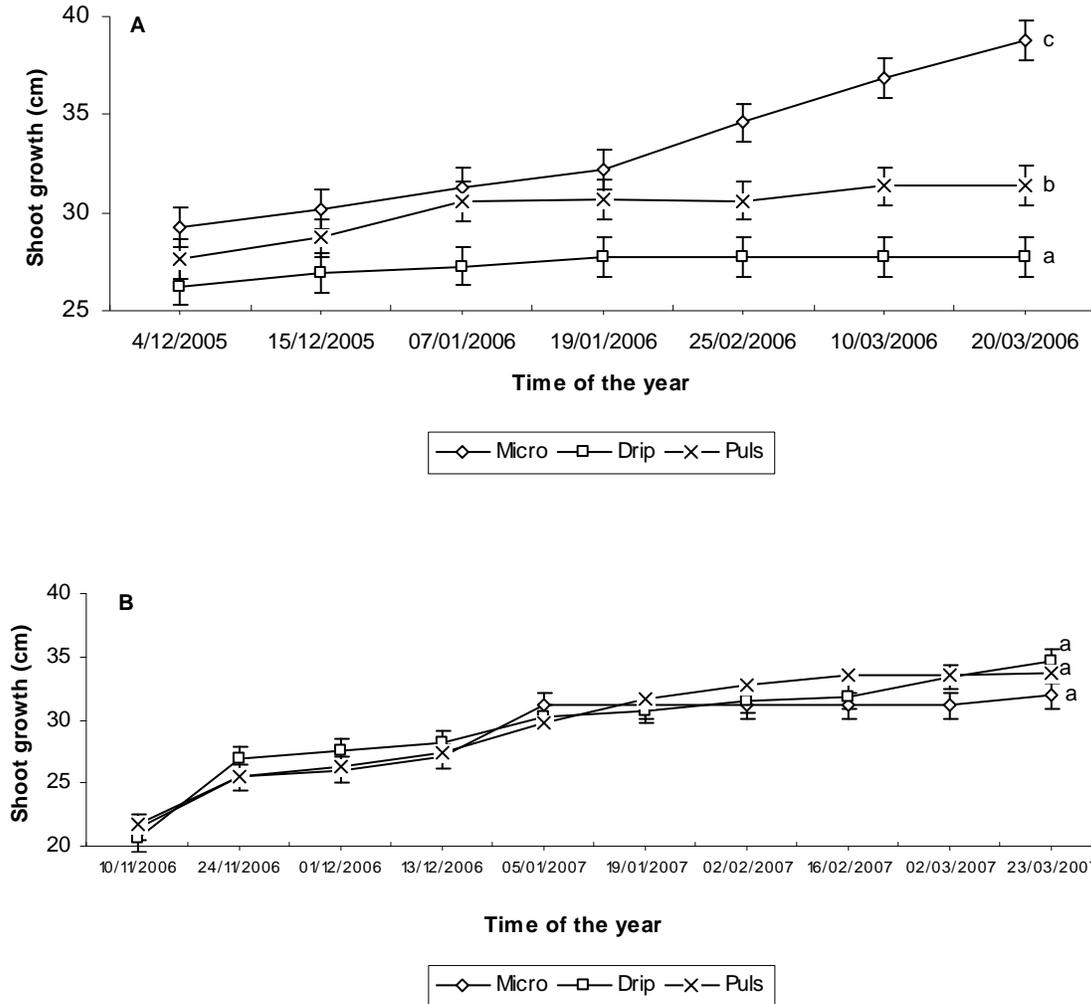
Treatment	TSS (% Brix)		Malic acid (%)		Citric acid (%)	
	2005/6	2006/7	2005/6	2006/7	2005/6	2006/7
Micro	13.04 b	14.12 a	0.44 a	0.44 a	0.42 a	0.42 a
Drip	14.48 a	14.31 a	0.46 a	0.38 b	0.44 a	0.36 b
Puls	14.20 a	14.34 a	0.44 a	0.38 b	0.42 a	0.36 b
SE (\pm)	0.11	0.18	0.01		0.01	0.01
P-value						
System	<0.0001	0.5481	0.2670	<0.0001	0.2868	<0.0001
Rootstock	0.0272	0.0473	0.0740	0.6827	0.0627	0.5722
System \times rootstock	0.6755	0.6374	0.1654	0.7972	0.1573	0.7648

Appendix 1, Table 1c: Fruit quality indices of ‘Brookfield Gala’ apples grown under different water and nutrient strategies (‘Micro’: micro sprinkler irrigation, ‘Drip’: daily drip irrigation and ‘Puls’: pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstock in 2005/6. Samples were kept for 10 days at room temperature (for shelf-life determination) following eight weeks in storage at -0.5°C . Probability values are according to split-plot ANOVA, followed by Tukey’s multiple range test at 5% level of significance. Mean values within a column followed by different letters are significantly different ($P < 0.05$), $n=8$.

Treatment	Firmness (kg/cm^2)	Starch conversion (%)	TSS (% Brix)	Malic acid (%)	Citric acid (%)
Micro	6.91 a	92.2 a	13.72 b	0.41 a	0.39 b
Drip	7.05 a	87.5 a	14.84 a	0.43 a	0.41 a
Puls	6.87 a	91.0 a	14.44 a	0.42 a	0.40 a
SE (\pm)	0.12	3.00	0.15	0.01	0.01
P-value					
System	0.4511	0.1473	0.0036	0.0692	0.0509
Rootstock	0.7300	0.1256	0.4277	0.2001	0.2019
System \times rootstock	0.6892	0.4189	0.6892	0.9774	0.9782



Appendix 1, Fig. 1: Fruit diameter growth (measured in mm) in ‘Brookfield Gala’ trees under three water and nutrient strategies, namely micro sprinkler irrigation (‘Micro’, A and B), daily drip irrigation (‘Drip’, C and D) and pulsing drip irrigation (‘Puls’, E and F). Measurements were taken in 2005/6 (A, C and E) and 2006/7 (B, D and F). Abbreviation: DAFB (days after full bloom).



Appendix 1, Fig. 2: Extension shoot length growth in 'Brookfield Gala' under three irrigation and nutrient strategies, namely micro sprinkler irrigation ('Micro'), daily drip irrigation ('Drip'), and pulsing drip irrigation ('Puls'). Different letters following one another in a figure symbolises significance at $P \leq 0.05$. Data pooled to represent only the main effects of irrigation and nutrient strategy, since there was no rootstock effect. Measurements were taken bi-weekly during 2005/6 (A) and 2006/7 (B).

Appendix 2, Plate 1: 'Brookfield Gala' apple tree roots budded on M793 rootstock under micro sprinkler irrigation (root studies done Jan 2007).



Appendix 2, Plate 2: 'Brookfield Gala' apple tree roots budded on M7 rootstock under micro sprinkler irrigation (root studies done Jan 2007).



Appendix 2, Plate 3: 'Brookfield Gala' apple tree roots budded on M793 rootstock under daily drip irrigation (root studies done Jan 2007).



Appendix 2, Plate 4: 'Brookfield Gala' apple tree roots budded on M7 rootstock under daily drip irrigation (root studies done Jan 2007).



Appendix 2, Plate 5: 'Brookfield Gala' apple tree roots budded on M793 rootstock under pulsing drip irrigation (root studies done Jan 2007).



Appendix 2, Plate 6: 'Brookfield Gala' apple tree roots budded on M7 rootstock under pulsing drip irrigation (root studies done Jan 2007).



4. Photosynthetic capacity and diurnal gas exchange of ‘Brookfield Gala’ apple leaves under three irrigation systems and two rootstocks

Abstract. Water and nutrient application using three irrigation systems, namely daily drip irrigation applied once to twice daily, pulsing drip irrigation applied several times a day, and micro sprinkler irrigation applied once or twice a week, were studied with respect to photosynthetic efficiency and leaf water relations in ‘Brookfield Gala’ apple trees during 2004/05 and 2005/06 in the Western Cape Province, South Africa. Trees were budded on either M793 or M7 rootstocks and planted in blocks using a split-plot experimental design with irrigation as the main effect and rootstock as the sub-plot. Photosynthetic response curves were generated on two mid-season days during each season and diurnal measurements were conducted prior to harvest. There were no main effects of rootstock or interactions between rootstock and irrigation treatments. Maximum light-saturated net CO₂ assimilation rate (A_{\max}) was consistently higher under pulsing drip irrigation compared to micro irrigation but significantly higher than daily drip irrigation only on one measurement date. From CO₂-response curves of A, the maximum rate of electron transport (J_{\max}) showed similar trends to A_{\max} during 2004/05, but not during 2005/06. The maximum rate of carboxylation by rubisco ($V_{c_{\max}}$) was lowest under micro irrigation, highest under daily drip irrigation, and intermediate under pulsing drip irrigation on the first day of 2005/06 only. A_{\max} peaked during midmorning (10h00) with a steady decline thereafter in all treatments, but with significantly lower rates under micro irrigation. Stomatal conductance (g_s) declined steadily throughout the morning, with higher g_s under the drip based systems compared to the micro system. Intrinsic water use efficiency (A_{\max}/g_s , WUE_i) was highest around noon (12h00) and lower under micro during early morning, early afternoon and late afternoon. Leaf water potential (ψ_l) was lower under micro than under drip systems between 08h00 and 14h00, with daily drip treatment having lower ψ_l than the pulsing drip during this period on 01/02/06. The implications are that irrigation application should be given early in the morning to sustain stomatal conductance and maximise CO₂ assimilation rates during the period between 08h00 to 12h00. End-season leaf chlorophyll concentrations (both seasons), area-based leaf nitrogen concentration (2004/05), and photosynthetic nitrogen use efficiency (2005/06) were lower under micro irrigation compared to both daily drip and pulsing drip irrigation. Results indicate higher photosynthetic capacity and

water use efficiency under both drip-based irrigation systems compared to micro irrigation. Differences in photosynthetic capacity were related to both stomatal and non-stomatal responses.

Key words: Daily drip irrigation, micro sprinkler irrigation, intrinsic photosynthetic water use efficiency, photosynthesis, stomatal conductance, water potential

4.1 Introduction

Water is a limited resource in South Africa. A high and increasing demand for water from agriculture, industry and towns puts a high demand on available water (Binns *et al.*, 2001). As a result, more efficient water management practices in deciduous fruit orchards are being developed to use scarce resources more efficiently, without forfeiting yield and fruit quality. Most of the apple (*Malus* spp.) orchards in the main apple production areas are still under medium density cropping. However, there has been a move to higher density orchards with planting densities of 1900 to 2500 trees per hectare. These higher density orchards have improved production efficiencies, but require more intensified irrigation systems. Currently, many producers make use of micro irrigation systems with hand fertilisation. However, new drip irrigation technologies and irrigation scheduling practices show a great potential for improving fruit quality and yield whilst minimising water use. Although very few studies have compared different irrigation systems in apples (e.g. micro sprinkler irrigation versus drip irrigation), it is widely believed that drip irrigation holds many benefits in terms of reduced water use (Elfving, 1982; Fallahi *et al.*, 2006; Wang *et al.*, 2006), allows irrigation according to consumptive water use, maintains soil water tension close to optimum available water for plants, restricts root volume thus allowing higher density per hectare and finally affects the balance of physiological processes such as fruiting and vegetative growth (Assaf *et al.*, 1984). Improved irrigation scheduling, for example by optimising application frequencies or times of application, could also hold benefits for fruit production and lead to more efficient water use.

Modern medium to high density apple orchards (including those in South Africa) use composite plants made up of an aboveground scion budded or grafted onto a clonally produced rootstock (Atkinson, 2001). Currently, dwarfing rootstocks such as M7 and the semi-vigorous rootstock M793 are used by most apple producers in South Africa. Use of these rootstocks has been found to

reduce vegetative growth, allowing reduction of row spacing and thereby increasing tree densities per hectare compared with more vigorous rootstocks. Apple trees are known to have high resistances to water transport from roots to shoots (low root hydraulic conductance) which causes marked effects of transpiration on water potential in the top of the tree (Landsberg & Jones, 1981; Schulze, 1986; Flore & Lakso, 1989). Transpiration and leaf water status are strongly dependent on the evaporative demand (VPD, leaf-to-air vapour pressure deficit) of the atmosphere (Jones, 1998). Leaf water status varies considerably diurnally and water deficits may occur under high evaporative demands even though soil water is adequate (Landsberg & Jones, 1981; Flore & Lakso, 1989). Net CO₂ assimilation rate is usually highest before noon as a result of high incident irradiance but moderate VPD, and decreases in the afternoon as a result of stomatal closure in response to high VPD (Schulze *et al.*, 1974; Kriedman *et al.*, 1976; Cheng *et al.*, 2001), and photo-assimilate feedback inhibition in apple trees (Flore & Lakso, 1989; Cheng *et al.*, 2001).

The influence of different irrigation systems and scheduling treatments on leaf photosynthetic characteristics, stomatal behaviour, leaf water potential, and leaf water use efficiency in apple trees has not been well studied. Use of drip irrigation systems has been considered as an alternative (to evaporative cooling) in reducing stomatal closure during midday and increasing biochemical photosynthetic capacity (Goldhamer, 1996; Romero and Botía, 2006). Current reviews focus more on deficit irrigation scheduling than on the irrigation systems used in apple orchards. These reviews found that deficit irrigation in apples reduces fruit growth, fruit size and yield if applied early in the growing season (Mills *et al.*, 1997; Bussakorn *et al.*, 2001; Naor, 2001), but not if applied late in the season. Interactive effects between deficit irrigation scheduling and crop load on fruit size have been associated with effects on tree and fruit water relations and photosynthetic rates. Apple trees are known to lose a lot of water to transpiration during CO₂ assimilation via the stomata (Cheng & Luo, 1997). Research by Lakso (1985; 1986) on photosynthesis in fruit trees in relation to environmental factors found that as water deficit occurs stomatal conductance declines proportionally to decreases in photosynthetic capacity to maintain high water use efficiency. Leaf water potential (which is a measure of plant water status) is dependent on the soil water, tree evaporative demand, stomatal closure and on flow resistance in the transport pathway (Landsberg & Jones, 1981). Stomatal aperture (stomatal resistance to gas exchange) is affected by light, VPD, CO₂ concentration and leaf water status (Flore & Lakso, 1989). To coordinate CO₂ gain, water loss

and energy balance, stomata must be able to adjust their aperture in response to environmental signals such as VPD, and internal signals from water potential and demand for intercellular CO₂ (C_i).

Chun *et al.* (2002) and Fallahi *et al.* (2002) studied the role of rootstocks on photosynthesis, yield, fruit quality and leaf nutrition in apples. Leaves from trees on more vigorous rootstocks had higher photosynthetic rates than those on dwarfing rootstocks, but yield and quality were higher on dwarfing rootstocks. There is little information on photosynthetic efficiency, water use efficiency and stomatal conductance in apple trees under higher density orchards in South Africa (Pretorius & Wand, 2003).

The objective of this study was to investigate apple leaf photosynthetic efficiency and water relations under three irrigation systems in a high density apple orchard, using 'Brookfield Gala' trees budded on semi-dwarfing M7 and semi-vigorous M793 rootstocks. The research hypothesis was that more frequent fertigation using a drip irrigation system would reduce tree stress levels in comparison with less frequent water application using a micro irrigation and hand fertilisation, thus reducing stomatal closure at midday as well as increasing biochemical photosynthetic capacity. In addition, it was expected that multiple applications per day (simulating a hydroponic system) would give better results than a conventional single daily application under a drip system, especially on the dwarfing rootstock.

4.2 Materials and Methods

4.2.1 Study site and plant material

The orchard was established in June 2003 in Genadendal, Western Cape Province, South Africa (34°03'S, 19°37'E). *Malus x domestica* Borkh 'Brookfield Gala' scions were budded on dwarfing M7 and standard M793 rootstocks and planted in a NE-SW row orientation at a spacing of 4.0m × 1.25m with a total of 2000 trees/ha. The soil was a sandy loam (Dundee soil series). Pre-plant soil preparation included rectification of soil pH to approximately 5.5 (KCl) and phosphorus to 30mg/kg (Bray II, as extraction solution). Trees were trained to a central leader spindle, using a four-wire support system with lateral branches bent according to the French solaxe principle (details in Chapter 2).

4.2.2 Experimental design and irrigation treatments

A split-plot design was used with irrigation treatments as main plots and rootstocks as sub-plots. The treatments were replicated in eight blocks and each experimental unit consisted of five trees and only the middle tree was used for the measurements. The irrigation treatments were a daily drip system with water applied once to twice daily, a pulsing drip irrigation system where water was applied between one to six times a day, and a micro sprinkler irrigation system with water applied once to three times a week (depending on the daily maximum temperatures). All the measurements were taken within one day after irrigation applications in micro irrigation. Each rootstock was randomly allocated in each system in each of the eight blocks. The actual water use for daily drip irrigation was 3429 and 3926m³.ha⁻¹.yr⁻¹ for 2004/5 and 2005/06 respectively, whilst pulsing drip irrigation used 3429 and 4047m³.ha⁻¹.yr⁻¹ for 2004/5 and 2005/06, respectively. The total annual amount of water needed was divided into monthly instalments according to the above-mentioned data and then distributed into phenological stages. Due to the inefficient water application of the micro sprinkler irrigation system, as a result of droplet drift, droplet evaporation, and a greater application radius, more water was required (5254 and 5661m³.ha⁻¹.yr⁻¹ in 2004/5 and 2005/6, respectively). Irrigation scheduling was based on soil moisture sensors, dendrometers, weather data, root and soil characteristics, and tree developmental stage (details in Chapter 2).

Earlier work by Stassen & North (2005) studied the annual nutritional requirements for pear trees. The guidelines developed from this study and studies done on 'Royal Gala' apple in Viliersdorp were adopted and the nutrients were applied in instalments distributed throughout the year based on the phenological stage of the tree and minor amendments were done accordingly (Chapter 2). Water and nutrient application were applied based on the above mentioned information using a computer program (P.G. Mostert, 2004, personal communication). In the micro sprinkler irrigation system the macro and micro elements were applied by hand within the drip row, which might have played a very significant role in the observed results. Nitrogen was given in five applications, K in three and all other nutrients in two applications according to standard commercial applications. Fruit thinning and pruning were done according to standard commercial practices (details in Chapter 2).

4.2.3 Light and CO₂ response curves

Photosynthetic light response curves were generated at air temperatures of 25°C, and an air-to-leaf vapour pressure deficit (VPD) of 1.0 to 2.0kPa. Cuvette CO₂ concentration was controlled at 380 μmol.mol⁻¹ with a CO₂ injection system and compressed CO₂ cylinders using a LI-6400 infrared gas analyzer (Li-Cor, Lincoln, Nebraska, USA) during two mid-season dates (12 Jan. 2005 and 01 Feb. 2005 in 2004/5 and 10 Jan. 2006 and 01 Feb. 2006 in 2005/6) prior to harvest. Fruits were harvested on 6 Feb. 2005 for the 2004/05 season and on 7 Feb. 2006 for the 2005/06 season. Irradiance levels of 2000, 1500, 1000, 800, 600, 400, 200 100 and 0 μmol.m⁻².s⁻¹ photosynthetic photon flux density (PPFD), provided by an internal red/blue LED light source, were used. One sun-exposed leaf on the west side of the tree was measured per tree per block. Only five replications were used for these measurements (n=5). The response of net CO₂ assimilation rate (A) to PPFD was modelled by a non-rectangular hyperbola where the initial slope represents the apparent quantum efficiency (QE), the rate of dark respiration was taken from the y-axis intercept, and the light-saturated A (A_{max}) was determined as the upper asymptote (Prioul & Chartier, 1977). Leaf stomatal conductance (g_s) was obtained from system equations derived by Von Caemmerer & Farquhar (1981). Intrinsic water use efficiency (WUE_i) was determined as the ratio of A_{max} to g_s.

Photosynthetic CO₂ response (A/Ci) measurements was determined on sunny exposed leaves under the following conditions: air temperature of 25°C, VPD of 1.0-2.0kPa (obtained by manipulating the flow rate through the desiccant) and PPFD of 1500 μmol. m⁻². s⁻¹ (provided by internal red/blue LED light source) during two mid-season dates (same dates as light response curves) prior to harvest, in 2004/05 and 2005/06. CO₂ was supplied by compressed CO₂ cylinders at cuvette CO₂ concentrations of 380, 300, 150, 100, 50, 380, 600, 800 and 1000 μmol.mol⁻¹. One sun-exposed leaf on the west side of the tree was selected per tree per block. The mechanistic model proposed by Farquhar *et al.* (1980) and later modified by Von Caemmerer & Farquhar (1981), Sharkey (1985) and Harley *et al.* (1992) was used to estimate the maximum rate of carboxylation (V_{cmax}) and the light-saturated rate of electron transport (J_{max}).

4.2.4 Diurnal gas exchange measurements and leaf water potential measurements

Diurnal gas exchange measurements were taken two-hourly between 06h00 and 18h00 under ambient sunlight and temperature conditions on 4 Feb. 2005 and 1 Feb. 2006 using the LI-6400

infra-red gas analyzer (Li-Cor, Lincoln, Nebraska, USA). The daily solar radiation was tracked using a Li-190SA quantum sensor (Li-Cor, Lincoln, Nebraska, USA). Intrinsic water use efficiency (WUE_i) was determined from the ratio of net CO_2 assimilation rate to stomatal conductance (A/g_s). Two leaves per plot were measured from six blocks.

Diurnal water potential measurements were done on the same days as the above measurements using a pressure chamber (PCI 600, PMS Instrument Co., Corvallis, Oregon, USA). At each sampling date three leaves per tree per treatment in six blocks were measured. Leaves were covered prior to the measurement with a black plastic zip lock bag. Measurements were done from 06h00 to 18h00 at intervals of 2 hours.

4.2.5 Chlorophyll and leaf nitrogen analysis

Fresh leaves were picked immediately after fruit were harvested and kept on ice in the dark until frozen in liquid nitrogen in the laboratory. Five leaves per treatment in six blocks were used. Three discs of 8-mm diameter each were extracted in 80% (v/v) acetone and ground with granite sand (Arnon, 1949). The extracted solution was centrifuged at $20,000 \times g$ for 10 minutes and stirred in the dark for 24 hours at $4^\circ C$. The absorbance of the supernatant was read at 470nm, 647nm and 663nm using a spectrophotometer (Cary 50 Bio, UV-visible Spectrophotometer, Varian Australia Pty Ltd., Australia). Concentrations of chlorophyll a (chl_a), chlorophyll b (chl_b) and total chlorophyll (chl_t) were determined using published equations (Lichtenthaler, 1987). Leaf nitrogen concentration was analysed by a commercial laboratory (Bemlab, Strand, South Africa) using a nitrogen analyzer (LECO FP528 Nitrogen analyzer, LECO Cooperation, St. Joseph, Michigan, USA) and expressed on a leaf area basis (N_a).

4.2.6 Relationships between A_{max} , g_s and N_a

Data obtained from photosynthetic light response curves and leaf chemical analyses were used to establish relationships between A_{max} , g_s , R_d (dark respiration), chl_t, and N_a for each irrigation treatment. Only the relationships between A_{max} and g_s (indicating intrinsic photosynthetic water use efficiency, WUE_i), and between A_{max} and N_a (indicating intrinsic photosynthetic nitrogen use efficiency, PNUE) showed clear trends and are presented.

4.2.7 Statistical analysis

Data were analyzed using a split-plot analysis of variance (ANOVA) with irrigation treatments as the main factor and rootstock as the sub-factor for both gas exchange and diurnal measurements (SAS GLM procedure, Enterprise Guide 6, release 1.3 SAS Institute, Cary, NC, USA, 2001). Mean separation was by Tukey's studentized range test ($P \leq 0.05$).

4.3 Results

4.3.1 Photosynthetic light and CO₂ response curves

There were no differences in A_{\max} , J_{\max} and $V_{c\max}$ between the two rootstocks (M793 and M7) and there was no interaction between irrigation systems and rootstocks. As a result the data were pooled and presented as main effects of the three irrigation systems. A_{\max} was higher in the pulsing drip system (on one measurement date, 1 Feb. 2005) than under the daily drip system, and the micro system was the lowest in both seasons (Table 1). There were no significant treatment differences in QE and g_s in the two seasons studied except on 1 Feb. 2006 in 2005/6 (Table 1). Higher J_{\max} was found in the 2004/05 season on both dates, but not in 2005/06 (Table 2). The two drip systems showed higher J_{\max} than the micro sprinkler system except on 1 Feb. 2005, where daily drip was not significantly different to micro sprinkler system. Increased rates of $V_{c\max}$ (2004/05) date 1 and J_{\max} (2005/06) date 1 and date 2 were observed (but were not significantly different) in trees under drip systems than in micro sprinkler irrigated trees. J_{\max} to $V_{c\max}$ ratio ranged from 1.4 to 2.9 (Table 2) in this study.

4.3.2 Leaf chlorophyll and nitrogen concentration

The type of rootstock used did not affect leaf chlorophyll or nitrogen concentrations (Table 3). Leaf chl_a, chl_b and chl_t concentrations were significantly higher under pulsing drip and daily drip irrigation systems than under the micro system in both seasons, except that chl_a was not significantly different between micro and daily drip systems in 2005/06 (Table 3). Leaf nitrogen concentration expressed on a leaf area basis was significantly higher in the two drip based systems than in the micro sprinkler system in 2004/05 but not in 2005/06. There were no differences in specific leaf area (SLA) between the three irrigation systems (Table 3).

4.3.3 Relationships between A_{\max} , g_s and N_a

A linear, positive relationship (R-squared) was found between A_{\max} and g_s (intrinsic photosynthetic water use efficiency, WUE_i) for each irrigation system (Fig. 1A). These showed no apparent differences between irrigation systems in the slope, but higher A_{\max} at comparable g_s (and thus higher WUE_i) under both drip systems compared to the micro system. A linear positive relationship existed between A_{\max} and N_a (photosynthetic nitrogen use efficiency, PNUE) for all three systems, though this could not be ascribed to be significantly different (Fig. 1B). Under both drip systems, PNUE was higher than under the micro sprinkler system (Fig. 1B).

4.3.4 Diurnal gas exchange and leaf water potential

PPFD and VPD showed low values in the morning and peaked during midday, remaining high in the early afternoon and declining in the late afternoon (Figs. 2A and B). The diurnal course for net CO_2 assimilation rate (A) was low early in the morning, peaking at mid-morning (10h00), whereafter it decreased gradually for the remaining time in all systems (Figs. 2C and D). The two drip systems had significantly higher A than the micro system on both dates throughout the day. However, the pulsing drip system had significantly higher A than daily drip on 4 March 2005 (06h00) and on 1 Feb. 2006 (10h00 and 18h00) (Figs. 2C and D). The g_s levels were highest in the early morning and decreased continuously during the course of the day, in all systems (Figs. 2E and F). There were significant differences between the three systems with the two drip systems experiencing a higher stomatal conductance than the micro sprinkler system, except on 04/02/05 (08h00 and 18h00) and on 1 Feb. 2006 (08h00, 10h00 and 12h00), when no differences were observed. The intrinsic WUE_i (A/g_s) increased steadily through the morning until midday due to reductions in g_s but maintenance of high A, and decreased during the afternoon with reductions in A (Figs. 2G and H). Pulsing drip and daily drip systems had higher WUE_i than the micro sprinkler system at those times when differences in A were high but differences in g_s were absent or low, for example at 08h00 on both dates. No differences in WUE_i were found on both dates at 10h00, 12h00 and 16h00 (Figs. 2G and H).

The diurnal course of leaf water potential showed high leaf water potential in the early morning followed by a steady decline until 12h00 and partial recovery for the remainder of the day (Figs. 3A and B). Trees under the micro system had a significantly lower leaf water potential than those

under pulsing drip irrigation and daily drip irrigation systems between 08h00 and 14h00 (Figs. 3A and B). No significant differences in leaf water potential were found between pulsing and daily drip irrigation systems.

4.4 Discussion

Higher diurnal gas exchange activity was observed in mid-morning measurements than in the afternoon with a maximum peak of A_{\max} , g_s and WUE_i before noon in all treatments. For an apple tree it appears likely that the most suitable time for high growth rates and increased leaf photosynthetic capacity occurs during 08h00 to 12h00. This implies that irrigation application should start early in the day to sustain stomatal conductance and CO_2 assimilation rates during this period (08h00 to 12h00). Higher values (A_{\max} , J_{\max} and $V_{c_{\max}}$) were observed in the pulsing drip system and daily drip system than in the micro sprinkler irrigation system. The frequent application of water on a daily basis improved growth (shoot growth and fruit growth, Chapter 3) and this in turn increased the demand for carbohydrates (photoassimilates) to compensate for more growth. Similar results have been obtained in almond (*Prunus amygdalus*) (Wartinger *et al.*, 1990) and in olives (*Olea europaea*), peach (*Prunus persica*) and apricot (*Prunus armeniaca*) (Larsen *et al.*, 1989). Reductions in A_{\max} and g_s as well as increases in transpiration when water stress increases could be assumed to be the effects of non-stomatal limitation of A_{\max} in the afternoon as a result of increased oxygenase activity of rubisco enzyme stimulated by leaf temperature which, in spite of increased transpiration, was higher in the morning (Cheng & Luo, 1997). The mechanism by which water stress affects photosynthetic capacity is not fully understood. Reduction in electron transport (Wong *et al.*, 1985) and/or a reduction in quantum yield of CO_2 fixation in leaves (Mohanty & Boyer, 1976) are possible. There were no increased rates in either the carboxylation efficiency or quantum efficiency due to use of different systems in this study except for J_{\max} and A_{\max} . However, irrespective of the way mesophyll energy transduction is affected, there is a possibility that similar effects are occurring in guard cells. The coincident decline in A_{\max} with the highest VPD suggests that this may be an important signal of the afternoon decline of A_{\max} (Singsaas *et al.*, 2000). VPD response included reductions in the carboxylation efficiency of the mesophyll, an effect commonly associated with the midday decline in A_{\max} (Geiger & Servaites, 1994). A report on VPD mediation and mesophyll sensitivity to the rate of transpiration has been published (Sharkey, 1984).

Net photosynthetic capacity under near optimal ambient environmental conditions of mature apple leaves often depends on the level of leaf nitrogen and the inter-specifications between leaf ontology expressed in leaf thickness/density (low specific leaf area, SLA). The three key parameters of photosynthesis increased linearly with increases in N_a in this study. Such linear relationships have been reported for different plant species, e.g. in cotton (*Gossypium hirsutum*) (Harley *et al.*, 1992) and *Pinus radiata* D. Don (Walcroft *et al.*, 1997). The dependency of chlorophyll membranes on PPFD has been mentioned in many studies (Cheng *et al.*, 2001; Warren & Adams, 2001). In this study both the drip systems showed higher total chlorophyll concentration than the micro system, and this led to higher A_{max} and g_s (Warren & Adams, 2001). The relationship between total chlorophyll and either A_{max} or g_s is dependent on the partitioning of non-cyclic electron flow between CO_2 assimilation and other electron sinks, such as nitrate reductions (Warren & Adams, 2001).

The chlorophyll concentration has been found to increase more with frequent application of water than in weekly irrigated trees, in spite of the same PPFD conditions under which the leaves were collected (Fig. 2A and B). This is thought to play a significant role in increases in A_{max} , g_s and WUE_i observed under pulsing drip and daily drip systems. There was a direct relationship between A_{max} and leaf N concentration on both area and weight basis. Increased leaf nitrogen was mainly associated with high A_{max} , g_s and WUE_i in the pulsing drip system and the daily drip system. Chun *et al.* (2002) reported higher A_{max} rates and leaf N concentrations in apple trees receiving higher N by micro sprinkler fertigation. The results are also consistent with a model of plant growth in which net C gain of the leaf is maximized when the leaf N is at an optimum (Gulman & Chu, 1981).

Other studies on irrigation and leaf photosynthesis have indicated benefits of using drip irrigation systems over micro irrigation systems (Mitchell & Chalmers, 1983, Fallahi *et al.*, 2008a). Drip based systems are known to improve tree fruit growth (less vigour, more bearing branches); trees crop early as a result of restricted root volume (Mitchell & Chalmers, 1983). In this study the micro irrigation wetted a surface area of the 1.2m-wide strip of the drip line and it could therefore be expected that this could encourage a larger root volume than in the drip systems where water

distribution usually forms a 'pot' around the emitter (Chapter 2). Mitchell & Chalmers (1983) in their studies on peaches found that micro irrigation delayed cropping and encouraged vegetative growth, and recommended that a micro system is a less suitable irrigation method for high density plantings. In Chapter 3 it was shown that the micro system had a more vigorous growth as evident by the rapid shoot growth; however, drip based systems showed a more restricted growth irrespective of the rootstock used. Again in Chapter 3 there was higher fruit yield under drip based systems (2005/6) than under the micro system but not during 2006/7 when the crop load was low. This is further supportive of results from other studies that photosynthesis is usually low under non-bearing trees than under bearing trees (Fallahi *et al.*, 2008b). Similar patterns have been observed in 'Royal Gala' and 'Fuji' apples where higher yields were recorded which corresponded with increased photosynthesis rates under heavy fruit load than under light fruit load (Fallahi *et al.*, 2008a). The results, therefore suggest that there is greater control of growth under drip irrigation systems with a well developed canopy, which allows proper light penetration and distribution to the spurs encouraging higher rates of A_{max} , WUE_i and PNUE than in a micro sprinkler irrigation system. In the micro sprinkler irrigation system the smallest wetted soil volume was observed on both vertical and horizontal axes (Chapter 3, Plates 1 and 2). Soil moisture tension remained within <30kPa in the upper 400mm and 40–60kPa within 400–800mm depths; this was found to be relatively dry compared to the drip irrigation systems where soil moisture tensions remained within <20kPa at 0–200mm soil depths, <40kPa at 200–400mm and \pm 60kPa at 400–800mm (Chapter 2). The results agree with studies by Assouline (2002) who found that micro sprinkler irrigation results in variable water for a specified diurnal period due to periodic wetting and drying, resulting from water applied at specific intervals, e.g. two to three times a week (in this study).

The rootstocks did not exert any significant effect in our study nor were there interactions with the type of irrigation system; however, M793 was more vigorous and had a higher trunk circumference area (TCA) than M7 which had greater yield efficiency (Chapter 3). Our studies also did not show any significant differences in gas exchange measurements and water use efficiency, despite evidence from other studies showing higher physiological tree performance (high A_{max} and water use) of apple trees on vigorous rootstocks than on dwarfing rootstocks (Ferree & Barden, 1971; Olien & Lakso, 1986; Schechter *et al.*, 1991; Bauger *et al.*, 1994, Fallahi *et al.*, 2008a, b). However, studies by Barden & Ferree (1979) showed no effect of rootstock on leaf photosynthesis,

dark respiration and transpiration of apple leaves. Trees in this study were young (1st leaf and 2nd leaf) and with future development and full establishment there may be some differences in leaf photosynthetic capacity between the two rootstocks.

The variations in leaf water potential are believed to have been caused by the temporal variations in evaporative demand concurrent to the correlation between stomatal conductance with leaf water potential. Trees grown under the micro system were seen to be under a relative stress (-2.5MPa) at noon to early afternoon, further implying the increase in evaporative demand due to weekly irrigation under this system. These results are in agreement with earlier studies in apples by Goode *et al.* (1979) and Jones & Higgs (1979), where the leaf water potential for well-watered apple leaves was between -0.6 to -2.0MPa and for stressed apple leaves between -1.9 and -2.5MPa . The minimum water potential was observed during maximum evaporative demand, which may be due to imbalances between different rates of absorption of water in the roots and xylem transport and rates of water loss by transpiration (Romero & Botía, 2006).

Apple tree gaseous exchange and water relations can be improved under field conditions in South Africa. The apple trees 'Brookfield Gala', in this study showed maximum leaf photosynthetic capacity at mid-morning and rates only decreased at 14h00 with no further recoveries in the afternoon (Chapter 5). From these diurnal photosynthesis curves it can be concluded that irrigation scheduling can, therefore, be applied early in the morning (06h00) to sustain stomatal conductance and further increase leaf photosynthetic activity during 08h00 to 12h00. This might further have significant effects on mitigating midday depression that continues in the afternoon. Irrespective of the amount of water in the soil leaf photosynthesis declines in the afternoon, because of closure of stomata (lower conductance) as a result of increased VPD and temperature. More refined irrigation systems can increase photosynthetic efficiency and leaf water potential in 'Brookfield Gala' apples. In this study, pulsing drip irrigation and daily drip irrigation systems were found to be better compared to the micro sprinkler irrigation system under high density apple plantations conditions. Maximum gain in photosynthetic efficiency during periods of low VPD and temperature has shown to increase apple yield and quality (Chapter 3).

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Table 1: Mean values for light-saturated net CO₂ assimilation rate (A_{\max}), apparent quantum efficiency (QE), and stomatal conductance (g_s) of apple leaves grown under micro sprinkler, daily drip or pulsing drip irrigation systems. Measurements were taken at air temperature of 25°C, leaf-to-air vapour pressure deficit of 1-2 kPa and carbon dioxide concentration of 380 $\mu\text{mol. mol}^{-1}$ on fully exposed spur leaves on the west side of the trees. Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=5$). SE = standard error of the mean at 5% probability level. Mean values followed by different letters in columns are significantly different, ns: not significant ($P > 0.05$).

Date	Treatments	2004/05		
		A_{\max} ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)	QE ($\mu\text{mol. mol}^{-1}$)	g_s ($\text{mol. m}^{-2}. \text{s}^{-1}$)
12 Jan. 2005	Micro	15.4 b	0.066 ns	0.504 ns
	Drip	20.1 a	0.039	0.517
	Puls	22.3 a	0.050	0.691
	SE(\pm)	1.27	0.021	0.153
	P-value			
	System	0.0015	0.2515	0.6669
	Rootstock	0.9185	0.5615	0.5763
	System \times rootstock	0.6256	0.5482	0.9613
<hr/>				
01 Feb. 2005	Micro	16.0 b	0.055 ns	0.257 ns
	Drip	18.8 b	0.051	0.268
	Puls	23.1 a	0.053	0.382
	SE(\pm)	1.41	0.004	0.047
	P-value			
	System	0.0003	0.4652	0.2649
	Rootstock	0.7393	0.6294	0.9465
	System \times rootstock	0.9867	0.7971	0.2004
<hr/>				
		2005/06		
		A_{\max} ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)	QE ($\mu\text{mol. mol}^{-1}$)	g_s ($\text{mol. m}^{-2}. \text{s}^{-1}$)
10 Jan. 2006	Micro	14.3 b	0.059 ns	0.366 ns
	Drip	17.9 ab	0.053	0.408
	Puls	19.6 a	0.053	0.550
	SE(\pm)	1.58	0.007	0.084
	P-value			
	System	0.0215	0.7992	0.2429
	Rootstock	0.0679	0.1817	0.7457
	System \times rootstock	0.3108	0.3702	0.1139
<hr/>				
01 Feb. 2006	Micro	14.3 b	0.053 ns	0.192 a
	Drip	19.8 a	0.053	0.302 b
	Puls	21.6 a	0.055	0.310 b
	SE(\pm)	1.30	0.006	0.052
	P-value			
	System	0.0078	0.8584	0.0022
	Rootstock	0.7510	0.7755	0.3813
	System \times rootstock	0.5985	0.2329	0.4692

Table 2: Mean values for the light- and CO₂-saturated rate of electron transport (J_{\max}) and rate of carboxylation by rubisco ($V_{c_{\max}}$) by apple leaves grown under micro sprinkler, daily drip or pulsing drip irrigation systems. Measurements were taken at air temperature of 25°C, leaf-to-air vapour pressure deficit of 1-2 kPa and photosynthetic photo flux density (PPFD) of 1500 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ on fully exposed spur leaves on the west side of the trees. Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=5$). SE = standard error of the mean at 5% probability level. Mean values followed by different letters in columns are significantly different, ns: not significant ($P > 0.05$).

Date	Treatments	2004/05	
		J_{\max} ($\mu\text{mol electrons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	$V_{c_{\max}}$ ($\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)
12 Jan. 2005	Micro	95.9 b	71.1 ns
	Drip	146.9 a	82.8
	Puls	166.0 a	143.2
	SE(\pm)	15.87	42.99
P-value	System	0.0034	0.2562
	Rootstock	0.3252	0.4147
	System \times rootstock	0.5784	0.6762
01 Feb. 2005	Micro	157.7 b	88.2 ns
	Drip	199.3 ab	95.7
	Puls	238.5 a	83.5
	SE(\pm)	21.87	16.07
P-value	System	0.0511	0.7229
	Rootstock	0.8657	0.4293
	System \times rootstock	0.9355	0.9853
		2005/06	
		J_{\max} ($\mu\text{mol electrons} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	$V_{c_{\max}}$ ($\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)
10 Jan. 2006	Micro	124.2 ns	74.1 c
	Drip	153.2	139.8 a
	Puls	156.9	90.9 b
	SE(\pm)	19.24	15.24
P-value	System	0.0950	0.0353
	Rootstock	0.1932	0.1481
	System \times rootstock	0.3440	0.1335
01 Feb. 2006	Micro	146.1 ns	87.2 ns
	Drip	198.7	69.3
	Puls	172.2	82.0
	SE(\pm)	19.74	20.43
P-value	System	0.4335	0.3627
	Rootstock	0.3559	0.2789
	System \times rootstock	0.5569	0.7015

Table 3: Chlorophyll a (Chla), chlorophyll b (Chlb) and nitrogen concentration expressed on leaf area basis (N_a) as well as specific leaf area (SLA) of apple leaves grown under micro sprinkler, daily drip and pulsing drip irrigation system on either semi-vigorous (M793) or semi-dwarfing M7) rootstocks. Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=6$). SE = standard error of the mean at 5% probability level. Mean values followed by different letters in columns are significantly different, ns: not significant ($P > 0.05$).

Season	Treatments	Chla ($\mu\text{gChla}_a \cdot \text{cm}^{-2}$)	Chlb ($\mu\text{gChla}_b \cdot \text{cm}^{-2}$)	Total Chl($\mu\text{g} \cdot \text{cm}^{-2}$)	N_a ($\text{g} \cdot \text{m}^{-2}$)	SLA ($\text{g} \cdot \text{cm}^{-2}$)
2004/05	Micro	17.8 b	4.9 b	22.7 b	2.5 b	125.3 ns
	Drip	30.8 a	12.3 a	43.1 a	3.1 a	142.1
	Puls	33.7 a	11.2 a	44.9 a	3.1 a	155.1
	SE (\pm)	2.97	1.32	4.11	0.08	23.90
	P-value					
	System	0.0005	0.0135	0.0017	0.0019	0.5166
	Rootstock	0.6216	0.5717	0.8614	0.1015	0.4189
	System \times rootstock	0.5681	0.9164	0.6644	0.9236	0.7418
2005/06	Micro	16.8 b	4.5 b	21.3 b	3.0 ns	153.4 ns
	Drip	28.4 ab	11.7 a	40.1 a	3.0	149.5
	Puls	33.1 a	12.5 a	45.6 a	3.0	140.2
	SE (\pm)	4.67	2.10	5.83	0.04	7.96
	P-value					
	System	0.0018	0.0296	0.0049	0.9199	0.3553
	Rootstock	0.9865	0.9967	0.9880	0.2291	0.4879
	System \times rootstock	0.6803	0.6155	0.6308	0.6195	0.1019

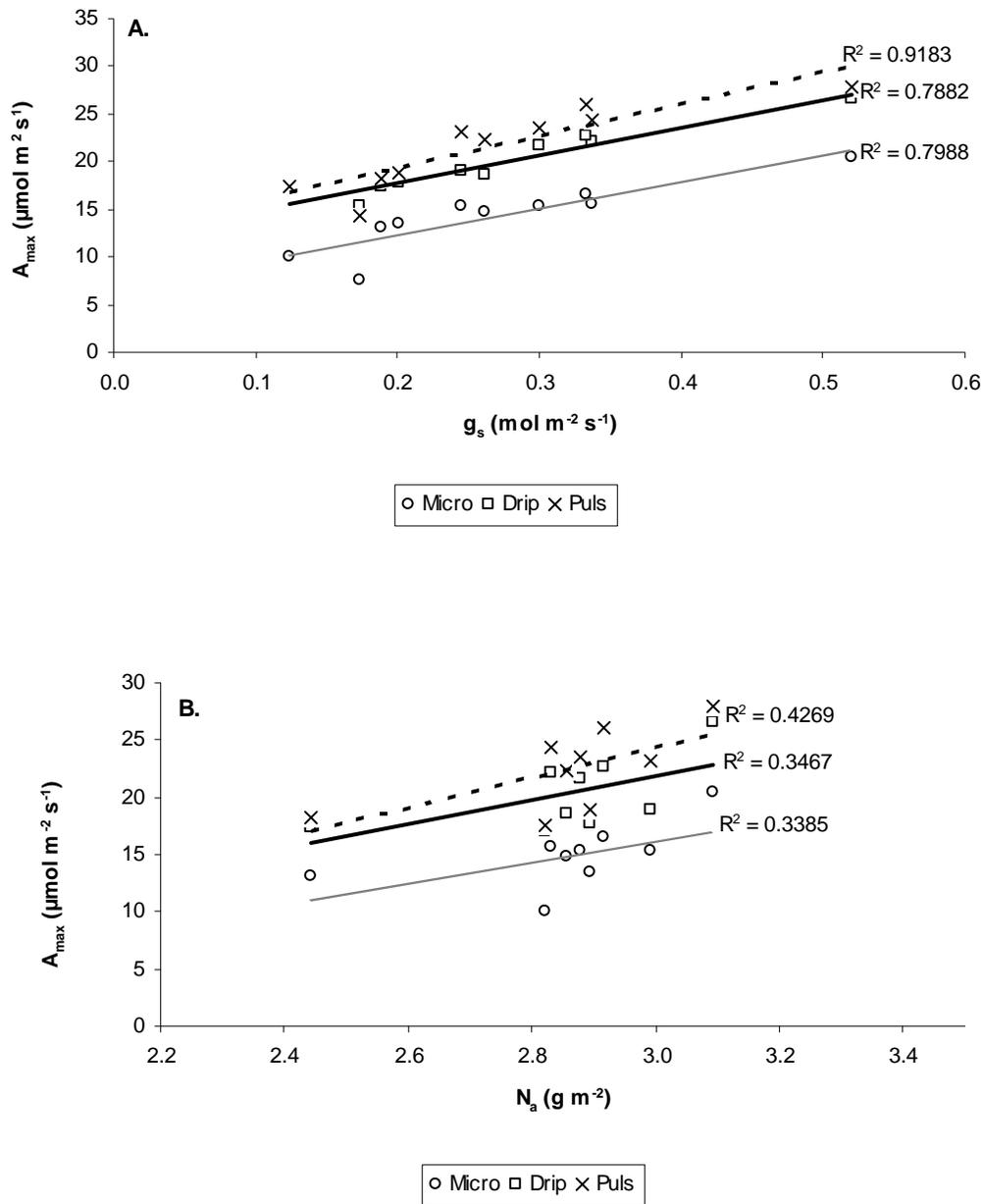


Fig. 1. Relationships between A: A_{\max} (light-saturated assimilation rate) and g_s (stomatal conductance), B: A_{\max} and N_a (leaf nitrogen per leaf area) in ‘Brookfield Gala’ apple leaves prior to harvest, in response to three irrigation systems, namely micro sprinkler irrigation (‘Micro’), daily drip irrigation (‘Drip’) and pulsing drip irrigation (‘Puls’) in 2005/06.

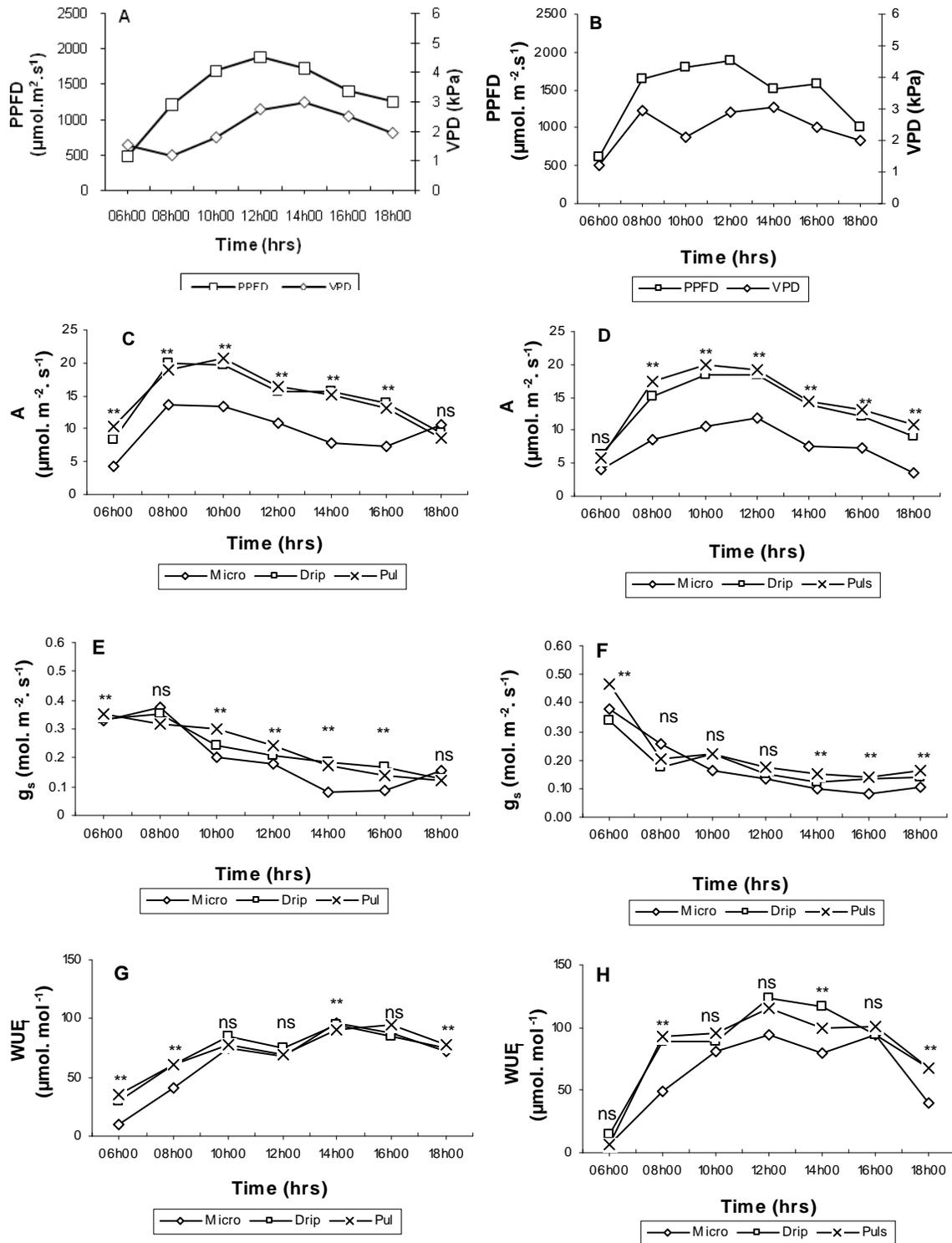


Fig. 2. Diurnal course of gas exchange in 'Brookfield Gala' apple leaves prior to harvest in response to three irrigation systems, namely micro sprinkler irrigation ('Micro'), daily drip irrigation ('Drip') and pulsing drip irrigation ('Puls'). Measurements were taken on 4 Feb. 2005 (A, C, E, and G) and 1 Feb. 2006 (B, D, F, and H). Abbreviations: PPFD (photosynthetic photon flux density), VPD (vapour pressure deficit), g_s (stomatal conductance) and WUE_i (intrinsic water use efficiency). Asterisks ** represent significant differences between treatments at $P < 0.05$, ns: not significant ($P > 0.05$) according to Tukey's multiple range test, $n=6$.

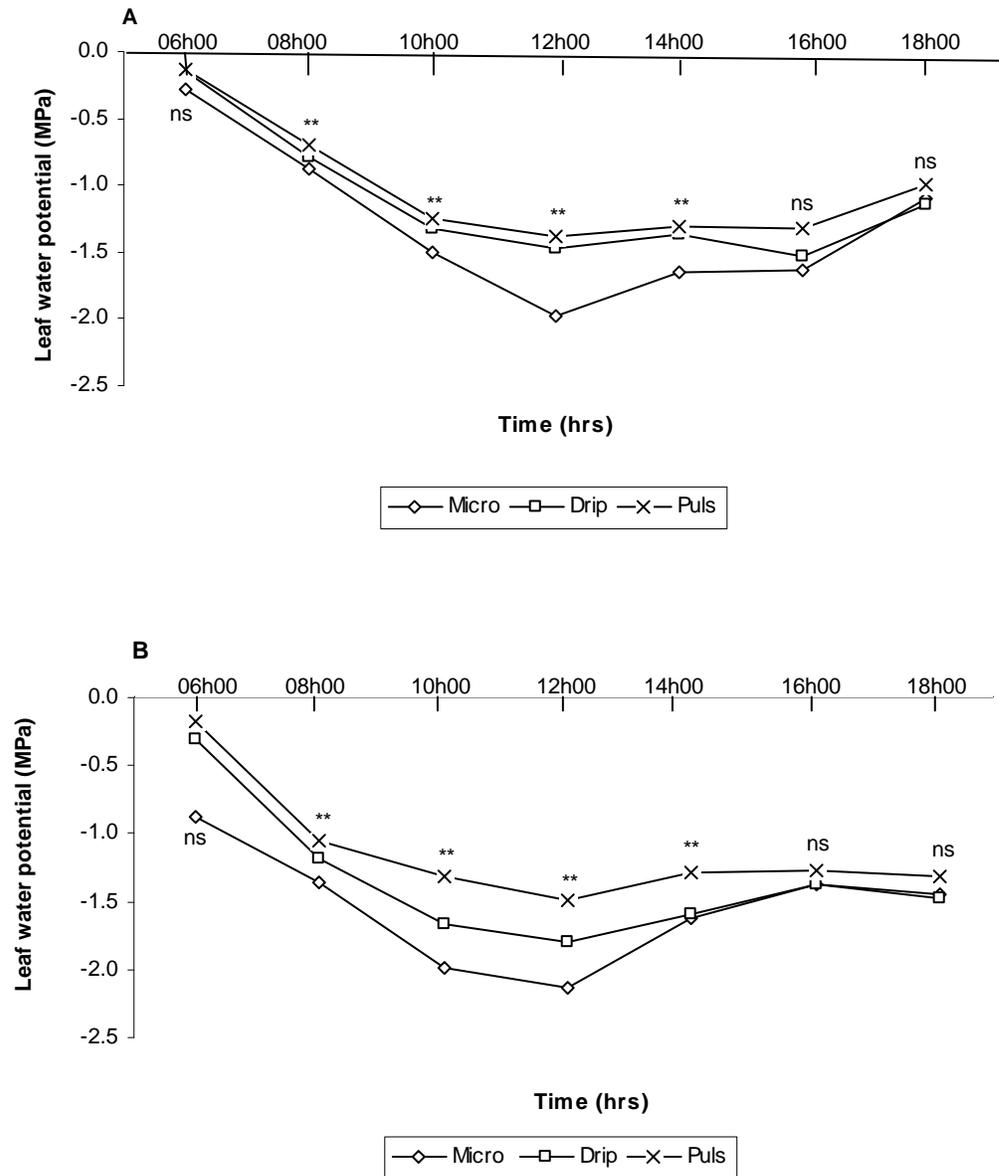


Fig. 3. Diurnal course of leaf water potential in 'Brookfield Gala' apple leaves prior to harvest, in response to three irrigation systems, namely micro sprinkler irrigation ('Micro'), daily drip irrigation ('Drip') and pulsing drip irrigation ('Puls'). Measurements were taken on 4 Feb. 2005 (A) and 1 Feb. 2006 (B). Asterisks **, represent significant differences between treatments at $P < 0.05$, ns: not significant ($P > 0.05$) according to Tukey's multiple range test, $n = 6$.

5. Diurnal and seasonal gas exchange of 'Brookfield Gala' apple leaves under three irrigation systems and two rootstocks

Abstract. In this study three water application strategies, namely daily drip (applied once to twice daily) more frequent pulsing drip and a conventional micro sprinkler irrigation system with hand fertilisation were compared. This was done on two to three-year-old 'Brookfield Gala' apple trees in the Western Cape Province, South Africa, with respect to leaf photosynthesis and leaf water relations during mid-morning and early afternoon measurements. Irrigation systems were studied in combination with two rootstocks, M793 and M7. During the 2004/05 and 2005/06 seasons, seasonal gas exchange measurements were made during mid-morning and early afternoon to determine net CO₂ assimilation rate, stomatal conductance, transpiration rate, and instantaneous leaf water use efficiency. Predawn and midday leaf water potential measurements were taken throughout the season using a pressure chamber. Photosynthetic rates, stomatal conductances and leaf water use efficiencies were consistently higher under daily drip irrigation and pulsing drip irrigation compared to the micro irrigation system, irrespective of the rootstock. Leaf water potential at predawn and midday was lower under micro irrigation compared to daily drip irrigation and pulsing drip irrigation systems. On some dates, but not consistently, gas exchange and water potential were higher under pulsing drip irrigation than under daily drip irrigation. Leaf water potential and gas exchange decreased from mid-morning to early afternoon under all systems. Results indicate higher net CO₂ assimilation rates and improved photosynthetic water use efficiency in daily drip irrigation and pulsing drip irrigation systems compared to the micro irrigation system in both morning and afternoon measurements. For irrigation scheduling, under drip irrigated systems irrigation should be applied early in the morning to maintain high leaf photosynthetic efficiency during the early afternoon period when stomata close as a result of increases in VPD and temperature.

Keywords: *Photosynthetic rate, stomatal conductance, leaf instantaneous water use efficiency, transpiration rate, leaf water potential.*

5.1 Introduction

Water demand and availability are known to be important factors influencing adaptation, development and growth of horticultural crops such as apples (*Malus domestica* Borkh.) (Dragoni *et al.*, 2005). Efficient tree management that ensures sufficiently high fruit quality and good yield, requires varying degrees of pruning or use of growth regulators to control tree size at maturity, the use of suitable training systems, thinning to reduce fruit numbers, as well as irrigation methods which ensure that water and nutrients are supplied in times of maximum tree demand (Jackson, 2003).

Fallahi *et al.* (2006) established that full sprinkler and partial root-zone drying sprinkler systems in 'Fuji' apple orchards used more water than drip based systems and tree growth (trunk cross-sectional area, TCA) was higher in full sprinkler systems than in drip systems. The use of soil moisture measurements for irrigation scheduling has been shown to be an important guide when crop evapotranspiration (ETc) for a particular area, precise apple crop factors (Kc) and precise estimate of tree canopy size are taken into consideration when calculating actual water requirements for apples.

One of the mechanisms through which apple leaves control water loss is by stomatal closure, which has been identified as a common and early event in plant responses to water deficit under field conditions (Chaves *et al.*, 2002). The decrease in gas exchange restricts water loss, but also reduces daily C assimilation at the leaf level, decreasing the long-term net C gain by the whole plant (Romero & Botía, 2006). The study of daily patterns of leaf water relations, gas exchange activity and water use efficiency (C gain per water lost) can provide useful information on plant responses to irrigation systems and scheduling. Many studies have proposed that frequent water application, in the form of daily drip irrigation systems compared to micro sprinkler irrigation during periods of high temperature and VPD can lead to high rates of A and g_s during midday (Unrath, 1972; Backes & Blanke, 2007).

Insufficient information exists on how various modern irrigation and fertigation systems together with rootstocks affect photosynthesis and stomatal regulation in field grown apples. The objective of this study was to determine the influence of different irrigation systems (daily drip, pulsing

drip and micro sprinkler irrigation systems) in combination with two rootstocks (M793 and M7) on net CO₂ assimilation rate, stomatal regulation, photosynthetic water use efficiency and leaf water potential in ‘Brookfield Gala’ apples under South African conditions as measured in the mid-morning and early afternoon. It was hypothesised that more frequent application of water would mitigate the reduction in midday leaf water potential in apples by maintaining higher leaf stomatal conductance and photosynthesis, with a stronger effect in the semi-dwarfing rootstock (M7) than in the semi-vigorous rootstock (M793).

5.2 Materials and Methods

5.2.1 Study site and experimental design

The study was conducted in Genadendal, Western Cape Province, South Africa (34°03'S, 19°37'E). *Malus x domestica* Borkh. ‘Brookfield Gala’ scions, budded on semi-dwarfing M7 and semi-vigorous M793 rootstocks, were planted out in June 2003 at a spacing of 4.0m × 1.25m in a sandy loam soil (Dundee soil series). Trees were trained to a central leader using a four-wire support system. Lateral branches were bent according to the French solaxe principle. The trees were planted in a NE-SW row orientation. Pre-plant soil preparation included rectification of soil pH to approximately 5.5 (KCl) and phosphorus to 30mg. kg⁻¹ (Bray II as extraction method). The experiment was designed as a split-plot with irrigation treatments as the main plot and rootstocks as the sub-plot, with eight replications. Each replication consisted of five trees and only the middle tree was used for the measurements. Fruits were harvested on 6 Feb. 2005 (2004/5) and on 7 Feb. 2006 (2005/6).

5.2.2 Irrigation treatments (This has been discussed in more detail in Chapter 2)

Annual water use of apple trees in the Genadendal area was determined by using long-term evaporation data from nearby weather stations (Villiersdorp and Caledon) and crop factors for deciduous fruit trees in the area. The actual water use for daily drip irrigation was 3429 and 3926m³.ha⁻¹.yr⁻¹ for 2004/5 and 2005/06 respectively, whilst pulsing drip irrigation used 3429 and 4047m³.ha⁻¹.yr⁻¹ for 2004/5 and 2005/06, respectively. The total annual amount of water needed was divided into monthly applications according to the above mentioned data and then distributed into six phenological stages (Chapter 2). Due to the inefficient water application of the micro irrigation system, as a result of droplet drift, droplet evaporation, and a greater application radius,

more water was required (5254 and $5661\text{m}^3\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in 2004/5 and 2005/6, respectively). Irrigation scheduling was done using different soil sensors, dendrometers, weather data as well as root and soil studies. In the daily drip irrigation system water was applied once daily, in pulsing drip irrigation between one and six times daily, while in the micro irrigation system water was given once or twice per week. Rainfall was recorded during the study (using an automated weather station) and used during interpretation of the results for irrigation system treatments (data presented in Chapter 2).

Annual nutrient requirement was adopted from Stassen and North (2005) and divided percentage-wise into five phenological stages throughout the year. Minor changes were made as necessary according to the tree performance as well as soil and leaf analysis. A computer program was developed to regulate water and nutrient application based on the above mentioned information. In the case of the micro irrigation system, the macro and micro elements were applied by hand within the drip area. Nitrogen was given manually in five instalments, potassium in three and all other nutrients in two instalments, according to standard commercial strategies based on seasonal nutrient uptake in apples. Fruit thinning and pruning were done according to standard commercial practices (details in Chapter 2).

5.2.3 Leaf gas exchange and leaf water potential measurements

During 2004/2005 and 2005/2006, net carbon dioxide (CO_2) assimilation rate (A) and stomatal conductance (g_s) were measured using a LI-6400 infrared gas analyzer (Li-Cor, Lincoln, Nebraska, USA) under ambient sunlight (photosynthetic photon flux density PPF $>1400\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), ambient air temperature and air relative humidity. Cuvette CO_2 concentration was controlled at $380\mu\text{mol}\cdot\text{mol}^{-1}$ using a CO_2 injection system and compressed CO_2 cylinders. A LI-190SA quantum sensor (Li-Cor, Lincoln, Nebraska, USA) attached to the LI-6400 was used to measure PPF. One sun-exposed leaf at a height of 1.2m–1.5m on the western side of the tree was measured per replication and six replications were considered for the purposes of these measurements ($n=6$). Measurements were taken replication by replication on the same leaf (for leaf gas exchange measurements), during the morning (09h00 to 11h00) and afternoon (12h00 to 14h00) on six different days throughout the season, from early December until mid-April. On the same days, leaf water potential measurements were taken on three leaves per tree using a pressure

chamber (PCI 600, PMS Instrument Co., Corvallis, Oregon, USA), at predawn (04h00–06h00) and at midday (12h00–14h00). All measurements were taken within one day after irrigation application. Instantaneous leaf water use efficiency (WUE) was calculated as A/E . All data were analysed statistically by split-plot ANOVA (SAS GLM procedure, Enterprise Guide 6, release 1.3 SAS Institute, Cary, NC, USA, 2001). Means separation was by Tukey's Studentized range test ($P \leq 0.05$).

5.3 Results

There were no main effects of rootstock for both morning and afternoon measurements of A and g_s in both 2004/05 (Tables 1 and 2) and 2005/06 (Tables 3 and 4). This could possibly be attributed to the fact that the systems were only running for two months and not much could be expected between and amongst the treatments. There were two instances of interaction between rootstock and irrigation system: for A on 2 March 2005 (Table 1) and for g_s on 6 Jan. 2006 (Table 3), but the trends were small and inconsistent. WUE was not influenced by rootstock during the first season (Tables 7 and 8) but on 6 Jan. 2006 (morning) was higher on M793 than on M7 under the drip irrigation systems (Table 7). On 1 Dec. 2005, WUE was higher on M7 than on M793 (Table 8). Rootstock effects on leaf water potential were limited to one instance (16 Dec. 2004) when water potential was lower on M7 than on M793 (Table 5).

The main effects of irrigation system showed that A was significantly higher under daily drip and pulsing drip than in micro sprinkler irrigation (Tables 1–4 and Fig. 1), except on 1 Dec. 2004 (morning and afternoon). Occasionally higher values of A were measured under pulsing drip than under conventional drip (Fig. 1). On 13 Dec. 2005 (afternoon), A was highest in micro sprinkler, followed by pulsing and daily drip systems (Fig. 1). Reductions in A during 2005/6 from 13 Dec. 2005 to 28 Jan. 2006 were greater than for the same period during 2004/5 (Figs. 1B and 1D compared to Figs. 1A and 1C).

During 2004/2005, g_s was significantly lower under micro irrigation than under conventional drip and pulsing drip systems only from end-January onwards in the morning (Tables 1–4 and Fig. 2A), but already from mid-December onwards in the afternoon (Fig. 2B). During 2005/2006, there was a smaller and sometimes non-significant difference in g_s between micro sprinkler and

daily drip systems in the morning, especially later in the season (Fig. 2C), whereas in the afternoon values were generally low and differences small, with daily drip and pulsing drip only showing improved g_s compared to micro irrigation at the end of the season (Fig. 2D). Reductions in g_s from mid-morning to early afternoon were strong during both seasons (Figs. 2B and 2D).

WUE was relatively low in spring and summer, increasing prior to harvest in early March and remaining relatively high in the postharvest period (Tables 5–8 and Fig. 3). WUE was, on most dates, significantly higher in the pulsing drip and daily drip treatments than in the micro sprinkler irrigation treatment.

The predawn leaf water potential was lower in micro irrigation than in daily drip and pulsing drip systems throughout the season (Tables 5–8, Figs. 4A and 4C). On two measurement days during the early 2005/2006 (Fig. 4C), leaf water potential was higher in the pulsing drip system than in the daily drip system. The midday leaf water potential followed a similar pattern (Tables 5–8, Figs. 4B and 4D), with the two drip-based systems generally showing higher values than the micro irrigation system. On a few dates, particularly later in the second season, the leaf water potential was significantly higher in the pulsing drip system than in the daily drip system.

5.4 Discussion

‘Brookfield Gala’ apple trees grown under daily drip and pulsing drip irrigation systems performed better when compared to the micro irrigation system with respect to A, g_s , WUE and leaf water potential. There were no consistent differences between the daily drip and pulsing drip systems in this study, illustrating that, irrespective of the frequency of daily water application, gas exchange and WUE were similar. Seasonal effects on leaf water potential suggest that apple trees under pulsing drip and daily drip systems were under lower water stress than the trees under the micro irrigation system. Production during the 2005/06 season was significantly higher for drip based systems (32 tons/ha) than for the micro sprinkler irrigation system (20 tons/ha) (Chapter 3).

The use of micro sprinkler irrigation systems and drip based systems have been studied in apples (*Malus domestica* Borkh.) (Chun *et al.*, 2001; Fallahi *et al.*, 2006), peaches (*Prunus persica*) (Mitchell & Chalmers, 1983) and in other crops (Assouline, 2002). Results from these studies

indicated that frequent application of water using drip irrigation systems creates a wetted region 'pot' within the soil profile, and that water is evenly distributed (both vertically and horizontally) around the tree (Assouline, 2002). Studies by Mitchell & Chalmers (1983) and Fallahi *et al.* (2006) suggest that less water is used under drip systems than under micro systems. Leaf photosynthesis and stomatal conductance are known to be affected by environmental factors (VPD and temperature) (Cheng & Luo, 1997), physiological processes within the leaf (Jones, 1985) and water deficit (leaf water content/soil water content) (Flore & Lakso, 1989). Measurements on soil moisture availability and soil moisture tension (Chapter 2) indicated that conventional drip irrigation and pulsing drip irrigation systems had more available water and less soil tension than micro sprinkler irrigation system, but there were no differences between daily and pulsing drip systems. Previous studies by Schulze (1986), Turner (1986), Flore & Lakso (1989) and Cheng & Luo (1997) indicated that plant water deficits either as soil water or atmospheric water affect both A and g_s . This has been attributed to low hydraulic conductivity of the root system that causes a pronounced effect of transpiration on water potentials in the top of the tree. Cheng & Luo (1997) mentioned the relationship between soil water and VPD, but the mechanism through which soil water and VPD in the atmosphere regulate stomatal conductance is unclear. However, an increase in abscisic acid in response to water stress in almond (*Prunus amygdalus*) (Wartinger, 1990) has been implicated to regulate g_s and other studies have mentioned a possible increase in root signalling activity in roots as a result of drying in apples (Gowing *et al.*, 1990).

Leaf photosynthesis and stomatal conductance were generally not affected by rootstock. However, shoot growth measurements and leaf area measurements (Chapter 3) indicated more vigorous growth and tree vigour development under the semi-vigorous (M793) rootstock than in the semi-dwarfing (M7) rootstock. Studies by Schechter *et al.* (1991a, b), Chun *et al.* (2001; 2002) and Fallahi *et al.* (2002) on different rootstocks indicated higher A , g_s , leaf nutrition and tree vigour (shoot growth and leaf area) effects on vigorous rootstocks than on dwarfing rootstocks. In the current study, however, such differences were not observed due to the trees being in their 2nd and 3rd leaf and having small trunk-cross sectional areas (Chapter 3), compared to full grown trees at full-bearing used in some studies. Midday depression in both A and g_s has been demonstrated in Chapter 4 under both drip based irrigation systems and the micro sprinkler

irrigation. However, in this study the frequent water application in the form of drip systems did not increase the A and g_s during the midday because both A and g_s are known to be regulated by leaf physiological processes as well as environmental factors such as leaf temperature and VPD. Irrespective of the soil water status at midday the rates in A and g_s were seen to continually decrease with increases in VPD and leaf temperature during the day. Similar results have been obtained under South African conditions in citrus where daily irrigation did not mitigate the midday depression (Schoeman, 2002). Potentially drip based systems need a constant supply of water and nutrients; however this can be of great challenge during power outages or in places where there is no power connections. Such observations could not be drawn in this study since water was flowing gravitationally to the trees from the hill. Data presented in this work did not show any nutrition deficiency or toxicities, however difference in application of nutrients between drip based systems and the micro irrigated trees warrants differences. However, the soil at the study site was a sandy loam soil and did not show any accumulation of nutrients or retention and presumably different effects could have been noted under clayey type of soils.

Based on the findings of this study, leaf CO_2 assimilation and water relations are improved under daily drip irrigation and pulsing drip irrigation systems (water application daily to several times daily) under field conditions compared to micro sprinkler irrigation (water application once or twice weekly), irrespective of the rootstock used in 'Brookfield Gala' apples. Differences were more pronounced in the afternoon than in the morning measurements, with the drip irrigation systems showing less early afternoon depression than the micro irrigation system. There was a lower early afternoon stress observed under the drip irrigation systems than in micro sprinkler irrigation system in both seasons. This means that more frequent water applications can improve leaf carbohydrate synthesis in the morning and rates can be sustained until early afternoon compared to less frequent water application under micro sprinkler irrigation. For irrigation scheduling, under drip irrigated systems irrigation should be scheduled early in the morning to maintain high leaf photosynthetic efficiency and other metabolic processes within the leaf and under micro sprinkler irrigation application frequency should be maintained at once a week to possibly three times a week especially during hot days.

5.5 References

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Table 1. Mean morning (09h00 to 11h00) net CO₂ assimilation rate ($\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$) and stomatal conductance ($\text{mol. m}^{-2} \cdot \text{s}^{-1}$) of 'Brookfield Gala' apple leaves as influenced by irrigation/different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2004/2005.

Treatment	Date					
	01/12/04	16/12/04	06/01/05	27/01/05	02/03/05	14/04/05
	Net CO ₂ assimilation rate (A)					
Micro M793	13.43	12.15	9.52	8.92	11.92	12.73
Micro M7	12.09	13.58	9.32	9.92	11.44	12.41
Drip M793	14.12	17.30	15.76	15.57	16.58	17.03
Drip M7	10.87	17.00	15.78	15.57	19.10	15.82
Puls M793	12.50	15.05	15.02	18.60	19.47	18.03
Puls M7	12.13	15.60	15.61	18.38	17.13	15.75
SE ¹	1.09	1.16	0.61	1.05	0.69	0.85
P-value ²						
System	0.9332	0.0170	≤0.0001	≤0.0001	≤0.0001	≤0.0001
Rootstock	0.0831	0.5624	0.7853	0.7646	0.8638	0.0690
System × rootstock	0.4251	0.7603	0.7952	0.8279	0.0108	0.6153
	Stomatal conductance (g _s)					
Micro M793	0.29	0.25	0.37	0.22	0.29	0.32
Micro M7	0.27	0.27	0.36	0.24	0.26	0.31
Drip M793	0.31	0.31	0.40	0.30	0.31	0.41
Drip M7	0.27	0.30	0.41	0.30	0.31	0.37
Puls M793	0.28	0.29	0.37	0.34	0.34	0.39
Puls M7	0.26	0.29	0.38	0.34	0.34	0.38
SE ¹	0.31	0.02	0.02	0.03	0.02	0.02
P-value ²						
System	0.8425	0.2504	0.2505	0.0160	0.0843	0.0329
Rootstock	0.0801	0.9747	0.6711	0.7685	0.5840	0.3775
System × rootstock	0.8490	0.8326	0.7908	0.8424	0.8712	0.8357

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 2. Mean afternoon (12h00 to 14h00) net CO₂ assimilation rate ($\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$) and stomatal conductance ($\text{mol. m}^{-2} \cdot \text{s}^{-1}$) of 'Brookfield Gala' apple leaves as influenced by irrigation/ different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2004/2005.

Treatment	Date					
	01/12/04	16/12/04	06/01/05	27/01/05	02/03/05	14/04/05
Net CO ₂ assimilation rate (A)						
Micro M793	13.08	6.27	8.26	9.69	7.33	11.76
Micro M7	14.73	6.02	7.69	9.79	7.55	12.06
Drip M793	13.88	13.28	12.60	14.63	14.75	16.15
Drip M7	11.80	12.46	12.82	14.12	13.60	16.70
Puls M793	13.45	13.65	14.88	15.45	16.34	18.13
Puls M7	13.72	12.17	14.52	14.70	15.00	17.23
SE ¹	0.96	1.01	0.62	0.67	0.97	1.02
P-value ²						
System	0.8138	0.0001	<0.0001	<0.0001	<0.0001	0.0011
Rootstock	0.9431	0.3153	0.6379	0.4886	0.3359	0.9818
System × rootstock	0.1782	0.8341	0.8068	0.8096	0.6844	0.7561
Stomatal conductance (g _s)						
Micro M793	0.15	0.08	8.26	0.12	0.18	0.20
Micro M7	0.16	0.07	7.69	0.12	0.14	0.13
Drip M793	0.17	0.18	12.60	0.19	0.19	0.28
Drip M7	0.13	0.17	12.82	0.16	0.17	0.26
Puls M793	0.16	0.17	14.88	0.18	0.21	0.27
Puls M7	0.16	0.14	14.52	0.17	0.17	0.28
SE ¹	0.02	0.02	0.02	0.01	0.03	0.04
P-value ²						
System	0.9277	0.0003	0.0025	0.0008	0.5280	0.0056
Rootstock	0.6672	0.1529	0.1249	0.2215	0.1214	0.3983
System × rootstock	0.7391	0.7849	0.8586	0.2407	0.9438	0.5373

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 3. Mean morning (09h00 to 11h00) net CO₂ assimilation rate ($\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$) and stomatal conductance ($\text{mol. m}^{-2} \cdot \text{s}^{-1}$) of 'Brookfield Gala' apple leaves as influenced by irrigation/ different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2005/2006.

Treatment	Date					
	01/12/05	13/12/05	06/01/06	28/01/06	04/03/06	12/04/06
Net CO ₂ assimilation rate (A)						
Micro M793	11.78	11.80	12.02	12.77	8.25	10.22
Micro M7	10.68	11.05	11.18	12.57	7.46	7.15
Drip M793	15.13	15.83	12.88	18.67	14.55	14.97
Drip M7	16.63	16.50	14.43	17.33	14.85	15.53
Puls M793	17.45	16.42	19.33	19.18	18.00	16.83
Puls M7	18.48	18.13	18.53	18.73	18.53	18.08
SE ¹	0.92	0.72	0.91	0.57	1.15	0.97
P-value ²						
System	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Rootstock	0.5360	0.3675	0.6299	0.1735	0.9870	0.6050
System × rootstock	0.3478	0.2574	0.6891	0.5858	0.8305	0.0884
Stomatal conductance (g _s)						
Micro M793	0.17	0.27	0.32	0.27	0.10	0.25
Micro M7	0.16	0.20	0.28	0.22	0.10	0.22
Drip M793	0.20	0.25	0.20	0.27	0.12	0.24
Drip M7	0.24	0.27	0.28	0.27	0.13	0.27
Puls M793	0.23	0.27	0.28	0.31	0.19	0.30
Puls M7	0.25	0.31	0.32	0.29	0.20	0.35
SE ¹	0.02	0.03	0.02	0.02	0.02	0.02
P-value ²						
System	0.0056	0.1955	0.0973	0.0295	0.0006	0.0015
Rootstock	0.3854	0.8814	0.1436	0.0977	0.8913	0.4698
System × rootstock	0.5385	0.1172	0.0117	0.3282	0.6637	0.1926

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 4. Mean afternoon (12h00 to 14h00) net CO₂ assimilation rate ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$) and stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$) of 'Brookfield Gala' apple leaves as influenced by irrigation/different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2005/2006.

Treatment	Date					
	01/12/05	13/12/05	06/01/06	28/01/06	04/03/06	12/04/06
	Net CO ₂ assimilation rate (A)					
Micro M793	4.22	11.80	8.81	9.83	3.62	3.01
Micro M7	4.87	11.97	6.52	10.05	3.33	5.38
Drip M793	9.39	7.18	11.73	14.28	8.21	11.76
Drip M7	9.91	6.01	11.86	13.05	11.69	11.85
Puls M793	12.31	9.22	11.25	15.51	10.89	13.87
Puls M7	11.01	9.31	9.97	14.62	14.08	11.67
SE ¹	0.98	0.94	1.30	1.17	1.26	1.32
P-value ²						
System	<0.0001	0.0082	0.0023	0.0229	<0.0001	<0.0001
Rootstock	0.9556	0.6959	0.2982	0.5169	0.0557	0.9343
System × rootstock	0.5586	0.7308	0.6556	0.8123	0.2801	0.2550
	Stomatal conductance (g _s)					
Micro M793	0.10	0.17	0.14	0.14	0.05	0.11
Micro M7	0.11	0.13	0.16	0.14	0.04	0.15
Drip M793	0.01	0.08	0.16	0.14	0.09	0.18
Drip M7	0.10	0.07	0.18	0.14	0.12	0.14
Puls M793	0.16	0.11	0.17	0.18	0.11	0.23
Puls M7	0.11	0.10	0.14	0.17	0.15	0.23
SE ¹	0.01	0.01	0.03	0.02	0.01	0.03
P-value ²						
System	0.0131	0.0065	0.6871	0.2050	0.0006	0.0288
Rootstock	0.3231	0.1246	0.7991	0.9614	0.0713	0.9665
System × rootstock	0.1342	0.2641	0.6386	0.9863	0.1811	0.4053

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 5. Mean morning (09h00 to 11h00) water use efficiency ($\text{mmol CO}_2 \cdot \text{mol}^{-1} \cdot \text{H}_2\text{O}$) and predawn leaf water potential (MPa) of 'Brookfield Gala' apple leaves as influenced by irrigation/different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2004/2005.

Treatment	Date					
	01/12/04	16/12/04	06/01/05	27/01/05	02/03/05	14/04/05
Water use efficiency (WUE)						
Micro M793	2.65	1.81	1.17	1.71	2.06	2.30
Micro M7	2.58	1.92	1.19	1.55	2.06	2.32
Drip M793	2.62	2.23	1.73	2.16	2.61	2.66
Drip M7	2.27	2.19	1.75	2.14	3.02	2.58
Puls M793	2.42	1.94	1.67	2.35	2.94	2.89
Puls M7	2.56	2.03	1.75	2.41	2.67	2.58
SE ¹	0.18	0.14	0.09	0.15	0.14	0.13
P-value ²						
System	0.3865	0.0037	0.0002	0.0016	0.0025	0.0277
Rootstock	0.5310	0.6273	0.6107	0.7446	0.6985	0.2808
System × rootstock	0.3898	0.8315	0.9409	0.7632	0.0886	0.4366
Predawn leaf water potential						
Micro M793	-0.61	-0.51	-0.50	-0.33	-0.41	-0.20
Micro M7	-0.56	-0.43	-0.55	-0.33	-0.43	-0.17
Drip M793	-0.33	-0.35	-0.27	-0.19	-0.19	-0.12
Drip M7	-0.38	-0.29	-0.24	-0.18	-0.23	-0.10
Puls M793	-0.35	-0.34	-0.24	-0.21	-0.16	-0.13
Puls M7	-0.35	-0.30	-0.25	-0.16	-0.14	-0.09
SE ¹	-0.08	-0.03	-0.02	-0.02	-0.03	-0.03
P-value ²						
System	0.0163	<0.0001	<0.0001	0.0002	<0.0001	0.0130
Rootstock	0.9812	0.0416	0.4974	0.2549	0.5830	0.1983
System × rootstock	0.8657	0.7713	0.0725	0.3730	0.6834	0.9304

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 6. Mean afternoon (12h00 to 14h00) water use efficiency ($\text{mmol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$) and midday leaf water potential (MPa) of 'Brookfield Gala' apple leaves as influenced by irrigation/ different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2004/2005.

Treatment	Date					
	01/12/04	16/12/04	06/01/05	27/01/05	02/03/05	14/04/05
	Water use efficiency (WUE)					
Micro M793	2.56	1.23	1.51	2.32	2.87	2.98
Micro M7	2.90	1.25	1.56	2.19	3.78	3.76
Drip M793	2.51	1.48	1.97	2.37	4.61	2.76
Drip M7	2.46	1.39	2.14	2.52	4.58	2.97
Puls M793	2.47	1.49	1.89	2.53	4.72	3.10
Puls M7	2.48	1.53	1.97	2.51	4.84	2.96
SE ¹	0.13	0.06	0.14	0.16	0.42	0.28
P-value ²						
System	0.3078	0.1511	0.0123	0.3647	0.0469	0.3009
Rootstock	0.3675	0.8452	0.3882	0.9804	0.3527	0.2336
System × rootstock	0.3234	0.5532	0.8943	0.6797	0.4957	0.2727
	Midday leaf water potential					
Micro M793	-1.51	-1.46	-1.58	-1.54	-1.70	-1.46
Micro M7	-1.63	-1.45	-1.54	-1.50	-1.65	-1.47
Drip M793	-1.21	-1.23	-1.45	-1.53	-1.22	-1.12
Drip M7	-1.18	-1.17	-1.44	-1.45	-1.23	-1.11
Puls M793	-1.19	-1.21	-1.11	-1.40	-1.13	-1.18
Puls M7	-1.26	-1.08	-1.07	-1.42	-1.10	-1.18
SE ¹	0.10	0.04	0.03	0.06	0.07	0.05
P-value ²						
System	0.0032	0.0003	<0.0001	0.2017	<0.0001	0.0003
Rootstock	0.5559	0.0704	0.2470	0.4771	0.7439	1.0000
System × rootstock	0.7580	0.4275	0.8786	0.7148	0.8959	0.9832

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 7. Mean morning (09h00 to 11h00) water use efficiency ($\text{mmol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$) and predawn leaf water potential (MPa) of 'Brookfield Gala' apple leaves as influenced by irrigation/different nutrient strategies ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation or 'Puls', pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2005/2006.

Treatment	Date					
	01/12/05	13/12/05	06/01/06	28/01/06	04/03/06	12/04/06
	Water use efficiency (WUE)					
Micro M793	3.01	2.50	1.38	2.43	4.79	1.74
Micro M7	2.61	2.77	1.41	2.84	4.70	1.38
Drip M793	3.26	3.51	2.02	3.25	6.31	2.56
Drip M7	3.14	3.32	1.70	3.05	6.07	2.47
Puls M793	3.30	3.27	2.34	3.03	5.69	2.47
Puls M7	3.29	3.36	2.06	3.10	5.53	2.42
SE ¹	0.20	0.23	0.08	0.17	0.38	0.11
P-value ²						
System	0.0437	0.0033	<0.0001	0.0174	0.0021	<0.0001
Rootstock	0.2942	0.7653	0.0119	0.5389	0.6004	0.0800
System × rootstock	0.6271	0.6068	0.0974	0.2383	0.9797	0.3408
	Predawn leaf water potential (Ψ_{pd})					
Micro M793	-0.45	-0.27	-0.25	-0.48	-0.17	-0.62
Micro M7	-0.46	-0.28	-0.28	-0.48	-0.19	-0.63
Drip M793	-0.26	-0.22	-0.09	-0.31	-0.09	-0.40
Drip M7	-0.23	-0.23	-0.11	-0.33	-0.10	-0.43
Puls M793	-0.19	-0.15	-0.10	-0.29	-0.09	-0.36
Puls M7	-0.16	-0.16	-0.08	-0.28	-0.06	-0.37
SE ¹	0.03	0.03	0.02	0.03	0.02	0.03
P-value ²						
System	0.0001	<0.0001	<0.0001	0.0013	0.0020	<0.0001
Rootstock	0.4579	0.5219	0.5007	0.8480	1.0000	0.6063
System × rootstock	0.7180	0.9735	0.4538	0.8366	0.2246	0.9567

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

Table 8. Mean afternoon (12h00 to 14h00) water use efficiency ($\text{mmol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$) and midday leaf water potential (MPa) of ‘Brookfield Gala’ apple leaves as influenced by irrigation/different nutrient strategies (‘Micro’, micro sprinkler irrigation, ‘Drip’, daily drip irrigation or ‘Puls’, pulsing drip irrigation system) and rootstock (semi-vigorous M793 or semi-dwarfing M7) during 2005/2006.

Treatment	Date					
	01/12/05	13/12/05	06/01/06	28/01/06	04/03/06	12/04/06
Water use efficiency (WUE)						
Micro M793	0.99	1.72	1.10	1.63	1.92	1.24
Micro M7	1.14	2.11	0.95	1.84	2.38	1.87
Drip M793	2.33	1.80	1.44	2.37	2.85	3.43
Drip M7	2.37	1.63	1.29	2.39	3.25	3.80
Puls M793	2.15	1.88	1.20	2.37	3.30	3.20
Puls M7	2.44	1.91	1.22	2.20	3.42	2.82
SE ¹	0.09	0.15	0.13	0.18	0.36	0.32
P-value ²						
System	0.0001	0.4861	0.0490	0.1365	0.0078	0.0004
Rootstock	0.0432	0.4956	0.4050	0.9024	0.2851	0.4451
System × rootstock	0.3665	0.2258	0.7544	0.5871	0.8762	0.2930
Midday leaf water potential (ψ_{md})						
Micro M793	-1.91	-1.48	-1.73	-1.72	-2.01	-2.01
Micro M7	-1.97	-1.53	-1.83	-1.80	-1.94	-2.10
Drip M793	-1.55	-1.68	-1.53	-1.48	-1.47	-1.61
Drip M7	-1.50	-1.66	-1.51	-1.47	-1.43	-1.47
Puls M793	-1.46	-1.55	-1.23	-1.43	-1.20	-1.35
Puls M7	-1.52	-1.56	-1.25	-1.53	-1.18	-1.45
SE ¹	0.7	0.04	0.06	0.06	0.07	0.05
P-value ²						
System	<0.0001	0.0315	<0.0001	0.0067	<0.0001	<0.0001
Rootstock	0.7000	0.6611	0.5490	0.2779	0.4763	0.6949
System × rootstock	0.6725	0.6824	0.5786	0.6636	0.9613	0.0525

¹ SE = standard error (n=6)

² Probability values are according to split-plot ANOVA

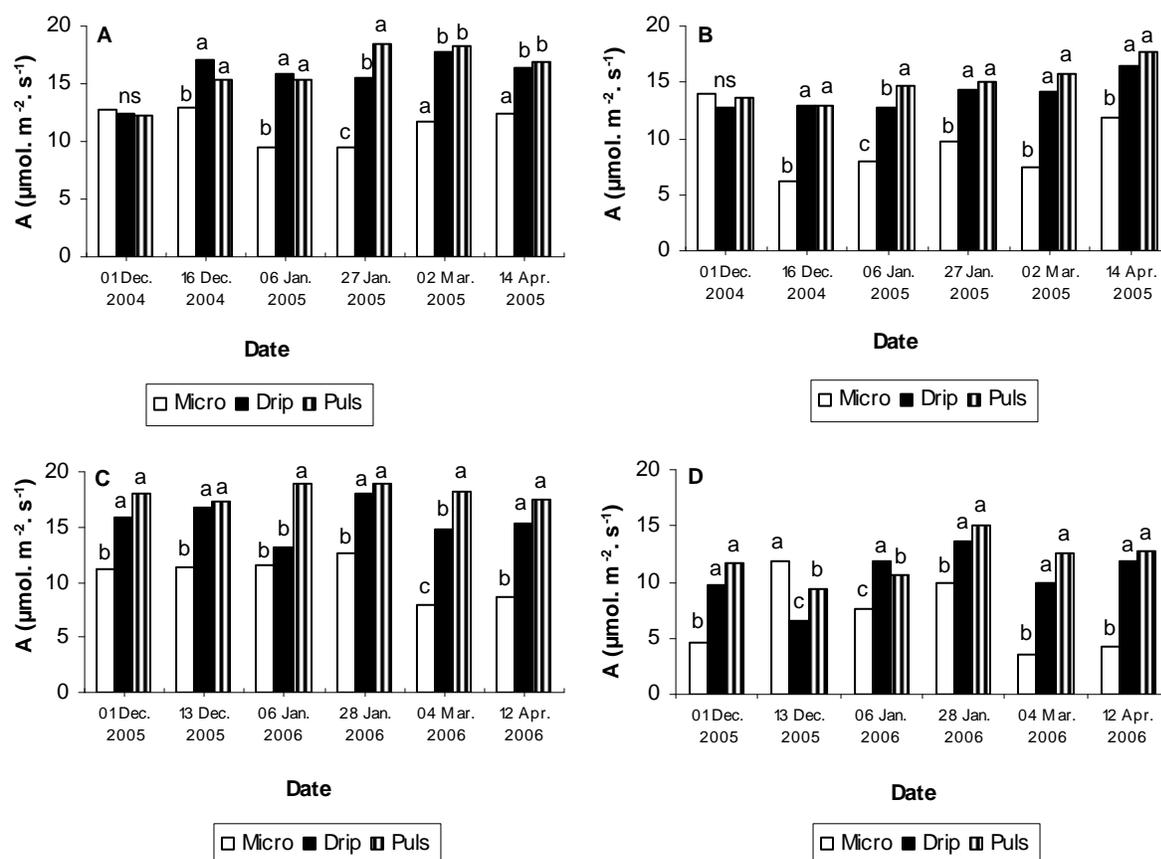


Fig. 1. The influence of different irrigation systems, 'Micro' (micro sprinkler irrigation), 'Drip' (daily drip irrigation and 'Puls' (pulsing drip irrigation), on apple leaf net CO₂ assimilation rate over two seasons: A (2004/05 morning), B (2004/05, afternoon), C (2005/06 morning), D (2005/06 afternoon). Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=6$). Mean values followed by different letters in a cluster (date) are significantly different and ns: not significant ($P > 0.05$).

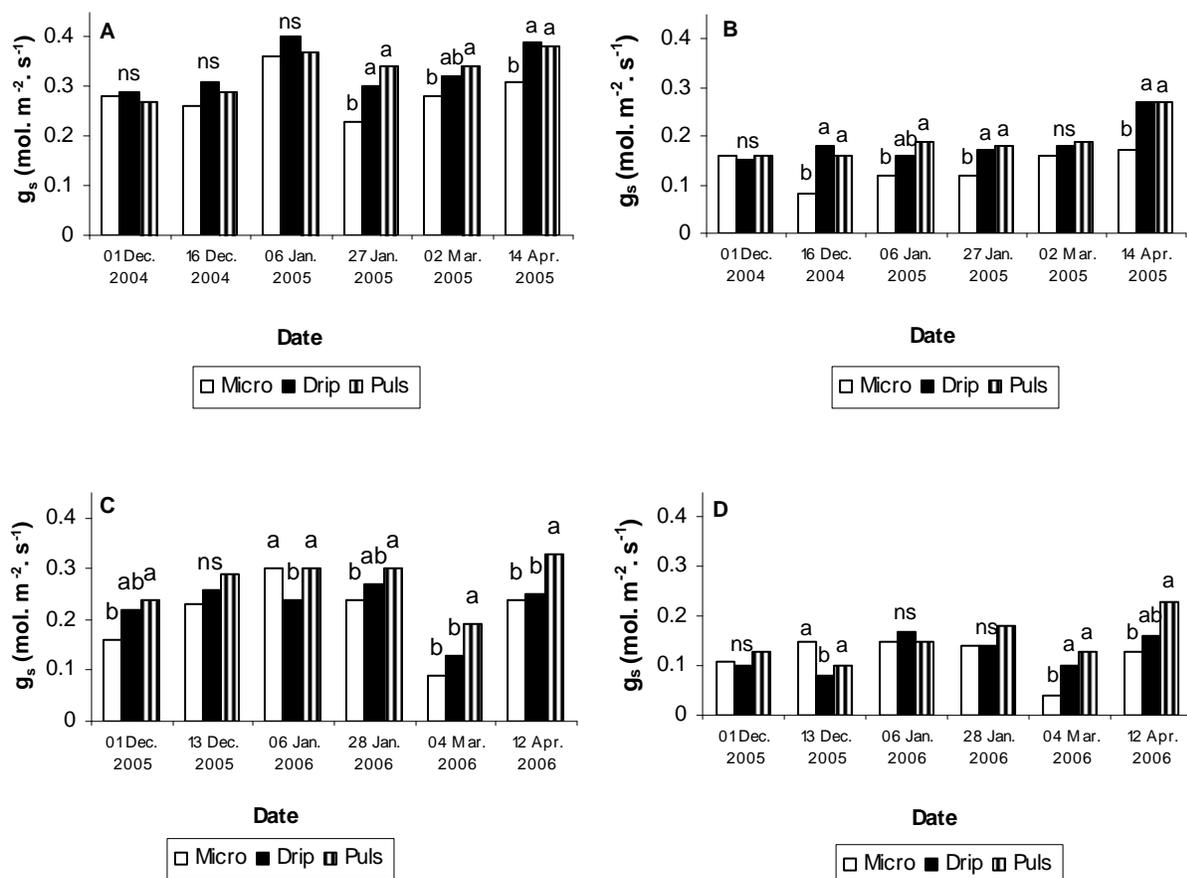


Fig. 2. The influence of different irrigation systems, 'Micro' (micro sprinkler irrigation), 'Drip' (daily drip irrigation and 'Puls' (pulsing drip irrigation), on apple leaf stomatal conductance (g_s) over two seasons: A (2004/05 morning), B (2004/05, afternoon), C (2005/06 morning), D (2005/06 afternoon). Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=6$). Mean values followed by different letters in a cluster (date) are significantly different and ns: not significant ($P > 0.05$).

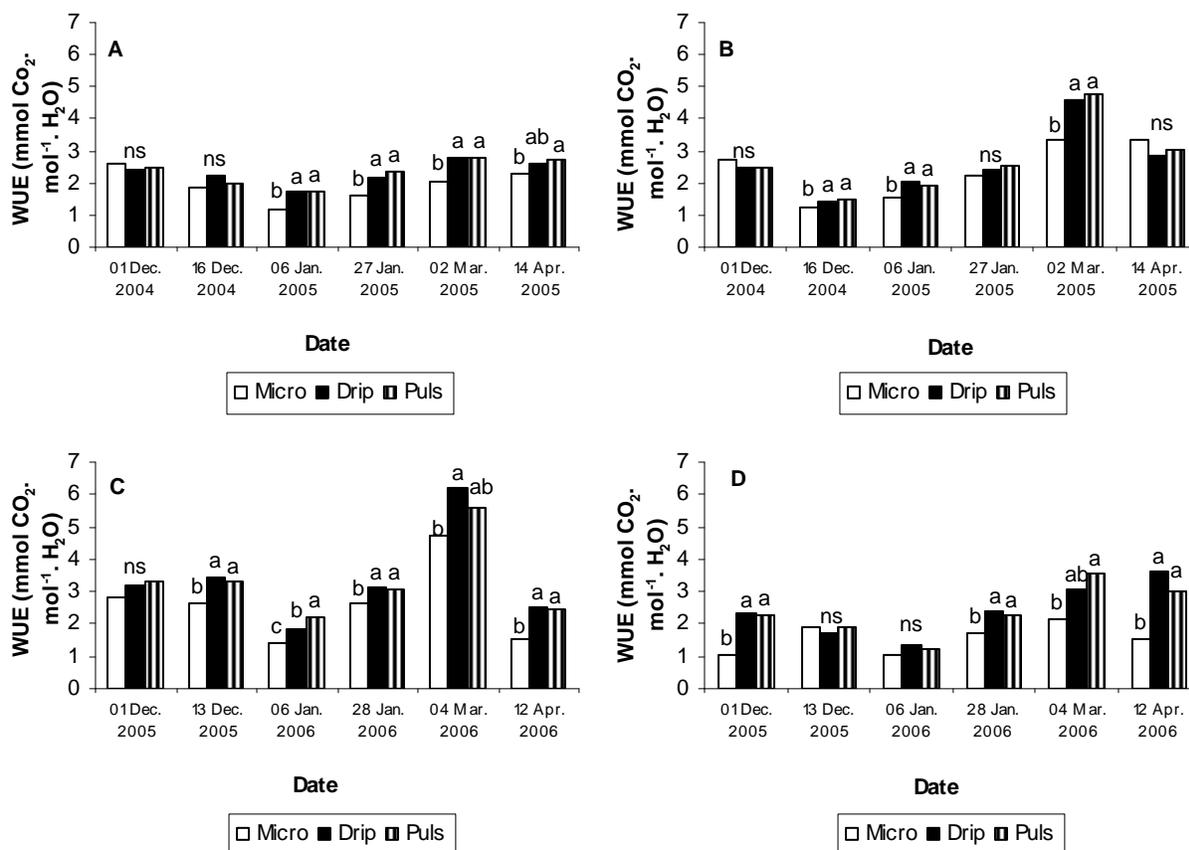


Fig. 3. The influence of different irrigation systems, ‘Micro’ (micro sprinkler irrigation), ‘Drip’ (daily drip irrigation and ‘Puls’ (pulsing drip irrigation) on apple leaf instantaneous water use efficiency (WUE) over two seasons: A (2004/05 morning), B (2004/05, afternoon), C (2005/06 morning), D (2005/06 afternoon). Mean separation by Tukey’s studentized test ($P \leq 0.05$, $n=6$). Mean values followed by different letters in a cluster (date) are significantly different and ns: not significant ($P > 0.05$).

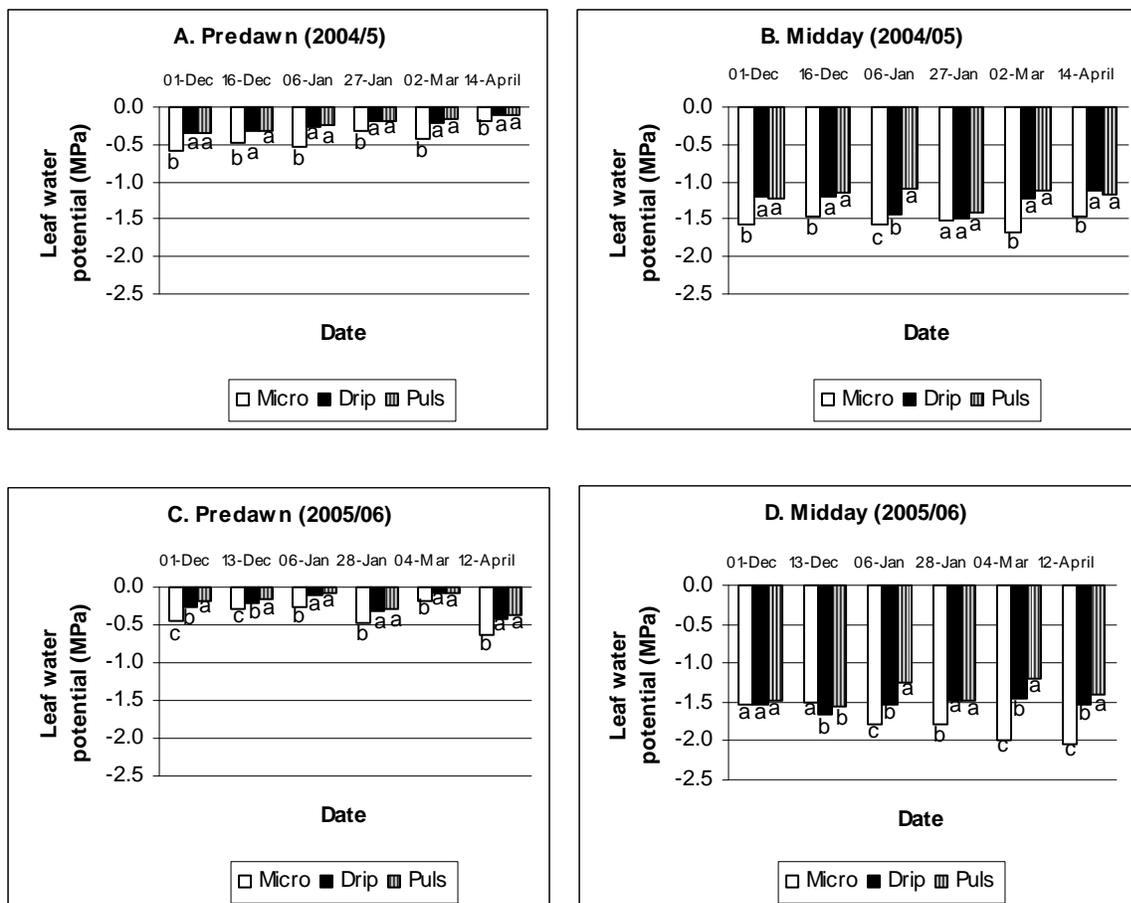


Fig. 4. Predawn and midday leaf water potential of apple leaves under different irrigation systems, 'Micro' (micro sprinkler irrigation), 'Drip' (daily drip irrigation and 'Puls' (pulsing drip irrigation): A (predawn, 2004/05), B (midday, 2004/05), C (predawn, 2005/06) and D (midday, 2005/06). Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=6$). Mean values followed by different letters in a cluster (date) are significantly different and ns: not significant ($P > 0.05$).

6. Post-harvest photosynthetic capacity and gas exchange of 'Brookfield Gala' apple leaves under three irrigation systems and two rootstocks

Abstract. Water and nutrient application frequency using different irrigation systems, namely daily drip irrigation (one to two times daily), pulsing drip (one to six times daily) and micro sprinkler irrigation (one to three times weekly) were studied to determine their influence on the CO₂ assimilation rate, chlorophyll degradation and nutrient concentration changes after harvest during 2005/6 under Western Cape Province (South Africa) conditions (harvest date was 6/02/2006). Two rootstocks, M793 (semi-vigorous) and M7 (semi-dwarfing) were evaluated under a split-plot experimental design with irrigation systems as main plots and rootstocks as sub-plots. Spot gas exchange measurements and leaf sampling for nutrient analysis were taken once prior to harvest (6/02/2006) and every 14 days thereafter, on five occasions, whilst light-responses of CO₂ assimilation rate were conducted starting a week prior to harvest, until two weeks following harvest. Both the choice of rootstock and the irrigation system influenced results. The interaction between irrigation system and rootstock was found to be significant at times. Higher light-saturated assimilation rates (A_{\max}), maximum rate of carboxylation by rubisco (J_{\max}), and maximum rate of electron transport ($V_{c_{\max}}$) were found prior to harvest, while rates decreased significantly after harvest in the cases of all three irrigation systems. The two drip irrigation systems had higher rates of A_{\max} , J_{\max} and $V_{c_{\max}}$ compared to the micro irrigation system. In the case of the micro irrigation system rapid chlorophyll degradation was observed, higher than in the cases of daily drip irrigation and pulsing drip irrigation. The maximum photochemical efficiency for the two drip irrigation systems remained constant at 0.8 (no signs of stress), with a lower maximum quantum efficiency of photosystem II (F_v/F_m) than in case of the micro sprinkler irrigation system (signs of stress). Apart from Fe, there was no significant nutrient accumulation of any of the nutrients analysed from fruit harvest until end of April. This was attributed to the time of taking the measurements (January to April), the age of the trees, and the presence of adequate nutrients to meet the trees' demand (these were found to be within existing norms). Results indicated that fruit removal led to changes in source-sink relationships within the tree and also to reductions in J_{\max} , A_{\max} and $V_{c_{\max}}$. However, the reductions were greater under the micro irrigation system than under the drip irrigation systems, but microelement nutrient concentrations changed more under the micro sprinkler irrigation system than under drip irrigation systems.

Key words: *Leaf photosynthesis efficiency, chlorophyll fluorescence, frequency of water and nutrient application, rootstocks, CO₂ assimilation rate*

6.1 Introduction

Apple fruits on the tree are generally considered to be strong sinks during growth and development in the season (Wibbe & Blanke 1995; Pretorius & Wand, 2003). The presence of fruits reportedly stimulates leaf CO₂ assimilation rate by acting as strong sinks for assimilates (Kriedemann *et al.*, 1976), altering carbon partitioning within the leaf (Hall & Milthorpe, 1978) and delaying the onset of leaf senescence on deciduous trees (Wood, 1988). Removal of such sinks at harvest often leads to increased leaf carbohydrates or a change in sugar content (Pretorius & Wand, 2003; Tartachnyk & Blanke, 2004). Removal of an apple fruit with its plant growth regulator synthesizing seeds may induce decreases in cytokinin levels in leaves, thereby accelerating chlorophyll breakdown. This can further lead to a feedback inhibition of photosynthesis (Kriedemann *et al.*, 1976; Palmer *et al.*, 1997), lower rubisco turnover and content, and chlorophyll degradation, which in turn results in the degradation of leaf components and remobilization of nutrients (Titus & Kang, 1982). There have been reports of a decline in absolute rates of photosynthesis following fruit harvest, mainly as a result of feedback inhibition of photosynthesis and more advanced leaf physiological ageing (Palmer *et al.*, 1997).

Leaf nutrient concentrations are known to fluctuate during the season, mainly because of changes in nutrient supply and internal cycling throughout the period of leaf and shoot development (Nielsen & Nielsen, 2003). Variations in irrigation frequency and the quality of water applied affects leaf nutrients, which vary in their solubility and reactivity with the soil (Nielsen *et al.*, 1995). Fallahi *et al.* (2006) reported increased leaf K and Zn under a microjet system compared to drip systems, and Nielsen *et al.* (1995) reported a decrease under frequent irrigation. Most studies have focused on the effects of N supply and its subsequent remobilization in spring in fruit trees. There have been many reports on N remobilization to storage forms in winter, and its use for new shoot growth in spring (Stassen *et al.*, 1981a, b; Weinbaum *et al.*, 1984; Nielsen *et al.*, 2001). However, the seasonal patterns of leaf nutrients such as N, P, K, Ca and Mg have been found to be unaffected by water stress during the season (Abdalla *et al.*, 1982). Studies of rootstock effects on leaf mineral nutrition have revealed lower concentrations of N and K under dwarfing rootstocks than under vigorous rootstocks (Chun *et al.*, 2001). Nutrients such as Mg, Na

and Al (Poling & Oberly, 1979), N and K (Chun *et al.*, 2001) and K (Abdalla *et al.*, 1982) have been found to be higher in vigorous rootstocks than in dwarfing rootstocks.

Drip irrigation has been regarded as an irrigation system whereby water and nutrients are applied at the base of a tree at frequent intervals, directly to a small soil surface, from single or multiple emission points (Mitchell & Chalmers, 1983), whilst in a micro irrigation system water is applied through a spray (Rodriguez & Lozano, 1991). However, both micro and drip irrigation systems have been reported to be adequate for areas where water availability is limited (Rodriguez & Lozano, 1991). Many studies seem to agree on the basic principle that it is easier to succeed with the use of drippers than micro sprinklers, and that drip irrigation, in addition to its many technical and cultural benefits, is thought to improve water use efficiency in apples (Assaf *et al.*, 1974; Richards & Rowe, 1977; Salmon, 1978; Elfving, 1982; Assaf *et al.*, 1984).

Drip irrigation has been used extensively in South Africa, especially in the citrus and subtropical fruit industries, with improvements in fruit yield and quality, improved water use efficiency and better nutrient management during the growing season (Du Plessis, 1985). However, there are no comparative studies between different types of daily drip irrigation schedules and the micro irrigation system, with respect to photosynthetic efficiency, chlorophyll degradation and nutrient concentration changes after harvest.

The objectives of this study were therefore to compare the photosynthetic capacity of apple leaves and the rate of nutrient concentration change and leaf chlorophyll degradation from fruit harvest to onset of leaf senescence under three irrigation systems (micro irrigation, daily drip irrigation and pulsing drip irrigation) in the same orchard in the Western Cape, South Africa, using 'Brookfield Gala' trees. It was hypothesised that frequent, late-season application of water by means of drip irrigation, particularly using pulsing drip irrigation, would delay the onset of leaf senescence, chlorophyll degradation and increase the rate of carbohydrate synthesis for storage than under micro irrigation system.

6.2 Materials and Methods

6.2.1 Study site

A 4-year old orchard of 'Brookfield Gala' apples on M7 and M793 rootstocks was used in Genadendal, Western Cape (South Africa) during 2005/6. The Western Cape area is

characterized by hot, dry summers and mild, wet winters, with an extended postharvest period prior to leaf senescence. A high density plantation of 2000 trees. ha⁻¹ spaced at 4m × 1.25m was used. The trees were planted in a NE-SW orientation and trained to a central leader with lateral branches bent according to the French solaxe principle.

6.2.2 Experimental design and treatments

(Further details are provided in Chapter 2).

Three irrigation treatments, namely micro sprinkler irrigation, daily drip irrigation and pulsing drip irrigation systems, were randomly distributed in eight rows. A split-plot design was used and each system was used as a main plot and the two rootstocks (M7 or M793) as sub-plots. Each experimental unit consisted of five trees, of which only the middle tree was used for measurements. The three irrigation systems were installed in 2003. For the daily drip irrigation system the discharge rate was 2.3l.h⁻¹ and for the micro sprinkler irrigation the discharge rate was 30l.h⁻¹, covering the entire 1.25m radius around the tree. The daily drip irrigation supplied water once daily whilst the pulsing drip ran several times a day (between once daily in the winter months to six times daily in the summer months). The micro sprinkler irrigation system delivered water one to three times a week (depending on the maximum daily temperatures). The rows were separated by a one-meter-deep polythene plastic liner in a trench to prevent any lateral movement of water between the treatments. The total annual water use (average between daily drip irrigation and pulsing drip irrigation) was 3429m³ yr⁻¹.ha⁻¹ and 3987m³ yr⁻¹.ha⁻¹ for 2004/5 and 2005/6 respectively. Due to the inefficient water application of the micro irrigation system, as a result of droplet drift, droplet evaporation, and a greater application radius, more water was required (5254 and 5661m³.ha⁻¹.yr⁻¹ in 2004/5 and 2005/6, respectively) (Chapter 2). This water requirement was based on crop factors and past evaporation weather data for the area and further adjusted according to the volumetric soil measurements done on the site using C-Probe meters and Watermark sensor (calibrated using Neutron probes) and ECH₂O soil moisture sensors (placed only under pulsing drip irrigation) (Decagon Devices, Inc. Pullman, USA) at different soil depths. The nutrients were supplied in aqueous solutions with irrigation water in the case of drip based systems, and manually applied in the case of the micro irrigation system (based on earlier work done by Stassen & North (2005) on pears). The nutrients were distributed percentage-wise, adjusted according to plant growth and phenological stages during the season, and continued after fruit harvest until winter. Higher rainfall was recorded in January prior to harvest (15mm)

compared to less than 5mm of rainfall for the months of February, March and April (Chapter 2). There was no rainfall recorded prior to taking measurements.

6.2.3 Measurements of spot, diurnal gas exchange and light response curves

Spot measurements of net CO₂ assimilation rate (A), diurnal measurements of A and photosynthetic light- and CO₂-responses of A were collected using a LI-6400 infrared gas analyser (Li-Cor, Lincoln, Nebraska, USA) under ambient sunlight (photosynthetic photon flux density PPFD >1400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), ambient air temperature and air relative humidity (Chapter 4 and 5). Cuvette CO₂ concentration was controlled at 380 $\mu\text{mol}\cdot\text{mol}^{-1}$ using a CO₂ injection system and compressed CO₂ cylinders. A LI-190SA quantum sensor (Li-Cor, Lincoln, Nebraska, USA) attached to the LI-6400 was used to measure photosynthetic photon flux density (PPFD). Only the middle tree in each replication was evaluated and one sun-exposed leaf at a height of 1.2–1.5m on the western side of the tree was measured per replication (n=6). Measurements were taken replication by replication, during the morning (09h00 to 11h00) and afternoon (12h00 to 14h00) on six different days, once prior to harvest (6/02/2006) and every 14 days thereafter, on five occasions.

Diurnal gas exchange measurements were carried out once prior to and once ± 14 days after fruit harvest. Measurements were done two-hourly between 06h00 and 18h00 under ambient sunlight and temperature conditions using the LI-6400 infrared gas analyser. The daily solar radiation was tracked using a Li-190SA quantum sensor. Only the middle tree in each replication was evaluated and one sun-exposed leaf at a height of 1.2–1.5m on the western side of the tree was measured per replication (n=6).

Photosynthetic light response curves were generated at an air temperature of 25°C (Chapter 4 and 5), and air-to-leaf vapour pressure deficit (VPD) of 1 to 2 kPa. The cuvette CO₂ concentration was controlled at 380 $\mu\text{mol}\cdot\text{mol}^{-1}$ using a CO₂ injection system and compressed CO₂ cylinders. Irradiance levels of 2000, 1500, 1000, 800, 600, 400, 200 100 and 0 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD (provided by an internal red/blue LED light source) were used. Measurements were taken on 31/01/2006 (6 days before fruit harvest) and on 24/02/2006 after fruit harvest. Intrinsic leaf water use efficiency (WUE_i) was determined as the ratio of A_{max} to leaf stomatal conductance (g_s) whilst instantaneous water use efficiency (WUE) was calculated as A/E. One sun-exposed leaf on the west side of the tree was measured per tree (one middle tree was used) per block (n= 5).

Photosynthetic CO₂ response measurements (A/C_i) were recorded at an air temperature of 25°C, VPD of 1–2 kPa (obtained by manipulating the flow rate through desiccant) and PPFD of 1500 $\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$ (provided by an internal red/blue LED light source), on the same dates as the light response curves. CO₂ was supplied by compressed CO₂ cylinders and different levels of cuvette CO₂ concentrations were used in the following sequence: 380, 300, 150, 100, 50, 380, 600, 800 and 1000 $\mu\text{mol. mol}^{-1}$. One sun-exposed leaf on the west side of the tree was selected per tree (one middle tree was used) per block. The response of A to PPFD was modelled by a non-rectangular hyperbola where the initial slope represents the apparent quantum efficiency (QE). The rate of dark respiration (R_d) was taken from the y-axis intercept and the light-saturated A (A_{max}) was determined as the upper asymptote (Prioul & Chartier, 1977). Leaf stomatal conductance (g_s) was obtained from system equations derived by Von Caemmerer & Farquhar (1981). The mechanistic model proposed by Farquhar *et al.* (1980) and later modified by Von Caemmerer & Farquhar (1981), Sharkey (1985) and Harley *et al.* (1992) was used to estimate the maximum rate of carboxylation ($V_{c_{\text{max}}}$) and the light-saturated rate of electron transport (J_{max}).

6.2.4 Leaf nutrient concentration

Healthy leaf samples with petioles attached, consisting of 40 leaves per sample, were randomly picked from each treatment in six blocks; picking commenced on 31/02/2006 and was carried out every fortnight thereafter until 26/04/2006. The leaves were collected from the mid-third portion of extension shoots of the current year's growth from each of the five trees. Mineral analysis was performed by a commercial analytical laboratory (Bemlab® Pty. Ltd, Strand, South Africa). The leaf samples were first washed in 1% v/v HCl solution, rinsed twice – first with tap water and then with deionized water, and subsequently dried in a forced-air oven at 80°C overnight. Nitrogen was analysed using a nitrogen analyser (LECO FP528 Nitrogen analyser, LECO Cooperation, St. Joseph, Michigan, USA). All other 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 percentage dry weight (%DW) for N, P, K, Ca, Mg and S and as mg/g DW for all other nutrients.

6.2.5 Leaf chlorophyll concentration

Fresh leaves were picked one week prior to harvest (31/01/2006) and every three weeks thereafter, until 26/04/2006. The leaves were immediately placed on ice in the dark and then stored under liquid nitrogen in the laboratory. Twenty leaves per treatment in six blocks were used. The leaves were sampled on one-year-old shoots, on the mid-third portion of the shoot on the west side of the tree at a height of 1.2m. The samples were then freeze dried (Freeze mobile, Virtis Company Inc., Gardiner, New York, USA) for three days, ground and sieved through a 500- μ m sieve, then kept at -80°C until analysis. From each sample aliquots of 0.05g were extracted in 80% (v/v) acetone (Arnon, 1949). The extracted solution was centrifuged at $20\,000\times g$ for 10 minutes and stirred in the dark for 24 hours at 4°C . The absorbance of the supernatant was read at 470nm, 647nm and 663nm using a spectrophotometer (Cary 50 Bio, UV-visible Spectrophotometer, Varian Australia Pty, Ltd. Australia). Concentrations of chlorophyll a (Chla), chlorophyll b (Chlb), total chlorophyll (Chlt) and carotenoids were determined using published equations (Lichtenthaler, 1987).

6.2.6 Chlorophyll fluorescence

During 2005/6 fruit harvest date was 6 February 2006. Leaf chlorophyll fluorescence was measured two weeks after fruit harvest (17/02/2006) and every two weeks thereafter until 21/04/2006, using a FMS2 modulated fluorescence measuring system (Hansatech, Norfolk, UK). The leaves were dark adapted for 30 minutes prior to each measurement, using leaf clips. The baseline fluorescence under modulating light (F_o) and maximum fluorescence yield following a saturated pulse of light (F_m) were recorded, and the maximum quantum efficiency of photosystem II (F_v/F_m) calculated (Schreiber, 1986). Five measurements per treatment in six blocks were done between 09h00 and 11h00.

6.2.7 Statistical analysis

All data were analysed by a split-plot analysis of variance (ANOVA) (SAS GLM procedure, Enterprise Guide 6, release 1.3 SAS Institute, Cary, NC, USA, 2001). Mean separation was performed by Tukey's studentized range test ($P\leq 0.05$).

6.3 Results

6.3.1 Spot gas exchange

The effect of environmental conditions under which morning and afternoon spot gas exchange measurements were taken, was determined. Results of measurements taken in the morning showed lower VPD, Tleaf (leaf temperature) and PPFD compared to measurements taken in the afternoon, and that readings were variable decreased somehow over the duration of the trial corresponding with fruit harvest to the onset of leaf senescence (Tables 1a and 1b). The ambient net CO₂ assimilation rate (A) was high in all the systems a week prior to harvest (27/01/2006) for both the morning (Table 2) and afternoon (Table 3) measurements. Both drip irrigation systems had significantly higher rates than the micro irrigation system, but no significant differences were observed between the two drip irrigation systems. Following fruit harvest, the morning A was significantly reduced in all three irrigation systems on 17/02/2006, but more so under the micro sprinkler irrigation system. Thereafter, rates remained stable or gradually decreased under micro irrigation and daily drip irrigation system, but recovered under pulsing drip irrigation, so that there were significant differences between daily drip irrigation and pulsing drip irrigation on 24/02/2006 and 26/04/2006 (morning measurements) (Table 2). Similar trends were also observed for the afternoon measurements (Table 3). The A value was more strongly reduced in the afternoon under the micro irrigation system compared to both drip irrigation systems, and showed a significant decrease following harvest. Both drip irrigation systems maintained similar postharvest afternoon rates for the duration of the experiment, but pulsing drip irrigation had higher rates than daily drip irrigation on 17/02/2006 and 29/03/2006.

Stomatal conductance remained relatively constant or showed only slight reductions from preharvest throughout the study period (Tables 2 and 3). However, higher conductance was measured under all irrigation systems on the first postharvest date (17/02/2006), followed by a reduction two weeks thereafter and almost full recovery for the remaining period. The pulsing drip irrigation system had significantly higher stomatal conductance compared to the micro sprinkler irrigation system, except on 17/02/2006 and 29/03/2006 (morning measurements). Higher values were obtained in pulsing drip irrigation compared to daily drip irrigation on 24/02/2006, 12/04/2006 and 26/04/2006 (morning measurements) and on 27/01/2006 and 29/03/2006 (afternoon measurements). Similar trends were found for the transpiration rates (Tables 2 and 3).

There were no differences between the irrigation systems in instantaneous WUE (A/E) on the first date of measurements (Tables 2 and 3). During the postharvest period, significantly higher WUE was found in the two drip irrigation systems compared to the micro sprinkler irrigation system on three of the five measurement days, both in the morning (Table 2) and afternoon (Table 3). Pulsing drip irrigation had higher WUE than daily drip irrigation on 17/02/2006 (afternoon, Table 3). The intercellular CO₂ concentration (C_i) was relatively constant throughout the entire postharvest period. There were significant differences in C_i between systems, with drip irrigation systems (especially daily drip irrigation) generally giving lower values than the micro sprinkler irrigation system on most dates, except 27/01/2006 (morning and afternoon; Tables 2 and 3). Significant interactions between the irrigation system and the rootstock were found only for transpiration (E) on 27/01/2006 and 12/04/2006 and for WUE on 29/03/2005 (Table 6). The main effects of rootstock on gas exchange were significant on some days in the morning (Table 4) and afternoon (Table 5). M793 rootstock gave higher rates of A_{max}, g_s and E compared to the M7 rootstock.

6.3.2 Diurnal gas exchange

The diurnal PPFD and VPD conditions on the measurement days are shown in Fig. 1A (preharvest) and Fig. 1B (postharvest). The diurnal course of A values both prior to and after fruit harvest showed a characteristic mid-morning peak, followed by a steady decline until 14h00, with rates remaining relatively low in the afternoon (Figs. 1C and D). Assimilation rates were, however, lower two weeks after fruit harvest compared to one week before harvest. The two drip irrigation systems showed consistently higher A values than the micro irrigation system on both dates. Stomatal conductance declined steadily throughout the day (Figs. 1E and F). Prior to harvest, drip irrigation systems showed significantly higher g_s than the micro sprinkler irrigation system from 10h00 onwards except at 12h00 (Fig. 1E). After harvest, g_s was significantly higher under the drip irrigation systems than under the micro sprinkler irrigation system throughout the day (except at 12h00), with pulsing drip irrigation being significantly better than the daily drip irrigation system and micro sprinkler irrigation system during mid-morning (Fig. 1F). WUE_i (A/g_s) prior to fruit harvest showed high values in the morning, which increased until midday and remained high in the afternoon, but declined at 18h00 (Fig. 1G). In Fig. 1H, WUE_i showed further increases during late afternoon. The drip irrigation systems gave higher WUE_i than the micro irrigation system at most measurement times.

6.3.3 Photosynthetic light- and CO₂-response curves

The two drip irrigation systems showed a higher A_{\max} compared to the micro sprinkler irrigation system. However, A_{\max} was significantly higher under the pulsing drip irrigation system than under the daily drip irrigation system prior to harvest (Table 7). The parameters J_{\max} and $V_{c\max}$ obtained from A/C_i response curves were substantially higher prior to fruit harvest under all irrigation systems, but J_{\max} tended to be higher under the two drip irrigation systems, although not significantly so (Table 8). There were no significant effects of rootstock on light response or A/C_i parameters (Tables 7 and 8).

6.3.4 Leaf nutrient concentration

Leaf nitrogen concentration ([N]) was low under all irrigation systems but remained stable during the study period (Table 9). The lower rates were more evident under micro irrigation than under both drip irrigation systems. Leaf phosphorus and potassium concentrations ([P] and [K]) preharvest were lower under both drip irrigation systems than under the micro sprinkler irrigation system, and [K] was also lower under drip irrigation system on 26/04/2006. Preharvest, leaf calcium concentration ([Ca]) was higher under daily drip irrigation than under the micro irrigation system, but lower under both drip irrigation systems than under the micro sprinkler irrigation system on 26/04/2007 (Table 9). A significant interaction between irrigation systems and rootstock was found preharvest (31/01/2006) due to a reduced [K] on M7 under both drip irrigation systems compared to M7 under micro sprinkler irrigation (Table 10). On 31/01/2006, [Ca] was significantly higher on M7 than on M793, and on 10/03/2006 [P] was higher on M793 than on M7 (Table 10). Leaf micronutrient concentrations preharvest showed a significantly higher manganese concentration ([Mn]) under both drip irrigation systems compared to micro irrigation (Table 9). Micronutrient concentrations were consistently higher under the micro sprinkler irrigation system than under the two drip irrigation systems (Table 9). Only (Fe) was seen to accumulate following fruit harvest until end-April, whilst the concentrations of the other micronutrients remained relatively stable or showed slight decreases.

6.3.5 Pigment concentration

Leaf pigment concentrations declined steadily from prior to fruit harvest until end-April, with a minor recovery on 12/04/2006 (Figs. 2A, 2B, 2D, 2E). The ratio between Chla and Chlb showed an increase on 26/02/2006, shortly after harvest, but remained constant thereafter throughout the study period (Fig. 2C). The concentrations of Chla, Chlb and Chlt were significantly lower under

micro sprinkler irrigation than under both drip irrigation systems, and their decline during the study period was more rapid than under daily drip irrigation and pulsing drip irrigation (Figs. 2A, 2B, 2E). This further implies a more degenerative effects on pigment molecules due to lack of sufficient water within the organelles under micro irrigation than under drip based systems. The carotenoid concentration was also significantly lower under micro irrigation than under drip irrigation systems, but the rates of decline were similar (Fig. 2D). The ratio between Chl_t and carotenoids in both drip irrigation systems remained constant until 24/03/2006, with increases thereafter, but under micro sprinkler irrigation there was a decline in the Chl_t:Car ratio, especially during the early period (Fig. 2F). This resulted in significantly higher ratios under drip irrigation than under micro sprinkler irrigation during the middle to late period (Fig. 2F).

6.3.6 Chlorophyll fluorescence

The F_v/F_m ratio remained constant around 0.8 throughout the experimental period under both daily drip irrigation and pulsing drip irrigation, but under the micro sprinkler irrigation system it showed a sharp decrease on the first day of measurement (04/03/2006). Values for the micro sprinkler irrigation system were significantly lower than values for the drip irrigation systems (Fig. 3A). The baseline fluorescence under modulating light (F_o) increased on 04/03/2006 for the micro sprinkler irrigation system, and thereafter declined throughout the study period, with no significant differences between the irrigation systems (Fig. 3B). The maximum fluorescence yield following a saturated pulse of light (F_m) declined on 04/03/2006 in the case of all irrigation systems, but was greater under micro sprinkler irrigation, and then declined steadily throughout April (Fig. 3C).

6.4 Discussion

The removal of fruit at harvest had a significant influence on leaf photosynthetic capacity under the micro irrigation system but less so under the two drip irrigation systems. Reductions in photosynthesis were due to both stomatal (high g_s following harvest) and non-stomatal limitations (decrease in daily temperature and sink effects). This further implies that source-sink relationships were more significant under the micro irrigation compared to under the drip irrigated systems, because of less frequent application of water. The results indicated higher leaf photosynthesis before harvest and a reduction in biochemical capacity (lower J_{max} and $V_{c_{max}}$) under all the irrigation systems. The two drip irrigation systems had higher rates of A_{max} , J_{max} and $V_{c_{max}}$ compared to the micro sprinkler irrigation system, which confirms high leaf biochemical

efficiency under the drip irrigation systems than compared to micro sprinkler irrigation. There were increases in g_s values immediately after harvest, resulting in no decrease in A_{max} under the two drip irrigation systems than under the micro sprinkler irrigation system. This is further confirmed by C_i concentrations, which showed no decline associated with lower g_s and A values. Similar patterns have also been confirmed in plums (Gucci *et al.*, 1991), with a depression of net photosynthesis for at least five days following fruit removal. WUE (A/E) was more dependent on daily carbon gain than on daily transpiration, and only occasionally on changes in g_s (Jarvis & Davies, 1998). Studies by Cheng & Luo (1997) on apples revealed WUE dependency on E rather than on g_s , however such dependency could not be confirmed in our studies. Daily fluctuations in A showed higher rates in the mid-morning and lower rates in the afternoon under all three irrigation systems (for details of diurnal photosynthetic assimilation rates see Chapters 4 & 5), and similar trends were observed following fruit harvest. Flore & Lakso (1989) have stated that, in apples, maximum A occurs before solar noon as incident irradiance and the temperature are rising and lower rates are evident in the afternoon at equivalent PPFD and optimum temperature. VPD or PPFD (Figs. 1A and 1B) were similar for all the irrigation systems and hence did not play a significant role in the differences in CO_2 assimilation rates between the irrigation systems following harvest. The decrease in the afternoon has been associated with stomatal closure or with the build up of photoassimilates as light remains saturated in the afternoon but temperature and VPD continue to rise (Jones *et al.*, 1985; Flore & Lakso, 1989; Cheng & Luo, 1997). Photosynthetic rates following harvest did not decrease under daily drip irrigation systems but only under micro sprinkler irrigation, possibly because frequent and daily irrigation systems resulted in optimal growing conditions that favour a high A (Wünsche *et al.*, 2000).

Delayed harvest is known to delay the onset of stomatal and mesophyll conductance decline in autumn (Avery *et al.*, 1979), but a sudden drop in photosynthesis after harvest has been reported (Kennedy & Fujii, 1986). Fruiting 'Starkrimson' spurs were found to exhibit an enhanced leaf photosynthetic rate as a result of higher carboxylation efficiency and lower mesophyll resistance (Kennedy & Fujii, 1986). The differences in A values under different irrigation systems, with a higher A under drip irrigation systems than under micro sprinkler irrigation, could presumably be due to less hydraulic conductivity of the root system that has a pronounced effect on water potential (less water potential) (details of daily water potential are discussed in Chapters 4 & 5), as a result of irrigating twice weekly compared to daily irrigation. The effects of fruit on photosynthesis, partitioning of assimilates and dry matter accumulation have shown higher leaf

photosynthetic efficiency and transpiration in fruiting apple trees compared to non fruiting apple trees (Fujii & Kennedy, 1985; Wünsche & Ferguson, 2005). Further studies by Palmer *et al.* (1997) between different apple cultivars provide clear evidence that the leaf assimilation rate is positively and curvilinearly related to crop load. The reduction in A_{\max} , J_{\max} and $V_{c_{\max}}$ observed in this study under the three irrigation systems following fruit harvest implies that photosynthesis reduction after harvest is not only dependent on stomatal limitation but rather partially attributable to carbohydrate accumulation, subsequent feedback inhibition and source-sink changes that occur after fruit removal (Monselise & Lenz, 1980; Pretorius & Wand, 2003; Tartachnyk & Blanke, 2004).

The growth and composition of apples is known to be dependent upon the fruit/leaf-ratio, however, other elements within the source-sink relationship of the tree such as top-root ratio are important (Toldam-Andersen & Hansen, 1995). Removal of fruit at harvest leads to changes in source-sink relationships (Wibbe & Blanke, 1995; Pretorius & Wand, 2003). Wright (1989) summarised sinks in their priority order as follows: seeds>fleshy fruit parts=shoot apices and leaves>cambium>roots>storage. In this study, A decreased only after harvest but remained constant until end-April under drip irrigation systems whilst it decreased significantly under micro irrigation. However, there was more root response under micro irrigation following fruit harvest as shown by significant accumulation of micronutrients compared to drip irrigation systems. The leaf ageing that ultimately leads to the onset of leaf senescence in apple has been reported to increase after fruit removal (Spencer & Titus, 1972; Smart, 1994), even though visible symptoms like yellowing don't necessarily mean absence of triggered senescence; drip based systems showed healthier leaves and activity than under micro sprinkler irrigation. A decrease in temperature of apple leaf has been reported to trigger the onset of leaf senescence, resulting in the synthesis of nucleic acids, protein and chlorophyll degradation (Spencer & Titus, 1972).

There were higher Chla and Chlb concentrations under drip irrigation systems than under the micro system for the duration of the study period. The down-regulation of photosynthetic capacity following fruit harvest seem to trigger reduction in chlorophyll concentrations under micro irrigation but not under drip irrigation systems, though this might not necessarily imply cause and effect relationship. Results in Chapter 3 indicated that trees growing under drip irrigation systems had a better root proliferation as a result of frequent water and nutrient application compared to trees under micro irrigation, where there was high shoot growth.

Chlorophyll content is known to be higher in sun-exposed and active leaves than in shaded leaves (Wüsche & Ferguson, 2005). Such a situation is more likely under the drip irrigation systems than under the micro irrigation system. This implies a high Chla and Chlb in sun-exposed branches under the drip irrigation systems, to supply the high demand in photosystem II under these systems. The photosynthetic disassembly involves extensive breakdown of Chl, which may or may not be accompanied by catabolism or retention of carotenoids (Merzlyak *et al.* 1999). In this study there was a quicker reduction in Chlb than Chla under all the irrigation systems following harvest. The changes in Chl and Car concentrations can be closely associated with the temporal increase in the Chla:b ratio, which resulted in a slight decrease in the Chl:Car ratio after harvest. This is regarded to be a direct negation of hormonal imbalances following fruit removal, in an attempt by the leaves to adjust to new conditions (Solovchenko *et al.*, 2005). The high chlorophyll concentrations are further indicative of the more efficient PS II photochemical energy conversion under drip irrigation systems than under micro irrigation.

The maximum photochemical efficiency (Fv:Fm) remained constant at 0.80 for trees under pulsing drip irrigation and conventional drip irrigation, which further indicated an efficient PS II photochemical energy conversion at levels that were not stressful to these trees. The decline in Fv:Fm on 4/03/06 under micro irrigation reflected an increase in Fo and a decline in Fm. The decrease in Fm implies that photosynthesis is taking place and as a result of continuous light illumination there is a more dominant PSI-linked photooxidation relative to photoreduction (Deell *et al.*, 1999). Similar patterns have been observed in apple leaves following harvest (Greer *et al.*, 1997; Solovchenko *et al.*, 2005). Wüsche *et al.* (2000) reported a reduction in photochemical efficiency in apple leaves with no crop, indicating a higher percentage of photosystem II reaction centre pool closure and a greater capacity for non-photochemical quenching (thermal dissipation). The leaf ageing that triggers the onset of leaf senescence was not discernible under drip irrigation but already measurable under the micro irrigation system due to excess light (photoinhibition). This relationship has been shown before in non-bearing apple trees (Osmond, 1994; Greer *et al.*, 1997; Wüsche *et al.*, 2000; Wüsche & Ferguson, 2005) but not on non-bearing apple trees growing under different irrigation systems. Studies by Osmond (1994) indicated that when the interception and absorption of light energy exceeds the light energy used in CO₂ fixation, part of the intercepted light energy becomes excessive and may inactivate the primary photochemical process occurring within the chloroplasts – a situation observed more often under micro irrigation than under drip irrigation systems.

There was no consistent rootstock effect between M793 and M7; however, occasionally there were instances where M793 was significantly better than M7. M793 showed higher values of A, g_s and E compared to M7. The trees under study were four years old, and in such young trees xylem transport of water and nutrients from the roots to the top of the tree is met with little resistance (Fallahi *et al.*, 2002), hence with future growth there might be possible differences in rootstock growth activity and conductivity. In Chapter 3, higher growth rates (high trunk cross-sectional area) were also confirmed with M793 than with M7, however M7 had a higher yield efficiency compared to M793. The effect of rootstock on leaf mineral nutrition has been noted in many studies (Westwood *et al.*, 1986; Chun *et al.*, 2001). Chun *et al.* (2001) found that apple trees ('Fuji') on B.9 (dwarfing rootstock) had relatively lower values for A, g_s , C_i and E than those on vigorous rootstocks. Also the soil used for the experiment provided ideal medium for root development (Chapter 2 & Chapter 3), further guaranteeing better growth and possible differences in the future.

Important nutrients such as N are known to play a major role in spring flush growth, floral initiation and fruit set in fruit crops (Stassen *et al.*, 1981a, b; Faust, 1989). The leaf [N] did not show any accumulation in leaves in autumn before onset of leaf senescence. This may however be due to high N availability relative to tree demand in the trees that were studied. Similar patterns have been noted by Neilsen *et al.* (2001), who recorded no N concentration accumulation by three-year-old 'Elstar' apple trees on M9 before leaf senescence. The leaf concentrations of N, P and K correlate well to the published norms of Faust (1989) and Kotzé (2001) for apple leaves. However, no effect of irrigation type was observed on the concentrations of Ca and P following fruit harvest. These data are in agreement with work done by Neilsen *et al.* (1995) who also found little or no effect of N/P-fertigation on leaf concentration and a lower K problem in drip irrigated trees than in sprinkler irrigated trees. There was consistency in the levels of leaf nutrient concentrations following fruit harvested under drip irrigation systems, and a higher concentration of micronutrients under the micro sprinkler irrigation system. These results were found to be in agreement with earlier work by Fallahi *et al.* (2006) who found higher K, Zn and Cu concentrations under sprinkler irrigation than under drip irrigation systems. The frequent application of water in drip irrigation systems following harvest enhanced proper leaf growth and possibly a longer leaf retention, which further delayed the leaf ageing, with further delays in the onset of leaf senescence, and reduced mineral accumulation. The management of nutrients and

their application in deciduous fruit trees is optimised according to tree phenology and plant mineral uptake, which is rapid during early season (the period before and slightly after bud burst) and minimal in summer, and again more rapid in the postharvest period for most nutrients (Nielsen & Nielsen, 2003). Root growth is known to be high following harvest, as a result of changes in source-sink relationships and the micro irrigation system resulted in a quicker change in root activity than drip irrigation systems, as evident by increased micronutrient uptake.

The leaf ageing, which leads to the onset of leaf senescence in apples, is associated with environmental factors limiting photosynthesis; in particular, a decrease in leaf photosynthesis is down-regulated by source-sink relationships following fruit harvest. In this study, the leaf photosynthetic rate and chlorophyll concentration decreased following fruit harvest, whilst leaf mineral concentrations remained consistent. The photosynthetic leaf reduction is related to both the stomatal and non-stomatal effects. The changes in source-sink relationships following harvest affected leaf efficiency irrespective of the type of irrigation system used, but reductions were more pronounced under micro irrigation than under drip irrigation systems. Net assimilation rates and chlorophyll concentrations remained higher until end of April under drip irrigation systems than under micro irrigation system and micro sprinkler irrigation resulted in significant micronutrient concentration differences following fruit harvest. Use of daily drip irrigation and pulsing drip irrigation strategies could possibly delay leaf ageing and thus the onset of leaf senescence, and prolong chlorophyll retention with no increase in nutrient concentrations. Micro sprinkler irrigation was seen to adapt better following fruit harvest as shown by a rapid micronutrient accumulation compared to the drip irrigation systems. This suggests that for drip irrigated systems the systems should be run for one month following harvest and the application of water and nutrients should be reduced to only once a day. This could encourage down-regulation of photosynthesis and trigger the mechanism of leaf ageing with an ultimate onset of leaf senescence and earlier leaf drop during winter. This would ultimately trigger early leaf drop and longer periods at dormancy and hence a better return to bloom in the following season.

6.5 References

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Table 1a: Monthly mean of daily maximum (Tmax) and minimum (Tmin) temperatures and rainfall for 2006 recorded by an automated weather station situated 50m from the experimental orchard.

Month	Tmax (°C)	Tmin (°C)	Rainfall (mm)
January	30	16	25
February	31	15	17
March	28	11	16
April	23	10	43
May	21	6	80
June	21	6	39
July	18	6	115
August	19	7	128
September	22	9	25
October	24	10	38
November	27	12	11
December	28	13	4

Table 1b: The effect of environmental conditions under which morning and afternoon spot gas exchange measurements were recorded. Leaf-to-air-vapour pressure deficit (VPD), leaf temperature (Tleaf), and photosynthetic photon flux density (PPFD) were recorded by the IRGA system whilst the daily mean air temperature (Tmean) was recorded by an automated weather station situated 50m from the experimental orchard.

Date	Environmental conditions						Tmean (°C)
	Morning			Afternoon			
	VPD (kPa)	Tleaf (°C)	PPFD ($\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$)	VPD (kPa)	Tleaf (°C)	PPFD ($\mu\text{mol. m}^{-2} \cdot \text{s}^{-1}$)	
27/01/2006	2.19	30	1489	4.38	37	1884	26
17/02/2006	3.17	32	1800	4.32	36	1822	21
24/02/2006	1.97	26	1667	3.32	38	1800	19
29/03/2006	1.48	21	1355	5.35	34	1698	23
12/04/2006	2.46	31	1513	2.18	33	1626	14
26/04/2006	1.17	24	1443	2.08	30	1591	16

Table 2: Mean (\pm SE) morning (09h00 to 11h00) net CO₂ assimilation, stomatal conductance, water use efficiency, transpiration and internal carbon dioxide concentration in ‘Brookfield Gala’ apple leaves as influenced by irrigation systems (‘Micro’, micro sprinkler irrigation, ‘Drip’, daily drip irrigation, ‘Puls’, pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstocks during 2005/2006 before and after harvest. Measurements were taken on clear days using an open cuvette attached to the IRGA leaf chamber. Probability values are according to split-plot ANOVA. Mean separation by Tukey’s studentized test ($P \leq 0.05$, $n=5$). SE = standard error of the mean at 5% probability level. Mean values followed by different letters in columns are significantly different, ns: not significant ($P > 0.05$). Arrow (\downarrow) indicates harvest date.

Treatment	27/01/2006 \downarrow	17/02/2006	24/02/2006	29/03/2006	12/04/2006	26/04/2006
Net CO ₂ assimilation rate ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)						
Micro	15.50 b	8.52 b	8.97 c	4.18 b	9.91 b	6.89 c
Drip	18.46 a	14.14 a	14.74 b	12.69 a	15.76 a	14.08 b
Puls	18.98 a	15.72 a	18.13 a	12.93 a	18.28 a	17.81 a
SE \pm	0.56	0.63	0.81	0.67	0.71	0.63
P-value						
System	0.0365	≤ 0.0001				
Rootstock	0.0269	0.1514	0.6167	0.9135	0.7169	0.7476
System \times rootstock	0.3172	0.3719	0.4463	0.9008	0.1934	0.8777
Stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$)						
Micro	0.26 b	0.45 ns	0.08 b	0.22 ns	0.24 b	0.18 b
Drip	0.28 ab	0.32	0.11 b	0.26	0.26 b	0.19 b
Puls	0.31 a	0.36	0.17 a	0.26	0.34 a	0.32 a
SE \pm	0.01	0.02	0.02	0.06	0.01	0.02
P-value						
System	0.0149	0.0868	0.0003	0.2187	0.0006	0.0015
Rootstock	0.0325	0.0385	0.9751	0.4701	0.4044	0.5430
System \times rootstock	0.0939	0.5479	0.6731	0.7950	0.0727	0.6502
Transpiration ($\text{mmol. m}^{-2}. \text{s}^{-1}$)						
Micro	5.33 b	11.55 ns	1.67 b	4.24 ns	5.73 b	1.99 b
Drip	5.91 a	9.94	2.11 b	3.73	6.25 b	2.19 b
Puls	6.29 a	10.49	3.03 a	3.77	7.34 a	3.14 a
SE \pm	0.15	0.30	0.23	0.22	0.18	0.24
P-value						
System	0.0020	0.1119	0.0006	0.4209	0.0024	0.0016
Rootstock	0.0055	0.1060	0.8951	0.6732	0.6478	0.7646
System \times rootstock	0.0343	0.8385	0.6515	0.8342	0.0195	0.6873
Water use efficiency ($\text{mmol CO}_2 \text{mol}^{-1} \text{H}_2\text{O}$)						
Micro	2.92 ns	0.75 b	5.91 ns	1.04 b	1.76 b	4.63 ns
Drip	3.12	1.44 a	7.17	3.43 a	2.52 a	6.80
Puls	3.01	1.50 a	6.19	3.49 a	2.49 a	5.74
SE \pm	0.09	0.07	0.4	0.19	0.07	0.65
P-value						
System	0.5087	≤ 0.0001	0.0214	≤ 0.0001	≤ 0.0001	0.0524
Rootstock	0.7498	0.5858	0.7226	0.7207	0.1746	0.8232
System \times rootstock	0.2820	0.6974	0.9830	0.8588	0.6367	0.8656
Intercellular carbon dioxide ($\mu\text{mol CO}_2 \text{mol air}^{-1}$)						
Micro	238.25 ns	307.75 a	152.68 a	341.00 a	274.75 a	276.75 a
Drip	224.67	257.58 b	120.17 b	266.17 b	235.33 b	217.75 b
Puls	229.50	256.50 b	154.67 a	262.00 b	240.42 b	243.83 ab
SE \pm	4.79	3.22	15.88	5.17	3.61	10.76
P-value						
System	0.3662	≤ 0.0001	0.0181	≤ 0.0001	≤ 0.0001	0.0066
Rootstock	0.9606	0.9297	0.6630	0.5726	0.1094	0.6485
System \times rootstock	0.4390	0.4475	0.9366	0.9194	0.5629	0.8513

Table 3: Mean (\pm SE) afternoon (12h00 to 14h00) net CO₂ assimilation, stomatal conductance, water use efficiency, transpiration and internal carbon dioxide concentration by ‘Brookfield Gala’ apple leaves as influenced by irrigation systems (‘Micro’, micro sprinkler irrigation, ‘Drip’, daily drip irrigation, ‘Puls’, pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstocks during 2005/2006 before and after harvest. Measurements were taken on clear days using an open cuvette attached to the IRGA leaf chamber. Probability values are according to split-plot ANOVA. Mean separation by Tukey’s studentized test ($P \leq 0.05$, $n=5$). SE = standard error of the mean at 5% probability level. Mean values followed by different letters in columns are significantly different, ns: not significant ($P > 0.05$). Arrow (\downarrow) indicates harvest date.

Treatment	27/01/2006 \downarrow	17/02/2006	24/02/2006	29/03/2006	12/04/2006	26/04/2006
	Net CO ₂ assimilation rate ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)					
Micro	9.68 b	4.07 c	4.77 b	2.94 c	5.77 b	3.68 b
Drip	12.71 a	6.74 b	10.91 a	10.06 b	10.92 a	13.69 a
Puls	15.27 a	10.46 a	14.15 a	13.49 a	11.32 a	15.08 a
SE \pm	0.80	0.58	0.97	0.88	1.25	0.77
P-value						
System	0.0002	≤ 0.0001	≤ 0.0001	0.0001	0.0117	≤ 0.0001
Rootstock	0.4370	0.0296	0.7587	0.7452	0.0607	0.2843
System \times rootstock	0.4633	0.5357	0.8482	0.4610	0.2309	0.3325
	Stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$)					
Micro	0.14 b	0.33 a	0.05 b	0.02 c	0.12 b	0.06 b
Drip	0.14 b	0.21 b	0.11 a	0.05 b	0.14 ab	0.11 ab
Puls	0.19 a	0.29 b	0.11 a	0.07 a	0.22 a	0.15 a
SE \pm	0.12	0.02	0.01	0.01	0.02	0.01
P-value						
System	0.0109	0.0103	0.0007	0.0005	0.0269	0.0007
Rootstock	0.4860	0.0251	0.8987	0.8612	0.5008	0.0462
System \times rootstock	0.1190	0.995	0.1769	0.4328	0.8703	0.3713
	Transpiration ($\text{mmol. m}^{-2}. \text{s}^{-1}$)					
Micro	6.03 ab	11.74 a	1.85 b	1.20 c	2.54 b	1.44 b
Drip	5.93 b	9.23 b	3.52 a	2.39 b	2.96 ab	2.17 ab
Puls	7.24 a	11.32 a	3.36 a	3.47 a	4.09 a	2.75 a
SE \pm	0.35	0.44	0.19	0.21	0.39	0.23
P-value						
System	0.0494	0.0141	0.0024	0.0002	0.0301	0.0009
Rootstock	0.4213	0.0060	0.7815	0.8270	0.4036	0.0930
System \times rootstock	0.4557	0.9837	0.1468	0.3250	0.8231	0.3695
	Water use efficiency ($\text{mmol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$)					
Micro	1.67 ns	0.36 c	2.63 b	2.19 b	2.36 b	2.47 b
Drip	2.16	0.72 b	3.13 a	4.20 a	3.81 a	6.38 a
Puls	2.12	0.92 a	4.18 a	3.90 a	2.87 ab	5.65 a
SE \pm	0.13	0.05	0.25	0.14	0.39	0.33
P-value						
System	0.1088	≤ 0.0001	0.0127	0.0055	0.0178	≤ 0.0001
Rootstock	0.7972	0.3609	0.6625	0.4501	0.1756	0.9921
System \times rootstock	0.8228	0.3591	0.7627	0.0454	0.3885	0.4721
	Intercellular carbon dioxide ($\mu\text{mol CO}_2 \text{ mol air}^{-1}$)					
Micro	214.83 ns	320.08 a	196.33 a	200.23 a	265.75 a	268.25 a
Drip	181.33	282.17 b	183.25 a	184.35 b	211.92 b	135.41 b
Puls	191.33	270.92 b	141.08 b	196.20 ab	253.75 a	173.08 b
SE \pm	13.45	3.93	11.46	11.92	15.21	13.05
P-value						
System	0.0780	≤ 0.0001	0.0487	0.0156	0.0229	≤ 0.0001
Rootstock	0.8494	0.7915	0.7604	0.7683	0.2028	0.8142
System \times rootstock	0.6056	0.4421	0.3846	0.1356	0.4978	0.3814

Table 4: Effect of rootstock (M793 and M7) on mean (\pm SE) morning (09h00 to 11h00) net CO₂ assimilation rate, stomatal conductance and transpiration rate of ‘Brookfield Gala’ apple leaves during 2005/2006 before and after harvest. Probability values are according to split-plot ANOVA followed by Tukey’s multiple range test at 5%. Mean values followed by different letters in columns are significantly different ($P < 0.05$), $n=6$.

Rootstock	Attributes			
		27/01/2006		17/02/2006
	Net CO ₂ assimilation rate ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)	Stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$)	Transpiration ($\text{mmol. m}^{-2}. \text{s}^{-1}$)	Stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$)
M793	18.43 a	0.30 a	6.12 a	0.40 a
M7	16.86 b	0.27 b	5.56 b	0.35 b
SE (\pm)	0.45	0.00	0.12	0.01
P-value				
Rootstock	0.0269	0.0325	0.0055	0.0385

Table 5: Effect of rootstock (M793 and M7) on mean (\pm SE) afternoon (12h00 to 14h00) net CO₂ assimilation rate, stomatal conductance and transpiration rate of ‘Brookfield Gala’ apple leaves during 2005/2006 before and after harvest. Probability values are according to split-plot ANOVA followed by Tukey’s multiple range test at 5%. Mean values followed by different letters in columns are significantly different ($P < 0.05$), $n=6$.

Rootstock	Attributes			
		17/02/2006		26/04/2006
	Net CO ₂ assimilation rate ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)	Stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$)	Transpiration ($\text{mmol. m}^{-2}. \text{s}^{-1}$)	Stomatal conductance ($\text{mol. m}^{-2}. \text{s}^{-1}$)
M793	7.90 a	0.31 a	11.58 a	0.12 a
M7	6.28 b	0.24 b	9.94 b	0.09 b
SE (\pm)	0.48	0.02	0.36	0.01
P-value				
Rootstock	0.0296	0.0251	0.0060	0.0462

Table 6: Effect of system ('Micro', micro irrigation, 'Drip', daily drip irrigation, 'Puls', pulsing drip irrigation) and rootstock (M793 and M7) interaction on mean (\pm SE) morning (09h00 to 11h00) and afternoon (12h00 to 14h00) gas exchange measurements, transpiration and water use efficiency of 'Brookfield Gala' apple leaves during 2005/2006 season before and after harvest. Probability values are according to split-plot ANOVA followed by Tukey's multiple range test at 5%. Mean values followed by different letters in columns are significantly different ($P < 0.05$), $n=6$.

System \times Rootstock	Morning		Afternoon
	27/01/2006	12/04/2006	29/03/2006
	Transpiration ($\text{mmol. m}^{-2}. \text{s}^{-1}$)		Water use efficiency ($\text{mmol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$)
Micro M793	5.94 b	6.15 bc	2.00 c
Micro M7	4.73 e	5.31 c	2.37 b
Drip M793	5.90 d	6.02 bc	3.94 a
Drip M7	5.92 c	6.48 b	4.46 a
Puls M793	6.54 a	7.01 b	4.16 a
Puls M7	6.05 a	7.68 a	3.65 ab
SE (\pm)	0.21	0.26	0.20
P-value			
System \times rootstock	0.0343	0.0195	0.0454

Table 7: Mean values for light-saturated net CO₂ assimilation rate (A_{max}) in 'Brookfield Gala' apple leaves grown under ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation, 'Puls', pulsing drip irrigation) on either semi-vigorous M793 or semi-dwarfing M7 rootstock. Measurements were taken at air temperature of 25°C, leaf-to-air vapour pressure deficit of 1-2 kPa and carbon dioxide concentration of 380 $\mu\text{mol mol}^{-1}$ on fully exposed spur leaves on the west side of the trees. Mean separation by Tukey's studentized test ($P \leq 0.05$, $n=5$). SE = standard error of the mean at 5% probability level. Mean values followed by different letters in columns are significantly different ($P < 0.05$), ns: not significant.

Date	31/01/2006 (before harvest)		24/02/2006 (after harvest)	
Treatments	A_{max} ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)	g_s ($\text{mol. m}^{-2}. \text{s}^{-1}$)	A_{max} ($\mu\text{mol. m}^{-2}. \text{s}^{-1}$)	g_s ($\text{mol. m}^{-2}. \text{s}^{-1}$)
Micro	15.07 c	0.102 b	13.02 b	0.264 ns
Drip	19.49 b	0.246 a	18.33 a	0.221
Puls	21.89 a	0.224 ab	22.38 a	0.324
SE \pm	0.57	0.04	1.27	0.04
P-value				
System	0.0027	0.087	0.0002	0.0736
Rootstock	0.4290	0.3465	0.4120	0.2762
System \times rootstock	0.0513	0.3612	0.9273	0.6725

Table 8: Mean values for the light- and CO₂-saturated rate of electron transport (J_{\max}) and rate of carboxylation by rubisco ($V_{c\max}$) by 'Brookfield Gala' apple leaves grown under 'Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation, 'Puls', pulsing drip irrigation on either semi-vigorous M793 or semi-dwarfing M7 rootstocks. Measurements were taken at air temperature of 25°C, leaf-to-air vapour pressure deficit of 1–2 kPa and photosynthetic photo flux density (PPFD) of 1500 $\mu\text{mol m}^{-2} \text{s}^{-1}$ on fully exposed spur leaves on the west side of the trees. Mean separation by Tukey's studentized test ($P \leq 0.05$, $n = 5$), ns: not significant ($P > 0.05$). SE = standard error of the mean at 5% probability level.

Date	Treatments	Attributes	
		J_{\max} ($\mu\text{mol elect. m}^{-2} \cdot \text{s}^{-1}$)	$V_{c\max}$ ($\mu\text{mol CO}_2 \text{m}^{-2} \cdot \text{s}^{-1}$)
31/01/2006 Before harvest	Micro	68.41 ns	103.77 ns
	Drip	108.80	172.80
	Puls	118.27	143.22
	SE \pm	13.01	39.52
	P-value		
	System	0.0784	0.3738
	Rootstock	0.5382	0.1811
	System \times rootstock	0.3048	0.2225
24/02/2006			
After harvest	Micro	35.25 ns	82.81 ns
	Drip	63.53	115.75
	Puls	58.05	107.26
	SE \pm	6.23	15.71
	P-value		
	System	0.0772	0.2222
	Rootstock	0.8213	0.5236
	System \times rootstock	0.1517	0.7672

Table 9: Trends in macro and micro nutrients in ‘Brookfield Gala’ apple leaves after fruit harvest as affected by irrigation system (‘Micro’, micro sprinkler irrigation, ‘Drip’, daily drip irrigation, ‘Puls’, pulsing drip irrigation). Mean separation by Tukey’s studentized test ($P \leq 0.05$, $n=8$). SE = standard error of the mean at 5% probability level. Different letters following one another within a column are significantly different at 5% level of significance, ns: not significant ($P > 0.05$).

Macronutrient	31/01/2006				10/03/2006				26/04/2006			
	N	P	K	Ca	N	P	K	Ca	N	P	K	Ca
	g/kg				g/kg				g/kg			
Treatment												
Micro	25.53 ns	2.25 a	16.37 a	17.19 b	19.32 b	2.38 ns	15.76 ns	21.23 ns	17.59 b	2.29 ns	15.20 a	19.58 a
Drip	24.93	1.75 b	13.71 b	19.21 a	22.70 a	1.83	15.03	20.65	22.02 a	1.96	13.18 b	17.81 b
Puls	25.49	1.85 b	13.78 b	18.17 ab	22.51 a	2.08	15.30	20.23	22.31 a	1.99	13.53 b	17.03 b
SE ±	0.03	0.01	0.03	0.04	0.04	0.01	0.05	0.06	0.03	0.02	0.07	0.07
P-value												
System	0.2975	0.0038	0.0004	0.0252	0.0011	0.1152	0.8389	0.5166	≤.0001	0.3054	0.0433	0.0135
Rootstock	0.0932	0.3174	0.0001	0.0149	0.5114	0.0425	0.2607	0.0850	0.1318	0.7812	0.6366	0.4738
System×rootstock	0.2263	0.7871	0.0293	0.5965	0.7717	0.3241	0.3033	0.6473	0.1751	0.9817	0.7145	0.3849
Micronutrients	Mn	Fe	Cu	Zn	Mn	Fe	Cu	Zn	Mn	Fe	Cu	Zn
	mg/kg				mg/kg				mg/kg			
Treatment												
Micro	151 b	201 ns	5.66 ns	66.75 ns	180 ns	295 a	6.58 a	90.41 a	179 a	367 a	5.83 ns	83.83 a
Drip	183 a	211	5.50	67.83	166	222 b	5.25 b	57.75 b	164 b	277 b	4.67	52.17 b
Puls	166 a	190	5.75	64.00	160	222 b	5.67 ab	60.41 b	148 b	313 ab	5.83	49.83 b
SE ±	5.39	9.60	0.21	1.91	6.87	7.63	0.31	4.97	9.76	23.58	0.21	4.48
P-value												
System	0.0216	0.4667	0.8743	0.2039	0.0851	≤.0001	0.0134	≤.0001	0.0007	0.0033	0.1418	0.0003
Rootstock	0.7195	0.3369	0.2834	0.5069	0.9725	0.1057	0.2403	0.9016	0.3376	0.5939	0.1997	0.3820
System×rootstock	0.7572	0.2813	0.7126	0.7712	0.8876	0.5318	0.8506	0.9775	0.8479	0.9296	0.5615	0.8524

Table 10: Effects of irrigation system ('Micro', micro sprinkler irrigation, 'Drip', daily drip irrigation, 'Puls', pulsing drip irrigation) and system rootstock interaction on mean values (\pm SE) for K, Ca and P of 'Brookfield Gala' apple leaves after fruit harvest. Probability values are according to split-plot ANOVA followed by Tukey's multiple range test at 5%. Mean values followed by different letters in columns are significantly different ($P < 0.05$), $n=8$.

Rootstock	Date		
	31/01/2006		10/03/2006
	K (g/kg)	Ca (g/kg)	P (g/kg)
M793	15.57 a	17.50 b	2.25 a
M7	13.67 b	18.88 a	1.93 b
SE (\pm)	0.03	0.04	0.01
P-value			
Rootstock	0.0001	0.0149	0.0425
	31/01/2006		
	K (g/kg)		
System \times rootsock			
Micro M793	16.37 a		
Micro M7	16.17 b		
Drip M793	15.25 c		
Drip M7	12.17 f		
Puls M793	14.88 d		
Puls M7	12.67 e		
SE (\pm)	0.05		
P-value			
System \times rootstock	0.0293		

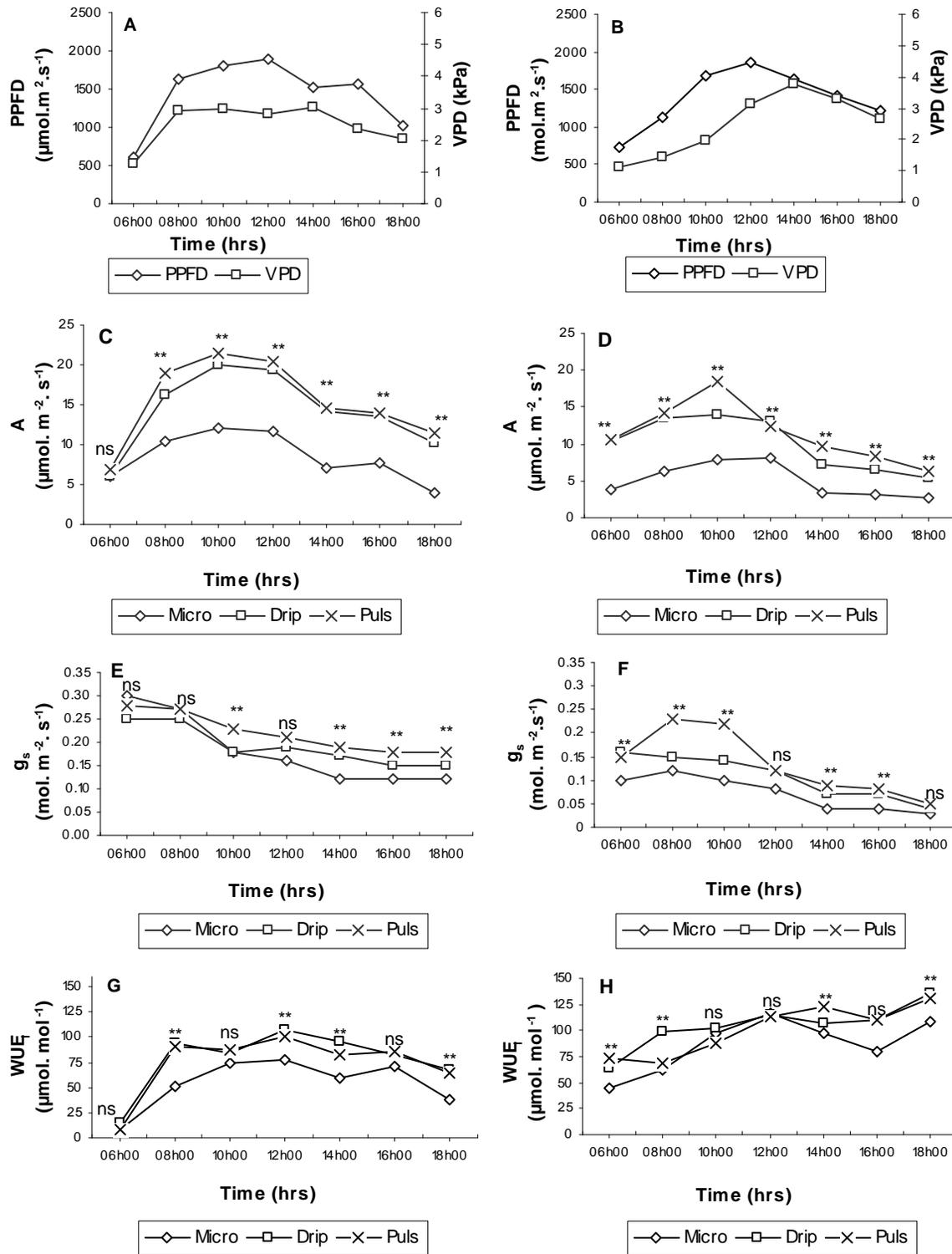


Fig. 1: Diurnal course of gas exchange in 'Brookfield Gala' apple leaves prior to harvest and after harvest, in response to three irrigation systems, namely micro sprinkler ('Micro'), daily drip ('Drip') and pulsing drip ('Puls'). Measurements were taken on 30/01/06 (A, C, E and G) and 17/02/06 (B, D, F and H). Abbreviations: PPFD (photosynthetic photon flux density), VPD (vapour pressure deficit), g_s (stomatal conductance) and WUE_i (intrinsic water use efficiency). Asterisks** represent significant variations between treatments at $P < 0.05$, ns: not significant ($P > 0.05$) according to Tukey's multiple range test, $n=6$.

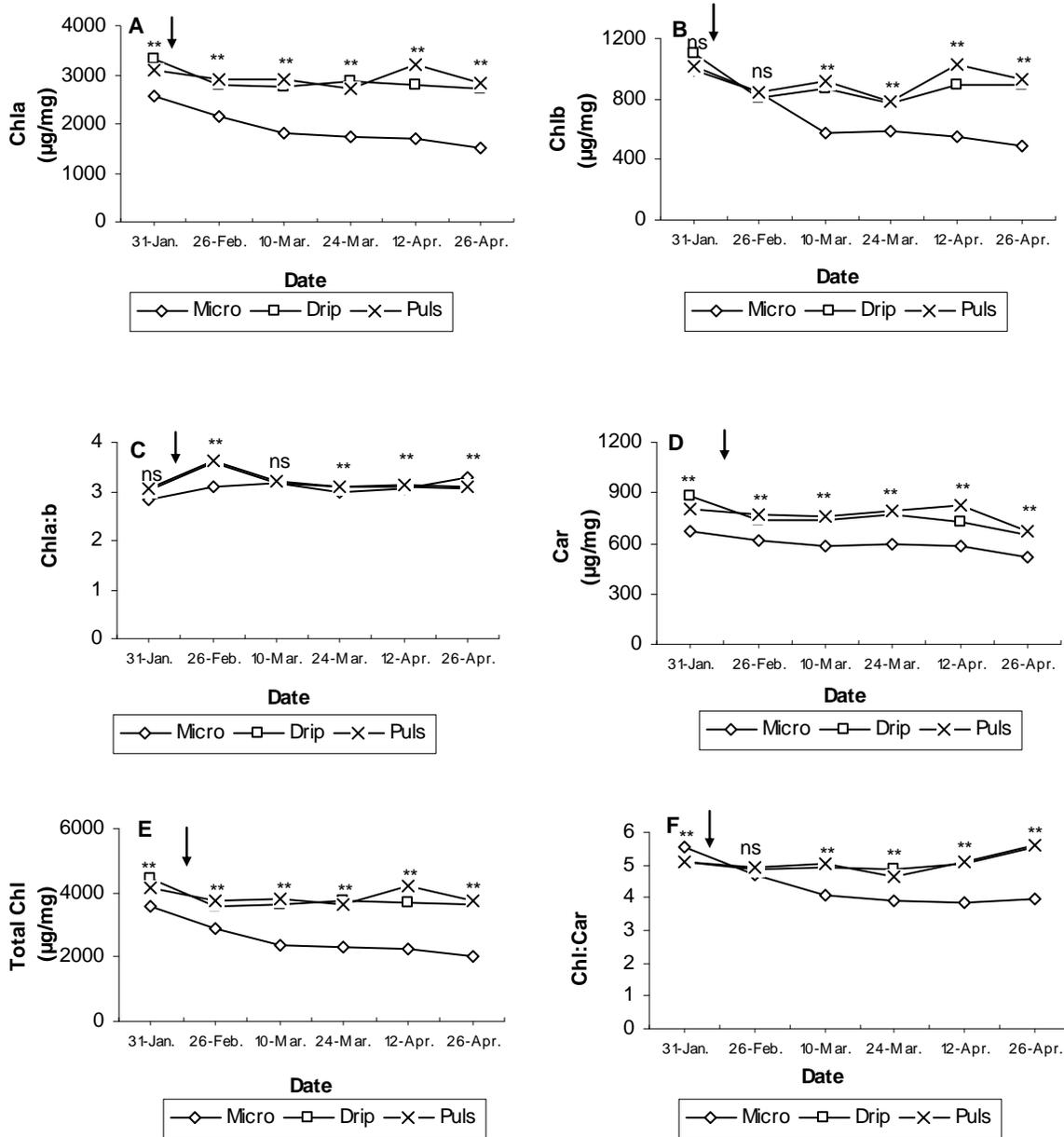


Fig. 2: Leaf pigment changes in 'Brookfield Gala' apple leaves prior to harvest and after harvest, in response to three irrigation systems, namely micro sprinkler ('Micro'), daily drip ('Drip') and pulsing drip ('Puls'). Measurements were taken on 31/01/06 (A, C and E) and 17/02/06 (B, D and F). Abbreviations: Chla (chlorophyll a), Chlb (chlorophyll b) and Car (carotenoids). Asterisks** represent significant variations between treatments at $P < 0.05$, ns: not significant ($P > 0.05$) according to Tukey's multiple range test, $n=6$. Arrows indicates harvest date for 2005/06 growing season.

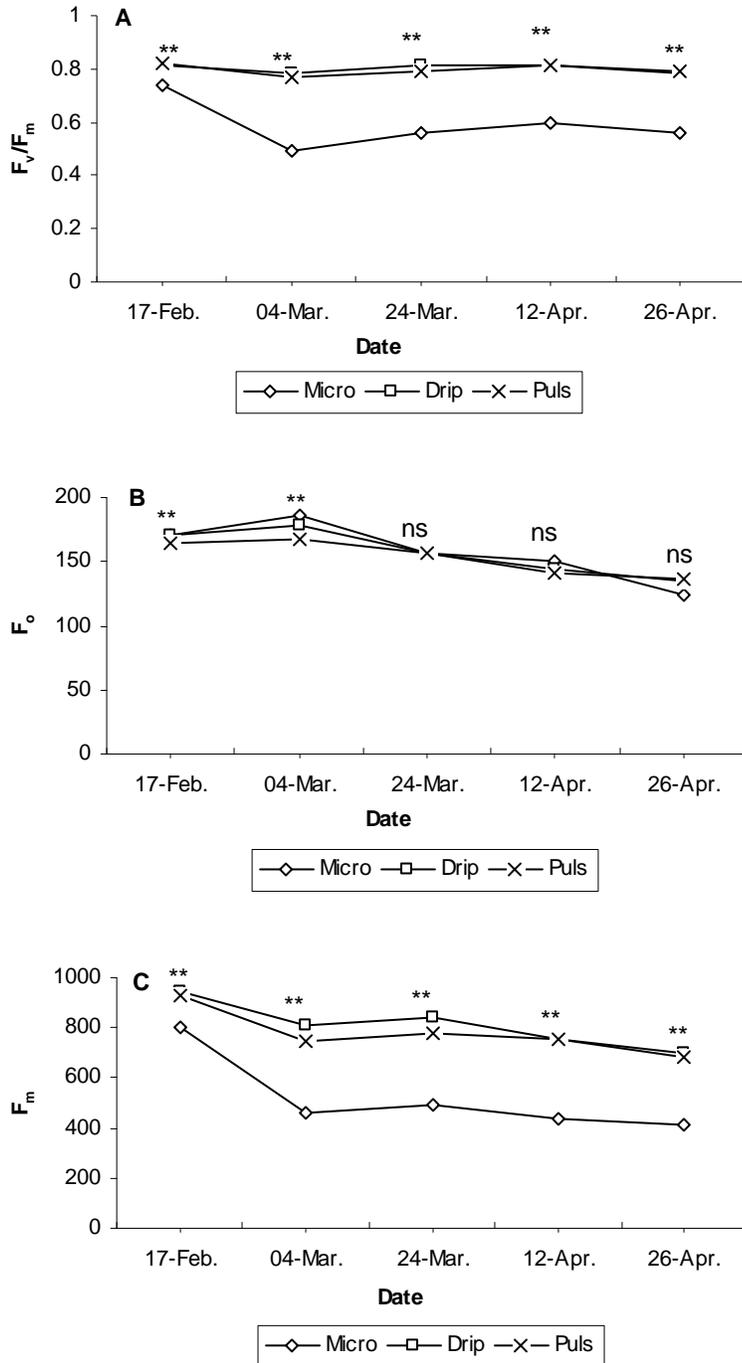


Fig. 3: Fluorescence readings on dark adapted ‘Brookfield Gala’ leaves following harvest, in response to three irrigation systems, namely micro sprinkler (‘Micro’), daily drip (‘Drip’) and pulsing drip (‘Puls’). A: F_v/F_m , B: F_o , C: F_m . Abbreviations: F_o (baseline fluorescence under modulating light), F_m (maximum fluorescence yield following a saturated pulse of light) and F_v/F_m (maximum quantum efficiency of photosystem II). Asterisks** represent significant variations between treatments at $P < 0.05$, ns: not significant ($P > 0.05$) according to Tukey’s multiple range test, $n = 6$.

7. Concluding remarks

The market preferences of both export and local markets put ever increasing pressure on fruit farmers to produce apples of good size and quality that will fetch high prices in the market, whilst maintaining high yields. Numerous cultural and management practices are employed in orchards with this objective in mind, including correct pruning, fruit thinning, use of girdling techniques, use of more dwarfing rootstocks, management of fertilizer programmes, and selection of the type of irrigation system and irrigation scheduling. Recently, in South Africa, there has been a significant increase in the use of more efficient irrigation systems, such as daily and pulsing drip irrigation that supply water and nutrients more frequently and accurately within the root system.

South Africa has limited water resources and experiences periodic droughts. The water resources for agricultural use are known to be diminishing and agriculture also faces very strong competition from industry, hence there is a need to use water optimally. The majority of apple production is in the Western Cape Province, a region characterised by winter rainfall and warm, dry summer months. All the apple orchards in this province are under irrigation, and with projected future water shortages from increasing domestic and industrial use, more efficient water management in orchards is becoming increasingly important.

The study was undertaken to test the hypothesis that more frequent water and nutrient application on a sandy loam soil will result in the following: stimulate the development of a more efficient root system, enhance rapid water and nutrient absorption and translocation, increase photosynthetic ability and water use efficiency, which will lead to increased carbohydrate and cytokinin synthesis (and possibly other plant growth regulators), and lead to efficient reproductive and vegetative balance, and ultimately improve fruit set yield and fruit quality.

In order to test the above mentioned hypothesis, young apple *Malus domestica* Borkh 'Brookfield Gala' trees in the second to fifth leaf were studied at Genadendal, in the Western Cape Province. The cultivar planted was selected based on the Richardson cold units (RCUs) which are 800 for this area and sufficient for the production of 'Brookfield Gala'. There is a significant production of 'Royal Gala' planted successfully within the surrounding areas such as at Villiersdorp, however 'Brookfield Gala' was used instead, since it is not widely planted

as 'Royal Gala' but has a superior quality attributes compared to 'Royal Gala'. The experimental site was situated at the foot of a hill alongside the river. The site was selected for its location and uniform, deep, well drained soils. The location is ideal for gravitational water and nutrient management, allowing tanks to be placed on top of the hill and water and nutrients to flow down the slope into the experimental orchard. The trees were planted in a Dundee soil, with good aeration that provided an excellent medium for tree development and root growth. Although sandy, this soil had high silt content (9.6%) as well as some clay (5.2%), which provided good water holding and nutritional capacity. The problem experienced with the site was that it is along the banks of the river feeding into the Theewaterskloof dam and the site has a water table of 0.5–1.1m during winter and spring. During the rainy season, when the dam is full the river might overflow its banks due to back pressure from the dam and the water could rise to the level of the trees in the orchard. However, high water levels last only for a few days and should not cause damage to the trees.

Three irrigation systems were used, namely micro sprinkler irrigation, daily drip irrigation and pulsing drip irrigation, in combination with either a semi-dwarfing rootstock (M7) or a semi-vigorous (M793) rootstock. Under micro sprinkler irrigation, water was applied once or twice weekly and fertilizer was applied manually. The objective of using this system was to apply water in a continuous strip (1.2m wide across the row) on both sides of the row with water from micro sprinklers overlapping with one another at a 0.6m radius. More frequent water and nutrient applications under daily drip irrigation (daily application) or pulsing drip irrigation (one to six times daily) were given using a drip irrigation system. Water and nutrients were supplied by the drippers along the drip area, with no overlap between the drippers, forming a 'pot' under each dripper.

This study covered the initial five years in the life of an apple tree. Several clear conclusions can be made:

1. Long-term evaporation data and correctly adjusted apple crop factors can provide a valuable basis for predicting monthly and annual water requirements. These requirements can then be managed on a daily basis by keeping the plant available soil water at an adequate level for the specific soil. In order to align predetermined water requirements with the actual water requirements, certain adaptations must be made to current crop factors for apples for the region studied. The currently used crop factors for November to February are adequate for the young trees, however, the April and

May crop factors (0.2) are too low and must be increased to 0.4, whilst crop factors for June to September are too high and must be adjusted to ± 0.07 and those for October to ± 0.3 . It is suggested that leaf area may provide a good indication of water requirements while trees are at developing phase. It was found that heatwave conditions based on weather forecasts for the period November to February in the Genadendal area can be managed adequately. Frequent water application at shorter cycles in the form of daily drip irrigation systems compared to micro sprinkler irrigation during periods of high temperature and VPD leads to high rates of A and g_s and mitigates the mid-day effects better. Irrigation can be applied earlier in the day, i.e. 05h30 to 06h00, to enhance prolonged stomatal opening during the day (this has been shown for the past two seasons). The effects of irrigating once to three times a week under micro sprinkler irrigation therefore poses serious threats during periods of heat waves especially under sandy loam soils, which further explains why there was less treatment effect under micro irrigated trees irrespective of high quantities of water applied. The effect of heatwaves can therefore be managed better, by establishing a daily water requirement programme that can be adjusted slightly upwards or downwards, depending on the temperature and humidity predictions, and the soil moisture status, however this would be impossible under micro sprinkler irrigation since water is applied once to three times a week not on daily basis.

2. Several water sensors are available to manage the water requirements according to the daily requirements of the fruit tree. Soil moisture sensors such as Watermark sensors, C-probes, Decagon sensors, neutron probes and others, which are of practical use in a commercial environment, can be used to fine-tune predetermined water requirements for apple trees. One must first determine the limits within which a particular soil water moisture status should be maintained. This can be achieved by irrigating the soil to its saturation point, followed by determining its field capacity and permanent wilting point. The C-probe and Watermark sensors were successfully used in this study. This was achieved by comparing them to a more accurate soil moisture instrument, the neutron probe, which is used worldwide and measures the soil moisture content in volumetric terms. However, price differences (as a result of scale of sophistication) between the sensors will ultimately determine which sensor will be selected for use. The Watermark sensor is simple to use and relatively inexpensive. On the other hand the C-probe is expensive (if more than one is required) but it can be fully integrated

into a computer-operated irrigation system. The neutron probe is more reliable and easy to calibrate, but its use is limited due to use of radioactive material, and can only be used by licensed personnel.

3. During 2003/04 all trees received water through daily drip irrigation and the total water application was $2450\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$. The actual water use in 2004/5, 2005/6, 2006/7 and 2007/8 for daily drip irrigation was 3429, 3926, 4087 and $4109\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$, respectively, whilst pulsing drip irrigation used 3429, 4047, 3985 and $4159\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ for 2004/5, 2005/6, 2006/7 and 2007/8, respectively. Due to the inefficient water application of the micro sprinkler irrigation system, as a result of droplet drift, droplet evaporation, and a greater application radius, more water was applied (5254, 5661, 4964 and $5755\text{m}^3\text{ha}^{-1}\text{yr}^{-1}$ in 2004/5, 2005/6, 2006/7 and 2007/8, respectively). The drip irrigation system used about $\pm 26\%$ less water than the micro irrigation system. The drip irrigation system lends itself to applying water at the soil level, and very specifically, into a limited area where root development is optimal. Under drip systems there is less drift, evaporation is limited, and leaching to the lower soil profiles is minimal. If producers wish to save on their running costs then drip irrigation systems are recommended over micro sprinkler irrigation systems.
4. This study clearly showed that nutrient solutions required by trees can be determined from nutrient requirements based on analysis of tree parts. The quantities of macro- and microelements needed to replenish those removed through fruit harvest, prunings, leaf loss, as well as those incorporated into the permanent structure, can be calculated from results gathered through tree analysis. In this study only leaf mineral analysis was done monthly and the mineral concentrations found conformed to results of previous studies on apples under South African conditions. No signs of deficiency or toxicities in the three irrigation systems used were detected. The findings of this study suggest that the annual nutrient requirements can be distributed percentage-wise across various phenological stages according to practices and experiences of each cultivar, based on soil and leaf analysis as well as tree yield. The annual water and nutrient requirements should then be fed into a software program to determine the correct balance and amount, using ordinary fertilizers. This further imply that different ways of applying nutrients leads to abundance and readily available nutrients all year round under drip based systems whilst there is a possibility of deficiencies, as a result of

leaching, adsorption or runoff of nutrients under micro sprinkler irrigation. Furthermore it is possible that the low performance of trees under micro irrigation irrespective of higher quantities of water applied might be due to differences in nutrient application strategies however, during the duration of the study there were no evident toxicities or deficiencies observed from leaf nutrient studies.

5. Significant differences in root number of thin plus medium roots (3mm and less in diameter) were found in the 0–800mm soil depth between the two drip irrigation systems compared to the micro sprinkler irrigation system. Total root number was three times higher under drip irrigation systems compared to under micro irrigation. About 66–77% of the thin plus medium roots were within 0–400mm soil depth under drip irrigation systems, whilst only 44% were observed within 0–400mm under micro sprinkler irrigation. During 2007/8 a significant difference in total mass was observed under daily drip and pulsing drip systems than under micro sprinkler irrigation. The higher number and mass of roots, and thus more root meristems, create an excellent environment for root development in the 0–800mm zone resulting in increased aeration and enough energy for root development. Under drip based systems there is a more continuous supply of nutrients with water. This suggests activation of more root development and growth at dripper level compared to growth from micro irrigated trees. More roots per unit of soil area imply higher rates of absorption of nutrients and better development of the above plant growth. This has been shown in this study with increased photosynthetic activity under drip based systems than under micro sprinkler system. From these studies it is clear that frequent water and nutrient management to the trees enhances prolific root growth.

6. Vegetative shoot growth was found to be more vigorous under micro irrigation compared to drip irrigation systems during 2005/06 when the crop load was high. Under micro irrigation, most carbon allocation could have been taken up by growing shoots, because of less competition from the fruits, with the end result of vigorous vegetative growth. A better vegetative to reproductive growth was achieved under drip-based systems compared to micro sprinkler irrigation during 2006/07. Drip irrigated trees gave adequate balanced development between reproductive and vegetative growth, resulting in efficient root development with more uniform trees. There were no significant shoot growth differences between drip-based irrigation

systems and micro sprinkler irrigation during 2006/07 but fruit size was high under all the three systems, possibly due to a better carbon assimilation rate (higher leaf photosynthesis), less fruit to fruit competition and fruit to shoot competition. The lower crop load led to reduced photosynthetic capacity at the leaf level, but higher vegetative growth could be due to increased carbohydrate synthesis by a larger canopy leaf area, in spite of lower photosynthesis at leaf level. Generally the drip-based systems lead to an increase in the photosynthetic leaf activity with benefits of better fruit quality and size a phenomenon that most producers would be grateful for in order to optimise their production and maximize their profits.

7. The choice of rootstock also needs to be taken into account. The semi-vigorous M793 rootstock gave significantly greater trunk growth than the semi-dwarfing M7 rootstock, but lower yield efficiency. It is expected that with future growth, as the tress increase in size and volume, the M7 rootstock will play a positive role in endeavours towards the management of the balance between vegetative and reproductive development, in terms of reducing pruning and improving light penetration and distribution within trees. It is therefore recommended that more dwarfing rootstocks can be combined with frequent daily irrigation systems such as daily drip and pulsing drip systems to optimise fruit production.
8. Significantly higher yields were achieved during the third year and fifth year (2005/6 and 2007/8) under both drip irrigation systems compared to the micro irrigation system. Micro sprinkler irrigation gave 20t/ha, daily drip irrigation and pulsing drip irrigation gave 30 and 34t/ha during 2005/6, respectively, but a smaller mean fruit size. The fruit yield for 2007/8 was much higher under daily drip irrigation (50t/ha) and pulsing drip irrigation (55t/ha) than under micro sprinkler irrigation (40t/ha). Fruitfulness was higher under drip-based systems because more bearing spurs than under micro irrigation. Fruit size increase, which has commonly been reported with more frequent fertigation, was not clearly illustrated in this study because fruit yield played an overriding effect. During 2006/7 when the crop load was low, due to cold and misty weather conditions and wet soil conditions during flowering, crop load was similar between treatments but mean fruit size and mass were higher under the two drip systems. Higher yield is a primary determinant of fruit size and it appears necessary that thinning procedures under different irrigation systems must be adjusted

accordingly, if fruit size is smaller than the export recommendation. Results of this study further suggest that fruit yield, fruit size and fruit quality can be optimised under the daily drip system and pulsing drip system than under micro sprinkler irrigation, and that if yields are to be sustained at their optimum levels in Western Cape, then both daily drip and pulsing drip irrigation systems should be utilized more than micro sprinkler irrigation system.

9. Fruit maturity index parameters indicated advanced fruit maturity (lower firmness and higher starch conversion) under micro sprinkler irrigation compared to drip irrigation during 2005/6 when the crop load was high (although lower under micro than under drip). During 2006/7, when the crop load was low and similar between irrigation treatments, fruit maturity was less advanced under micro irrigation. The fruit yield played a significant role in overriding some of the parameters and rendering them insignificant, especially when the fruit load was low (2006/7). Lower malic and citric acid concentration with a higher total soluble solute (TSS) concentration were measured in apples under drip irrigation compared to micro irrigation. The findings of this study suggest a more synchronised fruit maturity for 'Brookfield Gala' trees planted under daily drip and pulsing drip system than micro irrigation system. This in turn is viewed as a major break-through to the producers in reducing the number of harvests per crop (usually three) in 'Brookfield Gala' to two or even one, which can mean great savings in labour costs.
10. Diurnal leaf water potential, measured from pre-dawn until late afternoon, was generally lower in trees growing under micro sprinkler irrigation than in trees growing under the two drip irrigation systems. Pre-dawn water potential is a reflection of the soil water potential, and was significantly lower under micro sprinkler irrigation compared to drip irrigation, implying a better rehydration overnight under drip irrigation. Midday leaf water potential reflects the current leaf water status as determined by both the transpiration rate and water uptake by the roots, and was significantly lower under micro sprinkler irrigation compared to drip irrigation possibly due to both the lower pre-dawn potential (baseline) and lower water uptake rates by the roots during the morning period under micro sprinkler irrigation. The leaf water potential of all trees irrespective of irrigation system or frequency of irrigation decreased with increasing evaporative demand from morning to midday, however, drip

based systems responded better to the increasing evaporative demand than micro irrigation systems. High vapour pressure deficit at midday leads to partial closure of the stomata to limit transpiration and further reductions in water potential. Water supply from the roots cannot sufficiently replenish the losses through the stomata because of the high resistance to water flow from the roots to the tree xylem vessels, and as a result the tree water balance becomes more negative. However, the benefit that drip irrigation systems have over micro irrigation to the producers is that daily irrigation (one or more pulses) would mitigate the resultant midday effect. The greatest differences in leaf water potential between micro sprinkler and drip irrigation systems were found at midday.

11. The net carbon dioxide assimilation rate measured on a leaf area basis (A) was higher under the drip irrigation systems compared to the micro sprinkler irrigation system. However, no significant differences were seen between the two rootstocks M793 and M7. Diurnal patterns in A , stomatal conductance (g_s), and both photosynthetic water use efficiency ($WUE = A/E$ where E is the transpiration rate) and intrinsic water use efficiency (A/g_s) were observed under the three irrigation systems, with a mid-morning peak and reduced rates thereafter with no recovery. WUE was more dependent on leaf photosynthesis than on stomatal conductance in most instances. Irrespective of soil moisture conditions, A was reduced from early afternoon onwards, but the reduction was ameliorated through the use of drip irrigation. Daily drip irrigation and pulsing drip irrigation systems gave higher A and WUE values during midday and for the rest of the day compared to the micro irrigation system. Reduction in A in the afternoon is associated with a higher leaf-to-air vapour pressure deficit (VPD) and partial stomatal closure. In this study, daily application of water, possibly high leaf chlorophyll and nitrogen concentration under the drip systems allowed the stomata to remain open for a relatively longer period of time (and sustained higher rates of photosynthetic activity for a relatively longer time). Mitigation of the midday depression took place irrespective of the number of irrigation pulses per day, however effects were more pronounced under micro sprinkler irrigation than under drip irrigation systems. These results further suggest that producers practising either drip irrigation or micro sprinkler irrigation should irrigate early in the morning, especially when temperatures are expected to be high in the afternoon, to sustain high stomatal

conductance and high rates of leaf photosynthesis when conditions are still positive for assimilation.

12. Higher A in drip irrigation systems was mainly due to non-stomatal rather than stomatal causes. The decrease in leaf photosynthetic capacity could be associated with reductions in carboxylation efficiency of the mesophyll as a result of direct influence of enzyme concentrations and activity, mainly rubisco, and is also linked to N amongst other things during a decline in A at midday. Increased A under drip-based systems might be due to abundance of nitrogen concentration per leaf area, possibly as a result of a better canopy light environment.
13. Removal of fruit at harvest led to reductions in the light-saturated net carbon dioxide assimilation rate (A_{\max}), the maximum rate of carboxylation by rubisco ($V_{c_{\max}}$) and the light-saturated rate of electron transport (J_{\max}) as a result of lower sink strength one week following harvest. Both increased stomatal and non-stomatal limitations contributed to the reduction of photosynthetic capacity. Harvest led to changes in source-sink relationships and this in turn led to increased stomatal sensitivity and reduced water loss as a result of low carbohydrate requirement due to fruit removal. Daily or pulsing drip irrigation maintained higher leaf photosynthetic capacity following harvest compared to less frequent water application under micro sprinkler irrigation. There was gradual loss of leaf chlorophyll and carotenoids, and reduced maximum quantum yield of fluorescence (F_v/F_m) following harvest under micro irrigation but not under drip irrigation. The use of drip irrigation systems could possibly prolong chlorophyll retention and delay the onset of leaf senescence, leading to delayed leaf drop and continued vegetative growth, if water is continuously applied from harvest (February) to May/June. This could ultimately reduce postharvest root activity (mineral uptake) and delay entry into dormancy, which could have negative effects in the following year. Trees under micro sprinkler irrigation respond more rapidly to fruit harvest and may have resumed post-harvest root activity earlier, as shown by a greater micronutrient accumulation in leaves compared to trees under drip irrigation.
14. Few significant differences were found between daily drip and pulsing drip irrigation treatments in terms of yield, shoot growth, root development, leaf photosynthetic capacity and leaf water potential. This may be because the sandy soil on which the

experiment was conducted contained a high silt fraction (9.6%) as well as 5.2% clay. One drip early in the morning seems to be adequate (due to the water holding capacity of the soil) to last until the midmorning to early afternoon when the stomata partially close in response to high vapour pressure deficit. However, better results have been obtained under pulsing drip irrigation than under micro sprinkler irrigation. In a soil with less silt and clay more pulses per day might have been more significant in maintaining the water holding capacity during night-time rehydration (baseline). The VPD possibly dominates all tree physiological responses during the day, while soil moisture only provides the night-time rehydration (baseline). Hydraulic resistance in roots increases during the day, with increases in evaporative demand. It seems likely that a better baseline (in drip irrigated systems) might mitigate the strong hydraulic root resistance and provide a more positive equilibrium towards lower evaporative demand.

Under pulsing drip irrigation, which simulates a hydroponics system, both water and nutrients are constantly supplied to the roots. The continuous supply of nutrients increases the soil buffer capacity for both cation and anion absorption through the fine roots. Moisture availability is dependent on the distribution of the water-absorbing roots, the soil moisture distribution and the soil hydraulic properties. There was higher uptake of water by the better developed root system under drip irrigation systems than under micro irrigation, as shown by higher pre-dawn leaf water potential measurements. Apple trees require large volumes of water during the day and one or more pulses per day seemed to regulate the tree-water relations such that low turgor (as a result of adequate water supply from the roots (uptake) and loss through the stomata) combined with higher stomatal conductance resulted in low shoot growth but higher carbon assimilation under the Genadendal conditions.

South African apple producers are compelled to adopt cultural practices that ensure increased fruit size, high fruit quality and high yields. With the trends towards high-density orchards (>2000 trees ha⁻¹), more trees can be planted per hectare using more dwarfing rootstocks. Water use determination needs to be more precise and managed adequately to meet the plant's needs whilst avoiding excessive use of a scarce resource. This study showed that use of daily drip irrigation and pulsing drip irrigation systems increased fruit yield and maintained good fruit quality. Vegetative growth could be managed better because the balance was shifted

more towards fruit yield, and proliferation of finer and medium roots was stimulated more under the drip irrigation systems than under the micro irrigation system. Leaf photosynthetic capacity and leaf water use efficiency were improved under the drip irrigation systems, ultimately leading to better carbon allocation for reproductive development and yield efficiency.

In this study the hypothesis was that more frequent water and nutrient applications would improve tree efficiency both on a physiological basis and at production level. Increased performance of trees under drip based irrigation systems was found for leaf photosynthesis, leaf water potential, yield and the stimulation of more efficient root development. Fruit quality, fruit growth and shoot growth were influenced more indirectly by treatment effects and more directly by crop load effects between seasons.

In conclusion, this study demonstrates the benefits of more intensive water and nutrient application for apple trees. Increased irrigation frequency in the rooting zone under the drip system (daily or several times daily) increased the following: the development of more efficient finer roots and the sink demand for water and nutrients by roots, increases root absorption and transport of absorbed nutrients to other parts of the tree. Also there was increased photosynthetic ability of the leaves and higher carbohydrate synthesis, a better balance between vegetative and reproductive growth under drip-based systems than under micro sprinkler irrigated trees. Important information gathered from the use of sensors (C-probe and Watermark sensors calibrated against neutron probe) and dendrometers provide useful information that can be used to develop a model for apple trees for local conditions. Such a model would assist in the accurate determination of water and nutrient requirements, and its application in 'Brookfield Gala' apples from planting to full bearing.