Solute Dynamics
in
Advanced Fertigated Horticulture

Submitted by

Adam Frederick Sluggett
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Summary

Increasing demand for rapid crop establishment, high yields and better fruit quality has warranted a change in how irrigated horticultural crops are managed. An emerging trend in the industry is intensive fertigation to meet current crop requirements without the need to store water or nutrients in the soil for a substantial amount of time. This type of practice has been coined Advanced Fertigation (AF), where the fundamental principals include reducing the wetted zone and applying nutrients in smaller, and more frequent doses. There is little scientific literature regarding solute dynamics as affected by AF, which forms the premise of this thesis. The research was conducted at three differently managed citrus orchards within the Sunraysia fruit growing regions of Victoria and New South Wales, Australia.

The research begins with a numerical modelling study to investigate soil water movement as affected by suction cup soil water samplers. The suction cup actively samples water from the unsaturated zone by means of an applied vacuum and has been chosen as the main tool in this study to monitor solute dynamics within the soil. The model is the first to comprehensively investigate the suction cup influence under a wide range of soil types and soil moisture conditions while using a decreasing vacuum extraction process. The decreasing vacuum process is used by many suction cup practitioners, making this information vital.

The second stage of this research attempts to quantify deep drainage and nitrate leaching below the root zone of AF managed citrus orchards using *in situ* monitoring tools. No study has investigated deep drainage and nitrate leaching under AF management for Australian conditions, making the study important in determining the possible environmental and economic issues related to this type of management system. The method also critically assesses the influence of soil heterogeneity and measurement error on the estimate of deep drainage and nitrate leaching.

In the final stage of the research a comprehensive data set from three contrasting AF citrus orchards has been analysed. This data provides

information regarding the transport of solutes and possible strategies to enhance AF management. The interaction between the ceramic of the suction cup and two solutes (nitrate and phosphate) has also been investigated to determine the reliability of suction cups to represent the true soil solution.

This research assists in understanding the complexity of solute dynamics in the root zone of AF crops. It provides important information regarding the water extraction process, possible environmental issues and ways to use solute data to effectively manage AF.

Declaration of Originality

I certify that this thesis does not incorporate, without acknowledgement, any material previously submitted for a degree or diploma in any University; and that to the best of my knowledge and belief does not contain any material previously published or written by another person, except where due reference is made in the text.

Adam Sluggett

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Chapter 1: Introduction

1.1 Objectives

To effectively manage fertigated horticulture, a better understanding of solute processes is required. Although the principles of solute transport are largely understood, practically, little useful information is available regarding how to collect, analyse and interpret solute information for intensive fertigated horticulture. The soil solution is an important management tool because it provides information regarding spatial and temporal distribution of plant nutrients; salinity; trace elements; heavy metals; pesticides; soil acid neutralizing capacity; and the kinetics of solid-solution interaction (Corwin, 2002).

Fertigation has been used for many decades to deliver solutes directly to the crop via the irrigation water, although recent fertigation management has advanced greatly. Advanced Fertigation (AF) is a broad name given to the emerging intensive fertigation management systems used to accelerate orchard establishment and improve yield and fruit quality. AF uses intensive fertigation practices to meet the crop water and nutrient requirements, reducing the need to store water and nutrients in the soil for a substantial time (Falivene, 2005). Fertigation combined with micro-irrigation has the potential to precisely apply water and chemicals, both in amount and location, throughout a field at a rate comparable to plant uptake (Gardenas et al., 2005; Assouline, 2002). One type of AF is Open Hydroponics (OH) which derives its name from the principles adopted from soil-less hydroponics for field based production (Falivene, 2005). In the early 1990s, Professor Rafael Martinez-Valero from the University Miguel Hernandez, Spain brought together the many concepts of OH. The original reason for the development of OH was to create a management strategy to maximise citrus production on low fertility gravel based soils with poor quality water (Martinez-Valero and Fernandez, 2004). Professor Martinez-Valero commercialised his fertigation system, which is now referred to as Martinez Open Hydroponics Technology (MOHT). MOHT is protected by Intellectual Property laws and as a result little scientific literature is available.

Sustainable irrigation requires effective water and fertilizer management to ensure water and nutrients remain within the root zone and do not move below, thus causing environmental pollution. Methods to monitor and interpret soil solute data are required to manage fertigation effectively. The suction cup is an *in situ* monitoring tool capable of extracting the soil solution for analysis (Litaor, 1988; Corwin, 2002; Weihermüller et al., 2007). The principles of porous cup extraction were first described by Briggs and McCall (1904). The suction cup is made up of a porous material attached to a reservoir. Water flows through the porous material into the reservoir when a pressure gradient is induced between the soil solution and the reservoir by means of an applied vacuum (Litaor, 1988; Corwin, 2002; Weihermüller et al., 2007).

While the basic design has altered little, there have been many modifications to the suction cup. Cole (1968) described an automated suction cup system. Suarez (1986) described a suction cup that reduced the degassing of carbon dioxide and therefore the effect on solution pH. Lentz and Kincaid (2003) described an automated vacuum extraction control system that could maintain suction cup vacuum at levels proportional to ambient soil water pressures. Wood (1973) described a suction cup device that could collect a sample from depths greater than 10 m.

Along with the changes to the sampling system there have also been many types of porous materials proposed. The main types of materials include ceramic, sintered materials and membranes (Dorrance et al., 1991). Weihermüller et al., (2007) gives a thorough description of the different types of materials used and the advantages and disadvantages relative to the chemical substance being sampled. The majority of suction cups used in the literature are made from ceramic materials because of the ease of use and low cost (Biswas, 2006).

The influence of cup size has been investigated in the literature. Silkworth and Grigal (1981) compared small (2.2 by 5.7 cm) and large (4.8 by 6.2 cm) cups and cups made of ceramic, fritted glass and hollow cellulose fibres.

From the study it was concluded that the larger ceramic cups performed the "best" with regard to minimum soil solution alteration, adequate sample volume and low level of failure rate. It is speculated in the literature that short sampling intervals, uniform sampling lengths and same initial vacuum for all samples will provide the best chance in reducing sample variability (Hansen and Harris, 1975)

The research presented in this thesis investigated solute dynamics as affected by intensive fertigation management for citrus production. The study is split into chapters that examine different components of the research. The first component used a numerical model to investigate the influence suction cups have on the soil water status. The second component investigated a method to quantify deep drainage and nitrate leaching below the root zone using *in situ* monitoring tools. The third component used a combination of suction cup sampling and soil samples to monitor solute dynamics in three contrasting fertigated citrus orchards.

Although the suction cup is one of the most widely used soil solution extraction devices, there is much uncertainty concerning its accuracy and the volume of soil being represented (Wu et al., 1995). The influence suction cups have on soil water movement has been studied using laboratory and field based methods (Morrison and Lowery, 1990; Wu et al., 1995; Hart and Lowery, 1997), analytical solutions (Warrick and Amoozegar-Fard, 1977) and numerical simulations (van der Ploeg and Beese, 1977; Wu et al., 1995; Narasimhan and Dreiss, 1986; Tseng et al., 1995; Weihermüller et al., 2005). The paper by Narasimhan and Dreiss (1986) was the first to describe a numerical technique for modelling transient flow of water to a suction cup under a decreasing vacuum.

In Chapter Two, a numerical modelling technique, similar to that of Narasimhan and Dreiss (1986), was used to simulate the axi-radial influence a suction cup has on the soil water status under a decreasing vacuum. The activity and extraction domain and the time required to yield a sample was estimated for a range of soil moisture conditions for different soil types. This data provides vital information to suction cup practitioners regarding field installation, the volume of soil sampled, and the time required to extract a certain volume of water for different soil types.

There has been no deep drainage or nitrate leaching study conducted for AF management in Australian conditions, which forms the objective of Chapter Three. The study aimed to estimate deep drainage using two different methods and nitrate leaching using one. The Darcy-Buckingham approach and a water balance were used to estimate deep drainage. Nitrate leaching was estimated by combining the drainage flux determined from the Darcy-Buckingham method with the nitrate concentration in the suction cup below the root zone. In the past, the Darcy-Buckingham method has been used to quantify deep drainage and nitrate leaching for citrus production in Florida, USA (Paramasivam et al., 2001; Alva et al., 2006).

Speculation regarding the usefulness of this method has been raised in the literature due to the highly non linear unsaturated hydraulic conductivity function used to calculate the water flux, and the large spatial heterogeneity soils exhibit (Silva et al., 2007). In this thesis a range of deep drainage and nitrate leaching values were calculated to incorporate the variability likely to occur in the field.

In Chapter Four, solute results from AF managed citrus orchards with differing levels of management input are presented. The dynamics of the solute transport have been monitored using a combination of direct solute extraction from suction cups and bulk soil samples. The suction cup data provides frequent weekly solute data from point sources, while the soil sample provides a spatial solute representation approximately every three months. The influence that the ceramic material had on nitrate and phosphate concentrations sampled from an outside solution was also investigated. Nitrate was chosen because nitrogen is the major limiting nutrient for citrus production and is most readily available as nitrate (Obreza and Morgan, 2008). Phosphate was chosen because it has the potential to sorb strongly to ceramic (Litaor, 1988). The chapter furthers our understanding of solute dynamics under intensive fertigation and provides insight into how fertilizer management can be optimised.

Previously the incentive for adopting improved fertigation monitoring practices was limited, since fertilizer costs were only a small fraction of the total production costs and changes in fertigation practices did not guarantee significant yield increases. However, with recent increases in fertilizer prices, and the potential for energy costs to rise and groundwater contamination regulations to be imposed, improved fertigation practices may be essential.

The different chapters each contain literature reviews within their introductory sections.

1.2 Chapter framework

The following abstracts provide an outline of the content of the proceeding three chapters. Each chapter covers a different component of the research and has been written in a journal article format.

Chapter Two Outline: Suction Cup Extraction of Soil Water using a Decreasing Vacuum: Numerical Simulations

The suction cup is widely used to monitor solutes in the vadose zone. Research has focused on using continuous vacuum sources, whereas many suction cup practitioners use a decreasing vacuum source, where the cup is first evacuated before being closed off. Consequently, a numerical technique, using HYDRUS 2/3D, was developed to study the influence that a decreasing vacuum has on the suction cup's activity domain, extraction domain and time to collect a specific volume of water. Twenty-two simulations using four contrasting soil types, each with a range of moisture conditions, were analysed. The activity domain under a decreasing vacuum was markedly smaller, about fourfold, than that reported in the literature for continuous vacuum. The activity domain of the decreasing vacuum increased as the soil moisture decreased and the clay content of the soil increased. The activity domain radius was largest for the sandy clay

(17.2 cm) and smallest for the sand (7.1 cm). The extraction domain was larger for sandier soils than finer soils, but no simulation had an extraction domain radius larger than 5.5 cm. The results provide important information for placement of multiple suction cups, quantification of the soil water region being sampled and the time required to yield a sample for a variety of soil types and moisture conditions.

Chapter Three Outline: Water and Nitrate Movement under Advanced Fertigated Citrus

The horticulture industry is increasingly adopting high input but precise water and fertilizer management to obtain faster returns, larger yields and better fruit quality. Advanced Fertigation (AF) is a precision fertigation practice that maintains a restricted wetted zone by using low application rate drip irrigation and reducing the amount of drippers per tree. This high input management system has been used in several countries for a decade but has not been critically assessed for its environmental sustainability in Australian conditions.

This paper discusses the drainage flux and movement of nitrate under three different fertigated citrus plots within the Dareton Agricultural and Advisory Station, NSW. Tensiometers were used to calculate water flux using the Darcy-Buckingham approach. Nitrate leaching below the root zone was estimated using the relationship between drainage flux and nitrate concentration in suction cups below the root zone. Drainage calculated from a water balance was compared to the Darcy-Buckingham approach. Drainage calculated using the Darcy-Buckingham method incorporates several sources of error, including the measured hydraulic parameters and saturated hydraulic conductivity. This was investigated by using different hydraulic parameters and saturated hydraulic conductivities.

The Darcy-Buckingham results showed drainage and nitrate-N leaching for a mature citrus plot of 12% and 1.2 kg ha^{-1} in September 2006 and 18% and 12 kg ha^{-1} in January 2007. A young AF citrus plot's calculated range of drainage and nitrate-N leaching was assessed to be 8.15% to 24.52% and 6.96% to 19.42%, respectively. A young conventionally fertigated citrus plot's drainage and nitrate-N leaching range was assessed to be 6.56% to 10.51% and 1.96 kg ha^{-1} and 3.14 kg ha^{-1}, respectively. The AF water balance drainage was within the range calculated using the Darcy-Buckingham method. The water balance for the mature citrus and young conventionally fertigated citrus showed variation due to uncertainty in the soil water storage.

Although the method is theoretically sound, the variables involved make estimating deep drainage very difficult. However, by monitoring soil water using tensiometers and solutes using suction cups, fertigation management can be greatly improved by retaining nutrients and flushing salts from the root zone.

Chapter Four Outline: Understanding solute dynamics under advanced fertigated citrus

Intensive fertigation can meet crop nutrient requirements without storing the nutrients in the soil. Advanced Fertigation (AF) describes the many fertigation management strategies using the fundamental principle of applying nutrients regularly to a smaller soil volume and at a lower application rate to match crop demand. For AF to be sustainable a better understanding of the soil solute dynamics is required. The suction cup is able to sample soil water at any time and could be used to monitor fertilizer efficiency. This study used a combination of suction cups and bulk soil samples to monitor solute dynamics under three differently managed citrus orchards in the Sunraysia region, Australia. Two orchards used types of AF, with one fertigated weekly and the other managed under the Martinez Open Hydroponics Technology (MOHT) system. The third site was a conventionally fertigated citrus orchard, fertigated monthly.

The influence the suction cup's ceramic had on nitrate and phosphate was tested. For nitrate, the concentration of the extracted solution was not statistically different to the outside solution for outside solutions between 0 and 56.45 mg nitrate-N L^{-1}. For phosphate, the concentration of the extract solution was up to 25% less than the outside solution for outside solutions between 0.5 and 5 mg phosphate-P L^{-1}. This was attributed to sorption on the ceramic.

Nitrate at the advanced and conventionally fertigated orchards freely moved to a depth of 1.5 m. There was a strong positive correlation between nitrate concentration and electrical conductivity (EC) of the cup sample, indicating the potential to use the EC signature to predict nitrate movement under low salinity conditions. The inclusion of lateral suction cups at the MOHT site, placed further away from the drip source, provided vital information. These suction cups had high EC, chloride and nitrate concentrations compared to suction cups below the dripper. The saturation paste extract EC was also very low below the emitter but showed a clear build up of salt at the surface away from the emitter at both the advanced and conventionally fertigated sites. The results indicate solutes are transported to the margin of the wetted zone and then concentrated through evaporation. The pH cycled between acidic during the fertigation season and basic when no fertilizer was applied, indicating the soil currently has the capacity to buffer the soil solution.

The results demonstrate a need to strategically plan the location of suction cups. Suction cups directly below the drip emitter will typically have lower salinity compared to suction cups located in the margin of the wetted zone. From the solute dynamics observed, it is recommended suction cups be located approximately half way between the emitter and the edge of the wetted zone and at the depth of greatest root density. It is also recommended suction cups be placed at the base of the root zone and below the root zone. The suction cup at the base monitors whether nutrients are building up at the base of the root zone, while the suction cup below the root zone monitors for excessive leaching. To improve the nutrient efficiency a strategy is required that retains nutrients at the 0.25 m depth, but does not allow rapid increases in nutrient concentration to occur at 0.5 m depth.

Chapter 2: Suction Cup Extraction of Soil Water using a Decreasing Vacuum: Numerical Simulations.

2.1 Introduction

Measurement of the soil solution is becoming an increasingly important aspect of agricultural and environmental monitoring. Monitoring the soil solution is important because it provides information about spatial and temporal distributions of plant nutrients, salinity, trace elements, heavy metals, pesticides, soil acid neutralizing capacity and the kinetics of solid-solution interactions (Corwin, 2002). Specifically, the advent of precision irrigation, such as drip irrigation, has seen a marked increase in the efficiency of water use. However, the salts within the irrigation water accumulate due to evapotranspiration so monitoring is required for the control of soil salinity (Biswas, 2006). It is also becoming increasingly important to monitor nutrients in the soil solution due to increases in intensive fertilizer application, higher fertilizer costs and environmental concerns about excessive leaching of nutrients into the groundwater system (Alva et al., 2006).

Currently, suction cup extraction is the method of choice, for many agricultural and natural resource managers, to monitor the soil solution. The principles of porous cup extraction were first described by Briggs and McCall (1904), but the basic principle has changed little since then. The suction cup is made up of a porous material attached to a reservoir and, when a pressure gradient is induced between the soil solution and the reservoir by means of an applied vacuum, water flows into the cup (Litaor, 1988; Corwin, 2002; Weihermüller et al., 2007). One method of applying the suction cup vacuum is the continuous vacuum, in which the suction cup is attached to a pumping device (Cole, 1968). The other method is a decreasing vacuum, where the cup is evacuated before being sealed (Narasimhan and Dreiss, 1986). (A review of suction cups is given by Litaor (1988) and more recently by Weihermüller et al., (2007)) The use of the decreasing vacuum method is limited by uncertainties about where the suction cup samples from, defined as the extraction domain, and the extent soil-water is influenced by the extraction process, defined as the activity domain (Weihermüller et al., 2005). Knowledge of the activity domain is important because monitoring systems need to be designed so that suction cups do not influence one another (Morrison and Lowery, 1990). Similarly, knowledge of the extraction domain is important when quantifying the volume of soil being sampled and interpreting analytical results (Narasimhan and Dreiss, 1986). Another issue is the chemical processes which occur after the soil-water enters the suction cup (Weihermüller et al., 2007). A better understanding of the time required to fill the cup would ensure water is not in the cup for longer than necessary, while ensuring adequate sample volume is collected (Litaor, 1988).

Much of the research into the suction cup's influence on soil-water and solute transport has either used the constant vacuum extraction method (Morrison and Lowery, 1990; van der Ploeg and Beese, 1977; Weihermüller et al., 2005) or has examined one soil type specific to a trial site which is not transferable to other soil types and locations (Hart and Lowery, 1997). Most suction cup practitioners have opted to use the decreasing vacuum extraction method because it is simple to use, making the results of continuous vacuum studies unrealistic for many sampling situations (Narasimhan and Dreiss, 1986). It would be expected that a decreasing vacuum would have a smaller field of influence than a continuous vacuum because, as water enters the sampler, the volume of air decreases, causing back pressure and a consequent reduction in effective vacuum (Narasimhan and Dreiss, 1986). Consequently, it would be unwise to assume that observations made under a constant vacuum could be compared directly with observations made under decreasing vacuum.

There have been several techniques used to study the suction cup's influence on soil-water and solute transport. These have included, field and laboratory techniques (Morrison and Lowery, 1990), analytical solutions (Warrick and Amoozegar-Fard, 1977) and numerical simulations (van der Ploeg and Beese 1977; Narasimhan and Dreiss, 1986; Wu et al., 1995;

Weihermüller et al., 2005). The first numerical model to simulate the transient flow of water to a suction cup under a decreasing vacuum was given by Narasimhan and Dreiss (1986). A comprehensive analysis of the suction cup activity domain and extraction domain, including a variety of constant vacuums, three different soil types and two infiltration rates was reported in the literature (Weihermüller et al., 2005). However, the influence of a decreasing vacuum has never been comprehensively assessed across a range of soil types and soil-water contents.

This study aims to use a numerical modelling technique to simulate the axi-radial influence that a suction cup has on the soil-water for four contrasting soil types under a decreasing vacuum. Specifically three aspects will be analysed. Firstly, the suction cup activity domain will be assessed, which will improve how suction cups are installed. Secondly, the extraction domain will be assessed, providing a quantitative assessment of the soil being analysed. Thirdly, the time required to yield a sample volume will be assessed, which will reduce the possibility of chemical change occurring while the soil solution is within the cup.

2.2 Materials and Method

The soil profile was simulated using the axi-symmetrical form of the Richard's equation with the HYDRUS 2/3D numerical code. HYDRUS 2/3D numerically solves the Richard's equation for water flow in a variably saturated soil, based on the Galerkin procedure of the finite element method with linear basis functions (Simunek et al., 2006). The Richard's equation, in the axi-symetric form, for three dimensional water flow towards a suction cup, is defined in equation 2.1 (Istock, 1989),

$$C(h)\frac{\partial h}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[rK(h)\frac{\partial h}{\partial z}\right]+\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad (2.1)$$

where C(*h*) is the specific water capacity, *h* is soil-water pressure, t is time, r is radial distance, z is distance increasing upward to the soil surface from a reference and K(h) is the unsaturated hydraulic conductivity at pressure head h.

The van Genuchten-Mualem soil hydraulic model was used to represent the water retention (equation 2.2) and unsaturated hydraulic conductivity (equation 2.3) functions (van Genuchten, 1980).

$$\theta = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m}, & h < h_s \\ \theta_s, & h \geq h_s \end{cases} \tag{2.2}$$

$$K(h) = K_s S_e^{0.5}\left[1-(1-S_e^{\frac{1}{m}})^m\right]^2 \tag{2.3}$$

S_e is defined in equation 2.4,

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2.4}$$

where θ_s is the saturated water content, θ_r is the residual water content, α, m, n are empirical constants from the soil moisture release curve, h_s is the air entry value, S_e is the effective water content and K_s is the saturated hydraulic conductivity.

The governing equation for non reactive solute transport is defined in equation 2.5 (Istok, 1989),

$$\frac{\partial(\theta c)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\theta D_{rr} r \frac{\partial c}{\partial r}\right) + \frac{\partial}{\partial z}\left(\theta D_{zz}\frac{\partial c}{\partial z}\right) - \frac{1}{r}\frac{\partial}{\partial r}(rq_r c) - \frac{\partial}{\partial z}(q_z c) \tag{2.5}$$

where c is the solute concentration of the soil water and the other symbols are either defined above or below. The individual components (D_{rr} and D_{zz}) of the dispersion tensor are defined in equation 2.6,

$$\theta D_{rr} = D_L \frac{q_r^2}{|q|} + D_T \frac{q_z^2}{|q|} + \theta D_d \tau$$
$$\theta D_{zz} = D_L \frac{q_r^2}{|q|} + D_T \frac{q_z^2}{|q|} + \theta D_d \tau \qquad (2.6)$$

where q_r, q_z and |q| are radial, vertical and absolute value of the Darcian fluid flux densities, respectively; D_L and D_T are the longitudinal and transverse dispersivities, respectively; D_d is the ionic diffusion coefficient in free water; and τ is the tortuosity, which is taken as a function of θ (Simunek et al., 2006).

Figure 2.1 shows the axi-radial model domain, the scale, boundary conditions and a 2x magnified view of the cup boundary. The domain was 200 cm by 200 cm with the cup embedded in the middle of the z axis. The cup was 22 cm in length and had a radius of 2 cm. The porous ceramic formed the lower 6 cm of the cup and had a thickness of 0.5 cm. The nodal discretization was non-uniform with smaller nodal distances near the suction cup. There were a total of 3987 nodes. The bottom boundary for water flow was free drainage, which represents a unit gradient boundary condition, simulating a deep soil with no influence from a water table (Simunek et al., 2006). A variable head boundary condition was used for the ceramic boundary to simulate the suction cup vacuum.

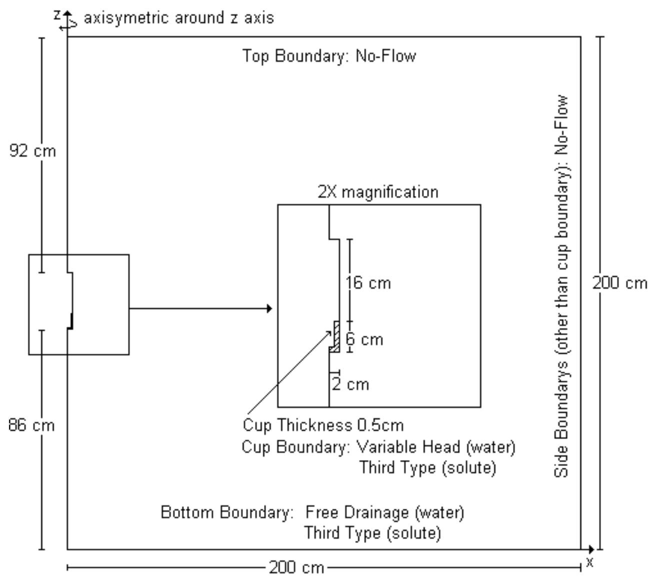

Figure 2.1: Axi-symetric model domain showing the geometry, scale and boundary conditions.
The cup boundary has been 2x magnified.

To simulate the decreasing vacuum as water entered the cup, a laboratory experiment was conducted. A cylinder, the same volume as the cup, was completely sealed. An inlet allowed the cylinder to be evacuated and water to enter. A vacuum gauge was used to record the change in vacuum with incoming water. A vacuum of 600 cm (H_2O) relative to atmospheric pressure was created and water was inserted at 10 mL increments. The change in vacuum after each insertion was recorded and used in the simulations. The laboratory experiment matched well with the theoretical Boyles law.

In HYDRUS 2/3D, the simulation was first run at the initial suction cup vacuum of 600 cm. The output was interpreted to determine when 10 mL of water passed the variable head boundary. The model input was then changed to reflect the reduction in vacuum due to the addition of water. This process, of adding another 10 mL, was repeated until the cup was full at 70 mL or until the soil water pressure was less than the variable head boundary, whichever occurred first. The reason for stopping the simulation early was the variable head boundary acted as an infinite supply of water when the governing conditions allowed water to flow out of the cup. In reality there would only be a finite amount of water in the cup and therefore the simulation was stopped before these conditions could come into fruition.

A third-type boundary condition was used for solute movement at the free drainage and variable head boundary. This type of boundary condition is mass conservative and when the water flux is zero or directed out of the domain the third-type boundary condition automatically switches to second-type (Neumann) boundary condition (Simunek et al., 2006). The remaining boundaries were no flow.

Four contrasting soils and the properties of the ceramic suction cup were used in the simulations. The first soil was a sandy loam from a citrus orchard within the Dareton Research and Advisory Station, located in the Coomealla irrigation area, New South Wales, Australia. The hydraulic parameters of the soil, shown in Table 1, were derived from a soil moisture release curve developed using the Tempe Pressure Cell method (Soil Moisture Equipment

Corp, 1986). A large undisturbed soil core was sampled from a depth of 100 cm in the tree line half way between two trees. An undisturbed subsample core, 2.75 cm radius and 3 cm height, was taken from the field core and used in the Tempe Pressure Cell. The saturated hydraulic conductivity was measured using the constant head permeameter method (Bosch and West, 1998). The measurement was conducted at 80 cm between two trees and the mean of three tests was taken. The sampling was conducted at 80 cm because this was the lowest measurement depth allowable by the constant head permeameter used. The remaining three soil types, including sand, clay loam and sandy clay, were selected from the soils catalogue inbuilt in HYDRUS 2/3D (Simunek et al., 2006). The three soils were the same as those used by Weihermüller et al. (2005) who used HYDRUS 2D to study the influence the suction cup has on soil-water flow under continuous vacuum. The ceramic cup was given hydraulic parameters which would ensure it remained saturated for all simulations. Saturated hydraulic conductivity of the ceramic was calculated using the falling head permeameter method (Klute and Dirksen, 1986). Klute and Dirksen (1986) described the falling head permeameter method as better than the constant head method for soils with small hydraulic conductivities, such as that exhibited in the ceramic. The hydraulic properties of the Dareton soil, the three hypothetical soils and the ceramic cup are listed in Table 2.1 and shown in Figures 2.2 and 2.3.

The reason for including the Sandy Loam from the Dareton Research and Advisory Station was because there is a larger solute dynamics research project occurring at the field site. Knowing more about how the suction cup samples the soil water would help with the analysis of data produced during the project.

Table 2.1: Hydraulic parameters of the four soils and the suction cup ceramic material.

Soil	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	α (cm^{-1})	*n*	*m* (1-1/n)	K_s (cm day^{-1})
Sand	0.045	0.43	0.1450	2.68	0.63	712.8
Sandy Loam	0.065	0.41	0.0390	2.38	0.58	150
Clay loam	0.095	0.41	0.0190	1.31	0.24	6.24
Sandy clay	0.100	0.38	0.0270	1.23	0.19	2.88
Ceramic	0.001	0.5	0.00005	3	0.67	0.026

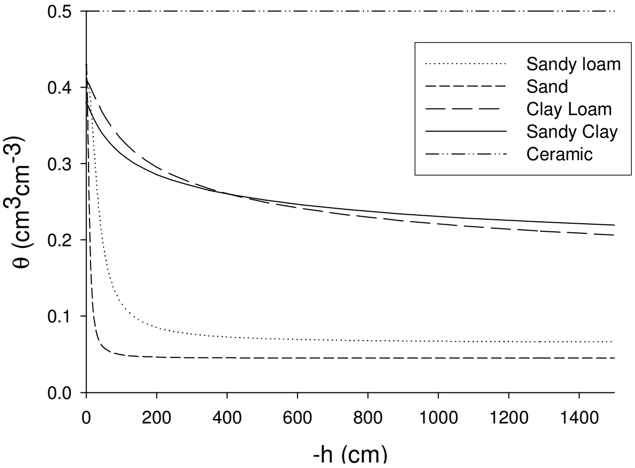

Figure 2.2: Soil moisture release curve for the four soils and ceramic cup.

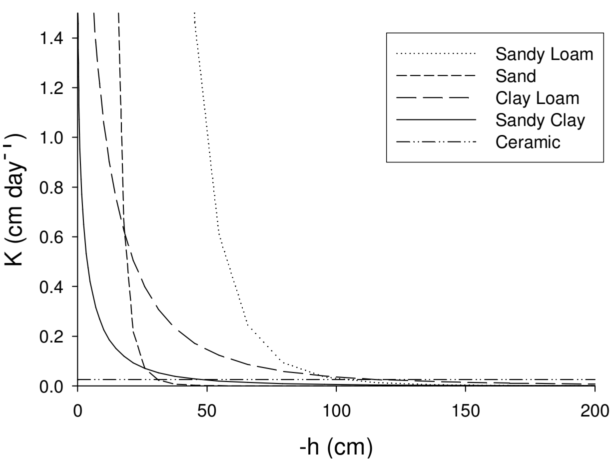

Figure 2.3: Unsaturated hydraulic conductivity functions for the four soils and ceramic cup.

In total twenty two scenarios were tested, including a range of soil-water contents for each soil. Table 2.2 lists the different simulations including the initial soil water pressures for each soil. The activity domain was calculated from a horizontal cross section, at the depth of the middle of the cup, at the last time step. Ninety percent of the maximum difference between the ambient soil water pressure and the maximum change in soil water pressure was used as the reference to compare the different scenarios.

The extraction domain was estimated by tracking solute bands. In total, nine non-reactive solute bands spanning the total vertical length of the domain were placed at 0.5 cm increments away from the suction cup. The solute concentration was set at 100 mmol cm^{-3}, D_L and D_T were set at 0.5 cm and

0.05 cm, respectively, and D_d was set at 0. The solute was used to estimate the distance water travelled. By determining which solutes reached the suction cup the extraction domain could be estimated within a 0.5 cm range.

At the end of each simulation the time required for every 10 mL increment of water to flow into the cup and the total time to fill the 70 mL reservoir was recorded.

Table 2.2: Soil water pressures scenarios tested for each soil type.

Soil Type	*Soil Water Pressure (cm)*
Sand	-10, -20, -30, -40, -50
Sandy Loam	-50, -75, -100, -110, -200
Clay loam	-50, -75, -100, -110, -200, -400
Sandy clay	-50, -75, -100, -110, -200, -400

2.3 Results and Discussion

Activity Domain

The activity domain was measured at the end of the final time step so no water redistribution occurred and the activity domain was at its maximum. For comparative purposes, the activity domain was taken to occur at a distance corresponding to 90% of the maximum difference between the background soil water pressure and the soil water pressure next to the suction cup.

The activity domain for the four soil types is shown in Figure 2.4. The activity domain radius for the sand simulation was between 4.65 cm and 7.1 cm for soil water pressures between -10 cm and -50 cm. The activity domain radius for the Sandy Loam simulation was between 8.6 cm and 15.85 cm for soil water pressures between -50 cm and -110 cm. The activity domain radius for the clay loam simulation was between 8.85 cm and 16.55 cm for soil water pressures between -50 cm and -110 cm. The activity domain radius for the sandy clay was between 8.45 cm and 17.2 cm for soil water pressures between -50 cm and -110 cm.

A key finding from this study is how the vacuum extraction process (continuous or decreasing) appears to influence the activity domain. The activity domain for the sand and sandy clay, under constant vacuum (600 cm H_2O) calculated by Weihermüller et al., (2005), is approximately four times higher than the maximum activity domain calculated from the decreasing vacuum used in this study. Similarly, the activity domain for the clay loam is at least six times higher for the constant vacuum. Thus, it is obvious that the type of extraction process must be identified prior to the installation of multiple suction cups to ensure their activity domains do not intersect.

The simulations show that the estimated activity domain increased as the soil water pressure became more negative. This indicates that drier conditions increase the activity domain for any soil type. Under continuous vacuum, simulations have indicated the activity domain is largest for highest ambient hydraulic conductivities (Weihermüller et al., 2005) indicating that, irrespective of the type of vacuum, there is an increase in activity domain when the soil dries. The activity domain also increased as the clay content of the soil increased. This result agrees with the findings of Warrick and Amoozegar-Fard (1977) who found the activity domain is smaller for coarser soils and larger for finer soils.

From the results, it is clear that if we are to ensure the activity domain of different suction cups do not overlap, there is a need to consider the type of vacuum (continuous or decreasing), the soil texture and the soil-water regime prior to installing suction cups

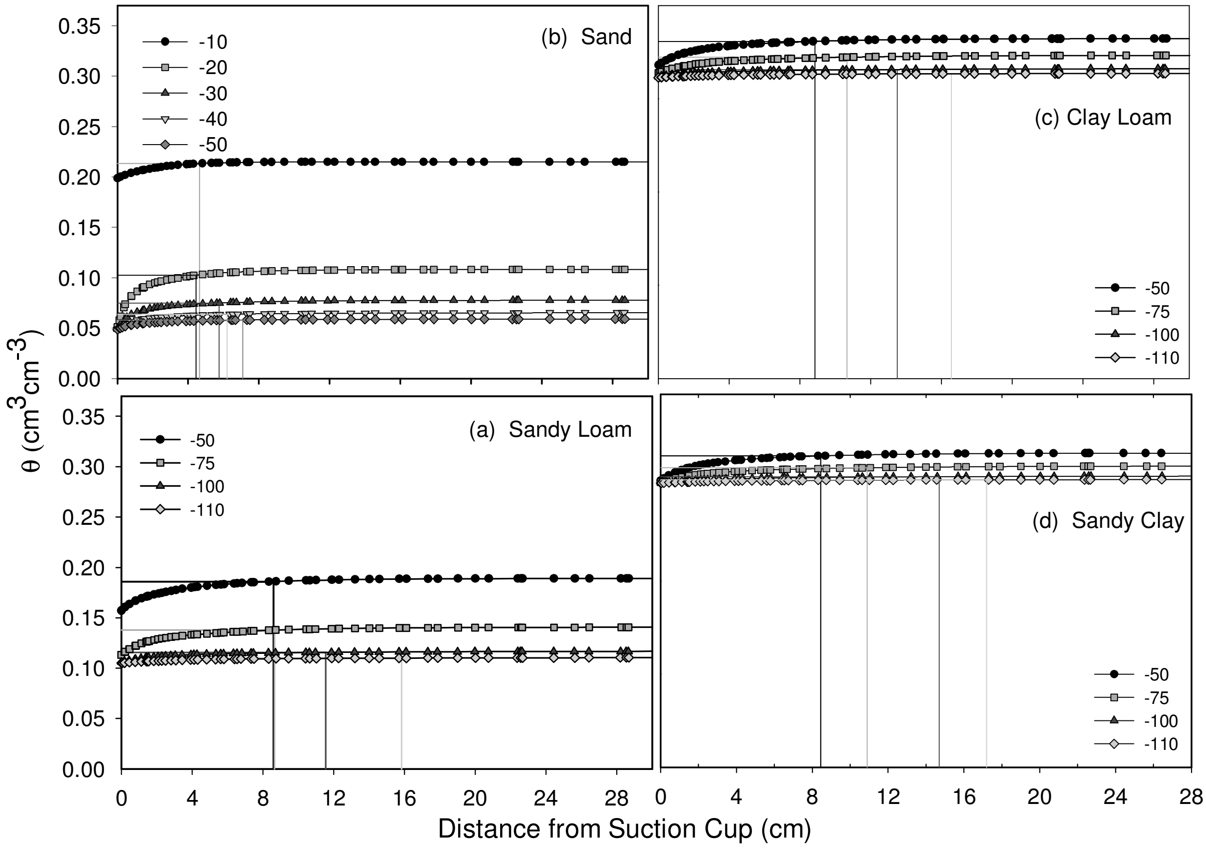

Figure 2.4: Cross sections showing the suction cups activity domain at different ambient states of soil water pressure: (a) Sand, (b) Sandy Loam, (c) Clay Loam, and (d) Sandy Clay. For each scenario the activity domain was taken to occur at a distance corresponding to 90% of the maximum difference between the background soil water pressure and the soil water pressure next to the suction cup. The cross section was taken horizontally from the midpoint of the suction cup and the soil water pressure units are in cm H2O.

Extraction Domain

The extraction domain for all the simulated soils was in the order of centimetres and was no larger than 5.5 cm, as shown in Figure 2.5. The extraction domain increases with decreasing soil water pressure for all soils simulated, similarly to Weihermüller et al. (2005), and was larger for the sandy soils compared to the finer soils.

As would be expected, the extraction domain was always smaller than the activity domain because water at the perimeter of the activity domain never reaches the cup before it filled (Weihermüller et al., 2005). The sand simulation extraction domain is similar to that reported by Morrison and Lowery (1990), who used a sand to examine the extraction domain, under a constant 70 kPa vacuum, and found an extraction domain radius in the order of centimetres. This indicates that, for sand, the extraction domain is not influenced greatly by the method of vacuum extraction.

Quantification of the extraction domain is required if solute results, from the suction cup, are going to be used for higher level analysis such as for nitrate leaching studies (Poss et al., 1995).

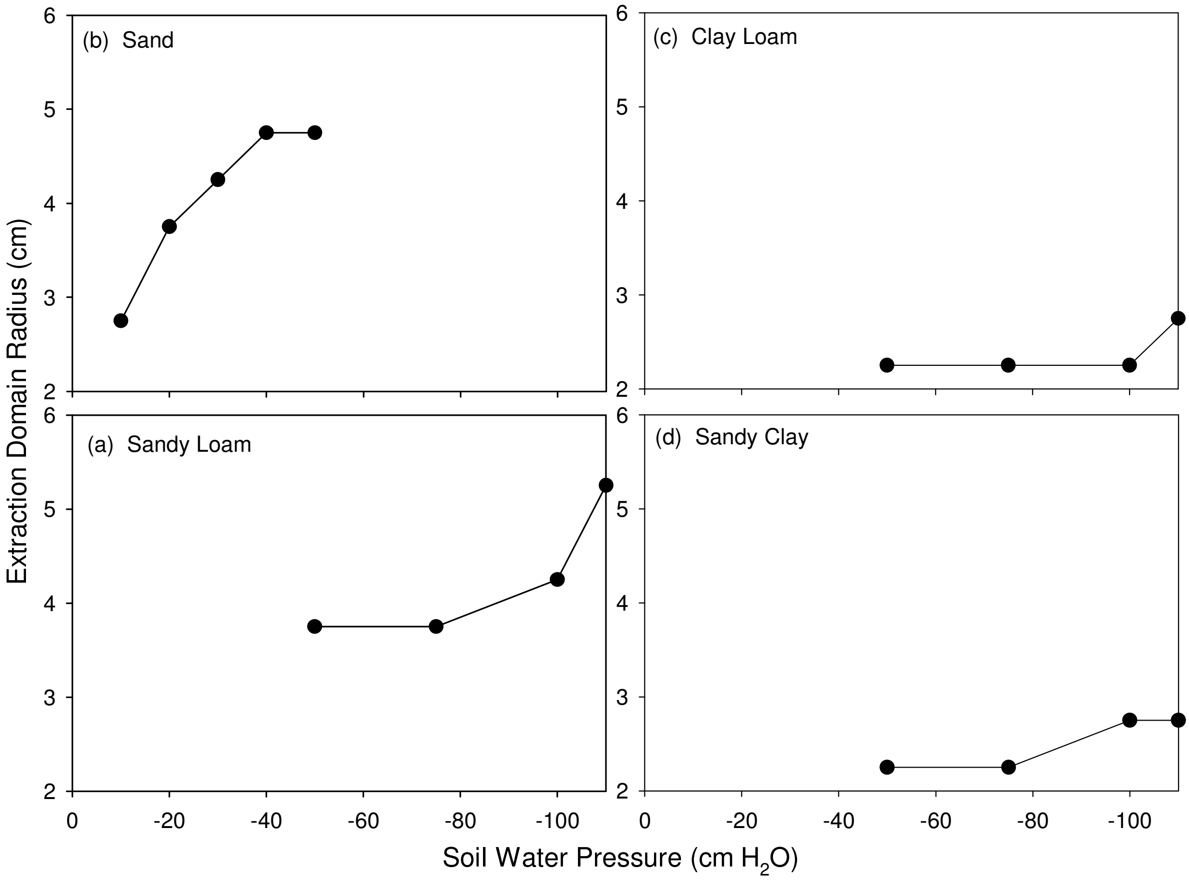

Figure 2.5: Suction cup extraction domain radius change with decreasing soil water pressure**: (a) Sand, (b) Sandy Loam, (c) clay loam, (d) sandy clay.**

Time Required to Collect a Sample

The estimated time taken to fill the suction cup (in 10mL increments) under the different scenarios is shown in Table 2.3. As the initial soil water pressure increased, indicating drier conditions, the time taken to fill the cup also increased. This was expected because of the reduced hydraulic conductivity, as indicated in Figure 2.3, and the increased distance the water was required to travel to reach the suction cup under the drier conditions (Weihermüller et al., 2007). The time taken to obtain a sample volume for a particular soil water pressure can be estimated for each soil type from Table 2.3. For example, the Sandy Loam suction cup filled after 0.13 days at a soil water pressure of -50 cm. after 0.59 days at a pressure of -75 cm, after 2.6 days at a pressure of -100 cm, after 5.4 days at a pressure of -110 cm and filled to only 60 mL after 42 days at a pressure of -200 cm.

The time needed to obtain the required volume of soil solution from a suction cup should be used to establish sampling regimes. The best sampling regime collects enough sample volume to conduct the relevant analysis while allowing the water to sit in the cup reservoir for as little time as possible. Short sampling intervals reduce the influence of sorption, leaching, diffusion and screening by the cup walls (Hansen and Harris, 1975). Researchers and managers can use the results given in this paper as a guide to determine an approximate time necessary to yield the desired volume of water.

It has to be emphasised that this study was a desktop numerical modelling exercise and no field validation was carried out. The simulations were conducted using a homogeneous soil profile and uniform initial water content with free drainage. Transient water flow, soil heterogeneity and preferential flow were not considered. Also, solute transport was not considered where dynamics such as dispersion, diffusion and suction cup surface reactions could be important under certain circumstances. Care should be taken when extrapolating these simulation results to field conditions.

Table 2.3: Predicted time (days) required to fill the suction cup reservoir for the four soil types at different ambient states of soil water pressure. Empty cells in the table indicate that the cup did not fill up; the simulation had to be truncated because the time domain exceeded the boundary condition.

Water into Cup (mL)	Sand					Sandy Loam					Clay Loam						Sandy Clay					
	Soil Water Pressure (cm H_2O)					Soil Water Pressure (cm H_2O)					Soil Water Pressure (cm H_2O)						Soil Water Pressure (cm H_2O)					
	-10	-20	-30	-40	-50	-50	-75	-100	-110	-200	-50	-75	-100	-110	-200	-400	-50	-75	-100	-110	-200	-400
10	0.0038	0.03	0.36	2.25	8.2	0.0062	0.024	0.1	0.15	4	0.0111	0.018	0.027	0.031	0.106	0.89	0.05	0.09	0.16	0.19	0.69	5.1
20	0.0081	0.1	1.13	6	21.25	0.017	0.078	0.3	0.48	10	0.034	0.055	0.084	0.1	0.335	2.7	0.18	0.325	0.53	0.62	2.05	15.5
30	0.0134	0.2	1.95	10	34.7	0.03	0.145	0.55	0.88	16.8	0.063	0.102	0.16	0.18	0.62	5.9	0.35	0.63	1	1.17	3.8	33
40	0.019	0.3	2.85	14	48.75	0.046	0.225	0.83	1.32	24	0.097	0.16	0.25	0.294	0.98	13.2	0.54	0.95	1.54	1.8	5.9	71.2
50	0.0254	0.415	3.79	18.5	63.1	0.062	0.3	1.12	1.775	31.9	0.134	0.225	0.35	0.4101	1.4		0.75	1.35	2.13	2.51	8.39	
60	0.034	0.525	4.75	23	77.9	0.082	0.4	1.46	2.275	42	0.18	0.3025	0.48	0.554	2.22		1.019	1.8	2.9	3.42	14.4	
70	0.054	0.67	5.85	28	94.9	0.13	0.59	2.6	5.4		0.294	0.6	1.46	2.95			1.55	3.25	8	15.8		

2.4 Conclusions

This is the first comprehensive analysis of the influence that a suction cup, with a decreasing vacuum, has on soil water movement for different soil types and moisture conditions. The main findings are that the extraction domain was never larger than 5.5 cm, and that the activity domain for finer textured soils was up to 17.2 cm and up to 7.1 cm for sand. The time required to collect a sample volume increased with increasing clay content and decreasing soil water pressure. These findings should be taken into account to determine correct suction cup placement, to quantify the soil volume the sample is collected from and to determine how long to leave a decreasing vacuum before the required volume of water is collected.

Acknowledgements

The support and funding by the Cooperative Research Centre for Irrigation Futures is greatly acknowledged.

Appendix 2A – List of abbreviations

c	solute concentration (mmol cm^{-3})
$C(h)$	specific water capacity (-)
D_d	ionic diffusion coefficient in free water (cm^2 day^{-1})
D_L	longitudinal dispersivity (cm)
D_{rr}	dispersion tensor (cm^2 day^{-1})
D_T	transverse dispersivity (cm)
D_{zz}	dispersion tensor (cm^2 day^{-1})
h	soil water pressure (cm)
h_s	air entry value (cm)
$K(h)$	unsaturated hydraulic conductivity at pressure head h (cm day^{-1})
Ks	saturated hydraulic conductivity (cm day^{-1})
m	van Genuchten parameter (-)
n	van Genuchten parameter (-)
$\|q\|$	absolute Darcian fluid flux (cm day^{-1})
q_r	radial Darcian fluid flux (cm day^{-1})
q_z	vertical Darcian fluid flux (cm day^{-1})
r	radial distance (cm)
Se	effective water content (-)
t	time (day)
z	distance increasing upwards to the soil surface from a reference (cm)
α	reciprocal value of the air entry value (cm^{-1})
θ	soil water content (cm^3 cm^{-3})
θ_r	residual soil water content (cm^3 cm^{-3})
θ_s	saturated soil water content (cm^3 cm^{-3})
τ	tortuosity (-)

Chapter 3: Water and Nitrate Movement under Advanced Fertigated Citrus

3.1 Introduction

Sustainable irrigation management requires effective water and fertilizer management to ensure excess water and nutrients do not move below the root zone causing environmental harm. Irrigation water contains salts which build up within the root zone. This requires extra water to leach the salts from the root zone (Biswas et al., 2006; White, 2006; Sukhija et al., 2003; van Hoorn, 1981). The conundrum becomes how to manage different solutes that have similar water flow characteristics. All salts create osmotic stress to plants and some salts such as chloride and sodium are toxic at high concentrations (Foth, 1990). However, some salts are vital to plant growth and are defined as either macro or micro nutrients (White, 2006). These salts are often not readily available in the soil and fertilizer is required to improve soil fertility.

Fertigation is defined as the application of fertilizers dissolved in irrigation water to allow water and nutrients to be placed in the zone of greatest root activity, allowing rapid utilisation by plants (Bar-Yosef, 1999). Fertigation has been used for many decades, although in recent times the management of fertigation systems has advanced greatly. Advanced Fertigation (AF) is one such fertigation management system for horticultural crops, developed over the past two decades to speed up orchard development, increase yield and improve fruit quality. The fundamental principle is that water and nutrients are applied regularly to a smaller volume of soil at a low application rate to meet crop demand (Falivene, 2005).

AF is a broad name given to the emerging use of intensive fertigation management systems. In reality, each AF system is different due to factors including climate, soil, water quality and level of management input. High levels of nutrients are usually applied to speed up the crop development time.

If excess water is applied, there is the potential for nutrients to leach below the root zone and cause environmental damage.

The major limiting macro nutrient for citrus is nitrogen, most readily available in the form of nitrate. Nitrate moves freely in mineral soil and hence has the potential to leach into groundwater and waterways if fertigation is not well managed (Paramasivam et al., 2002; Gardenas et al., 2005; White, 2006). Nitrate is removed from the soil by plants or decomposed by micro-organisms in the process of denitrification. In well aerated soils, denitrificaiton is often negligible because of a lack of favourable conditions (Alva et al., 2006). High nitrate concentrations in groundwater are hazardous for two reasons. Firstly, nitrate has been linked to blue baby syndrome in infants when concentrations in groundwater used for drinking purpose are over 10 mg nitrate-N L^{-1} (NWQMS, 2004). Secondly, high levels of leached nitrate can lead to eutrophication of surface water bodies where the groundwater discharges.

Irrigation management must aim to keep nutrients such as nitrate in the root zone while removing salts to maintain adequate soil salinity levels for the crop. The only way this can be realistically achieved is through the use of targeted leaching periods when conditions are optimum. Leaching is optimum when soil moisture content is uniformly high and crop uptake, biological activity and soil nutrient content is low (Biswas, 2006). To determine when soil nutrient levels are low soil based monitoring is required.

There are several techniques to estimate nitrate leaching. The most precise measurement technique uses a lysimeter to measure actual volumes of drainage and concentration of the drainage water. The study by Syvertsen and Smith (1995) used lysimeter grown citrus trees fertilized at three nitrogen rates. The nitrogen concentration in the drainage water increased with rising N application rate and exceeded 10 mg L^{-1} for trees receiving the highest rate. However, lysimeters are expensive and the installation process can cause considerable soil destruction, resulting in different water transport conditions compared to the surrounding intact soil. The bottom boundary of the lysimeter can also cause non realistic deep drainage measurements.

Computer based models can also be used to estimate deep drainage and nitrate leaching. There are several models capable of simulating unsaturated water flow, with each model having its own advantages. Models such as HYDRUS-2/3D and LEACHM use the Richards' equation and the convection/dispersion equation to simulate water flux and solute movement. Paramasivam et al., (2002) utilised a combination of water balance and modelling, using the LEACHM model, to estimate nitrate leaching and deep drainage in Florida, USA. It was found that 21-36% of the fertilizer N applied leached below the root zone in the sandy Entisol soil, whereas citrus tree uptake could account for only 40-53% across all N treatments used in the study (112-448 kg ha^{-1} yr^{-1}).

The Darcy-Buckingham approach is a field based method used to estimate soil water flux and therefore deep drainage below the root zone. The method is based on the flux-gradient approach, which includes a unsaturated hydraulic conductivity function (K(h)) based on the soil medium (Silva et al., 2007). These functions have been extensively used in laboratory and field based studies to estimate soil water fluxes (Kutilek and Nielsen, 1994). It has been reported that for field situations in which these functions are obtained using the same soil body in which soil water fluxes are estimated, results have been successful (Larue et al., 1968; Minasny et al., 2004; Lazarovitch et al., 2005). However, the exponential nature of the K(h) function combined with the inherent soil heterogeneity makes estimates of flux difficult (Silva et al., 2007). The shape of the K(h) function results in very large differences in unsaturated hydraulic conductivity for small changes in water content. The error range of some tensiometers can make deep drainage estimation impossible (Silva et al., 2007). In the paper by Silva et al. (2007) the tensiometers used to determine the flux gradient had an error of ±10 cm H_2O.

Nitrate leaching has been estimated by combining the soil water flux determined using the Darcy-Buckingham approach with the nitrate concentration below the root zone using suction cups to extract the soil water (Paramasivam et al., 2001; Alva et al., 2006). Paramasivam et al, (2001) used this approach in Florida, USA and reported that nitrate-N leaching losses below the root zone increased with rising N application (112 – 280 kg N ha^{-1} yr^{-1}) and the amount of water drained. Nitrate-N leaching accounted for 1-16% of applied fertilizer N. They also reported that the nitrate-N concentration at the bottom of the root zone stayed below 10 mg L^{-1} for most of the testing period. Alva et al. (2006) reported a 15% leaching loss at an applied N rate of 280 kg ha^{-1} $year^{-1}$ in Florida, USA. Alva et al. (2006) commented that the actual quantity of nitrate-N leached was underestimated due to the infrequent sampling of nitrate.

Biswas et al., (2006) used a similar method to assess deep drainage below a mature citrus property in the Sunraysia region of NSW, Australia between 2002 and 2003. Instead of tensiometers, multi-sensor capacitance probes were used to assess deep drainage using the Darcy-Buckingham approach. The rationale of this method was that the large number of existing capacitance probes used to schedule irrigation could also be used to estimate deep drainage. The results of this research showed both daily and seasonal variations, with a daily drainage value of up to 2 mm day^{-1}. During the whole year, a total of 250 mm of water drained below the root zone, which accounted for 17% of the total amount of irrigation and rainfall.

To ensure AF management systems are sustainable, soil based monitoring should be conducted, especially below the root zone where the nitrate can reach the groundwater system and cause environmental harm. There has been no deep drainage or nitrate leaching study conducted for AF management in Australian conditions, which forms the objective of this paper. The study aims to estimate deep drainage using two different methods and nitrate leaching using one. The Darcy-Buckingham approach and a water balance have been used to estimate deep drainage. Nitrate leaching was estimated by combining the drainage flux determined from Darcy-Buckingham with the nitrate concentration in suction cup below the root zone. Three field sites have been selected to test the methodology. The three sites include a developing AF citrus orchard, a more conventionally fertigated young citrus orchard, and a conventional mature citrus orchard. The study does not represent a controlled trial and instead aimed to test the methods, investigate the errors associated with the deep drainage calculations and make recommendations for sustainable management of AF systems.

3.2 Materials and Method

3.2.1 Field Site Description

The deep drainage and nitrate leaching assessment was conducted at the Dareton Agricultural and Advisory Station, NSW. The research station is located in the Coomealla irrigation area which forms part of the Sunraysia fruit growing district of NSW and Victoria (Figure 3.1). The soils were alkaline (Class IIIA), with red sandy to sandy loam topsoils overlaying a heavier sub soil. The site had a top soil and root zone depth of 1.05 m. The first 0.6 m of the soil profile had a loamy sand texture while the remainder of the profile down to 1.5 m had a loam texture. The total organic carbon content was very low at 0.4% in the first 0.3 m and below 0.25% for the remainder of the root zone. The property was irrigated with Murray River water which has salinity level below 0.3 $dS.m^{-1}$. The climate is characterised as dry with warm to hot summers and mild winters. The average yearly rainfall is 280 mm with rainfall evenly distributed throughout the year. Potential evapotranspiration is high at 1247 mm in 2007.

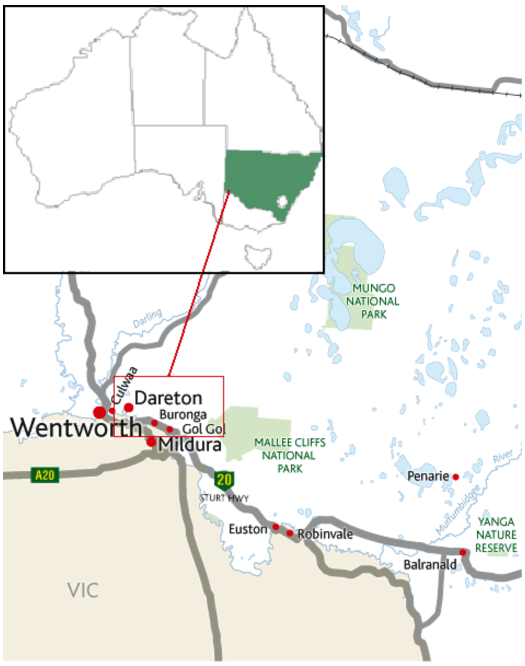

Figure 3.1: Field site location map.

Three trial sites were established within the Dareton Agricultural and Advisory Station. An advanced fertigated site (AFS) consisting of a number of mandarin varieties and a conventionally fertigated site (CFS) consisting of Cara Cara Navel were both established on 10 October 2005. An adjacent sprinkler irrigated Nova Mandarin site (NOVA), planted in 1987, was also monitored. The rootstock for all sites was Citrange. The three field sites do not represent a controlled experiment and instead demonstrate the deep drainage and nitrate leaching methods on three differently managed citrus orchards.

AFS - Drip irrigated citrus fertigated weekly

- Planted: 10 October 2005
- Number of rows: 3
- Row length: 104 m
- Row spacing: 5 m
- Tree spacing: 2 m
- Irrigation system: Drip double lines per tree row (1.6 L/h Drippers)
- Dripper Spacing: 0.4 m
- Application rate: 1.6 mm/hr
- Surface wetted distance (perpendicular to tree row): 1.3-1.4 m

CFS - Drip irrigated citrus fertigated monthly

- Planted: 10 October 2005
- No of rows: 13
- Row length: 105 m
- Row spacing: 5 m
- Tree spacing: 3 m
- Irrigation system: Drip double lines per tree row (2 L/h drippers)
- Dripper Spacing: 0.5 m
- Application rate: 1.6 mm/hr
- Surface wetted distance (perpendicular to tree row): 1.3-1.4 m

NOVA - Under canopy sprinkler irrigated

- Planted: 1987
- Number of rows: 3
- Row length: 60 m
- Row spacing: 5.6 m
- Tree spacing: 3.25 m
- Irrigation system: Water Birds, 115 L hr^{-1} at 200 kPa
- Emitter spacing: 3.15 m
- Application rate: 6.1 mm hr^{-1}
- Wetted area: Full cover

3.2.2 Fertigation, irrigation and weather data

Irrigation and fertigation records were collected from the Dareton Research and Advisory Station. Total water usage for 2006/07 and 2007/08 was 4 ML ha^{-1} and 5.9 ML ha^{-1} for AFS, 1.6 ML ha^{-1} and 2.7 ML ha^{-1} for CFS, and approximately 12 ML ha^{-1} for both years for NOVA. Fertilizer usage data during the same period is given below in Table 3.1. Weather data was collected from an automated weather station located within the research station. Potential evapotranspiration (ETo) was calculated using the FAO 56 method (Allen et al., 2006). ETo was converted to ETc using equation 3.1

$$ET_o \cdot K_c \cdot A_c = ET_c \qquad (3.1)$$

where K_c is the crop coefficient and A_c is the crop age coefficient. The K_c values were compiled by the Irrigated Crop Management Service (ICMS) at Rural Solutions, South Australia. The K_c values were taken from FAO 56 and fitted to the Southern Hemisphere. The A_c is a canopy area coefficient used to correct ET_o for the age of the crop and its canopy area (RMCWMB, 2004). The canopy growth at AFS was much greater than at CFS and as a result the A_c for a citrus tree two years older was chosen. The decision was made by comparing the canopy size to different aged citrus trees within the research station. The K_c and A_c used are included in Appendix 3B.

Table 3.1: Fertiliser use for the three trial sites.

Treatments	N (kg ha^{-1} yr^{-1})		P (kg ha^{-1} yr^{-1})		K (kg ha^{-1} yr^{-1})	
	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
AFS	164	142	37	23	225	97
CFS	96	79	23	19	43	36
NOVA	115 (32 Foliar)		0		0 (33 foliar)	
Mature tree Standard	110		50		50	

At AFS, a number of different fertilizer types were used including ammonium nitrate and mono ammonium phosphate up until 9 April 2007. Ammonium sulphate, magnesium nitrate, potassium nitrate and mono ammonium phosphate were then used after 27 August 2007.

3.2.3 Soil solution monitoring equipment

The soil water below the main root zone was sampled using suction cup soil water samplers (Litaor, 1988; Corwin, 2002; Biswas 2006; Weihermüller et al., 2007). The suction cup is a porous ceramic cup connected to a PVC sample reservoir. Tubing from the reservoir to the soil surface is used to apply the vacuum and extract the solution for analysis. A vacuum of 60 kPa was applied before the suction cup was sealed. Soil water was drawn into the suction cup due to the pressure gradient caused by the vacuum. A week later the sample was extracted. The suction cup used in the study was developed at the South Australian Research and Development Institute and is commercially available as the SoluSAMPLER through Sentek Pty Ltd. Suction Cups were installed below the main root zone, at each site, to monitor for nitrate leaching. AFS and CFS had two suction cups installed at 1.5 m depth while NOVA had two existing suction cups at 0.9 m depth. The reason for the shallower depth at NOVA was that these suction cups had been previously installed with the aim to measure solutes at the base of the main root zone and it was decided that the information generated would still be useful. When installing the suction cups at AFS and CFS, a conscious effort was made to install the suction cups well below the rooting depth to ensure any nitrate found would be lost to the crop. AFS and CFS suction cups were located at a distance of 0.1 m from the drip emitter, while the NOVA suction cups were located within the tree row, 0.75 m from the sprinkler emitter.

AFS samples were taken weekly while CFS samples were taken fortnightly. The reason for the difference was that the research station staff had limited capacity to perform the sampling and it was decided to prioritise AFS as this site had a more intensive fertigation regime. For AFS and CFS, sampling commenced on 28 August 2006 and continued until 20 June 2008. NOVA was sampled weekly for the two months of analysis, as explained in 3.2.8.

3.2.4 Soil water analysis for nitrate

Soil water samples from the suction cups were stored in a freezer (-18 ^{o}C) before being analysed for nitrate. The presence of nitrate was determined either by using an Autoanalyzer (cadmium reduction procedure) or by liquid chromatography. The Autoanalyzer procedure involved nitrates reducing to nitrite by a copper cadmium reductor column. The nitrite ion then reacts with sulphanilamide under acidic conditions to form a diazo compound and, when coupled with gentisic acid, forms a reddish purple azo dye. The intensity of the colour measured with a colorimeter gives the nitrate concentration in the sample.

The liquid chromatography procedure involved the sample passing through an anion exchange column, where the anions in the sample are separated as the KOH eluent pushes the different anions off the exchange surface. As the anions come out of the column, the electrical conductivity is measured and referenced to standards to determine nitrate concentration (Dionex, 1996). Five recovery tests were conducted with 5 mg L^{-1} nitrate and the lowest recovered sample was 97%.

Samples were initially analysed using the Autoanalyzer from 28 August 2006 until 10 December 2007. After this date the samples were analysed by liquid chromatography.

3.2.5 Soil tension monitoring equipment

USM T8 tensiometers were installed to measure the soil water pressure (www.usm.muc.de). The T8 tensiometer has a measurement range and accuracy of +100 to -85 kPa and ±0.5 kPa, respectively. At all three sites, a set of two tensiometers were installed at depths of 0.9 m and 1.2 m. The installation procedure involved driving a specially designed auger into the ground at a 25^{o} angle to the desired depth and then inserting the tensiometer, ensuring a firm fit. A cover was used to prevent preferential flow of water down the tube. The tensiometers were installed so that the 1.2 m tensiometer was located directly below the 0.9 m tensiometer. The AFS and CFS tensiometers were placed in the tree row between two trees while the NOVA tensiometers were located 1.0 m from a tree within the tree row

At AFS and CFS the tensiometers were installed on 30 August 2007 and were logged hourly until 20 June 2008. The CFS tensiometer malfunctioned for much of the time and the data set spans from 21 December 2007 until 3 February 2008. At the NOVA site the two tensiometers were installed on 20 November 2004 and logged hourly for the two months of analysis, as explained in 3.2.8.

3.2.6 Deep drainage calculation

The Darcy-Buckingham approach was used to assess deep drainage from the difference in soil water pressure (h) between the two tensiometers, located at 0.9 m and 1.2 m depth, and the unsaturated hydraulic conductivity.

Darcy's flux equation is described in equation 3.2.

$$Jw = -K(h)\left(\frac{d(h)}{dz} - 1\right) \qquad (3.2)$$

J*w* is the water flux density (m day^{-1}), K(*h*) is the unsaturated hydraulic conductivity (m day^{-1}), *d(h)* is the difference in pressure between 0.9 and 1.2 m depth (m) and *dz* is the distance between the two tensiometers (m). The negative sign accounts for the direction of flow being opposite to the direction of increasing head.

The unsaturated hydraulic conductivity for different soil water pressures was estimated using measured saturated hydraulic conductivity (*Ks*; m day^{-1}), the average soil water pressure (*h*), and fitting parameters (*α, n and m*) from van Genuchten (1980) (equation 3.3).

$$K(h) = Ks(1+(\alpha h)^{n})^{-m/2}(1-(\alpha h)^{n-1}(1+(\alpha h)^{n})^{-m})^{2} \qquad (3.3)$$

Ks was measured in the field using a Guelph Permeameter which uses the constant head permeameter method (Bosch and West, 1998). The mean of five measurements for AFS and two for CFS was used. The measurement was taken from a depth of 0.8 m between two trees. Measurements were taken at 0.8 m because the scale on the Guelph Permeameter was not visible past this depth.

The Tempe Pressure Cell method was used to develop a soil moisture release curve (Klute, 1986). The soil moisture release curve represents the relationship between θ and *h*, and when the van Genuchten (1980) function is fitted to the curve the hydraulic parameters can be derived. Three large undisturbed soil cores were sampled from a depth of 1.0 m in the tree line half way between two trees at the AFS and CFS sites. An undisturbed subsample core, 2.75 cm radius and 3 cm height, was taken from the field core and used in the Tempe Pressure Cell. Due to seal problems with the Tempe Pressure Cells, several of the measurements could not be completed. AFS had two soil moisture release curves completed while CFS had one. The hydraulic parameters for NOVA were supplied through personal communications with Tapas Biswas from the South Australian Research and Development Institute. Figure 3.2 and 3.3 show the soil moisture release curves for AFS and CFS, respectively. The dots represent the experimental results, with the line representing the fitted van Genuchten (1980) function. The soil hydraulic parameters and the *Ks* are shown in Table 3.2 and 3.3.

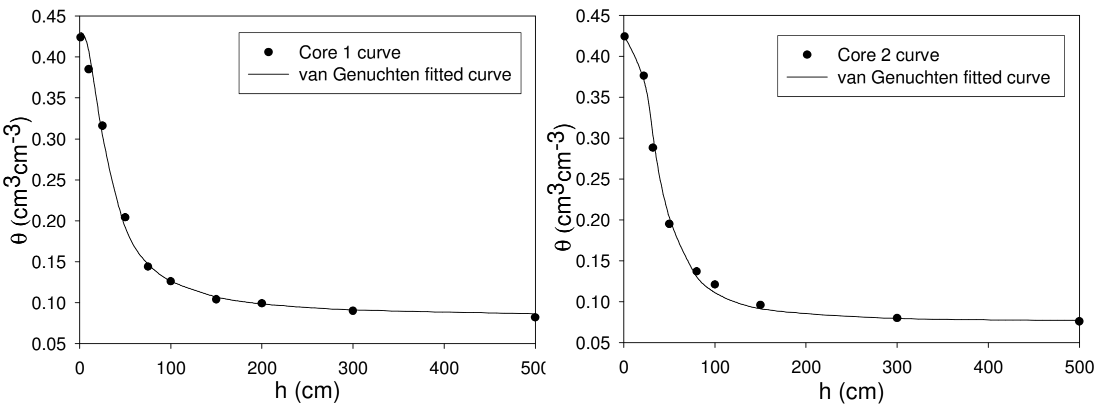

Figure 3.2: Soil moisture release curve for cores 1 and 2 from AFS with the van Genuchten function fitted.

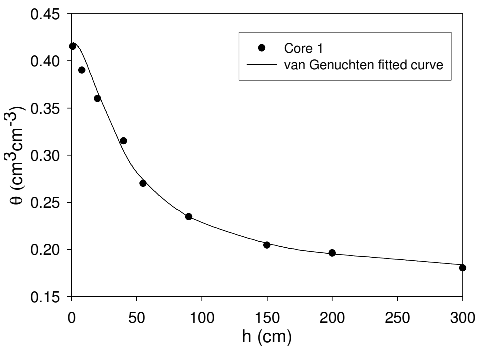

Figure 3.3: Soil moisture release curve for core 1 from CFS with the van Genuchten function fitted.

Soil naturally exhibits very large heterogeneity which must be taken into account when assessing the deep drainage. The Ks and K(h) function exhibit high variation in the field (Nielsen et al., 1976) and several scenarios, of different hydraulic parameters and Ks, were used to examine the influence of soil variability on the final drainage calculation.

To establish the hydraulic parameter scenarios, different ±5% combinations of the α and *n* parameters from the soil moisture release curves were used, while the Ks was maintained constant. This type of variation is commonly observed in the hydraulic parameters and when measuring soil water pressure with tensiometers. The resulting soil moisture release curve for AFS and CFS can be seen in Figure 3.4. The hydraulic parameters can be seen in Tables 3.2 and 3.3.

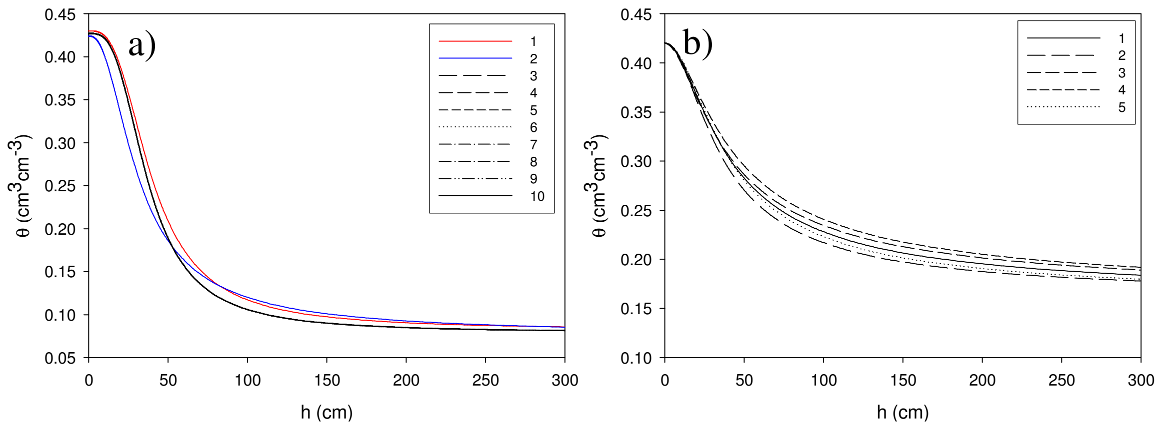

Figure 3.4: Soil moisture release curve scenarios used for deep drainage calculation. (a) represents the AFS and (b) represents the CFS scenarios. For (a) numbers 1 and 2 are the experimentally derived curve for cores 1 and 2, respectively. The remaining numbers represent different ±5% combinations of the α and *n* hydraulic parameters. For (b) number 1 represents the experimentally derived curve and the remaining numbers represent the different ±5% combinations of the α and *n* hydraulic parameters. The hydraulic parameters are given in Tables 3.2 and 3.3.

To observe the variation in deep drainage as affected by changing Ks, the measured hydraulic parameters were maintained and a range of Ks values were selected. The Ks values used included 1.0, 1.2, 1.4, 1.5, 1.6, 1.8, 2.0 m day^{-1} for AFS. The Ks values for CFS included 0.5, 0.7, 0.9, 1.1, 1.3 m day^{-1}.

Table 3.2: AFS soil hydraulic parameters including the ±5% α and *n* combinations.

Scenario	*Core*	*Change to α and n parameter*	α (cm^{-1})	*n*	*m* (1- (1/*n*)	*Ks* (m day^{-1})	θ_s ($cm^3 cm^{-3}$)	θ_r ($cm^3 cm^{-3}$)
1	1	No change	0.03	3.07	0.674	1.6326	0.42	0.076
2	2	No change	0.042	2.43	0.588	1.63.26	0.42	0.082
3	1	a and n 5% higher	0.032	3.22	0.6898	1.63.26	0.42	0.079
4	1	a 5% higher, n 5% lower	0.032	2.92	0.657	1.6326	0.42	0.079
5	1	a 5% lower, n 5%% higher	0.029	3.22	0.6898	1.6326	0.42	0.079
6	1	a and n 5% lower	0.029	2.92	0.657	1.6326	0.42	0.079
7	2	a and n 5% higher	0.044	2.55	0.607	1.6326	0.42	0.079
8	2	a 5% higher, n 5% lower	0.044	2.3	0.566	1.6326	0.42	0.079
9	2	a 5% lower, n 5% higher	0.04	2.55	0.607	1.6326	0.42	0.079
10	2	a and n 5% lower	0.04	2.3	0.566	1.6326	0.42	0.079

Table 3.3: CFS soil hydraulic parameters including the ±5% *α* and *n* combinations.

Scenario	*Core*	*Change to α and n parameter*	*α* (cm^{-1})	*n*	*m* (1- (1/*n*)	*Ks* (m day^{-1})	θ_s ($cm^3 cm^{-3}$)	θ_r ($cm^3 cm^{-3}$)
1	1	No change	0.038	1.98	0.495	0.7045	0.42	0.16
2	1	a and n 5% higher	0.0399	2.079	0.519	0.7045	0.42	0.16
3	1	a 5% higher, n 5% lower	0.0399	1.881	0.468	0.7045	0.42	0.16
4	1	a 5% lower, n 5%% higher	0.0361	1.881	0.468	0.7045	0.42	0.16
5	1	a and n 5% lower	0.0361	2.079	0.519	0.7045	0.42	0.16

3.2.7 Nitrate leaching calculation

The nitrate leached below the root zone was estimated using the concentration of nitrate-N in the suction cup at 1.5 m depth for AFS and CFS and 0.9 m for NOVA. At this depth there is little root activity and therefore it is assumed that nitrate is lost to the plant and subject to leaching (Castle, 1980). It was also assumed that there was minimal denitrification due to the sandy soil texture making anoxic conditions highly unlikely (Alva et al., 2006). The mass of nitrate-N leached over a hectare (*NL*; kg/ha) was calculated from the nitrate-N concentration in the suction cup ($C_{NO3\text{-}N}$; kg L^{-1}) multiplied by the volume of drainage, calculated over a hectare (equation 3.4).

$$NL = QC_{NO3-N} \tag{3.4}$$

Assuming steady state water flow, the volume of drainage (Q) was calculated by multiplying the water flux density (J*w*), over a hectare, by the time period (Δt) for which drainage was calculated (equation 3.5).

$$Q = Jw\Delta t \tag{3.5}$$

3.2.8 Deep drainage calculation periods

Deep drainage and nitrate leaching were assessed for two contrasting months at NOVA. In order to capture a month of peak fertigation and a month of low fertigation, September 2006 and January 2007 were assessed. The suction cups were sampled four times for each month.

For AFS, the deep drainage and nitrate leaching assessment was conducted between 30 August 2006 and 20 June 2008. As a result of the tensiometer malfunction, the data set for CFS spans from 21 December 2007 until 3 February 2008.

For all sites, deep drainage was calculated hourly and summed to determine a daily total drainage depth (mm). Nitrate-N leaching (kg ha^{-1}) was also calculated daily. However, as the soil solution was sampled either weekly or fortnightly, a linear interpolation between the sampling events was performed to obtain a daily nitrate-N concentration. The total deep drainage and nitrate-N leached is presented for each site and where possible the water and fertilizer-N input has been analysed to determine the percentage lost through leaching.

3.2.9 Water Balance

A water balance was conducted for the three field sites. The water balance was calculated at a daily time step and then summed to determine the total drainage for the measured period. Similar to the drainage estimation using the Darcy-Buckingham approach, a water balance for NOVA was conducted over two contrasting months. These were September 2006 and January 2007. Deep drainage was estimated for AFS and CFS for 2007. Deep drainage was also estimated over the time period that the Darcy-Buckingham approach was applied to compare the two methods.

The one dimensional water balance for a perennial row crop can be described in equation 3.6 as.

$$\Delta S = I + P + CR - ETc - RO - DD \qquad (3.6)$$

where ΔS is the change in storage, I is the irrigation input, P is precipitation, CR is capillary rise from below the root zone, ETc is the crop evapotranspiration, RO is runoff and DD is the deep drainage below the root zone. For simplicity, CR and RO are assumed to be zero and there is no lateral flow into or out of the root zone, resulting in equation 3.7.

$$DD = P + I - ETc - \Delta S \qquad (3.7)$$

The ΔS was calculated as the change in soil water content between the first day and the last day of the water balance calculation. The soil water content, expressed as a depth of water, was determined from multi-sensor capacitance probe readings. The soil water content was summed over the root zone to a depth of 1.1 m with sensors located at depths of 0.1, 0.3, 0.5, 0.9 and 1.1 m.

NOVA had two multi-sensor capacitance probes while AFS had one. The AFS capacitance probe was located 0.1 m from the drip emitter while the CFS capacitance probes were located 0.7 m from the sprinkler head. For CFS the ΔS was assumed to be zero due to a lack of capacitance probe data.

The percentage of deep drainage was calculated using equation 3.8.

$$DD(\%) = \frac{DD}{(P+I)} \cdot 100 \tag{3.8}$$

3.3 Results and Discussion

3.3.1 NOVA site deep drainage and nitrate leaching

The methodology to estimate deep drainage and nitrate leaching was first tested at NOVA. In order to capture a month of peak fertigation and a month of low fertigation, January 2007 and September 2006 were analysed. Although fertigation is lowest winter, the tensiometers failed in May 2006 and were only operating in August 2006. Hence September was chosen as the low activity month.

The nitrate-N concentrations in the soil solution at 0.9 m for September 2006 and January 2007 are shown in Figure 3.5. During September the nitrate-N concentration increased from 3.8 mg L^{-1} to 16.2 mg L^{-1}. During the month, as the fertilizer moved through the soil profile the nitrate-N concentration below the root zone exceeded the 10 mg L^{-1} guideline proposed for environmental sustainability. The nitrate-N concentration at 0.9 m depth in January remained at levels well above 10 mg L^{-1} nitrate-N indicating the potential for excessive leaching.

Figure 3.5: Suction cup nitrate-N concentration for September 2006 and January 2007 at NOVA.

The cumulative drainage and nitrate leaching, calculated daily, along with irrigation and drainage volumes for September 2006 and January 2007 are shown in Figure 3.6. In September there was one small rainfall event and three irrigations. In contrast, there were four irrigation and three rainfall events in January, which contributed to the higher drainage and leaching. In total, there was 187 mm of applied water in January compared to 78 mm in September. Consequently, the total amount of drainage that went past the root zone was 9 mm in September compared to 34 mm in January. Resultant leaching fractions (LF) were 18% and 12% for January and September, respectively. The total amount of nitrate leached for January and September was 12 and 1.2 kg nitrate-N ha^{-1}, respectively. The higher nitrate-N concentration at 0.9 m, combined with more deep drainage explains the ten fold increase in nitrate leaching for January as compared to September.

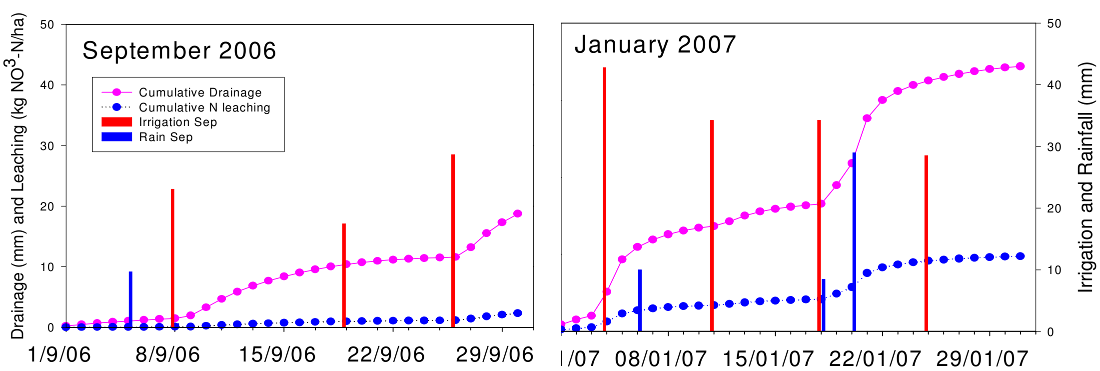

Figure 3.6: Comparison between cumulative drainage and nitrate leaching for September (2006) and January (2007) for NOVA.

Biswas et al., (2006) used a number of methods to estimate deep drainage at the same site for a year. The techniques used included a water balance, chloride tracing and estimation of flux using capacitance probes with an average LF of 17% estimated. This value is similar to the LF derived in this study and gives confidence to this method to estimate deep drainage.

3.3.2 AFS deep drainage and nitrate leaching

Soil water from AFS was sampled weekly, commencing on 28 August 2006 and continuing through to 20 July 2008. Soil nitrate-N concentration at 1.5 m depth is shown in Figure 3.7. Irrigation, rainfall, ET_c and nitrogen input through fertigation are also shown in Figure 3.7. Any nitrate-N present at 1.5 m was assumed to be lost to leaching. The line at 10 mg L^{-1} nitrate-N was taken as the maximum concentration before there was a greater risk of groundwater contamination.

During the 88 week sampling period the nitrate concentration at 1.5 m was above 10 mg L^{-1} 51 times, indicating that it was over the upper limit for 58% of the time. At the beginning of the two fertigation periods the nitrate concentration was very low and increased through the season as the applied fertilizer surpassed the tree requirement. At the end of the first fertigation period the nitrate concentration reduced to a negligible amount during the winter months between May and October 2007. During the first fertigation period the nitrate concentration peaked on 1 January 2007 at 41 mg L^{-1} nitrate-N.

In the second fertigation season the nitrate concentration peaked at 62.5 mg L^{-1} nitrate-N on 31 March 2008. The nitrate concentration increased rapidly in October and November 2007 as the result of very high fertilizer input and then began to reduce as the fertilizer input was lowered. However, the nitrate concentration did not lower to negligible amounts as it had done in the previous year and instead increased and then fluctuated around 40 mg L^{-1} nitrate-N.

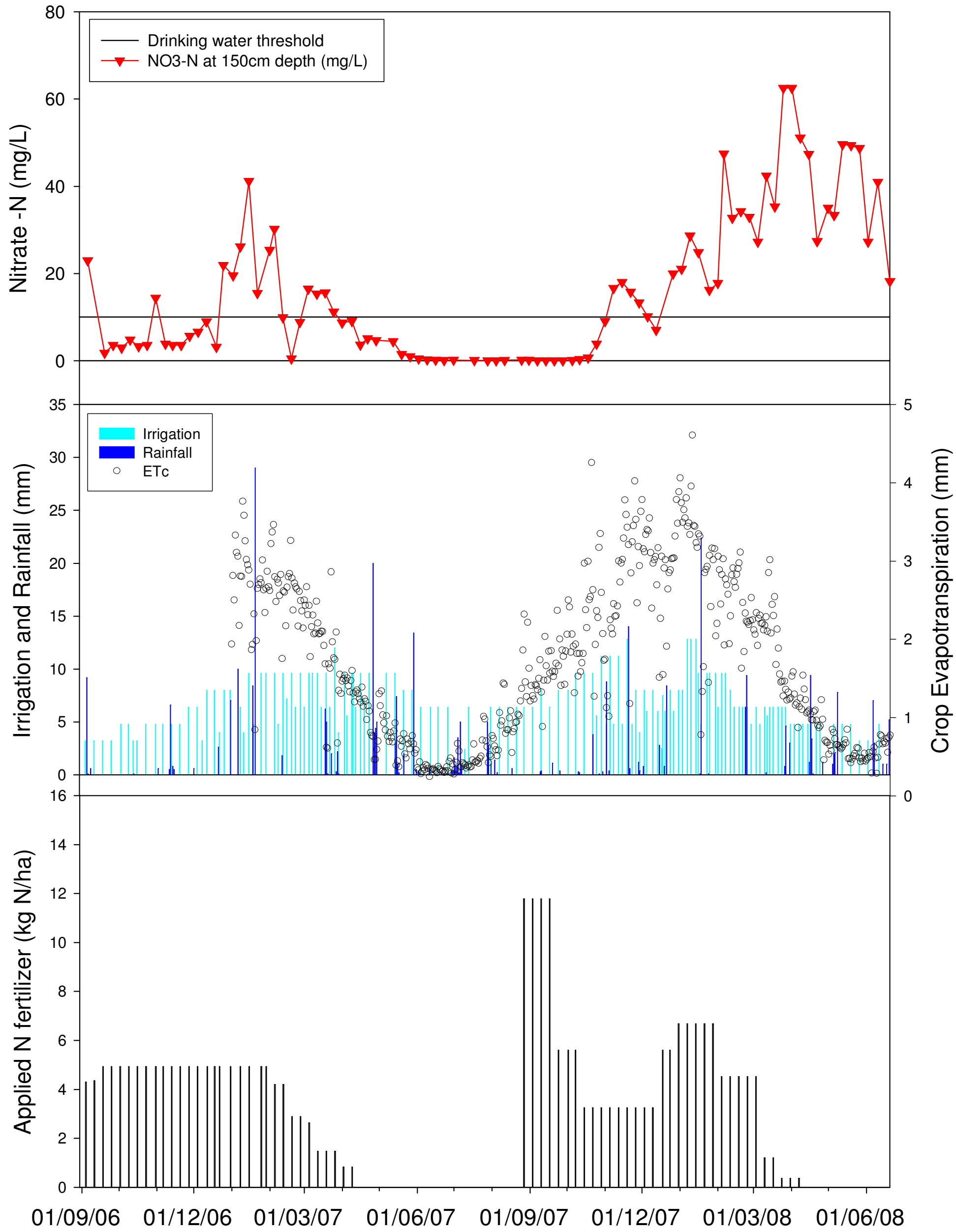

Figure 3.7: Suction cup nitrate-N concentrations in relation to water input, crop evapotranspiration and fertilizer application at AFS.

At these high concentrations any excess water draining would leach nitrate, potentially causing environmental damage. The irrigation management would also play a significant role in increasing the depth of nitrate. Any optimisation of the management system would therefore need to consider the amount of water applied, to what depth the water reaches, and how much the crop is extracting. This combined with refined fertilizer management would ensure that nitrate does not exceed the threshold level, thus optimising fertilizer efficiency and reducing the environmental threat. The results indicate that nitrate fertilizer is being overused and, depending on the water flux, considerable amounts of nitrate could be lost from the root zone.

Figure 3.8 shows the hourly AFS soil water pressure results from the tensiometers between 30 August 2007 and 20 June 2008. The figure shows wetting fronts frequently reached the 0.9 m and 1.2 m depths. The soil water potential at the two depths remained between -5 and -15 kPa for the majority of the period, with wetting and drying related to the irrigation and rainfall. The results indicate that even at these depths the soil moisture was high. It also confirms the nitrate concentration results, where nitrate moved rapidly down to 1.5 m depth. With wetting fronts reaching this depth with regularity and the moist conditions, it would be expected that there would be substantial deep drainage. Figure 3.8 also shows that in February and March 2008 there was a distinct drying of the profile, with the 0.9 m tensiometer going below -40 kPa and the 1.2 m tensiometer below -30 kPa. This drying coincides with a period of very warm weather. The irrigation was not increased and therefore the soil dried.

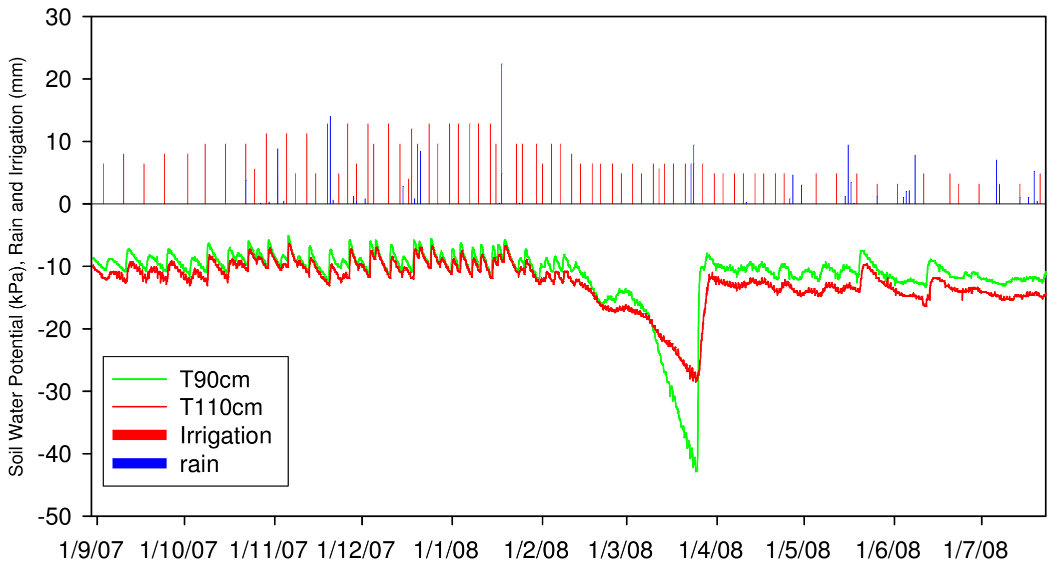

Figure 3.8: Hourly soil water pressure at 0.9 and 1.2 m depths and irrigation and rainfall depths for AFS.

Between 30 August 2007 and 20 June 2008 the total amount of water applied was 681.9 mm and the nitrogen fertilizer applied for the season was 142 kg ha^{-1}.

In Table 3.4, the ten deep drainage and nitrate leaching scenarios were used to test the influence of changing the α and *n* hydraulic parameters is presented for this period.

Scenario 1 is the results from core 1, where there was 136.46 mm of drainage and 22.5 kg nitrate-N ha^{-1} leached. This accounted for 20.01% and 15 % of the water and nitrogen applied, respectively. Scenario 2 is the results from core 2, where there was 75.7 mm of drainage and 13.44 kg nitrate-N ha^{-1} leached. This accounted for 11.1% and 9.46% of the water and nitrogen applied, respectively. Already it can be seen soil heterogeneity, as indicated by the two different cores, has caused substantial variability in the drainage and leaching assessed.

The remaining 8 scenarios have had different combinations of the *α* and *n* parameter changed by ±5% for the two cores. For the combinations with one parameter increased and the other decreased the resulting drainage and leaching estimated was reasonable compared to the initial estimates. For the parameters where both were increased or decreased there was a large amount of difference. For example, scenario 6 had both parameters lowered for core 1 and the result was drainage of 30.21% and nitrate-N leaching of 30.04%.

If the scenario where both parameters were increased or decreased are ignored, the soil heterogeneity as indicated by the first two scenarios had a larger influence on drainage than the scenarios where *α* and *n* parameters were changed. From this assessment it can be fairly safely estimated that deep drainage and nitrate-N leaching for AFS was somewhere between 10.72% and 21.15% and 8.99% and 16.83%, respectively.

Table 3.4: AFS drainage estimates for all α and n hydraulic parameter scenarios tested.

Scenario	Core	Deep drainage (mm)	Deep drainage (%)	Nitrate-N leached (kg ha^{-1})	Nitrate-N leached (%)
1	1	136.46	20.01	22.5	15.85
2	2	75.7	11.1	13.44	9.46
3	1	70.03	10.27	11.36	8
4	1	133.43	19.57	22.36	15.75
5	1	144.21	21.15	23.9	16.83
6	1	253.76	37.21	42.65	30.04
7	2	41.41	6.07	7.23	5.09
8	2	83.51	12.25	15.19	10.7
9	2	73.11	10.72	12.77	8.99
10	2	138.04	20.24	25.04	17.63

In the Lower Murray region, a leaching fraction of 15% is the benchmark (RMCWMB, 2004). The drainage assessed is around this mark but, because of soil heterogeneity, precise quantification is impractical. The nitrate-N leaching is not extreme but does indicate that nitrogen is moving below the root zone. The level of leaching is similar to what was found in the citrus producing regions of Florida, USA (Paramasivam et al., 2001; Alva et al., 2006).

Leaching below the root zone is just one component of the nitrogen cycle. Nitrogen could also be lost to crop uptake by lateral movement, ammonia volatilisation and denitrification (White, 2006). Denitrification could be high near the surface drip emitter where the soil is often saturated, but would be low for the majority of the unsaturated sandy soil (Alva et al., 2006). It has been reported in recent literature that more than 20% of surface applied N, in the form of urea or ammonium sulphate, can be lost through volatilisation from a calcareous soil (He et al., 2003). Paramasivam et al., (1999) reported in a six year old citrus study that 8-25% of the applied N could be lost through the ammonia volatilisation process during the growing season. Mattos et al., (2003) observed significant volatilisation losses in Hamlin orange trees on sandy Entisol, which accounted for 13% of applied N as ammonium nitrate. Lateral solute movement under drip irrigation can be high and therefore a large proportion of the nitrate could have been deposited in the mid row (Assouline, 2002). Although these losses are merely speculation, it does indicate nitrogen loss could be much higher than the drainage component which was assessed here.

For the previous scenarios the Ks was fixed at the mean of five field measurements using a Guelph Permeameter. The Ks measured in the field were 1.92, 1.3, 1.67, 1.97 and 1.3 m day^{-1} showing considerable variation. To account for this variation the hydraulic parameters of the two cores were fixed and a range of Ks values were used (Table 3.5). For core 1, drainage ranged from 14.71% to 24.52% and nitrate-N leaching ranged from 11.65% to 19.42%. For core 2, drainage ranged from 8.15% to 13.6% and nitrate-N leaching ranged from 6.96% to 11.59%. Once again the soil heterogeneity, as measured by differences in Ks, has resulted in the drainage assessment showing a considerable range.

Table 3.5: AFS deep drainage estimate for all Ks scenarios tested.

Ks	Core 1				Core 2			
(m day^{-1})	Deep drainage (mm)	Deep drainage (%)	Nitrate-N leached (kg ha^{-1})	Nitrate-N leached (%)	Deep drainage (mm)	Deep drainage (%)	Nitrate-N leached (kg ha^{-1})	Nitrate-N leached (%)
1.2	100.34	14.71	16.55	11.65	55.66	8.15	9.88	6.96
1.4	117.47	17.23	19.31	13.6	64.92	9.52	11.52	8.11
1.6	133.75	19.61	22.06	15.54	74.19	10.88	13.17	9.27
1.8	150.46	22.06	24.82	17.48	83.45	12.24	14.81	10.43
2.0	167.22	24.52	27.58	19.42	92.72	13.6	16.46	11.59

3.3.3 CFS deep drainage and nitrate leaching

Figure 3.9 shows the CFS nitrate-N concentration at 1.5 m depth as well as the irrigation, rainfall, crop evopotranspiration and the nitrogen fertilizer. The fertigation at CFS was applied every month instead of weekly and at higher doses. The results show the 1.5 m depth nitrate-N concentration was low in the first fertigation season and only went above the 10 mg L^{-1} nitrate-N five times. In the second fertigation season the nitrate-N concentration increased drastically in January 2008, peaked at 66 mg L^{-1} nitrate-N on 18 February 2008 and remained high for the remainder of the sampling period.

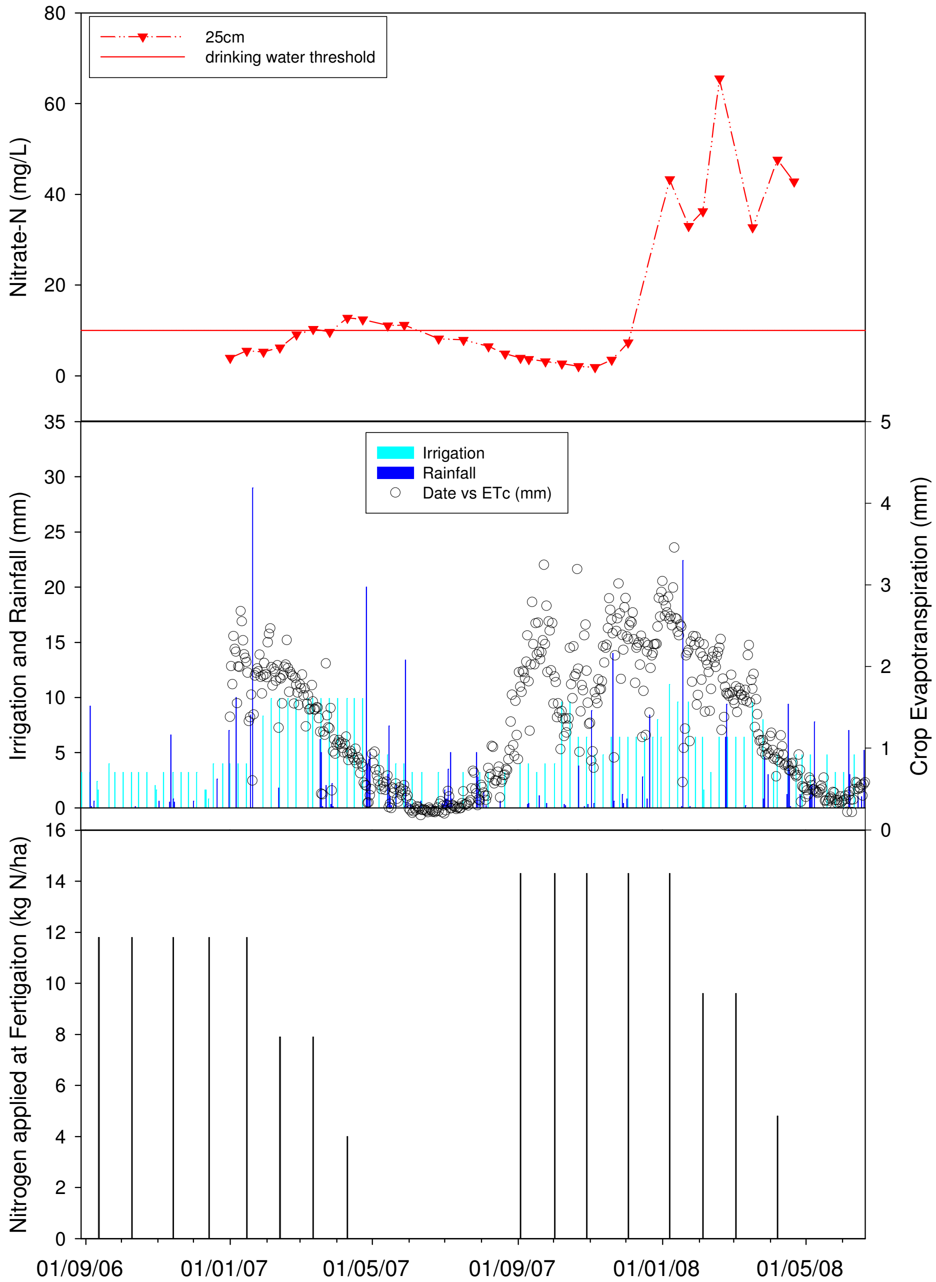

Figure 3.9: Suction cup nitrate-N concentrations in relation to water input, crop evapotranspiration and fertilizer application at CFS.

Figure 3.10 shows the hourly soil water pressure, irrigation and rainfall results for CFS. There were technical difficulties with the tensiometers and as a result there is data for only a portion of the time period. Deep drainage was assessed for the period when both tensiometers were working between 21 December 2007 and 3 February 2008. The figure shows the soil water pressure was lower at CFS compared to AFS as a result of the different soil type and irrigation practices. For the period where there was data, the soil water pressure was between -10 and -30 kPa. The total water input for this period was 88.6 mm.

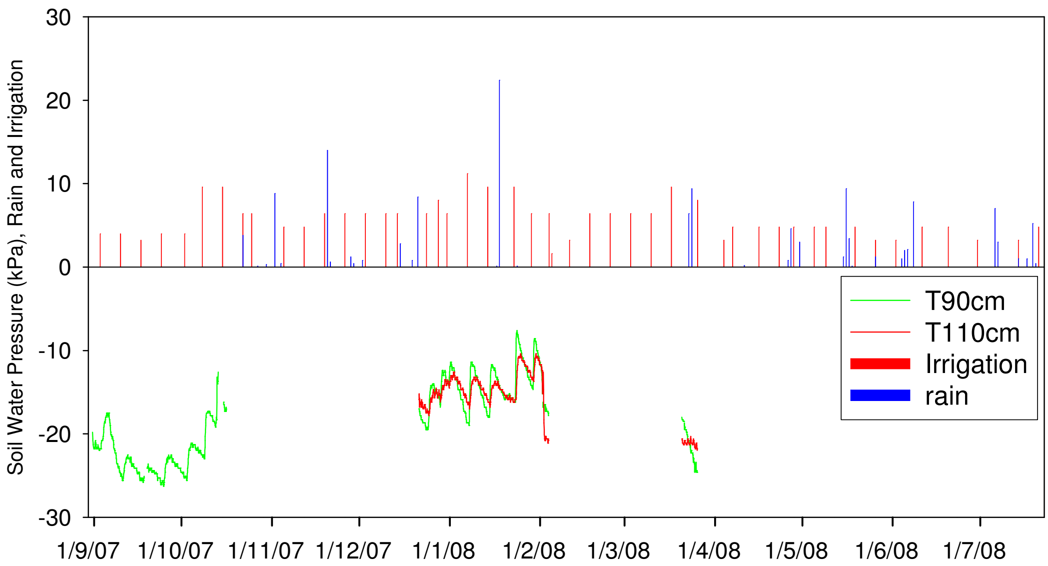

Figure 3.10: Hourly soil water pressure at 0.9 and 1.2 m depths and irrigation and rainfall depths for CFS.

Table 3.6 shows the scenarios used to test changes to the α and *n* hydraulic parameters. Scenario 1 is the unchanged parameters and shows drainage and nitrate leaching of 6.56% and 1.96 kg ha^{-1}, respectively. Because the deep drainage was assessed for a part of the season, the percentage of total nitrogen lost to leaching could not be determined.

The variation in deep drainage and nitrate-N leaching, due to changes to the α and *n* parameters, is once again evident. If the scenarios where both the parameters were increased or decreased are removed, the deep drainage was between 6.56% and 10.51% and the nitrate-N leaching between 1.96 and 3.14 kg ha^{-1}.

The results indicate CFS had less drainage compared to AFS. This is most probably due to AFS receiving more irrigation than CFS. The soil also drains more quickly at AFS which can be seen from the soil moisture release curves in Figures 3.2 and 3.3.

Table 3.6: CFS drainage estimate for all *α* and *n* hydraulic parameter scenarios tested.

Scenario	Deep drainage (mm)	Deep drainage (%)	Nitrate-N leached (kg ha^{-1})
1	5.81	6.56	1.96
2	3.51	3.97	1.19
3	6.22	7.02	2.09
4	9.31	10.51	3.14
5	5.54	6.25	1.88

The scenarios to test variation in Ks on the deep drainage and nitrate-N leaching estimate can be seen in Table 3.7. The two measurements of Ks taken in the field were 0.62 and 0.78 m day^{-1}. These Ks values were substantially lower than AFS due to the heavier soil texture at CFS. From the range of Ks used, the deep drainage and nitrate-N leached were 4.7% to 12.1% and 1.39 to 3.62 kg ha^{-1}, respectively. The large variation creates doubt regarding the use of the Darcy-Buckingham method to quantify deep drainage but does show a rough indication of the level of deep drainage.

Table 3.7: CFS deep drainage estimate for all Ks scenarios tested.

Ks (m day^{-1})	Deep drainage (mm)	Deep drainage (%)	Nitrate-N leached (kg ha^{-1})
50	4.12	4.65	1.39
70	5.77	6.51	1.95
90	7.42	8.37	2.5
110	9.07	10.24	3.06
130	10.72	12.1	3.62

3.3.4. NOVA water balance

The NOVA water balance for September 2006 and January 2007 can be seen in Table 3.8. From the irrigation, rainfall, and evapotranspiration depths it can be seen there was more water applied in January and the evapotranspiration was higher. The ΔS was calculated from multi-sensor capacitance probes at two points with the average change in water content determined. There was considerable difference observed between the two probes in September, with one showing an increase of 6 mm and the other a decrease of 11 mm. As a result, the range of drainage was between -4.8% and 17% of the total water input with a mean of 6.1%. The negative drainage could be the result of capillary rise of water from deeper in the soil profile but is more likely the result of measurement error. In any case, it does indicate that there was very little deep drainage. In January ΔS was -13.3 mm and -20.9 mm with a mean of -17.1 mm. The range of drainage was estimated to be between 31.2% and 36% of the total input with a mean of 33.7%.

The drainage determined by the Darcy-Buckingham approach estimated drainage of 12% in September and 18% in January. Although the drainage calculated from the water balance is substantially different, the two methods calculated a higher drainage for January as compared to September. It is difficult to apply mass balance over such a short period (one month) and a longer time would yield a better estimate of drainage.

Table 3.8: NOVA Water Balance for September 2006 and January 2007.

	September	January
I (mm)	68.4	139.7
R (mm)	9.9	18.4
ET_c (mm)	76	122
ΔS (mm)	6 and -11 (-2.5)	-13.3 and -20.9 (-17.1)
DD (mm)	-3.7 and 13.3 (4.8)	49.4 and 57 (53.2)
DD (%)	-4.8 and 17 (6.1)	31.2 and 36 (33.7)

Note: Numbers in brackets indicate an average

3.3.5 AFS and CFS water balance

The AFS and CFS water balance calculations are shown in Tables 3.9 and 3.10. Table 3.9 shows the water balance for the same time period as the Darcy-Buckingham method while Table 3.10 shows a water balance for 2007. The AFS water balance in Table 3.9 resulted in an estimated drainage of 21.9%, as compared to between 8.15% and 24.52% using the Darcy-Buckingham method. The drainage estimated by the water balance is at the upper bounds of the drainage calculated using the Darcy-Buckingham method.

CFS on the other hand showed drainage of -15.39% compared to between 4.65% and 10.51%, using the Darcy-Buckingham method. CFS drainage was only calculated for a short period between 21 December 2007 and 3 February 2008. No ΔS data was available and it was assumed to be zero. There could have been water input not taken into account by the ΔS or the ET_c may have been set too high.

Table 3.9: AFS and CFS water balance for the same time length as Darcy-Buckingham method.

	AFS	CFS
I (mm)	544	57.6
R (mm)	137.9	31
ET_c (mm)	533.11	102.24
ΔS (mm)	-0.53	0
DD (mm)	149.32	-13.64
DD (%)	21.9	-15.39

The 2007 water balance estimated the drainage to be 25.35% and -5.34% for AFS and CFS, respectively. The calculation for AFS is more accurate because ΔS was taken into account.

Table 3.10: AFS and CFS water balance for 2007.

	AFS	CFS
I (mm)	595.2	227.2
R (mm)	203.7	203.7
ET_c (mm)	571.62	453.89
ΔS (mm)	24.74	0
DD (mm)	202.54	-22.99
DD (%)	25.35	-5.34

3.4 Conclusions

The study used two different methods to assess deep drainage and one method to assess nitrate leaching from three different citrus orchards within the Dareton Agriculture and Advisory Station, NSW. Two tensiometers below the root zone were used to determine water flux using the Darcy-Buckingham method. A water balance was also used to estimate deep drainage as a comparison to the Darcy-Buckingham approach. Nitrate leaching was assessed by combining the drainage volume calculated using the Darcy-Buckingham approach with the nitrate concentration in suction cups below the root zone.

To test the influence of soil variability on drainage and nitrate leaching, two sets of scenarios were tested. The first set included different hydraulic parameters while Ks was constant, and the second set included different Ks values while the hydraulic parameters were constant. For AFS the hydraulic parameters from two different soil cores and ±5% variations in the hydraulic parameters were tested. It was found that if the α and n parameters were both increased or decreased there was a large difference in the resulting soil moisture release curve. These scenarios were not included in the final drainage estimate for AFS and CFS. The drainage and nitrate leaching at AFS between 30 August 2007 and 20 June 2008 was between 10.72% and 21.15% and 8.99% and 16.83%, respectively. For CFS the hydraulic parameters from one soil core and the different ±5% variations in hydraulic parameters were tested. The drainage and nitrate leaching between 21

December 2007 and 3 February 2008 was between 6.56% and 10.51% and 1.96 and 3.14 kg nitrate-N ha^{-1}, respectively.

For the Ks scenarios, AFS core 1 had drainage and nitrate leaching of 14.71% to 24.52% and 11.65% to 19.42%, respectively. AFS core 2 had drainage and nitrate leaching of 8.15% to 13.6% and 6.96% to 11.59%, respectively. CFS had drainage and nitrate leaching of 4.65% to 12.1% and 1.39 to 3.62 kg nitrate-N ha^{-1}, respectively.

The variation in results shows that the Darcy-Buckingham method has a large amount of uncertainty due to soil heterogeneity. The variation from using different cores to derive hydraulic parameters was the largest form of variation. This was followed by the variation due Ks and finally the difference due to hydraulic parameters.

The AFS water balance drainage was within the range calculated using Darcy-Buckingham. CFS on the other hand was not, which was attributed to the lack of soil moisture data at the site and the shorter assessment period.

The drainage calculated using the Darcy-Buckingham method was much higher at NOVA during January, as compared to September. This was attributed to the larger water and fertilizer input in January. The water balance for NOVA also showed higher drainage for January but the exact number was quite different, probably due to the large variations in the soil moisture and measurement error.

Although the water balance is a one dimensional model for a three dimensional drip irrigation system and does not take into account lateral movement, it did give a good estimate to compare the drainage calculated by the Darcy-Buckingham method.

It has been shown that drainage under AFS was greater than CFS, which was attributed to the greater water input and larger Ks at AFS. There was a large amount of uncertainty due to soil heterogeneity and therefore only a rough estimate of drainage could be calculated. These methods can be used to get a picture of drainage but are not accurate enough to be used in a regulatory sense. There is much more power in using the tensiometers or capacitance probes as monitoring tools to ensure wetting fronts do not move deep into the profile, resulting in drainage. Irrigation scheduling should use soil water monitoring to only wet the major root zone. The increase in root zone salinity, as salt in the irrigation water is left behind by the crop, is an indicator of efficient irrigation management. Wetting fronts should then only be detected below the root zone when a leaching irrigation is being performed based on a salinity assessment indicating a requirement and optimum leaching conditions. Optimum leaching conditions include uniformly high water content and low nutrient content, low evapotranspiration, and low biological activity.

Solute monitoring using suction cups is vital to understanding what the nitrate status of the soil below the root zone. If irrigators are able to maintain nitrate-N concentrations underneath the root zone below 10 mg L^{-1} their irrigation practices are on the road to being sustainable. In the end, nitrate below the root zone is bad economic and environmental practice and without monitoring can never be mitigated and the fertigation management improved.

Acknowledgements

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Appendix 3A – List of abbreviations

A_c	crop age coefficient
AF	Advanced Fertigation
AFS	Advanced Fertigation Site
CFS	Conventional Fertigation Site
$C_{NO3\text{-}N}$	nitrate concentration at 1.5 m depth (mg nitrate-N L^{-1})
CR	capillary rise (mm)
DD	deep drainage (mm)
$d(h)$	difference in pressure head (m)
dz	distance between tensiometers (m)
ET_c	crop evapotranspiration (mm)
ET_o	potential evapotranspiration (mm)
h	soil water pressure (m)
I	irrigation (mm)
J_w	water flux density (m day^{-1})
K_c	crop coefficient (-)
K(h)	unsaturated hydraulic conductivity at pressure head h (m day^{-1})
Ks	saturated hydraulic conductivity (m day^{-1})
m	van Genuchten parameter (-)
MOHT	Martinez Open Hydroponics Technology
n	van Genuchten parameter (-)
NOVA	Nova Mandarin site
NL	nitrate leaching (kg ha^{-1})
OH	Open Hydroponics
P	precipitation (mm)
RO	run off (mm)
α	reciprocal value of the air entry value (m^{-1})
ΔS	change in storage (mm)
Δ_t	time period (days)
θ	soil water content (cm^3 cm^{-3})
Q	volume of deep drainage (L)

Appendix 3B – K_c and A_c

Crop Coefficient

Crop	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	April	May	June
Citrus-No Cover	0.7	0.7	0.69	0.67	0.66	0.65	0.65	0.65	0.65	0.66	0.68	0.69

Irrigated Crop Management Service, Rural Solutions, South Australia
(http://www.pir.sa.gov.au/__data/assets/pdf_file/0018/23805/crop_coefficients.pdf)

Proportional adjustment of Crop factor for crop age

Crop	Yr0	Yr1	Yr2	Yr3	Yr4	Yr5	Yr6	Yr7	Yr8	Yr9	Yr10+
Citrus	0.4	0.47	0.53	0.6	0.67	0.73	0.8	0.87	0.93	1.0	1.0

(RMCWMB, 2004)

Chapter 4: Understanding solute dynamics under advanced fertigated citrus

4.1 Introduction

To effectively manage fertigated horticulture, a better understanding of the solute processes occurring is required. Solute information could effectively be used as feedback into the decision support systems to improve fertigation amounts and timing. Although the principles of solute transport are largely understood, there is little practical information available regarding how to collect, analyse and interpret solute information for intensive fertigation in horticulture.

Historically, decision support for citrus fertigation management has used plant tissue analysis and bulk soil testing (Obreza and Morgan, 2008). Plant tissue analysis quantitatively determines the N, P, K, Ca, Mg, S, Mn, Zn, Cu, Fe, B and Cl concentrations in the leaf dry matter. The tissue analysis is a standardised method and yearly analysis is recommended to adjust fertilization programs and prevent nutritional problems (Obreza and Morgan, 2008). Citrus leaves reflect nutrient accumulation and redistribution throughout the plant, so the deficiency or excess of an element in the soil is often reflected in the leaf. Tissue analysis also shows the relationship of nutrients to each other. For example, K deficiency may result from a lack of K in the soil or from excessive Ca, Mg or Na. Similarly, adding N when K is low may cause K deficiencies because the increased growth requires additional K. Like leaves, soil analysis is most useful when carried out over several years to observe trends. However, the soil analysis can not be used alone to diagnose nutritional problems and calibration with the plant response is required (Obreza and Morgan, 2008).

Yearly leaf tissue analysis combined with soil testing provides the best means of integrating the many variables which influence crop nutrition and therefore the yearly fertilizer requirement. However, recently the adoption of intensive fertigation practices, where the annual fertilizer input is split into smaller doses throughout the crop growth stages, has warranted a change in fertigation management. Yearly nutrition monitoring does not provide the necessary information to manage intensive fertigation and a different approach is required to monitor the effectiveness of fertilizer usage.

The suction cup is one viable method to monitor nutrient concentrations in the soil solution. The suction cup has been used for many years and has proven to be an excellent method of extracting soil solution for analysis. The principles of the suction cup were first described by Briggs and McCall (1904). The suction cup is made up of a porous material attached to a reservoir allowing water to flow through the porous material into the reservoir when a pressure gradient is induced between the soil solution and the reservoir by means of an applied vacuum (Litaor, 1988; Corwin, 2002; Weihermüller et al., 2007). The suction cup samples gravitational water down to water that is held under suction equal to the applied vacuum (Essington, 2004). Therefore the water sample represents water from the macro and micro pores. If the applied vacuum of the suction cup is comparable to the suction that plant roots exert, the soil water sample directly represents the plant available nutrient pool (Litaor, 1988).

Because the suction cup is an *in situ* monitoring tool, a sample can be extracted at any time, potentially making it a powerful tool for fertigation management. It is not proposed that suction cup monitoring be used instead of plant tissue or soil analysis but rather as an additional tool for fertigation management. The tissue and soil tests would be used to monitor crop nutrition and correct imbalances, while the suction cup would be used to retain solutes within the root zone and adjust fertigation during the season.

The suction cup material can influence the soil solution as it enters the cup. Early testing conducted by Zimmerman et al., (1978) reported the ceramic suction cups used in the study collected 11% of the ammonium and 43% of the phosphate in the outside solution. A comprehensive study by Silkworth and Grigal (1981) used different types of porous materials, including ceramic (small and large), fritted glass and hollow cellulose fibres. It was concluded that the larger ceramic cup was the best sampler with regards to the level of alteration to the soil solution, the failure rate and the capacity to obtain adequate volumes of solution for analysis. More recently, the study by Poss et al. (1995) conducted a laboratory test to determine the retention of nitrate as it passed through ceramic suction cups from an external solution. The mean internal and external nitrate concentrations were 4.65 mg L^{-1} and 4.75 mg L^{-1}, respectively. Approximately 2% of the external nitrate was retained by the ceramic material and it was concluded that retention by the ceramic material was negligible for nitrate concentrations above 5 mg L^{-1}. Suarez (1986) also showed that degassing as a result of the extraction process can cause an upward shift in the pH of up to 1 unit for a closed vacuum system. A comprehensive analysis of different suction cup materials and their effect on the soil solution was presented by Weihermüller et al., (2007).

Fertigation has been used for many decades, although recently the management of fertigation systems has advanced greatly. Advanced Fertigation (AF) is a broad name given to the emerging intensive fertigation management systems used over the past two decades to hasten crop establishment time and improve yield and fruit quality. In reality each AF system is different due to factors including climate, soil, water quality and level of management input. AF uses intensive fertigation practices to meet the crop water and nutrient requirement, reducing the need to store water and nutrients in the soil for substantial periods (Falivene, 2005). The fundamental principle is that water and nutrients are applied regularly to a smaller volume of soil and at a lower application rate to meet crop demand (Falivene, 2005). Ionic balance is also considered in the fertigation solution formulation which is claimed to reduce the energy required for root extraction of nutrients and reduce the risk of soil acidification (Martinez-Valero and Fernandez, 2004). Fertigation combined with micro-irrigation (low application rate drip emitters) has the potential to precisely apply water and chemicals both in amount and location throughout a field at a rate comparable to plant uptake (Gardenas et al., 2005; Assouline, 2002).

One type of AF is Open Hydroponics (OH) which gets its name from the principles adopted from soil-less hydroponics for field based production. Professor Rafael Martinez-Valero from the University Miguel Hernandez, Spain brought together the many concepts of OH in the early 1990s. The original reason for the development of OH was to create a management strategy to maximise citrus production on low fertility gravel based soils with poor quality water (Martinez-Valero and Fernandez, 2004). These soils had extremely low water holding capacity and therefore there was an emphasis on supplying the current crop requirement because excess water and nutrients drained rapidly. Martinez commercialised the management system as Martinez Open Hydroponics Technology (MOHT) (Falivene, 2005).

For soil solute data from suction cups to be used in fertigation management, methods to interpret the data must be developed. Two methods which could be used include the application of threshold levels for specific nutrients; and monitoring the rate a solute concentration changes at multiple depths over time. The thresholds would be used similar to soil water scheduling. There would be a lower and upper concentration limit and the suction cups would be monitored to ensure the solute concentration is within this range. The fertigation management would then be adjusted to ensure soil solute concentrations are optimum for crop growth. Like soil moisture monitoring, the suction cup is a point source measurement in a three dimensional root zone and therefore care is required in the placement of the cup. The ideal placement would be where the root density is greatest. Currently, there is limited scientific literature regarding nutrient uptake at different citrus growth stages. This represents a potential area for further research.

To this author's knowledge, in the scientific literature there are no reliable published guidelines for suction cup thresholds for citrus. However, thresholds for a range of solutes for citrus production have been proposed by horticultural consultants. Consultants from a horticultural services company, Agriexchange, have been using suction cups to manage citrus fertilizer use for several years. Together with a Western Australian horticultural consultancy group, Rootzone Solutions, they have applied their practical experience to set standards for several important parameters for citrus production. They recommend monitoring at 0.2 m depth below the emitter (personal communications). Table 4.1 shows the thresholds proposed by the

Agriexchange consultants for several of the important soil solution factors measured (unpublished data).

Table 4.1: Suction cup thresholds for citrus (measured 0.2 m below emitter).

	Low	Moderate	High
Nitrate-N (mg L^{-1})	15		40
Potassium (mg L^{-1})	10		30
Phosphate-P (mg L^{-1})	5		
Calcium (mg L^{-1})	40		60
Electrical Conductivity (dS m^{-1})	0.7	2.0	3.6
pH	6	7	8

Monitoring at several depths below the root zone can be used to observe trends and alter the fertigation management. For example, a well managed system could have a suction cup in the main root zone, one at the base of the main root zone and a third suction cup well below the root zone. The solute concentrations could be managed to allow concentrations to be continually high in the main root zone but low at the base of the root zone. If a particular solute concentration begins to increase at the base, the fertilizer input would be reduced and the influence on the two suction cups monitored.

The suction cup located below the main root zone would act as an environmental safety measure to reduce excessive solute leaching. A plethora of studies have examined nitrate leaching below the root zone of horticultural crops and shown it to be an important aspect. There are several methods to quantify nitrate leaching. The study by Syvertsen and Smith (1995) used lysimeter grown citrus trees fertilized at three nitrogen rates to monitor nitrate leaching. Paramasivam et al., (2002) used a combination of water balance and modelling using the LEACHM model to estimate nitrate leaching and deep drainage. Nitrate leaching has been estimated by combining the soil water flux, determined using tensiometers, with the nitrate concentration below the root zone using suction cups (Paramasivam et al., 2001; Alva et al., 2006). These scientific methods are complex, have many limitations and are generally not suitable for normal farm management. However, monitoring the soil below the root zone to ensure nitrate concentrations remain low is a powerful means to ensure the fertigation management is environmentally and economically sustainable.

The fertigation timing has a profound influence on the fate of solutes and several studies have investigated this influence (Bristow et al., 2000; Cote et al., 2003; Li et al., 2003; Li et al., 2004; Gardenas et al., 2005; Hanson et al., 2006). Li et al. (2003) investigated the influences of emitter discharge rate, input nutrient concentration, and applied volume on water movement and nitrogen distribution. Nutrients were applied continuously at a constant concentration from a surface point source. The study found nitrate accumulated toward the boundary of the wetted volume for any combination of discharge rate, input concentration, and volume applied. This suggested nitrate is susceptible to movement out of the root zone by mismanagement of fertigation, thus leading to nitrate contamination of surface and groundwater sources. Li et al. (2004) used a wedge shaped Perspex container with repacked sand and loam soil to monitor different fertigation timing strategies. The study reported the strategy of first applying water for one fourth of the total irrigation time, then applying fertilizer solution for one half of the total irrigation time, followed by applying water for the remaining one fourth of the total irrigation time left most nitrate close to the source and therefore optimised nutrient use efficiency.

Gardenas et al., (2005) simulated different fertigation strategies using HYDRUS 2D and found fertigation at the beginning of the irrigation cycle increased seasonal nitrate leaching. In contrast they found fertigation at the end of the irrigation cycle reduced the potential for nitrate leaching. Hanson et al., (2006) used the same approach as Gardenas et al., (2005) to investigate the influence of fertigation strategy on nitrogen distribution but used a urea-ammonium-nitrate fertilizer instead of a nitrate only fertilizer. It was found the nitrification of ammonium retained more nitrogen near the drip line compared to the nitrate only fertilizer. It was also shown short injection times near the beginning of long irrigation events should be avoided for surface drip systems (Hanson et al., 2006).

Bristow et al., (2000) simulated the distribution of a non reacting solute under two fertigation strategies. The solute was applied at the beginning and the end of an irrigation cycle from a buried point source. They reported that applying solute at the beginning of an irrigation cycle could help maintain larger amount of nutrients near to, and above the emitter thereby making them less susceptible to leaching loss. Cote et al., (2003) simulated the flow of a pulse of solutes from drip irrigation and showed that solute applied at the end of the irrigation ended up deeper in the soil compared to when it was applied at the start of the irrigation, owing to an increase in the ratio of downward to lateral water flux over time.

The majority of the studies have investigated the distribution of nitrogen, most likely because it is the major limiting nutrient for most crops and has a high leaching potential in the form of nitrate. Such contradictory studies suggest more research is required to understand solute transport in drip systems especially over an irrigation cycle and during rainfall events (Raine et al., 2007).

Another issue is the risk of soil acidification in the root zone caused by acidifying fertilizer substances entering the root zone. Soil pH greatly influences nutrient availability and most deficiencies can be avoided by maintaining soil pH between 6.0 and 6.5 (Obreza and Morgan, 2008). Problems associated with soil acidity include slow turn over of organic matter, poor nodulation and N_2 fixation, P, Ca and Mg deficiencies and Al and Mn toxicities. Root growth also rarely occurs in soils with a pH below 4, mainly due to Al, Cr, Cu, Ni, Zn and Mn toxicities (Hughes et al., 2004). Canterella et al., (2003) reported that high rates of nitrogen application in a Valencia citrus orchard caused acidification at the 0 to 0.2 m and 0.2 to 0.4 m soil depths after five years of fertilizer treatment and was related to the N rates applied. However, acidification was more pronounced in ammonium nitrate fertilized plots compared to urea fertilized ones. This could be due to more ammonia volatilisation losses from urea. Higher depletion of Ca and Mg was observed with increasing N rates and urea in the upper layer. Lime is a readily available product which is utilised to maintain the soil pH at the desired level (Pierzynski et al., 2005); however, injection of adequate supplies of soluble lime in acidic soils is difficult.

This study aimed to present solute results from AF managed citrus orchards with different levels of management input. The dynamics of the solute transport have been monitored using a combination of direct solute extraction using suction cups and bulk soil samples. The suction cup data provides frequent weekly solute data from a point source at different depths while the soil sample provides spatial solute representation roughly every three months.

The influence the ceramic material had on nitrate and phosphate concentrations sampled from an outside solution was also investigated. Nitrogen is the major limiting nutrient for citrus production and is most readily available as nitrate. Phosphate sorbs strongly to ceramics and it was important to investigate to what degree this occurs.

The study furthers our understanding of solute dynamics under intensive fertigation and provides insight on how fertilizer management can be optimised. Previously the incentive for adopting improved fertigation monitoring practices may have been limited, since fertilizer costs were only a small fraction of the total production costs and changes in fertigation practices may not affect crop yield significantly. However, fertilizer prices have increased greatly in recent times and when energy costs and potential groundwater contamination regulations are also considered, improved fertigation practices may be essential.

4.2 Materials and Method

4.2.1 Field Site Description

Three sites were instrumented to observe the solute dynamics under fertigated citrus. Two sites were located within the Dareton Agricultural and Advisory Station, NSW and one at a commercial citrus property in Colignan, Victoria. Both locations were within the Sunraysia fruit growing district of NSW and Victoria (Figure 4.1). The soils were alkaline (Class IIIA), with red sandy to sandy loam topsoils overlaying a heavier sub soil. The sites have top soil and root zone depths of approximately 1.0 m. The total organic carbon content is very low at 0.4% in the first 0.3 m and below 0.25% for the remainder of the root zone. The properties are irrigated with Murray River water which has a salinity level below 0.3 dS.m^{-1}. Figure 4.2 shows the variation in irrigation water salinity between December 2004 and June 2008. The climate is characterised as dry with warm to hot summers and mild winters. The average yearly rainfall is 280 mm with rainfall evenly distributed throughout the year. Potential evapotranspiration is high at 1247 mm in 2007.

Figure 4.1: Field site location map.

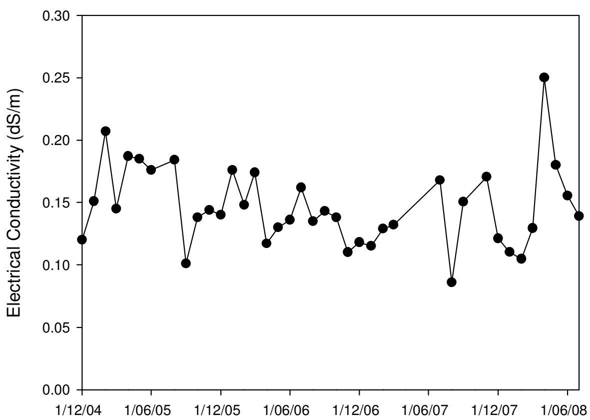


Figure 4.2: Dareton Irrigation Water electrical conductivity.

At the Dareton field site an advanced fertigated site (AFS) containing a number of mandarin varieties and a conventionally fertigated site (CFS) containing Cara Cara Navels were established on 10 October, 2005. The Colignan (Farm 8) site consisted of navel oranges planted in 1999 and managed under the MOHT fertigation management system. The rootstock for all sites was Citrange. The three field sites do not represent a controlled trial site and instead demonstrate solute dynamics under three differently managed citrus orchards.

AFS - Drip irrigated citrus fertigated weekly

- Number of rows: 3
- Row length: 104 m
- Row spacing: 5 m
- Tree spacing: 2 m
- Irrigation system: Drip double lines per tree row (1.6 L/h drippers)
- Dripper Spacing: 0.4 m
- Application rate: 1.6 mm/hr

CFS - Drip irrigated citrus fertigated monthly

- Number of rows: 13
- Row length: 105 m
- Row spacing: 5 m
- Tree spacing: 3 m
- Irrigation system: Drip double lines per tree row (2 L/h drippers)
- Dripper Spacing: 0.5 m
- Application rate: 1.6 mm/hr

Farm 8 – Drip irrigated fertigated daily

- Row spacing: 5 m
- Tree spacing: 2 m
- Irrigation system: Single drip line (1.6 L/h drippers)
- Dripper Spacing: 1 m
- Application rate: 0.32 mm/hr

For AFS, fertigation injections commenced two hours before the end of irrigation. The fertilizer takes one and a half hours to inject, leaving half an hour for the lines to be flushed. The CFS was less precise and the fertilizer was typically injected for thirty minutes half way through irrigation and the lines were flushed for the remainder. The fertigation for Farm 8 site was daily during the fertigation season but the timing of the fertilizer injection is not known. However, it is understood the MOHT system slowly injects the fertilizer almost continually during each irrigation event.

4.2.2 Suction cup extraction of soil solution

Figure 4.3 depicts the design of the suction cup, showing the lure lock used to maintain the vacuum, the extraction tube spanning from the cup to the soil surface, the PVC conduit which acts as the reservoir and the ceramic cup. The cup was sourced from Cooinda Ceramics, Victoria. The bubbling pressure of the cup was measured to be 250 kPa. The hydraulic conductivity of the ceramic was 0.026 cm day^{-1} measured using the falling head permeameter method (Klute and Dirksen, 1986). It is predicted the cup would have similar physical properties to the one used in the study by Silkworth and Grigal (1981) where the ceramic pore size was 2.9 um.

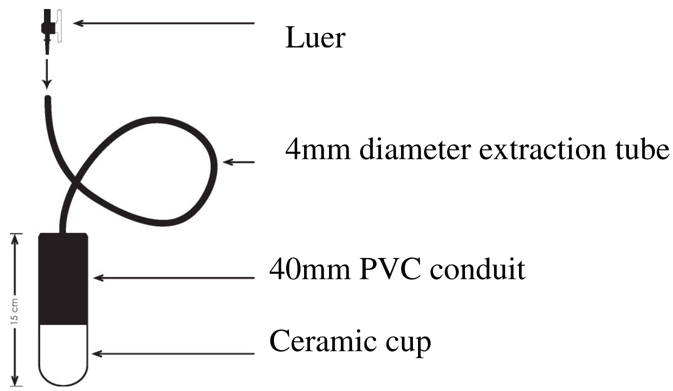


Figure 4.3: Suction cup design.
(Biswas and Schrale, 2007)

A vacuum of 60 kPa was applied before the suction cup was sealed. Soil water was drawn into the suction cup due to the pressure gradient caused by the vacuum. A week later the sample was extracted. The suction cup used in the study was developed at the South Australian Research and Development Institute and is commercially available as the SoluSAMPLER through Sentek Pty Ltd. AFS, CFS and Farm 8 had two suction cup replications. For all three sites the soil water was sampled at 0.25, 0.5, 1.0 and 1.5 m depths, with the suction cup located 0.1 m from the emitter. Farm 8 also had a set of suction cups at 0.6 m depth located 0.5 m from the drip emitter to observe lateral solute movement. AFS and Farm 8 samples were collected weekly while CFS samples were collected fortnightly. The vacuum was applied several hours after irrigation and maintained for a week before the solution was extracted and stored in a freezer (-18 ^{o}C). By applying the same vacuum at the same time and maintaining it for the same period there was less chance of soil moisture differences interfering with the solute concentrations. Samples were collected between 28 August 2006 and 20 June, 2008 for AFS and CFS and from 14 February to 23 July, 2008 for Farm 8.

4.2.3 Soil water analysis

All the soil solutions were analysed for electrical conductivity (EC), pH and nitrate. Other ions, including sodium, ammonium, chloride, sulphate, potassium, magnesium and calcium, were analysed for parts of the sampling period. EC and pH were analysed using calibrated desktop EC and pH metres. Nitrate was either determined using an Autoanalyzer (cadmium reduction procedure) or by liquid chromatography. The Autoanalyzer procedure involved nitrates reducing to nitrite by a copper cadmium reductor column. The nitrite ion then reacts with sulphanilamide under acidic conditions to form a diazo compound and, when coupled with gentisic acid, forms a reddish purple azo dye (Maynard and Kalra, 1993). The intensity of the colour measured with a colorimeter gives the nitrate concentration in the sample. The liquid chromatography procedure involved the sample passing through either an anion or cation exchange column where the ions in the sample are separated as eluent pushes the different anions off the exchange surface of the column. As the ions come out the column the electrical conductivity is measured and referenced to standards (Dionex, 1996). Five recovery tests were conducted with 5 mg L^{-1} nitrate and the lowest recovered sample was 97%. Samples were initially analysed using the Autoanalyzer from 28 August, 2006 until 10 December, 2007. After this date, the samples were analysed by liquid chromatography. Liquid chromatography was also used for the analysis of the other ions.

4.2.4 Plant tissue analysis

Plant tissue analysis was carried out on 4 to 6 month spring flush leaves (Koo, 1984). The leaves were collected in February of 2007 and 2008. In 2007 leaves were analysed at AFS and CFS while in 2008 leaves were analysed at AFS, CFS and Farm 8. The leaves were washed to remove residual chemicals on the surface and oven dried at 65 ^{o}C. The nutrients analysed included N, P, K, Ca, Mg, Na, Cl, Zn, Mn, Fe, Cu and B. Plant total nitrogen was measured by the Dumas method (LECO). P, K, Ca, Mg, Na, Zn, Mn, Fe, Cu and B were measured by nitric perchloric acid digestion and ICP analysis. Cl was measured by colourmetric analysis.

4.2.5 Saturation Paste Extraction

The saturation paste extraction method (Rhoades, 1982) was used to analyse soil salinity and pH for samples collected at AFS and CFS. The method effectively measures total salt concentrations in the soil solution but does not accurately reflect ionic composition of the solution, particularly in regard to calcium concentrations (Janzen and Chang, 1988). The method is reproducible related to field soil water contents and compensates for variation in soil moisture retention.

Soil samples were collected at several depths and distances away from the drip line. In total five depths were sampled with a 40 mm auger. The five depths included; 0.25, 0.5, 0.75, 1.0 and 1.5 m. Ten centimetres of soil was removed with the reported depth indicating the middle of the sample. The sampling distance into the row included -0.5, 0, 0.25, 0.5, 1.0 and 1.5 m. The -0.5 m represents the tree row and the mid point between the two drip lines while 0 represents the drip emitter location. Soil samples were collected in April, July and December of 2007 and March and July of 2008. The sampling aimed to provide a means to monitor the spatial solute movement in the root zone as compared to the suction cup, which was fixed at one location but sampled more frequently. The saturation paste also provided a comparison to the salinity readings obtained from the suction cup.

The soil samples were stored in plastic zip lock bags in the refrigerator before analysis. For analysis, 200 to 400 g of soil with known moisture content was weighed in a container. The total mass of the container and soil sample was recorded. In general, approximately one third of the water added was recovered in the saturation extract. Deionised water was added while mixing to saturate the soil sample. At saturation, the soil paste glistened, flowed slightly when the container was tipped and slid cleanly from the spatula. The sample was allowed to stand overnight. If free water accumulated on the surface, a known amount of soil was added. If the soil had stiffened or did not glisten, distilled water was added. The container with wet soil was weighed.

The saturation percentage (SP) was calculated from equation 4.1.

$$SP = \frac{(mass\,of\;H_2O\,added + mass\,of\;H_2O\,in\,sample)}{oven\,dry\,soil\;mass} \cdot 100 \qquad (4.1)$$

A Buchner funnel fitted with Whatman 42 filter paper was used to extract the sample. Initially the filter paper was moistened and vacuum applied to ensure a good filter paper contact with the funnel. The excess water was discarded, the paste was transferred to the funnel and the vacuum reapplied. The extract was collected until air passes through the filter. The assembly comprised a manifold which allowed six saturation pastes to be extracted using the one vacuum pump.

The EC and pH of the extract was measured using calibrated desktop EC and pH meters.

4.2.6 Ceramic influence on nitrate and phosphate

Four suction cups were used to test the retention of both nitrate and phosphate by the ceramic material at different external solution concentrations. Outside nitrate concentrations included 2.26, 11.29, 22.58 and 56.45 mg nitrate-N L^{-1}, while phosphate concentrations included 0.5, 1, 2.5 and 5 mg phosphate-P L^{-1}. The concentrations of nitrate were selected to represent the range found at AFS. Selecting the sampling range for the phosphate test was more difficult. Before the experiment, no phosphate sampling had been conducted at the field site. A nearby mature conventionally fertigated Nova mandarin site sampled the highest phosphate concentration at 0.79 mg phosphate-P L^{-1} (unpublished data). He et al., (1999) observed phosphate concentrations in the soil solution from 0.031 to 0.976 and 0.002 to 0.83 mg phosphate-P L^{-1} at depths of 1.2 m and 1.8 m, respectively. The phosphate concentration range was made larger because in this study sampling is conducted at a shallower depth where the phosphate concentration is expected to be higher.

The suction cups were first cleaned by flushing with dilute hydrochloric acid to remove impurities from within the exchange complex of the ceramic cup. The cups were then placed in a bucket of boiling water and vacuum applied. Half an hour later the water was extracted and vacuum reapplied. This process was repeated ten times to ensure proper cleaning.

The nitrate test was conducted first. The four nitrate solutions were prepared, using a 1000 mg nitrate L^{-1} standard solution, and poured into 500 mL measuring cylinders. The suction cups were immersed, a vacuum of 60 kPa was applied, the cups were sealed and the extract was collected after thirty minutes. After thirty minutes about 50 mL of sample was extracted. The solution in the measuring cylinder was re filled and suction reapplied for a further thirty minutes to obtain a second sample. In total four extract solutions were collected. The aim of sampling several times was to observe the change in extract concentration as the ceramic came into equilibrium with the passing solution. The first sample would also be diluted due to the water trapped in the pores of the ceramic after the washing procedure. Four extractions were selected to validate the recommendations made by Biswas et al., (2006) who suggested discarding four sample solutions before analysis. Before the phosphate test the ceramic cups were cleaned using the same procedure reported earlier. The method of extracting the phosphate sample was the same as for nitrate.

The initial solution and extracted samples were analysed for nitrate and phosphate using a HACH DR/850 Colorimeter (HACK, 2005). The nitrate test used the cadmium reduction method. The reported error for the test was ±1.7 mg nitrate-N L^{-1} and the estimated detection limit was between 0.8 and 30 mg nitrate-N L^{-1}. The phosphate test involved orthophosphate reacting with molybdite in an acid medium to produce a phosphomolybdate complex. Ascorbic acid then reduced the complex, giving an intense molybdenum blue colour (HACK, 2005). The reported error for the test was ±0.016 mg phosphate-P L^{-1} and the detection limits between 0 and 0.815 mg phosphate-P L^{-1}. The nitrate and phosphate concentrations out of the analysis range were diluted before analysis.

4.2.7 Soil Moisture release Curve

Three large undisturbed soil cores were sampled from depths of 0.25, 0.5 and 1.0 m in the tree line half way between two trees at the AFS and CFS sites. An undisturbed subsample core, 2.75 cm radius and 3 cm height, was taken from the field cores and used in the Tempe Pressure Cell (Klute and Dirksen, 1986) to develop a soil moisture release curve. The soil moisture release curve represents the relationship between volumetric water content (θ) and soil water pressure *(h)*. Figures 4.4 and 4.5 show the soil moisture release curves for AFS and CFS. Several of the soil cores did not yield a soil moisture release curve because of seal leekages with the Tempe Pressure Cells. At AFS, two of the 0.25, 0.5 and 1.0 m tests worked while at CFS only one of the 1.0 m tests worked. This yielded seven soil moisture release curves.

The residual volumeteric water content θ_r was measured using a 15 Bar Pressure Plate Extractor (www.soilmoisture.com). Table 4.2 shows the θ_r measured at -1500 kPa soil water pressure was between 0.037 and 0.044 (cm^3 cm^{-3}) for ten samples tested. The soil was collected from a 40 mm diameter soil core sampled to a depth of 1.0 m. The soil was combined and ten disturbed samples taken.

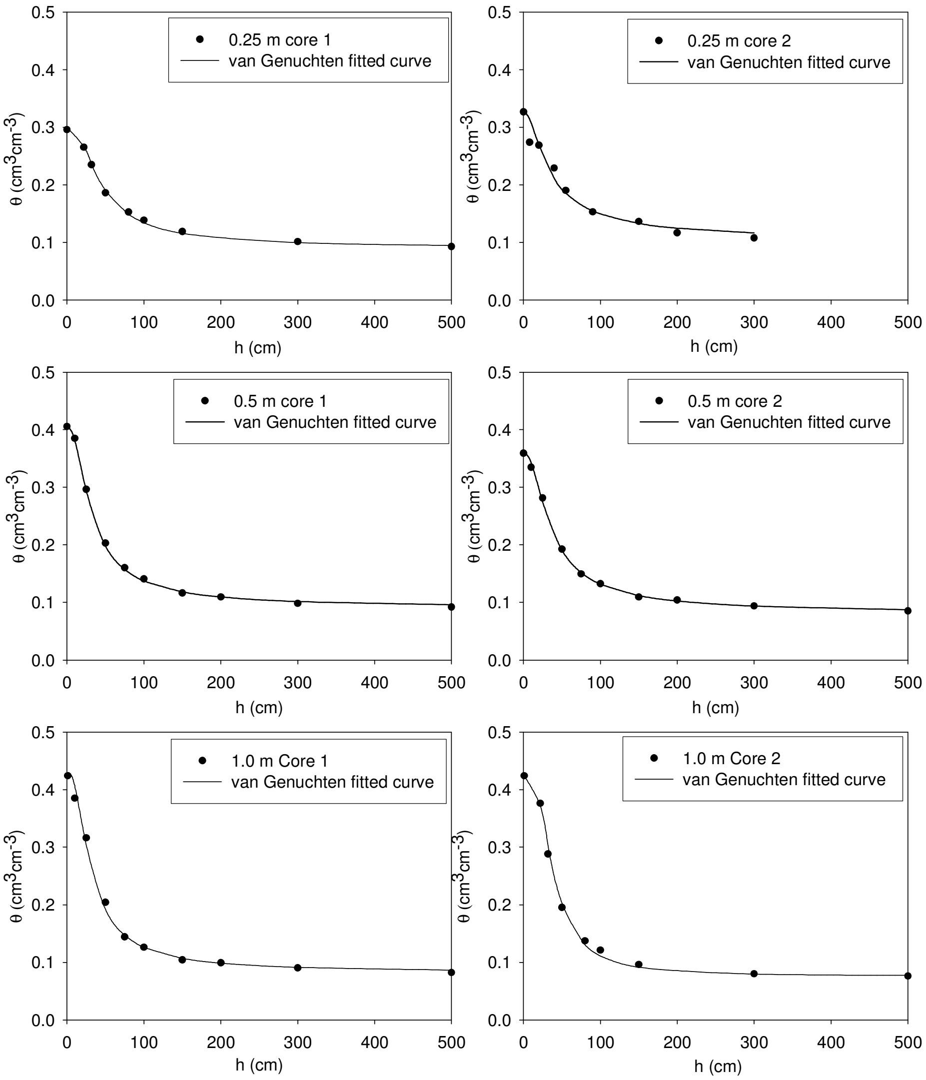


Figure 4.4: AFS soil moisture release curves.

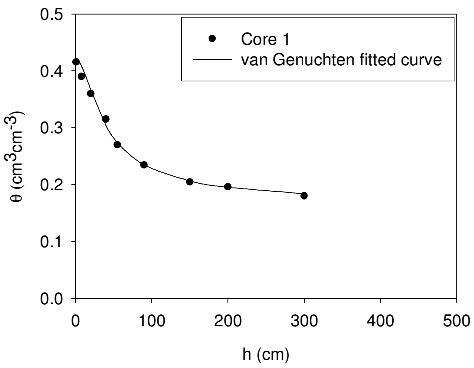


Figure 4.5: Soil moisture release curve for CFS at 1.0 m depth.

Table 4.2: Volumetric water content at a soil water pressure of -1500 kPa for AFS.

Sample Number	θ_v ($cm^3\ cm^{-3}$)
1	0.044
2	0.042
3	0.037
4	0.042
5	0.044
6	0.044
7	0.042
8	0.041
9	0.038
10	0.04

4.2.8 Fertigation, irrigation and weather data

Irrigation and fertigation records were collected from the Dareton Research and Advisory Station. Total water usage for 2006/07 and 2007/08 was 4 and 5.9 ML ha^{-1} for AFS, 1.6 and 2.7 ML ha^{-1} for CFS. Fertilizer usage data during the same period is given below in Table 4.3. Weather data was collected from an automated weather station located within the Dareton research farm. Potential evapotranspiration (ETo) was calculated using FAO 56 method (Allen et al., 2006). ETo was converted to ETc from equation 4.2

$$ET_o \cdot K_c \cdot A_c = ET_c \qquad (4.2)$$

where K_c is the crop coefficient and A_c is the crop age coefficient. The K_c values were compiled by the Irrigated Crop Management Service (ICMS) at Rural Solutions, South Australia. The K_c values were taken from FAO 56 and fitted to the Southern Hemisphere. The A_c is a canopy area coefficient used to correct ET_o for the age of the crop and its canopy area (RMCWMB, 2004). The canopy growth at AFS was much greater than at CFS and as a result the A_c for a citrus tree two years older was chosen. The decision was made by comparing the canopy size to different aged citrus trees within the research station. No fertilizer use, irrigation volume or weather data is available for Farm 8.

Table 4.3: Fertiliser use for the AFS and CFS trial sites.

Treatments	N (kg ha^{-1} yr^{-1})		P (kg ha^{-1} yr^{-1})		K (kg ha^{-1} yr^{-1})	
	2006/07	2007/08	2006/07	2007/08	2006/07	2007/08
AFS	164	142	37	23	225	97
CFS	96	79	23	19	43	36
Mature tree Standard	110		50		50	

4.3 Results and Discussion

4.3.1 Ceramic influence on nitrate and phosphate

The nitrate extraction results are shown in Figure 4.6. The figure shows each of the four standard solution concentrations and the corresponding four consecutive extraction solution concentrations. For the 2.26 mg nitrate-N L^{-1} standard, the outside concentration was 3.14 mg nitrate-N L^{-1} while the consecutive extracts were 3.11, 3.13, 3.18 and 3.9 mg nitrate-N L^{-1}. All the nitrate concentrations were within the ±1.7 mg nitrate-N L^{-1} error. As all the readings were within the error range, no difference between the outside solution and extract solution could be detected.

The 11.29 mg nitrate-N L^{-1} standard had an outside concentration of 14.68 mg nitrate-N $L^{-1}$and extract concentrations of 12.13, 13.14, 12.94 and 13.8 mg nitrate-N L^{-1}. There was a statistically significant difference between the outside concentration and the first extract but no difference between the three others. The difference for the first extraction was probably due to dilution from water retained in the porous cup after the cleaning process.

Similar to the previous concentration, the 22.58 mg nitrate-N L^{-1} results showed a significant difference between the outside concentration and the first extract only. Here the outside concentration was 24.48 mg nitrate-N L^{-1} and the consecutive extracts were 21.45, 23.98, 23.4 and 25.03 mg nitrate-N L^{-1}.

The results for the 56.45 mg nitrate-N L^{-1} solution show the outside concentration at 65.99 mg nitrate-N L^{-1} and the consecutive extract solutions at 60.85, 65.89, 64.63 and 58.96 mg nitrate-N L^{-1}. Like the other concentrations the first extract was low due to dilution but the fourth extract also had a low concentration. It was probably not due to sorption on the cup and more likely due to measurement error.

The results show no retention of nitrate for this type of suction cup. Therefore, for the range of nitrate concentrations tested this type of suction cup can be used for the analysis of nitrate.

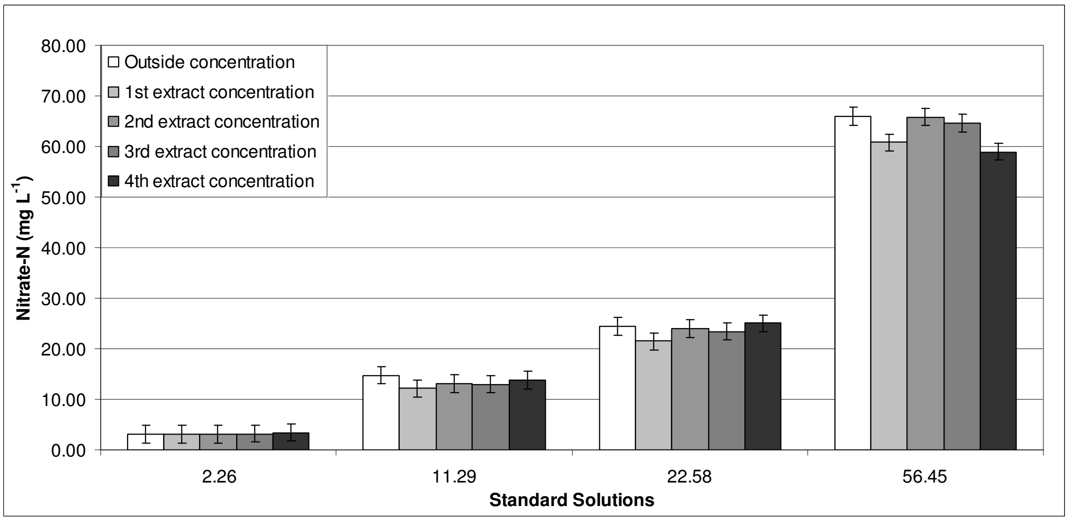


Figure 4.6: Results of the nitrate extraction test.
Results show the outside solution concentration and the concentration of the four extracted solutions. The error bars indicate the instrument error limits of ±1.7 mg nitrate-N L-1.

The results for the phosphate test are shown in Figure 4.7. For the 0.5 mg phosphate-P L^{-1} standard the outside concentration was 0.52 mg phosphate-P L^{-1} and the consecutive extract concentrations were 0.41, 0.41, 0.39 and 0.39 mg phosphate-P L^{-1}. The results indicate the outside concentration was much higher than any of the extract concentrations with a difference of 0.13 mg phosphate-P L^{-1} for the final extraction. This indicates 25% of the phosphate was retained by the ceramic.

The 1.0 mg phosphate-P L^{-1} standard had an outside concentration of 0.73 mg phosphate-P L^{-1} and extract concentrations of 0.54, 0.58, 0.54 and 0.62 mg phosphate-P L^{-1}. There was variation in the extract concentration but the final extract concentration was the highest indicating the phosphate ion was occupying space on the exchange surface of the ceramic resulting in higher concentrations for subsequent extractions. The difference between the outside and final extract solution was 0.11 mg phosphate-P L^{-1} representing 15% of the phosphate retained by the ceramic.

The 2.5 mg phosphate-P L^{-1} standard had an outside concentration of 2.0 mg phosphate-P L^{-1}, the first extraction was 1.16 mg phosphate-P L^{-1} and the next three extractions were 1.6, 1.72 and 1.64 mg phosphate-P L^{-1}. The very low concentration of the first extraction could be due to water left in the cup, therefore diluting the extract solution. The difference between the outside solution and last extract was 0.36 mg phosphate-P L^{-1} representing 18% of the phosphate retained by the ceramic.

The final standard solution of 5 mg phosphate-P L^{-1} had an outside solution of 4.4 mg phosphate-P $L^{-1}$and the four extractions were 2.75, 3.55, 3.7 and 3.7 mg phosphate-P L^{-1}. The phosphate showed a marked concentration increase with increasing extractions indicating the exchange surface was being occupied by phosphate ions. The difference between the last extract and the outside solution was 0.7 mg phosphate-P L^{-1} representing 16% of the phosphate retained by the ceramic.

The phosphate test shows there was interaction between the ion and the exchange surface of the ceramic as the outside solution entered the cup. It seems the extract concentration increased with successive extractions due to saturation of the ceramic exchange surface. The extract concentration could match the outside solution more closely with more extractions but further research would be required to test this. This study found that after four extractions, up to 25% of the phosphate was excluded by the ceramic material. This is a significant amount and should be taken into consideration when using suction cups to monitor phosphate.

Further research should also investigate how phosphate concentration in the cup is affected when a high outside concentration is followed by a low concentration solution. It is hypothesised that in this scenario the suction cup will overestimate the true soil solution phosphate concentration.

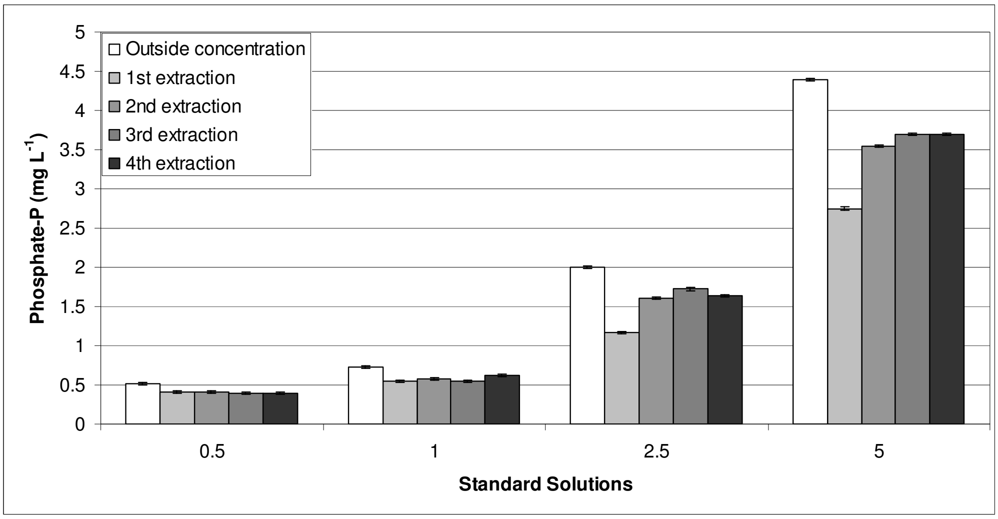


Figure 4.7: Results of the phosphate extraction test.
Results show the outside solution concentration and the concentration of the four extracted solutions. The error bars indicate the instrument error limits of ±0.016 mg phosphate-P L-1.

4.3.2 Plant Tissue Analysis

Plant tissue analysis currently is the most important diagnostic method for monitoring fertigation programs' influence on crop health. It is recommended that analysis is carried out annually and the resulting trends is combined with other data such as yield, tree health and leaf colour to fine tune the total annual fertilizer used. This study has been conducted over two years and the Farm 8 site was only sampled in the second year. As a result, the guidelines given in the International Fertilizer Association's World Fertilizer Use Manual have been used as the indicator of tree nutritional health.

The plant tissue results can be seen in Table 4.4. The colour coding indicates elements which were either above or below the optimum range given in Table 4.5 (Smith, 1966; Koo, 1984; Malavolta, 1989). The red indicates deficient conditions, yellow is low, green is high and blue is excessive. AFS in 2007 had high K, low Ca, Fe and B and deficient Mg. AFS in 2008 had high N and P and low Ca and Mg. CFS in 2007 had high N, P and K, low Mn and B and deficient Zn. CFS in 2008 had high N, low Mn and B and deficient Zn. Farm 8 had excess Fe. The MOHT management programme uses iron chelate in the fertigation programme which has resulted in large quantities stored in the leaves.

The limitation of plant tissue analysis is that it is a yearly diagnostic tool and the AF management system aims to supply the actual crop nutrient requirement by applying frequent fertigations at lower nutrient concentration (Martinez-Valero and Fernandez, 2004). Yearly plant tissue analysis does not provide the information required for intensive fertigation applications and therefore only provides a yearly indicator of crop nutritional health. On the other hand, soil solution monitoring using suction cups is a viable method to monitor the soils labile nutrient pool at discrete times during the growth cycle. The labile nutrient pool is where the crop obtains most of its nutrients and therefore monitoring the soil solution could be used as a diagnostic tool for fertigation management, similar to plant tissue analysis. The soil nutrient concentration does not exactly represent crop nutritional health but it is a good proxy available for sampling at regular intervals.

There is little information in scientific literature regarding soil solution nutrient concentration as a tool for optimising fertilizer requirement. Issues include where to place suction cups for a representative measurement of the plant available nutrients; where the suction cup is drawing the soil water from; and what the data means with regards to crop health. Chapter 2 presented results from a numerical model study into the influence suction cups have on the soil moisture under a decreasing vacuum system. It was found that the extraction domain for a wide range of soil textures and moisture levels was below 5.5 cm for an initial applied vacuum of 60 kPa. Consultants have used their experiences in monitoring soil solutes with suction cups to propose upper and lower thresholds for nutrient concentrations (Table 4.1).

Table 4.4: Plant tissue analysis results for AFS, CFS and Farm 8.

Block	Year	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	Cl (%)	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Cu (mg kg^{-1})	B (mg kg^{-1})
AFS	2007	2.6	0.15	2.0	2.1	0.2	0.03	<0.07	97	63	58	5.7	33
AFS	2008	2.9	0.18	1.5	2.9	0.25	0.01	<0.07	58	36	107	4.5	37
CFS	2007	2.9	0.17	2.2	3.2	0.3	0.03	0.07	17	20	67	5.0	32
CFS	2008	2.9	0.16	1.7	3.9	0.32	0.03	0.09	9.5	22	98	5.9	34
Farm 8	2008	2.6	0.15	1.7	3.1	0.34	0.02	0.07	66	41	340	12	61

#- deficient, #- low, #- high, #- excess

Table 4.5: Citrus spring flush tissue standards.

Macro nutrients

Range	% dry matter					
	N	P	K	Mg	Ca	S
Deficient	<2.20	<0.09	<0.70	<0.20	<1.50	<0.14
Low	2.20-2.40	0.09-0.11	0.70-1.10	0.20-0.29	1.50-2.90	0.14-0.19
Optimum	2.50-2.70	0.12-0.16	1.20-1.70	0.30-0.49	3.00-4.90	0.20-0.39
High	2.80-3.00	0.17-0.29	1.80-2.30	0.50-0.70	5.00-7.00	0.40-0.60
Excess	>3.00	>0.30	>2.40	>0.80	>7.00	>0.60

Micro nutrients

Range	mg kg^{-1} dry matter					
	Fe	Mn	Zn	Cu	B	Mo
Deficient	<35	<17	<17	<3	<20	<0.05
Low	36-59	18-24	18-24	3-4	21-35	0.06-0.09
Optimum	60-120	25-100	25-100	4-16	36-100	0.10-1.0
High	121-200	101-300	101-300	17-20	101-200	2.0-5.0
Excess	>200	>500	>500	>20	>250	>5.0

Source: www.fertilizer.org/ifa/Home-Page/LIBRARY/World-Fertilizer-Use-Manual/by-common-names

4.3.3 Water distribution around the drip emitter

Solute transport is greatly influenced by the water distribution as shown by Li et al., (2004) and Assouline (2002). This is especially true for nitrate which does not sorb strongly to the soil and moves freely with the soil water. To investigate the water distribution around the drip emitter, gravimetric soil samples were taken at AFS on 19 December, 2007.

The samples were taken twenty four hours after irrigation because by this time the wetting front had fully penetrated the soil profile, as indicated by capacitance probe data (not published). Soil samples were taken from several depths and distances from the emitter, into the mid row using a 40 mm auger. The soil was weighed in the field, dried at 105^{o}C for twenty four hours and reweighed to determine the gravimetric water content. Two separate drip emitters were sampled and the results are shown in Figure 4.8. The purple areas indicate no data, either because the tree got in the way of sampling or the soil was dry in the mid row.

The results show the gravimetric water content (%) was highest at the emitter and reduced with radial distance from this point. Assouline (2004) described water distribution for drippers with a discharge rate of >2.0 L h^{-1} as a saturated zone close to the emitter, and a zone of water content decreasing toward the wetting front. There was no saturated zone because the samples were taken a day after irrigation. However, there is a definite wet zone around the emitter. The shape of the wetted zone combined with the fertigation strategy (timing and volume of fertilizer) would dictate the maximum distribution of nutrients in the soil. Figure 4.8 indicates the surface wetting front extended to almost 1.0 m for Replication A but only to about 0.6 m for Replication B. At 0.8 m directly below the emitter the water content was high (>10%) but samples below this depth were not taken because the tree interfered with sampling. At 0.2 m from the emitter the water content was ≥7% below 0.8 m depth, indicating there was moisture at depth. Replication B shows the wetting front went down to about 0.8 m but there was also moisture deeper at 1.2 m.

The results in Figure 4.8 show the two dimensional distribution of water around the drip emitter and consequently the possible locations solutes could be transported to. The results also show the heterogeneity found under field conditions. This site is a very uniform sandy loam but there was substantial heterogeneity in the water distribution around the two emitters.

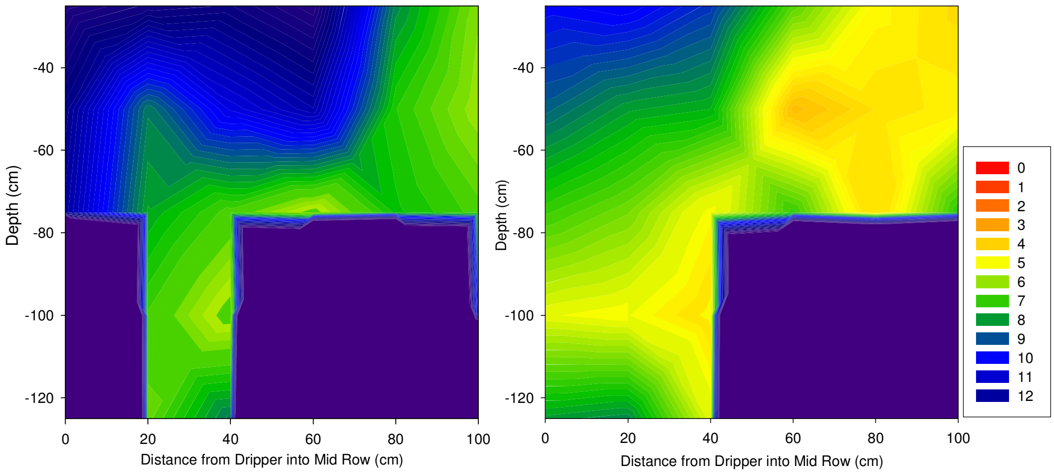


Figure 4.8: Gravimetric water content (%) at AFS taken on 19 December 24 hours after irrigation ceased.
Left side is Replication A while right side is Replication B. Purple indicates no data.

4.3.4 Nitrate transport in the soil

Figure 4.9 shows the nitrogen concentration of the incoming fertigation solution for AFS and CFS. The concentration was calculated from the mass of nitrogen fertilizer and the volume of water applied during the fertilizer injection period. For AFS the nitrogen concentration was also split into the ammonium and nitrate based nitrogen inputs. Even though AFS received more nitrogen per year, the nitrogen concentration in the irrigation water was less for AFS than for CFS because AFS was fertigated weekly while CFS was fertigated monthly. For AFS there was slightly more ammonium than nitrate based nitrogen in 2006/07, but in 2007/08 there was more nitrate-N supplied. A number of different fertilizer types were used including ammonium nitrate and mono ammonium phosphate up until 9 April 2007 and ammonium sulphate, magnesium nitrate, potassium nitrate and mono ammonium phosphate after 27 August 2007. For both fertigation seasons CFS received nitrogen from urea and a balanced fertilizer mixture.

Nitrate can move freely with the soil water and therefore it is predicted nitrate concentration at depth will be higher in 2007/08 compared to 2006/07. For both AFS and CFS the nitrogen input was greatest at the beginning of the season in August and reduced through the remainder of the season. One exception to this was in the second fertigation season where AFS received extra nitrogen in January and February. This was because the fertigation programme was changed from a tree establishment to a fruit production programme. Nitrogen input was reduced in November and December to reduce flush growth during Stage 1 fruit growth and increased in January for Stage 2 fruit growth.

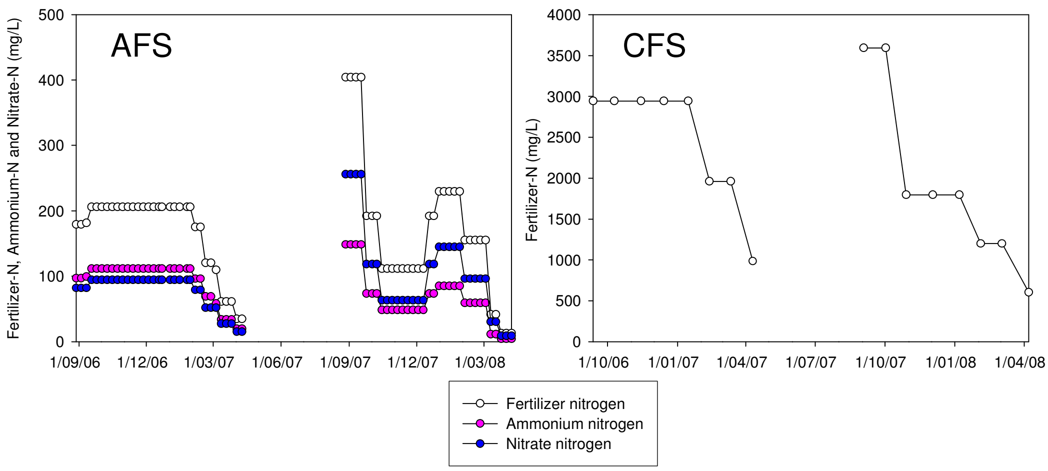


Figure 4.9: Irrigation water nitrogen concentration for AFS and CFS.

The AFS soil nitrate-N concentration at 0.25, 0.5, 1.0 and 1.5 m depths are shown in Figure 4.10. Irrigation, rainfall, ET_c and nitrogen input through fertigation are also shown in Figure 4.10. The crop evapotranspiration was highest in the summer at up to 4 mm day^{-1} and reduced to well below 1 mm day^{-1} during the winter. Irrigation was roughly twice a week and there were several large rainfall events during the monitoring period.

In Figure 4.9 the nitrogen concentration in the irrigation was up to 400 mg L^{-1} for AFS but was reduced significantly in the soil indicating rapid crop uptake. However, the results in Figure 4.10 show the nitrate concentration did increase at all depths during the fertigation season. The 0.25 m suction cup was within the Agriexchange 15 to 40 mg nitrate-N L^{-1} threshold indicating there was a good supply of nitrogen for the crop. This is substantiated by the plant tissue analysis in Table 4.4 where the nitrate was optimum in 2007 and slightly high in 2008.

In both fertigation seasons the shallower suction cups responded to the fertilizer input first, followed by the successively deeper suction cups. This was especially pronounced at the beginning of the 2007/08 fertigation season. The first four weeks of the fertigation season, starting on 27 August 2007, applied large amounts of nitrogen at 11.8 kg nitrogen ha^{-1} per fertigation. The 0.25 m suction cup responded first on 10 September, 2007 followed by the 0.5 m and 1.0 m suction cups on 17 September, 2007 and the 1.5 m suction cup last on 22 September, 2007. The breakthrough of nitrate is likely the time taken for the supply of nitrate to become higher than the crop can use allowing nitrate to penetrate further into the soil profile. Because ammonium based fertilizers are also used, there would also be a time lag for the ammonium sorbed to the soil to undergo nitrification into nitrate (Hanson et al., 2006).

For most citrus 0.5 m is roughly the base of the main feeder root zone and nitrate located below this depth is expected to be largely lost to the crop. Management should aim to allow high nitrate concentrations in the shallow suction cup at 0.25 m, but increases at 0.5 m depth would indicate nitrate is moving below the root zone. It is alarming that nitrate concentrations increased at 1.5 m where nitrate leaching into the groundwater system is likely. After the fertigation seasons the nitrate concentrations reduced to negligible concentrations at all depths except at 1.5 m depth after the 2007/08 fertigation season. It is unclear why nitrate concentration remained high but could be due to the wetting fronts depositing nitrate where there was little water flow and no crop uptake.

To improve the nitrate efficiency a strategy is required which retains nitrate at the 0.25 m depth but does not allow rapid increases to occur at 0.5 m. The deep drainage and nitrate leaching chapter presented tensiometer data that showed wetting fronts continually reaching 0.9 m and 1.2 m depths. The first step to reducing nitrate leaching would be to reduce the wetting front depth through the application of less water per irrigation. The reduced application volume would require more frequent applications to meet crop water requirement but would be more efficient. Currently the irrigations are scheduled twice per week, which is not frequent enough for this soil type. Once the wetting fronts have been controlled to only wet the main root zone the suction cups can be monitored to ensure concentrations are within the threshold at 0.25 m but not increasing rapidly at 0.5, 1.0 and 1.5 m depths.

This research demonstrates the importance of monitoring more than one depth. One suction cup placed in the main root zone could show the nitrate concentration is within the threshold for optimum growth but would not monitor the excess nitrate moving below the root zone.

The suction cup locations were fixed at 0.1 m from the drip emitter and therefore no information regarding the lateral nitrate transport can be determined. However, the results from the soil sampling conducted will provide insight regarding the dynamics of solute transport.

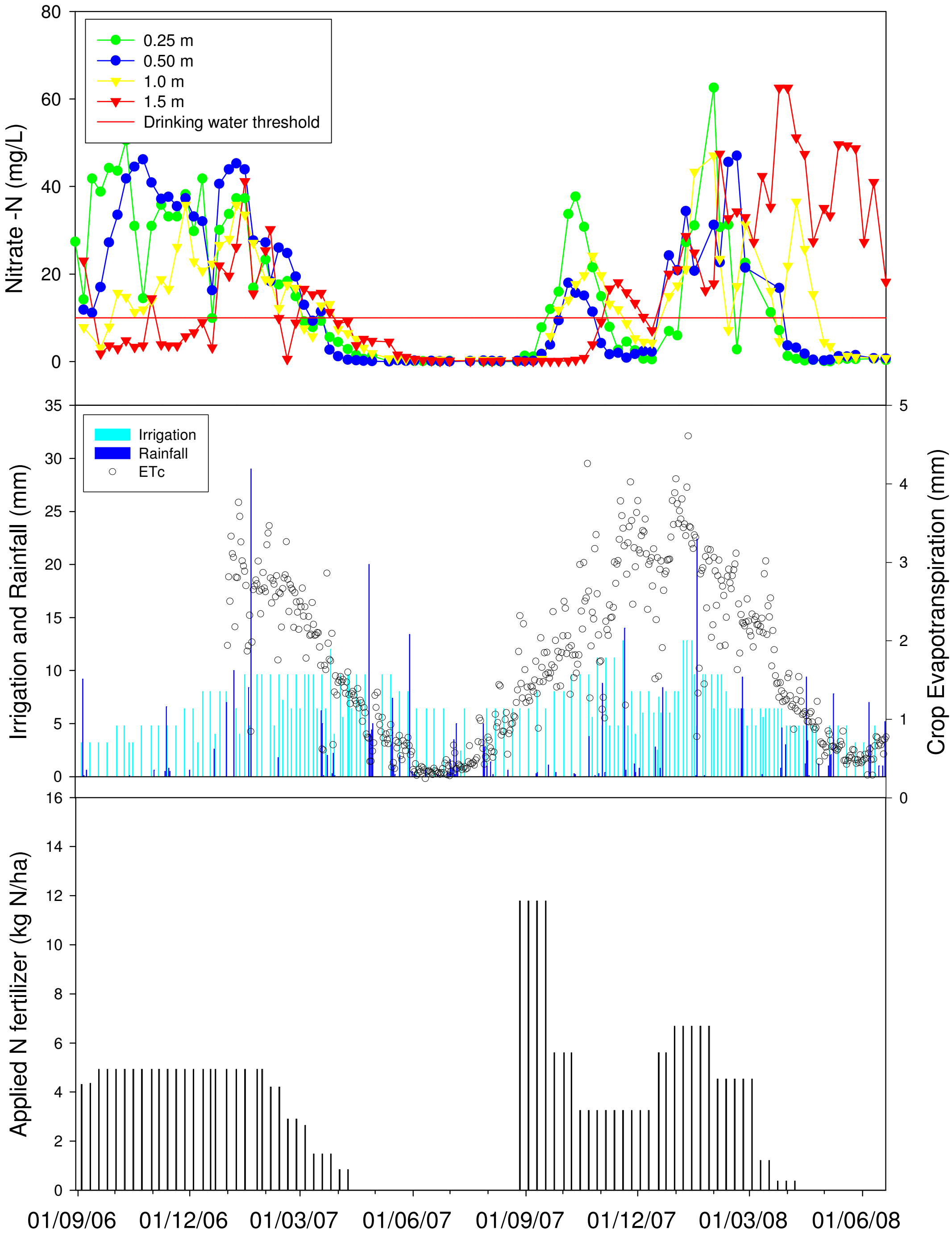


Figure 4.10: Suction cup nitrate-N concentrations in relation to water input, crop evapotranspiration and fertilizer application at AFS.

Figure 4.11 shows the nitrate-N concentration from CFS and the irrigation, rainfall, crop evapotranspiration and nitrogen fertilizer amounts. The crop evapotranspiration was less than at AFS and peaked at about 3 mm day^{-1} in summer. The nitrate concentration at all depths during the first fertigation season was much lower compared to AFS but the nitrate concentrations increased during the second fertigation season. The nitrate concentration of the 0.25 m was at the lower end of the Agriexchange threshold but the plant tissue analysis in Table 4.4 indicated the nitrogen concentration was slightly higher than the optimum level. The nitrate concentration at 0.5, 1.0 and 1.5 m depths were generally higher than the 0.25 m depth. This could be because the nitrogen concentration in the irrigation water was much higher for the monthly fertigations, as indicated in Figure 4.9, and the nitrate concentration exceeded the crop uptake and therefore moved deeper into the profile. The CFS irrigation system was changed from a single drip line per tree row to a double drip line on 8 October 2007 which could have contributed to the increased nitrate concentration at depth during the second fertigation season.

Because the fertigation supplies fertilizer for a month, it is much more difficult to control the nitrate concentrations at the optimum level. However, suction cups can be used to ensure the fertilizer does not penetrate too deeply into the profile, where it is lost to crop uptake.

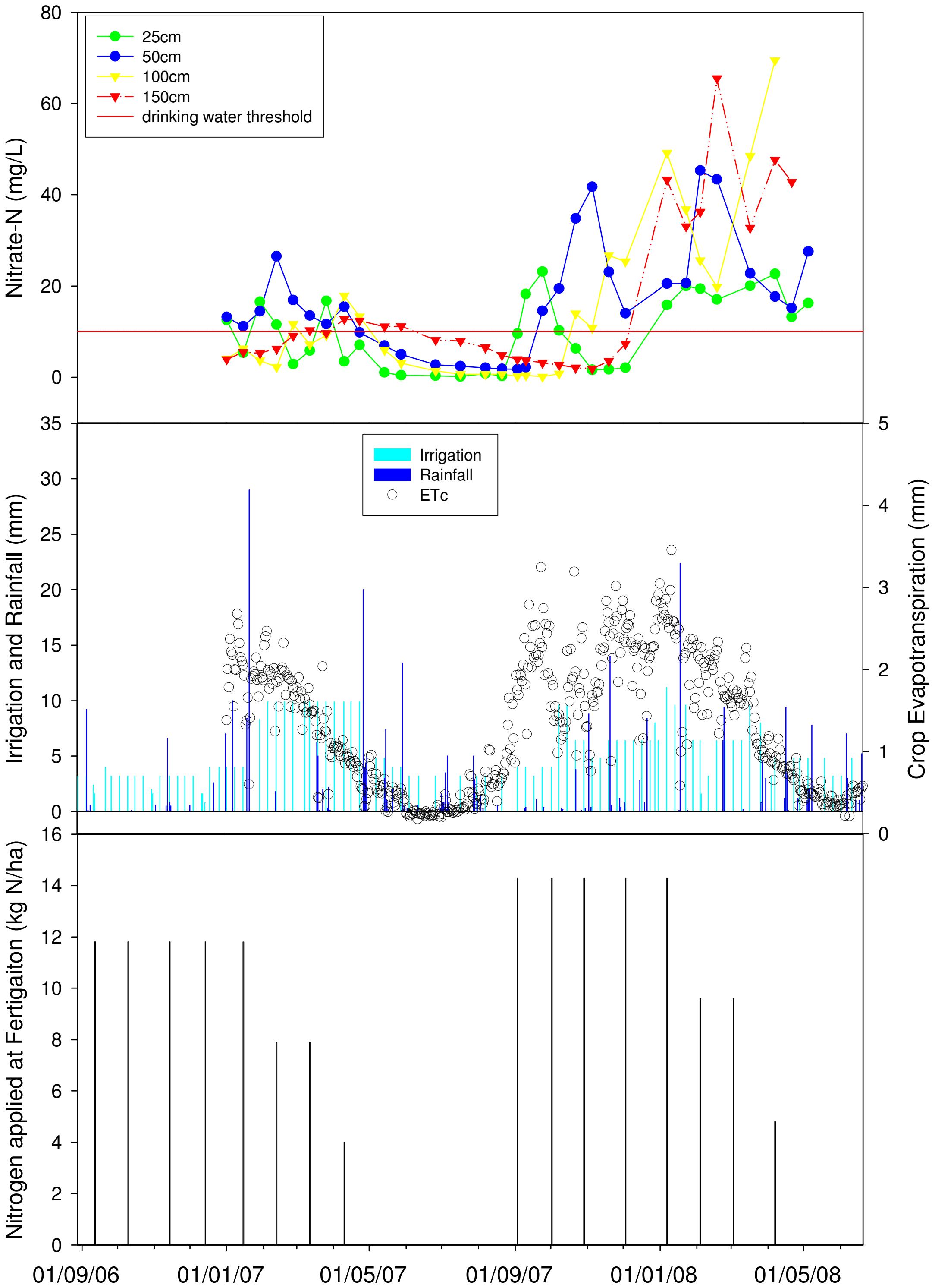


Figure 4.11: Suction cup nitrate-N concentrations in relation to water input, crop evapotranspiration and fertilizer application at CFS.

Figure 4.12 shows the relationship between nitrate concentration and EC for the suction cup samples collected at AFS between 21 August 2006 and 10 December 2007. The figure shows a positive correlation between nitrate concentration and EC at all depths. The R^2 value for the 0.25, 0.5, 1.0 and 1.5 m depths were 0.91, 0.9, 0.88 and 0.75 respectively. The correlation decreases with depth, probably due to the accumulation of other salts due to leaching. The soil has low salinity and the EC signature predominantly represents the fertilizer as it moves through the soil. There could be potential to use the EC signature to predict nitrate movement under low salinity conditions. EC analysis is cheap and easy compared to nitrate analysis techniques and could be used to manage fertigation. There would be much more uncertainty in the interpretation but some monitoring is better than no monitoring for nitrate leaching control.

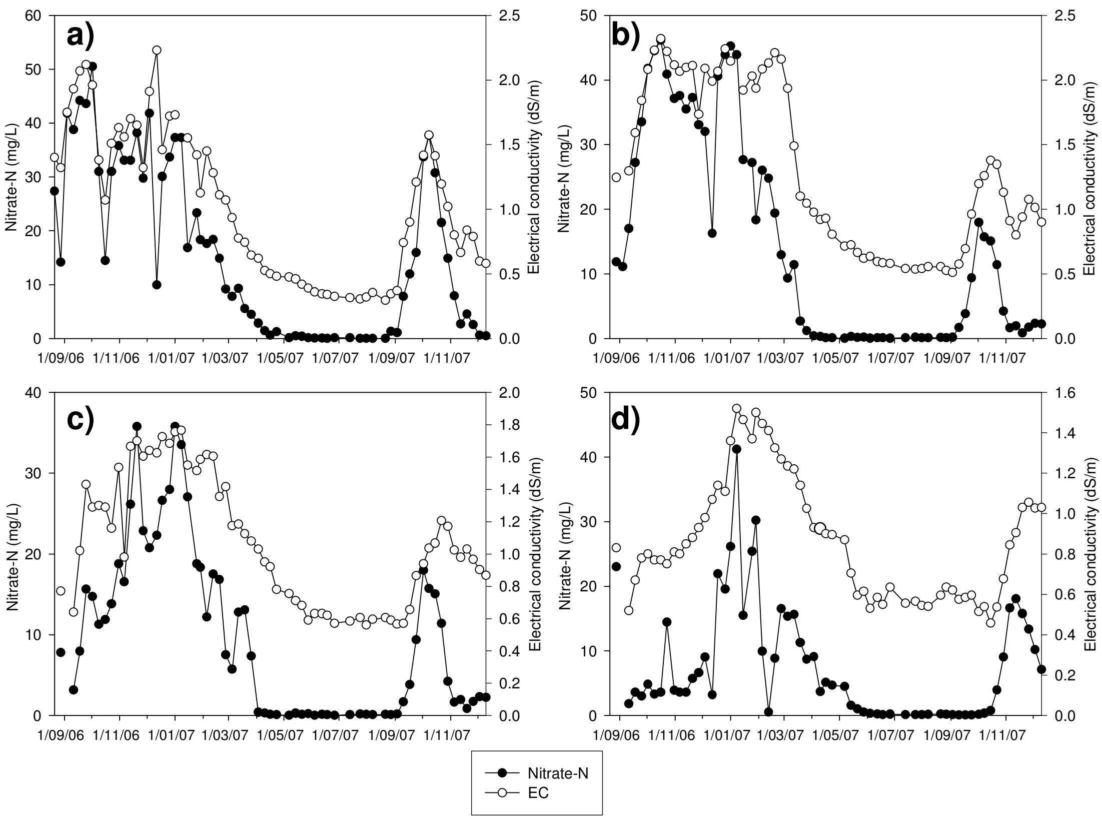


Figure 4.12: AFS suction cup nitrate-N and EC.
Measured at 0.25 m (a), 0.5 m (b), 1.0 m (c) and 1.5 m (d) depths.

Figure 4.13 shows the relationship between nitrate concentration and pH for the suction cup samples collected at AFS between 21 August 2006 and 10 December 2007. The figure shows a predominant shift in pH as a result of the fertilizer input. Nitrate does not affect the pH but it does act as an indicator for the other compounds, such as ammonium and sulphate which do. In the winter the pH increased to about 7.8, 8.2, 8.9 and 8.8 at the 0.25, 0.5, 1.0 and 1.5 m depths respectively. These pH levels are indicative of the alkaline soil. However, during the fertigation season the pH at 0.25, 0.5, 1.0 and 1.5 m depths reduced to 6.6, 7.1, 7.2 and 7.2, respectively.

For citrus it is recommended that the pH determined with a $CaCl_2$ solution should be between 6.0 and 6.5 to avoid most nutrient toxicities or deficiencies (Obreza and Morgan, 2008). In this situation the pH was determined from the soil solution and is expected to be slightly higher than natural conditions due to degassing (Suarez, 1986). At 0.25 m the soil solution is not excessively acidic and there should be no problem with acid based deficiencies or toxicities. However, the pH may be much lower closer to the drip emitter where the nutrients sorb to the soil and have a greater impact. The soil sampling presented later in the report will explore this issue further. The results also show a cyclic trend in the pH indicating that the buffering capacity of the soil is strong enough to return the soil solution pH to background levels during the winter. The soil solution monitoring should continue to ensure the pH remains at an appropriate level and lime is not required.

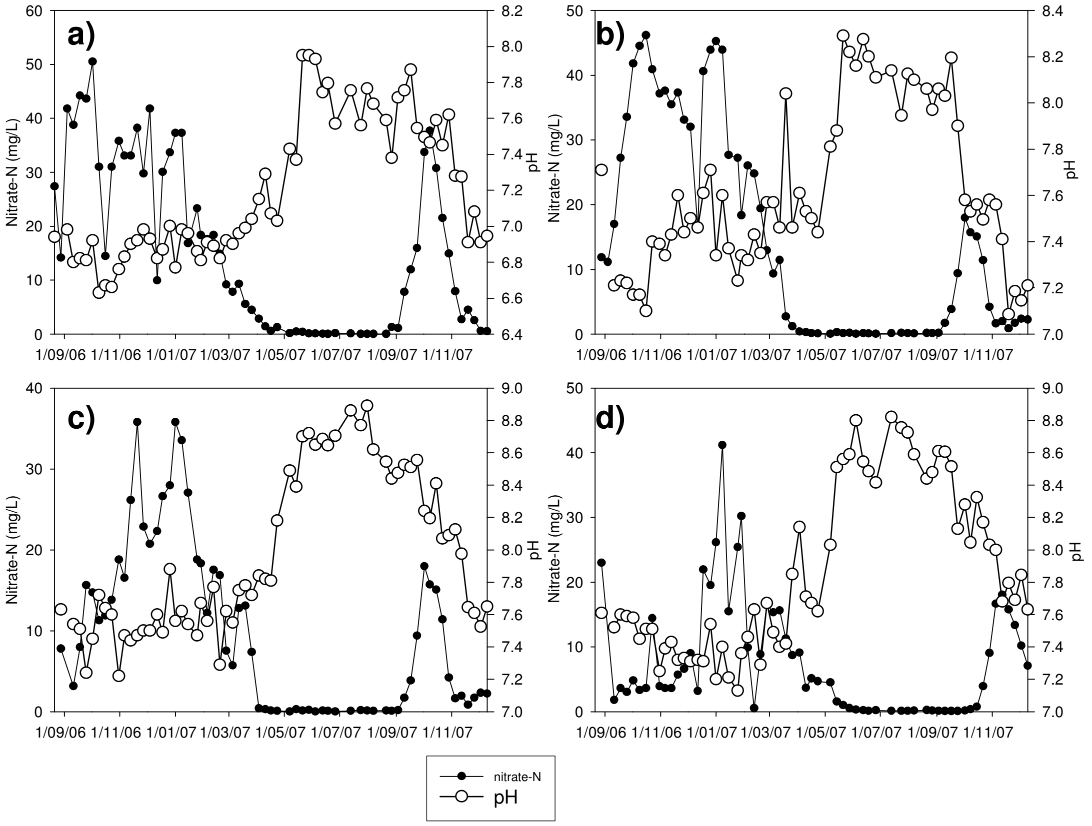


Figure 4.13: AFS suction cup nitrate-N and pH.
Measured at 0.25 m (a), 0.5 m (b), 1.0 m (c) and 1.5 m (d) depths.

The relationship between the nitrate and EC for the CFS suction cup samples collected between 22 August 2006 and 3 December 2007 is shown in Figure 4.14. Once again there is a positive correlation between the nitrate concentration and the EC with R^2 values of 0.95, 0.93, 0.97 and 0.73 for the 0.25, 0.5, 1.0 and 1.5 m depths, respectively.

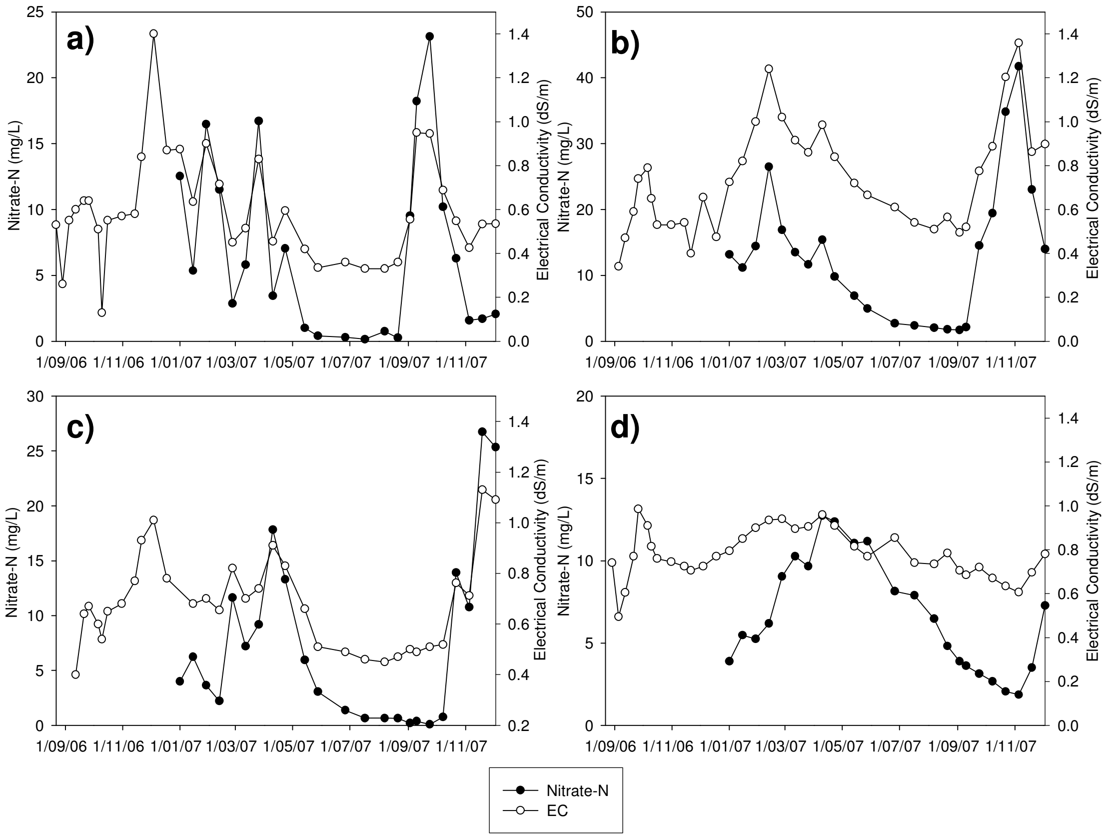


Figure 4.14: CFS suction cup nitrate-N and EC.
Measured at 0.25 m (a), 0.5 m (b), 1.0 m (c) and 1.5 m (d) depths.

Figure 4.15 shows the relationship between the nitrate and pH for the suction cup samples collected between 22 August 2006 and 3 December 2007 at CFS. As with AFS the pH was highest during the winter when no fertilizer was applied and decreased when the nitrate concentrations rose during the summer fertigation period. Again, it must be emphasised that nitrate does not affect the pH but indicates the presence of fertilizers which do influence the pH by disassociating H^+ ions in solution. The pH reduction is not necessarily a bad side effect of fertigation and can actually improved nutrient availability for the plant by lowering the pH to optimum levels.

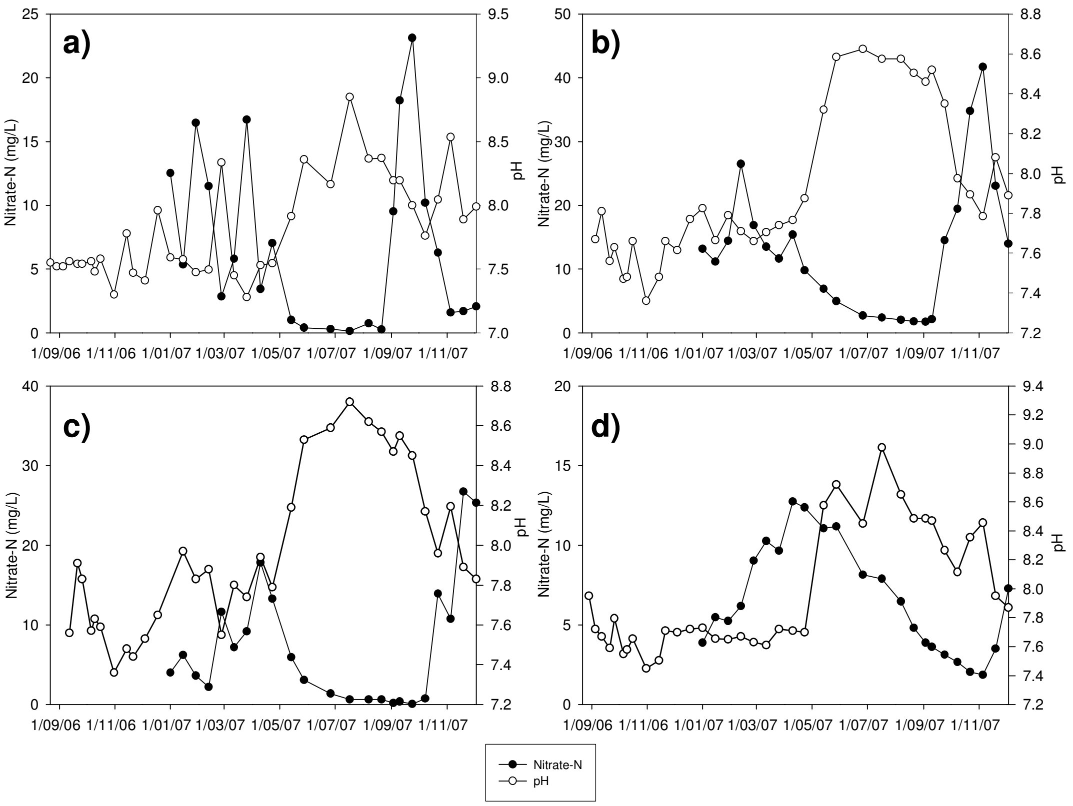


Figure 4.15: CFS suction cup nitrate-N and pH.
Measured at 0.25 m (a), 0.5 m (b), 1.0 m (c) and 1.5 m (d) depths.

4.3.5 Suction cup solute dynamics in the root zone

Figure 4.16 depicts the nutrient concentration for the AFS suction cup samples analysed by Ion Chromatograph between 24 December 2007 and 20 June 2008. The incomplete set of samples, especially for the cations, was a result of system malfunction and a lack of time. The nitrate concentration data was previously described in Figure 4.10. However, the figure does highlight the high concentration at all depths between December 2007 and March 2008. The nitrate concentration at 0.25 m and 0.5 m depth lowered to negligible levels after the fertigation season ended in April. The 1.0 m nitrate concentration peaked at >60 mg nitrate-N L^{-1} in April and the 1.5 m nitrate concentration remained high throughout.

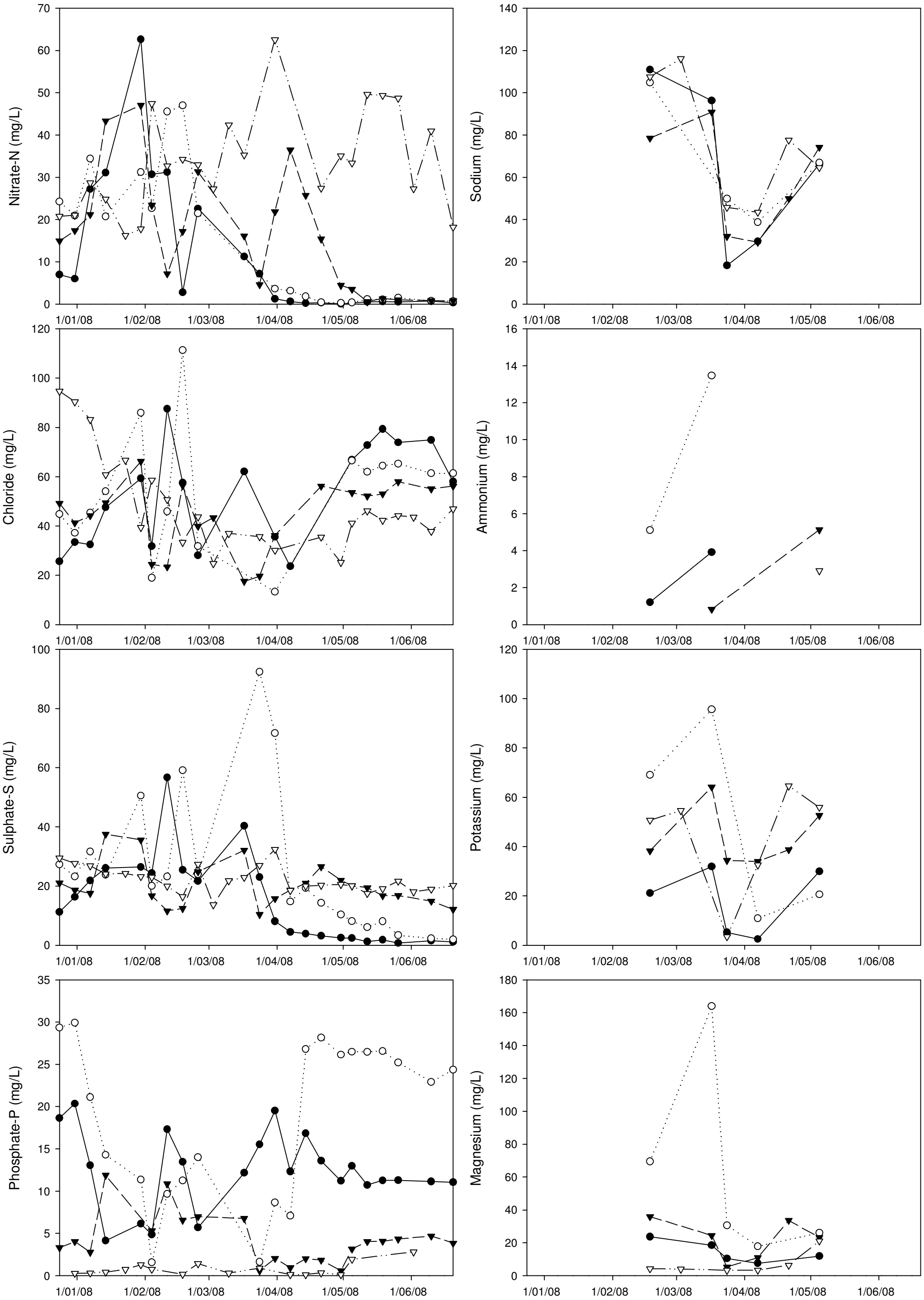
The chloride concentration fluctuated between 20 and 100 mg L^{-1} at all depths and no discernable trend was observed. The sulphate concentration generally reduced at all depths during the analysis period but also had several peaks especially at the 0.25 m and 0.5 m depths. Sulphate concentrations were generally between 20 and 60 mg sulphate-S L^{-1} during the fertigation season and dropped to negligible levels at 0.25 m and 0.5 m depths and around 20 mg sulphate-S L^{-1} at 1.0 m and 1.5 m depth by June. Phosphate concentrations were well above the 5 mg phosphate-P L^{-1} threshold at the 0.25, 0.5 and 1.0 m depths but was low at 1.5 m depth. Phosphate concentration peaked at 30 mg phosphate-P L^{-1} at 0.5 m depth in December. At other depths, phosphate concentrations were generally between 5 and 20 mg phosphate-P L^{-1} at 0.25 m depth and between 0 and 10 mg phosphate-P L^{-1} at 1.0 m depth. Phosphate sorbs strongly to clay minerals and usually is only detectable near the soil surface. The high concentrations at 0.5 m and 1.0 m depth are indicative of the low clay content in the soil. The higher concentrations also indicate ample supply of phosphorous for the plant. This is reinforced by the plant tissue analysis in Table 4.4, which had slightly higher than optimum levels of phosphorous.

All the cations followed a similar trend and started relatively high in February 2008, reduced to low levels in April 2008 and then increased through May 2008. Calcium peaked at >100 mg L^{-1} at 0.5 m but was generally below 60 mg L^{-1} and dropped to as low as 5 mg L^{-1} at 0.25 m in April The soil solution thresholds developed by Agriextchange recommend Ca concentrations between 40 and 60 mg L^{-1}. Although the sampling was not conducted for the entire growth period it would seem calcium may have been deficient. The calcium levels in the plant tissue, in Table 4.4, were low indicating the fertigation could be improved. Calcium is important for citrus production in November and December because it reduces albedo breakdown. Nitrogen can compete with calcium and therefore is kept to a minimum during this period. Low pH can also result in Ca deficiencies.

Sodium concentrations were reasonably constant with depth and were highest in March at around 120 mg L^{-1} and lowest in April at 20 mg L^{-1}. Ammonium was only detected in the root zone on a few occasions. This would be due to the fairly rapid conversion of ammonium to nitrate which generally occurs over several days (Hanson et al., 2006). The potassium levels in the soil were adequate when compared to the Agriexchange thresholds (10 to 30 mg L^{-1}). The plant tissue analysis also indicated slightly higher than optimum levels of potassium. Magnesium concentrations in the 0.25, 1.0 and 1.5 m depths were below 40 mg L^{-1} while at 0.5 m the concentration increased to well over 160 mg L^{-1} in March. The plant tissue analysis indicated the Magnesium levels were deficient in 2007 and low in 2008.

Although the data was analysed for part of the fertigation season, it is evident that there is benefit from monitoring nutrient concentrations in the soil. The soil solution can be monitored and compared to the plant tissue analysis to determine where nutrient imbalances are occurring and how to best improve the fertigation strategy.

Care must be taken when interpreting data from suction cups. The suction cup influence on phosphate concentration, presented earlier, indicated the cup could intercept up to 25% of the phosphate. Other ions could also have similar interactions with the ceramic, resulting in difficultly interpreting results. It is recommended that monitoring for nutrients be used as a trending tool to compare to plant tissue analysis. For example, the tissue analysis will indicate actual nutrient imbalances and the soil monitoring can be drawn upon to identify fertigation strategies to improve the imbalance.


Nitrate-N (mg/L)
Sodium (mg/L)
Chloride (mg/L)
Ammonium (mg/L)
Sulphate-S (mg/L)
Potassium (mg/L)
Phosphate-P (mg/L)
Magnesium (mg/L)
1/01/08
1/02/08
1/03/08
1/04/08
1/05/08
1/06/08

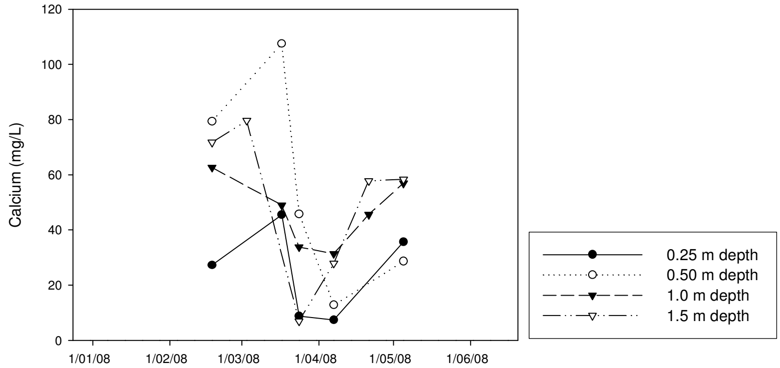


Figure 4.16: AFS results from the Ion Chromatograph for suction cup samples collected between 24 December 2007 and 20 June 2008.

Figure 4.17 shows the CFS suction cup samples analysed with the Ion Chromatograph between 24 December 2007 and 5 May 2008. The nitrate results were previously presented in Figure 4.11. Figure 4.17 indicates the nitrate concentration was lower at 0.25 m compared to the other depths, indicating that the less frequent fertilizer applications push nitrate deeper into the soil profile.

The chloride concentration increased between December 2007 and May 2008 at all depths. The sign of efficient irrigation management is an accumulation of salt in the soil from the irrigation water, during the season until the salinity starts to become excessive and leaching is required. The chloride concentrations were not excessive and the irrigation scheduling should be maintained to allow salt to continue to build.

Sulphate concentration increased from a low of 2 mg sulphate-S L^{-1} at 0.25 and 1.0 m to 14.2 mg sulphate-S L^{-1} at 0.5 m between December 2007 and May 2008.

The phosphate concentration at CFS was much lower than at AFS. At 0.25 m depth the concentration was between 1 and 3 mg phosphate-P L^{-1}. At the other depths phosphate was only detected in a couple of samples. Even though the phosphate concentration in the suction cups at CFS were low compared to the Agriexchange minimum threshold and well below the phosphate concentrations observed at AFS, there is no nutritional problem. The plant tissue analysis in Table 4.4 actually reported optimum phosphorous levels. The reason for the low phosphate concentration in the suction cup could be due to the higher clay content at the CFS site resulting in more phosphate stored at the soil surface.

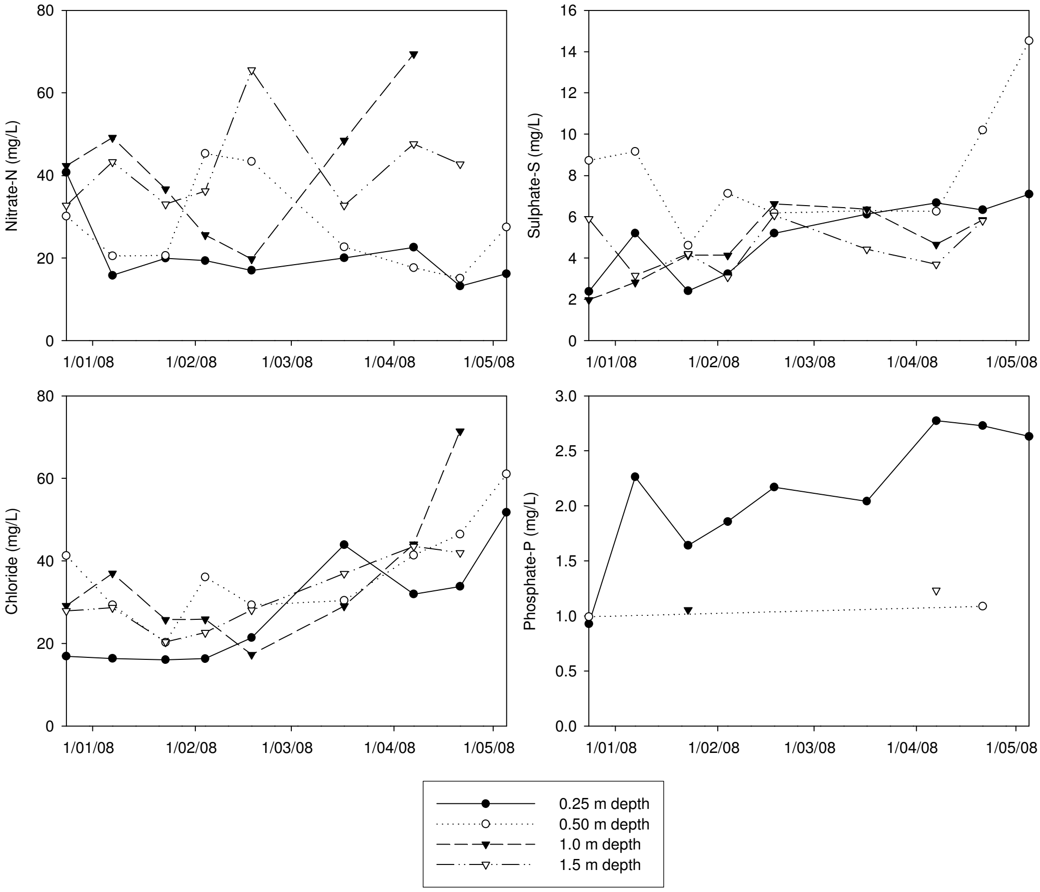


Figure 4.17: CFS results from the Ion Chromatograph for suction cup samples collected between 24 December 2007 and 5 May 2008.

4.3.6 Farm 8 (MOHT) solute results

Figure 4.18 shows the suction cup results from the Farm 8 (MOHT) trial site for the period between 14 February and 23 July 2008. The figure shows the suction cup sample EC, nitrate-N, sulphate-S, chloride, phosphate-P and pH results. The Farm 8 site had suction cups located at 0.25, 0.5, 1.0 and 1.5 m depths, similarly to AFS and CFS but also had suction cup replications 0.5 m away from the emitter at 0.6 m depth. The aim of this suction cup was to observe lateral solute movement from the drip emitter.

The inclusion of the lateral suction cup was a success and provided information regarding the dynamics of solute transport around a drip emitter.

In February 2008, the lateral suction cup had a much higher EC compared to any of the suction cups underneath the emitter. The EC in the lateral suction cup reduced during March and April. The suction cups underneath the emitter had low EC, under 0.4 dS m^{-1}, and lowered to about 0.2 dS m^{-1} by July 2008.

The 1.5 m suction cup did not yield a sample until 27 March 2008 because the soil at this depth was very dry. The lack of sample at the 1.5 m depth is not necessarily a bad result. No sample at 1.5 m indicated that the wetting fronts were not reaching this depth and nitrate leaching below the root zone would be negligible.

The nitrate and chloride concentration followed the same trend as the EC, where they were initially high at the lateral suction cup and then reduced during February and March 2008. The results clearly show the lateral transport occurring and the deposition of mobile solutes, such as nitrate and chloride, at the margins of the wetted zone. Possible reasons for the reduction in the nitrate and chloride concentration include crop extraction after the fertigation supply stopped in early February 2008; the nitrate and chloride could have been transported either deeper or further away from the emitter; or the extractions could have reduced the mass of nitrate and chloride from directly around the suction cup. Because the fertigations stopped in early February, the area around the suction cup could be diluted with irrigation water.

The sulphate was also high, at >100 mg sulphate-S L^{-1}, at the laterally placed suction cup but did not begin to increase until late February 2008 and then proceeded to reduce in March 2008. Phosphate concentration at 0.25 m and 0.5 m depths below the emitter peaked at about 2.5 mg phosphate-P L^{-1} in late March 2008. The laterally placed suction cup detected phosphate concentrations at about 1 mg phosphate-P L^{-1} on two occasions. Phosphate was also detected at 1.0 m depth at <1.0 mg phosphate-P L^{-1} on two occasions but was not detected at 1.5 m depth. The pH at 0.25 m and 0.5 m depth were lower than the other suction cup locations and were often below 6. At this level problems such as poor turn over of organic matter, P, Ca and

Mg deficiencies and Al and Mn toxicities could occur. On one occasion in March the 0.25 m pH was even <4. At a pH below 4 root growth rarely occurs due to toxicities related to Al, Cr, Cu, Ni, Zn and Mn (Hughes et al., 2004).

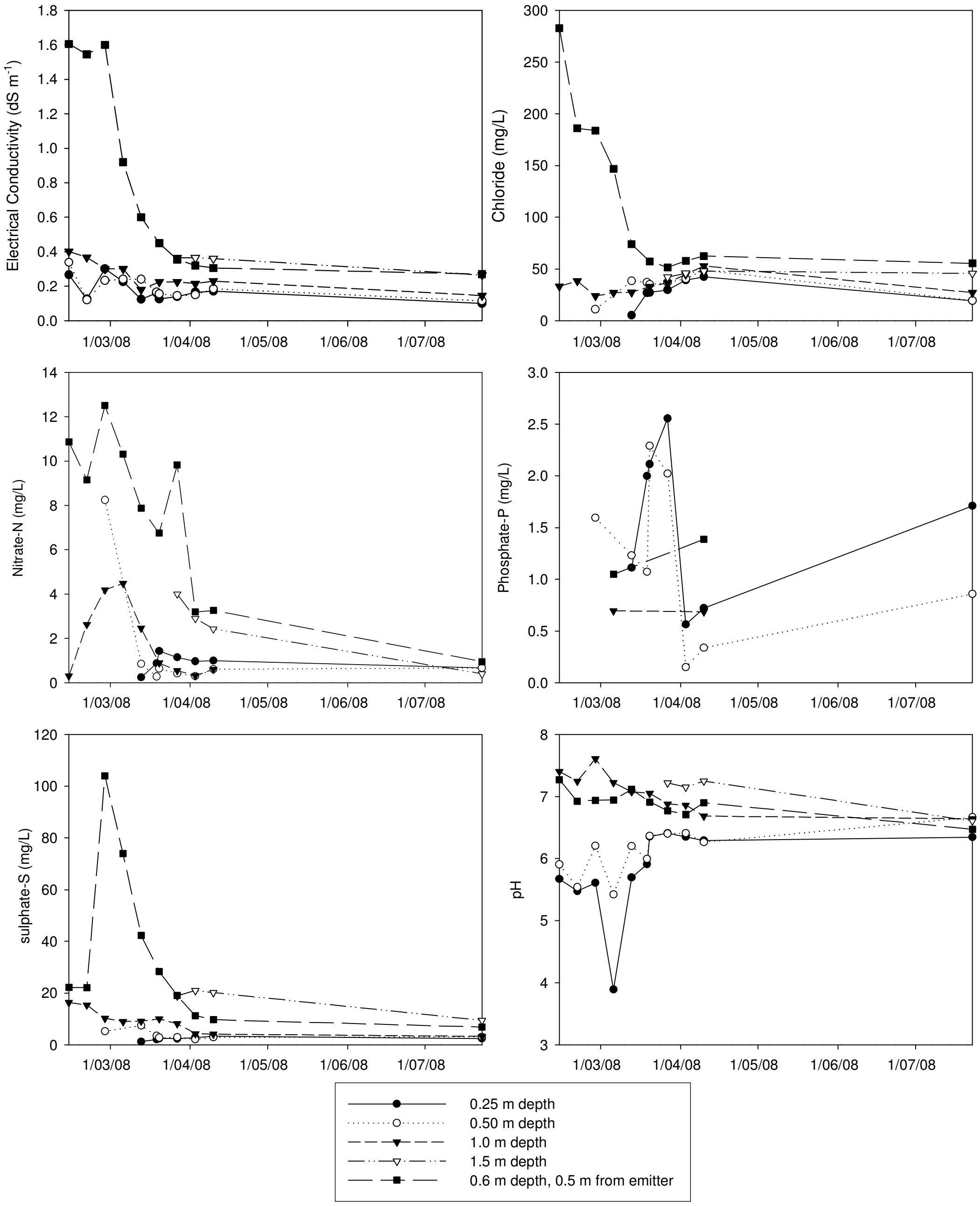


Figure 4.18: Farm 8 suction cup sample results collected between 14 February 2008 and 23 July 2008.
Samples were analysed for EC, chloride, nitrate, phosphate, sulphate and pH.

4.3.7 Solute dynamics from soil samples

Figure 4.19 presents the EC_e results from soil samples taken around the drip emitter at different times during the year for AFS and CFS. Soil samples were taken from around two drip emitters at each site and the results represent the mean EC_e. The x-axis is the distance into the mid row, perpendicular to the tree line, where -50 cm is the tree line, 0 cm the emitter location and the positive numbers indicate distance into the mid row. The y-axis is the depth from the soil surface. Samples were taken in April, July and December of 2007 and March and July of 2008. The left column is the AFS samples while the right is the CFS samples.

EC_e below the emitter was very low at ≤1.0 dS m^{-1} right down to the lowest sampling depth at 1.5 m. The results show a clear build up of salt at the surface away from the emitter into the mid row for both sites. It is evident solutes were being transported with the wetting front to the margins of the wetted zone and concentrated due to evaporation. The salt build up was especially pronounced at AFS in April 2007 and July 2008. There is evidence that the salt was also building deeper in the profile over time. The soil should be monitored to ensure the salt at the margins of the wetted zone does not build to excessive levels. The middle of the tree row, -50 cm, had a very low EC_e because it is the middle of the two drip lines and therefore receives the most water.

It has been reported in the literature, that salt at the margins of the wetted zone can redistribute back into the root zone after rain (Raine et al., 2007). The type of salt being deposited at the margins of the wetted zone is unclear but would most probably be ions which move freely with the water such as nitrate, chloride and potassium. The suction cup results from Farm 8 clearly showed chloride and nitrate build up at 0.5 m away from the emitter at 0.6 m depth which is most probably also occurring at AFS.

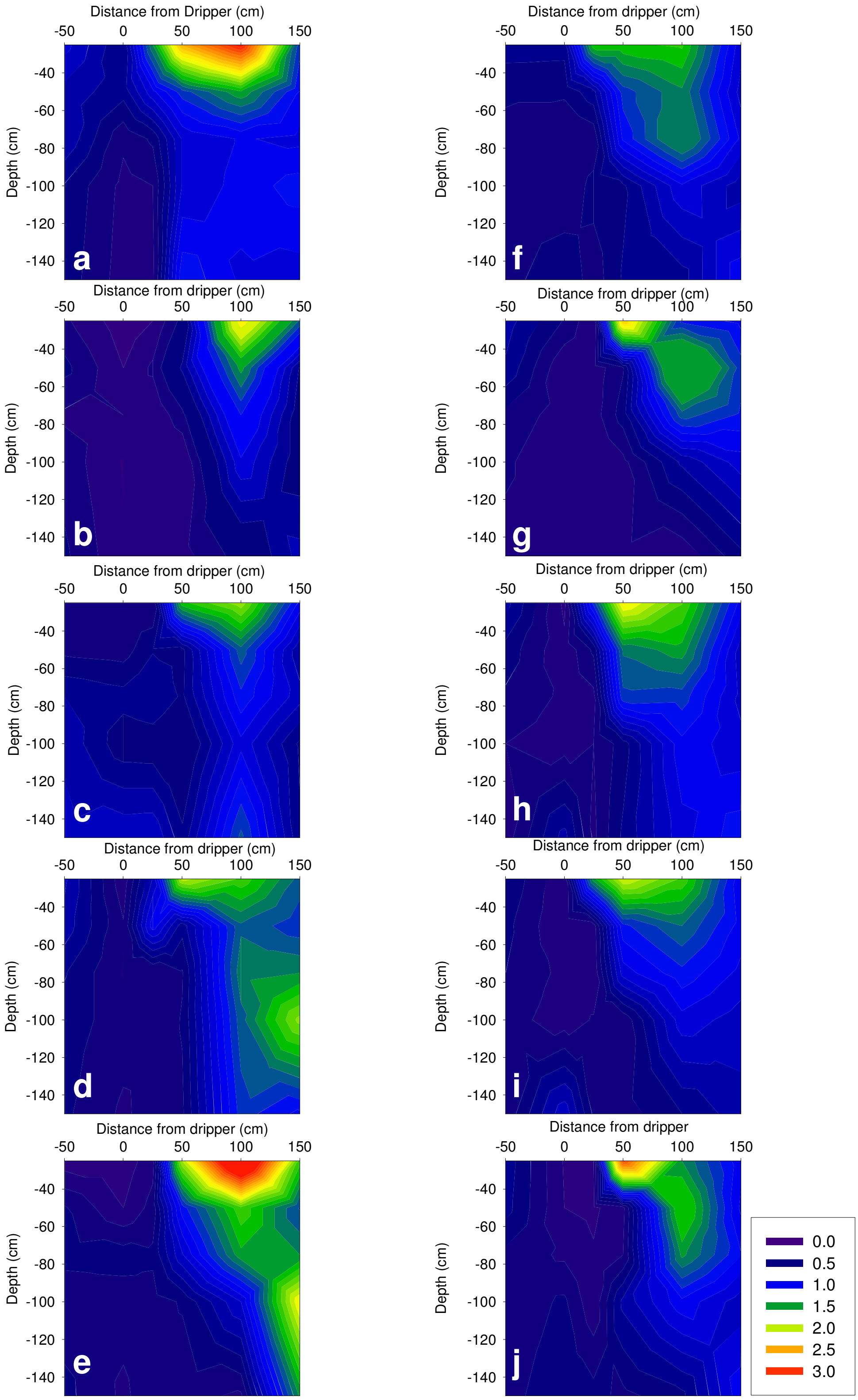


Figure 4.19: AFS and CFS electrical conductivity of the saturation paste (ECe, dS m^{-1}).
AFS: a) April 2007, b) July 2007, c) December 2007, d) March 2008, e) July 2008
CFS: f) April 2007, g) July 2007, h) December 2007, i) March 2008, j) July 2008

Figure 4.20 shows the pH of the saturated paste extract from the soil samples collected at AFS and CFS. The sampling time was the same as for the EC_e analysis. AFS had a definite acidification of the surface layer to a depth of about 0.4 m, directly below the emitter and into the tree row. Conversely, CFS showed no sign of acidification below the emitter. The majority of the extract solutions had a pH between 7.5 and 8.5 which is indicative of the alkaline soil type.

The results at AFS are similar to the study by Pierzynski et al., (2005), who witnessed acidification at the 0 to 0.2 m and 0.2 to 0.4 m soil depths in a Valencia orchard. Pierzynski et al., (2005) observed the acidification was more pronounced in ammonium nitrate fertilized plots compared to urea fertilized plots. AFS was fertilized with ammonium nitrate and mono ammonium phosphate in 2006/07 and mono ammonium phosphate, potassium nitrate and ammonium sulphate in 2007/08, while CFS was fertilized with urea and a blended fertilizer formula. The different fertilizer types used, combined with the more frequent fertilizer application, was attributed to the greater acidification at AFS.

Similar to the suction cup pH data at AFS presented in Figure 4.13, the solution extract pH had a cyclic pattern, where it was more acidic during the summer when fertilizers were applied. The soil solution returned to the normal alkaline condition in the winter when there was no fertilizer application. The pH determined from the solution extract undergoes an upward shift compared to pH determined using 0.01 M $CaCl_2$ due to differences in the ionic strength (Rayment and Higginson, 1992). Therefore, the acidity directly under the dripper at AFS, which was often below 5, represents a problem which may need to be addressed through lime addition.

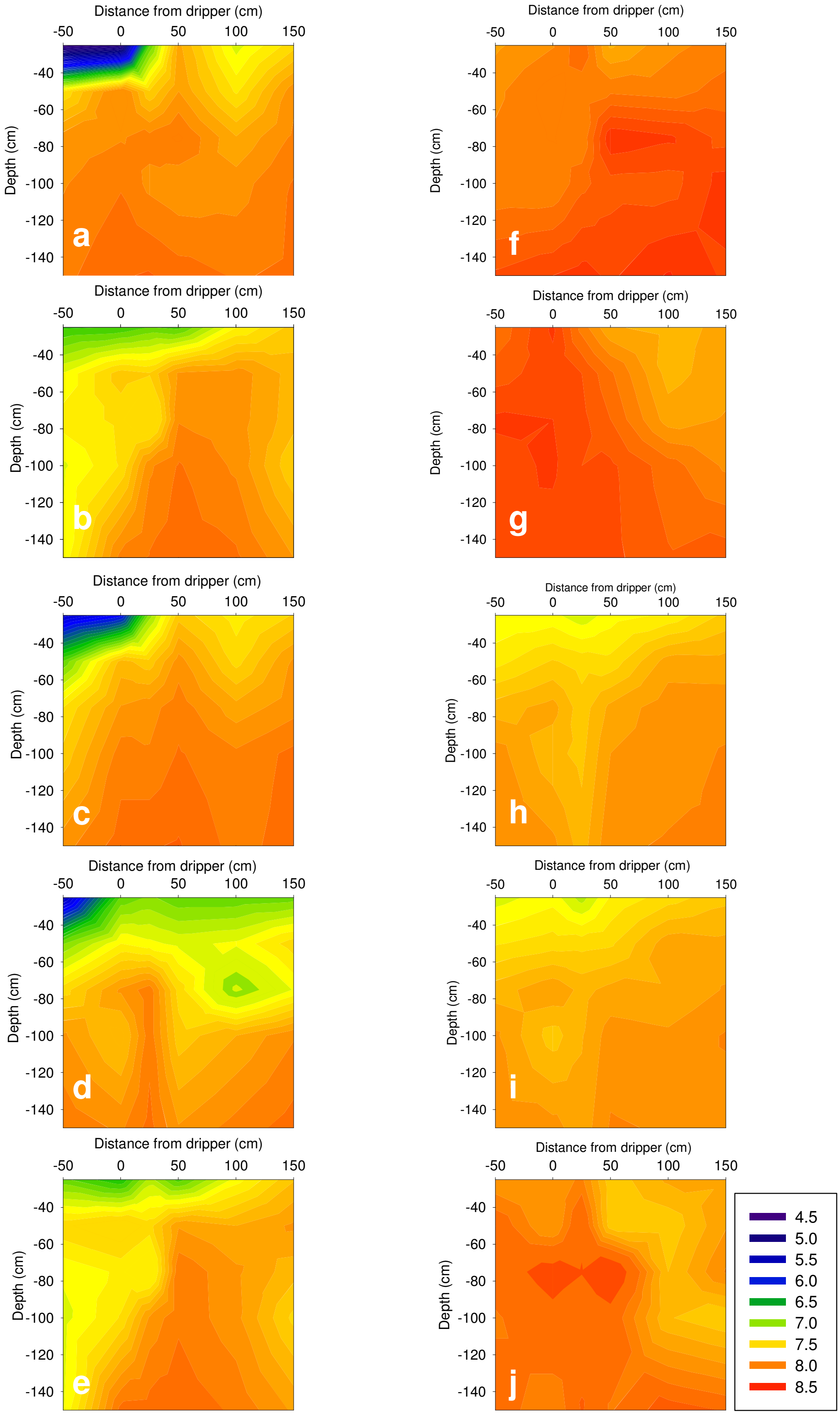


Figure 4.20: pH of the saturation paste extract for AFS and CFS
AFS: a) April 2007, b) July 2007, c) December 2007, d) March 2008, e) July 2008
CFS: f) April 2007, g) July 2007, h) December 2007, i) March 2008, j) July 2008

4.4 Conclusions

A better understanding of solute dynamics under intensive fertigated horticulture is required to effectively manage fertilizer usage. Historically, plant tissue analysis has been used as the diagnostic tool to determine nutrient imbalances and adjust the fertilizer programme. However, the adoption of intensive fertigation management, coined Advanced Fertigation, has warranted a change in how the fertilizer use is monitored. The suction cup is a viable method to manage frequent fertilizer applications because a sample of soil water can be analysed at any time during the year. The soil solution does not provide a direct measure of crop health but, if combined with yearly plant tissue analysis, could be effectively used to monitor and manage fertigation programs. This study used a combination of suction cup extractors and soil samples to monitor solute dynamics under three differently managed citrus orchards. Two of the orchards were within the Dareton Agricultural and Advisory Station while one was within a commercial citrus property. At the Dareton field site there was an advanced fertigated citrus orchard where the fertigations were weekly, and a more conventionally fertigated citrus orchard where the fertigations were monthly. The commercial site was fertigated using the MOHT management system.

The influence the suction cup material had on the incoming nitrate and phosphate concentration was tested for a range of outside solution concentrations. After four extractions the difference between the outside solution and the extracted solution concentration was determined. For nitrate the concentration of the extracted solution was not statistically different compared to the outside solution for a concentration range between 0 and 56.45 mg nitrate-N L^{-1}. For phosphate, the concentration in the extracted solution was up to 25% less than the outside solution concentration between 0.5 and 5 mg phosphate-P L^{-1}. The difference was attributed to sorption on the ceramic material. To improve our understanding of the phosphate reaction with the ceramic cup, more than four extractions is required to determine if the ceramic can come into equilibrium with the outside solution. The test could be furthered by using different (higher and lower) outside concentrations and observe the influence on the extracted concentration.

This type of analysis is important to gain confidence in the measured results when using suction cups in field conditions to monitor and understand the chemical processes occurring within the vadose zone.

Nitrate at the advanced and the more conventional fertigated orchards showed nitrate freely moved to depths as great as 1.5 m during the fertigation season. To improve the nitrate efficiency, a strategy is required which retains nitrate at the 0.25 m depth but does not allow rapid increases to occur at 0.5 m. Tensiometer data (not shown) indicated wetting fronts continually reached the 0.9 m and 1.2 m depths. The first step to reducing nitrate leaching would be to reduce the wetting front depth through the application of less water per irrigation. The reduced irrigation volume would require more frequent applications to meet crop water requirement but would be more efficient. Once the wetting fronts have been controlled to only wet the main root zone, the suction cups can be monitored to ensure concentrations are within the threshold at 0.25 m but does not increase rapidly at the 0.5 m depth.

There was a strong positive correlation between nitrate concentration and the electrical conductivity of the suction cup samples. There could be potential to use the electrical conductivity signature to predict nitrate movement under low salinity conditions, which is cheaper and easier than nitrate analysis techniques.

The inclusion of the lateral suction cup at the MOHT site was a success and showed the dynamics of solute transport around a drip emitter. The lateral suction cup had a much higher EC compared to any of the suction cups underneath the emitter. The nitrate and chloride concentrations were also high for the lateral suction cup, clearly showing lateral distribution occurring and the deposition of mobile solutes, such as nitrate and chloride, at the margins of the wetted zone. The EC_e measured from the soil samples was very low right down to 1.5 m below the emitter. However, there was a clear build up of salt at the surface away from the emitter into the mid row for both the advanced and conventionally fertigated sites. It is evident solutes were being transported with the wetting front to the margins of the wetted zone and concentrated due to evaporation. Although this type of solute transport is well documented in the literature, it is important to understand the solute transport dynamics at a specific site so an effective monitoring regime can be implemented.

The advanced fertigated and MOHT sites had a definite acidification of the surface layer to a depth of about 0.4 m, directly below the emitter. Conversely, the CFS site showed no sign of acidification below the emitter. The pH showed a cyclic pattern, where it was more acidic during the summer when fertilizers were applied and returned to the normal alkaline conditions in the winter when there was no fertilizer. This indicates the soil currently has the capacity to buffer the H^+ accumulation.

The results demonstrate the need to strategically plan the location of suction cups. Suction cups directly below the drip emitter will typically show much less salinity than suction cups located in the margin of the wetted zone. From the solute dynamics observed in this study it is recommended that for nutrient and salt monitoring at one location the suction cup be located approximately half way between the emitter and the edge of the wetted zone and at the depth of greatest root density. This zone will provide the greatest indicator of average root zone conditions. Each field site is different due to irrigation system, irrigation practices, crop type, climate, soil and topography. The exercise used in this study to determine gravimetric water content around the emitter is a good method to determine the suction cup location. It is highly recommended that a suction cup also be placed at the base of the root zone, underneath the suction cup in the main root zone. This suction cup would be used to ensure the majority of the nutrients remained in the main root zone and do not leach below the root zone. Without the second suction cup the conditions could be optimum within the root zone but excess nutrients leaching below the root zone would not be detected. The final suction cup location recommendation is well below the root zone directly underneath the emitter. This suction cup is an indicator for environmental and economic sustainability.

Nutrients located below the root zone are a waste of money for the farmer and an environmental hazard for the groundwater and eventually the surface water system. There is no hard and fast rule for the number of suction cup replications. Soil naturally exhibits huge spatial variability and the influence of farming practices further increases variability. However, some monitoring is better than no monitoring at all. The number of replications should reflect factors such as funds for suction cup capital, allowable time for the sampling process, and analysis capabilities.

Acknowledgements

Support and funding from the CRC for Irrigation Futures and South Australian Research and Development Institute was greatly appreciated. Also thanks to the staff at the Dareton Agricultural and Research Station for their support and help during field work and sampling.

Appendix 4A – List of abbreviations

AF	Advanced Fertigation
AFS	Advanced Fertigation Site
AWR	Air to Water Permeability Ratio
A_c	Crop Age Coefficient (-)
CFS	Conventional Fertigation Site
EC	Electrical Conductivity (dS m-1)
ECe	Electrical Conductivity of the Saturated Paste Extract (dS m-1)
ESP	Exchangeable Sodium Percentage (%)
ETc	Crop Evapotranspiration (mm)
ETo	Potential Evapotranspiration (mm)
Farm 8	MOHT Trial Site
h	Soil Water Pressure (m)
Kc	Crop Coefficient (-)
MOHT	Martinez Open Hydroponics Technology
OH	Open Hydroponics
θ	Soil Water Content (cm^3 cm^{-3})
θ_r	Residual Soil Water Content (cm^3 cm^{-3})

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