Water and Nitrate Movement under Advanced Fertigated Citrus

Adam Sluggett[1, 2], Tapas Biswas[3], John Hutson[1]

[1]School of Chemistry, Physics and Earth Sciences, Flinders University of South Australia, GPO Box 2100, Adelaide, SA 5001, [2]Cooperative Research Centre for Irrigation Futures, PO Box 56, Darling Heights Qld 4350, [3]South Australian Research and Development Institute, GPO Box 397, Adelaide, SA 5001

Corresponding author – slug0003@flinders.edu.au

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Biography

Adam Sluggett began his PhD candidature at Flinders University, Adelaide in March 2007. His research is involved in the evaluation of solute movement in irrigated citrus using a combination of field techniques and computer based numerical models to monitor and predict the movement and fate of water and solutes. Before this Adam Studied Environmental Science (First Class Honours) at Flinders University and for his honours year conducted a research project on the quantification of leaching efficiency and salinity profile of irrigated vineyards in the Riverland region. Adam has been involved with the Cooperative Research Centre for Irrigation Futures and the South Australian Research Development Institute during his Honours and PhD candidature and in the summer of 2006/07 participated in a Summer Internship with South Australian Research and Development Institute and produced a report on a new method to estimate leaching efficiency.

Abstract

The horticulture industry has been increasingly adopting the practice of high but precise water and fertilizer input to obtain faster returns, larger yields and better quality fruit. Open hydroponics, an Advanced Fertigation (AF) technique, is one such 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 over a decade but has not been critically assessed for its environmental sustainability in Australian conditions. This paper discusses the deep drainage fluxes and movement of nitrate under both advanced and conventional fertigated citrus in Sunraysia region of Australia. A trial site was developed at the Dareton Agricultural and Advisory Station, NSW. Monitoring of deep drainage and nitrate leaching was conducted using tensiometers and the ceramic cup soil water samplers. Two tensiometers at 0.9 and 1.2 m depth were logged every hour and used to calculate a Darcy flux. Nitrate leaching below the root zone was estimated using the relationship between drainage flux and nitrate concentration in the soil solution below the root zone.

Introduction

Advanced Fertigation (AF) is a fertigation management system has been developed over the last two decades to increase yield and quality of many permanent horticultural crops. Fertigation can be defined as the application of fertilizers dissolved in irrigation water and allows water and nutrients to be placed in the zone of greatest root activity, allowing rapid utilization by plants (Bar-Yosef, 1999). The overall aim of AF is to develop an irrigation and nutrition management program that increases yield and fruit quality, where the fundamental principle is that nutrients are applied regularly to a smaller volume of soil at a low application rate and at a high frequency to meet crop demand (Falivene et al., 2005). AF is a broad description given to the emerging intensive fertigation management. In reality each AF system is different due to factors including climate, soil, water quality and level of management. Open Hydroponics (OH) is another name for AF and gets its name from the principles it adopts from soil-less hydroponics for field based production. Professor Rafael Martinez-Valero from the University Miguel Hernandez in Spain brought together the many concepts of OH in the early nineties. The original reason for the development of OH was to develop a management strategy to maximise citrus production on low fertility gravel based soils with poor quality water (Martinez-Valero and Fernandez, 2004). Martinez then commercialized the management system and named it Martinez Open Hydroponics Technology (MOHT) (Falivene, 2005).

It is claimed that by achieving a small, concentrated root system, AF is able to meet all the crop's water and nutrient needs and also manipulate and control the plants water and nutrient uptake through all stages of the productive cycle (Edwards, 2007). The soil fertility is not considered important and the soil is regarded as a medium to anchor the plant and accommodate the root system. It is claimed that even calcareous and saline soils can be utilised to grow citrus under AF as long as the soil is well drained (Edwards, 2007). Ionic balance is an important consideration while formulating a nutrient mixture for application to the orchards and will help in preventing soil acidification (Martinez-Valero and Fernandez, 2004).

Nitrogen is the key limiting nutrient for citrus and is therefore the main fertilizer input for citrus production. Nitrate is the final form of transformation from both organic and inorganic sources (Hillel, 2004). The main source of nitrate in citrus production is through mineral fertilizers in the irrigation water but nitrate also forms in situ by the decomposition of organic matter in well-aerated soils (Hillel, 2004). Nitrate is removed from the soil by plants or decomposition 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). Nitrate, being an anion moves freely in mineral soil and hence has the potential to leach into the groundwater and waterways if fertigation is not well scheduled (Paramasivam et al 2002; Gardenas et al., 2005; White, 2006). Li et al., (2004) found that 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 optimized nutrient use efficiency. High nitrate concentrations in groundwater are hazardous for two reasons. Firstly, the nitrate content of the groundwater used for drinking purpose needs to be below 10 mg NO3- -N l-1 (NWQMS, 2004). Concentrations higher than this have been linked to blue baby syndrome which can develop in infants. Secondly, high levels of leached nitrate can lead to eutrophication of surface water bodies where the groundwater discharges.

There are several techniques that can be used 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 N application rate and exceeded 10 mg L-1 for trees receiving the highest rate. However, lysimeters are expensive to install and during the installation cause considerable soil destruction and therefore the soil in the lysimeter is often different to the surrounding intact soil. 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-2D and LEACHM use the Richards' equation to simulate water flux. Paramasivam et al., (2002) used 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 a sandy Entisol 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). Nitrate leaching has been estimated by determining a flux below the root zone using tensiometers and ceramic soil water extractors to measure nitrate concentration. Paramasivam et al, (2001) reported that NO3-N leaching losses below the root zone increased with increasing N application (112 – 280 kg N ha-1 yr-1) and the amount of water drained, and 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.

There has been no nitrate leaching study conducted for AF management in Australia, which forms the objective for this study. The aim is to develop methodology to measure deep drainage and nitrate leaching at an AF trial site in the Sunraysia citrus growing region. This paper presents drainage and nitrate leaching data for part of the 2007/08 fertigaiton season and therefore can not compare nitrate leaching with the total applied N fertilizer, however by the end of the season this analysis will be conducted.

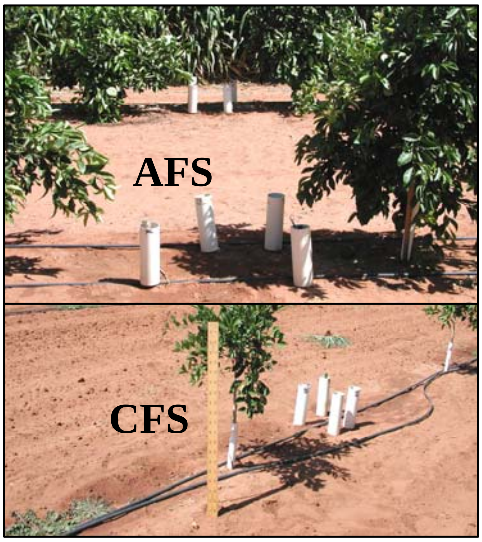
Materials and Method

Experimental site

The field experiment was conducted at the Dareton Agricultural and Advisory Station, NSW. The station is located in the Coomealla irrigation area, 3 km from Dareton and 10 km from Wentworth in NSW. The research station forms part of the Sunraysia fruit growing District of NSW and Victoria. The soils are alkaline (Class IIIA), with red sandy to sandy loam topsoils overlaying a heavier sub soil. The site has a top soil and root zone depth of 1.05 m. The first 0.15 m consists of loamy sand, 0.15 to 1.05 m consists of a sandy loam and 1.05 to 1.70m depth consists of a loamy sand clay loam texture. There is a topsoil and root zone RAW of 0.61 m. The property is irrigated with Murray River water, which has a low salinity, under 0.3 $dS.m^{-1}$. The climate is characterized 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 1400 mm per year. Mild frost conditions occur in the winter months.

Trial site details

Three trial sites were established within the Dareton Agricultural and Advisory Station. An advanced fertigated (AFS) site consisting of a number of mandarin varieties and a conventionally fertigated (CFS) site consisting of Cara Cara Navel (both Citrange rootstock) was established on 10^{th} October 2005. An adjacent sprinkler irrigated Nova Mandarin (NOVA) site (Citrange rootstock), which was planted in 1987, was also included to compare its performance against the AFS. Although all three sites are included, only the AFS and NOVA site have been assessed for deep drainage and nitrate leaching due to a malfunction with the tensiometers at the CFS site.



AFS - Drip irrigated citrus fertigated weekly

- Row Length: 104 m
- Row spacing: 5 m
- Tree spacing: 2 m
- Irrigation system: Drip double lines (1.6 L/h)
- Application rate: 1.6 mm/hr
- Wetted area: 1.3-1.4 m

CFS - Drip irrigated citrus fertigated monthly

- No of Rows: 13
- Row Length: 105 m
- Row spacing: 5 m
- Tree spacing: 3 m
- Irrigation system: Drip double lines (2 L/h)
- Application rate: 0.8 mm/hr
- Wetted area: 1.3-1.4 m

NOVA Mandarin (common irrigation practice for citrus)

The irrigation system consists of low level sprinklers (Water Birds, 115L/hr at a working pressure of 200 kPa) with an emitter spacing of 3.15m and an application rate of 6.1mm/hr. The row spacing is 5.6m and the distance between emitters is 3.15m.

Soil solution monitoring equipment

Soil Water was sampled weekly using SoluSAMPLER™ (Biswas 2006; Biswas and Schrale 2008). The SoluSAMPLER is a porous ceramic cup connected to a PVC sample reservoir and tubing from the reservoir to the soil surface, which is used to apply the suction and extract the solution. The sample is drawn through the ceramic into the reservoir by applying a suction of -60 kPa and then a week later the sample is extracted. The technique of soil solution extraction utilizing porous ceramic cups was first described by Briggs and McCall (1904) and since then there have been several changes to the design with changes in shape, size and material used (Litaor, 1988). The SoluSAMPLER used in this study were developed at the South Australian Research and Development Institute and are now distributed by Sentek Pty Ltd. The AFS site has SoluSAMPLER's located at depths of 0.25, 0.5, 1.0 and 1.5 m and a distance of 0.1 m from the drip emitter with two replications. The NOVA site has SWE located at depths of 0.3, 0.6 and 0.9 m and located within the tree row half way between two trees. The SoluSAMPLER's are used to track salt and nutrients within and below the root zone and monitor the long term soil pH trend. In this study only the nitrate data from the deepest SoluSAMPLER has been reported for the nitrate leaching assessment.

Soil tension monitoring equipment

T8 Tensiometers were installed to measure matric potential (USM, www.usm.muc.de). The T8 tensiometer has a measurement range and accuracy of +100 to -85 kPa and ±0.5 kPa, respectively. At both sites a set of two tensiometers were installed and were located at depths of 0.9 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 two tensiometers were installed parallel to each other with the 0.9 m depth located 0.42 m and the 1.2 m depth located 0.56 m from the sampling site to ensure the ceramic tips of the tensiometers were at the same location. At the AFS site the tensiometers where installed on the 30th of August 2007 and located in the tree row directly between the two drip irrigation lines and approximately 0.15 m from the SWE. At the NOVA site the two tensiometers were installed on the 20th November 2004 and located 1.0 m from a tree within the tree row. Both sets of tensiometers log matric potential hourly.

Soil water analysis for nitrate

All soil water samples from the SoluSAMPLER's located at 1.5 m for AFS and 0.9 m for NOVA were analysed for nitrate. Nitrate analysis was conducted using the cadmium reduction method (HACH, 2005). In this method cadmium metal reduces nitrates present in the sample to nitrite. The nitrite ion reacts in an acidic medium with sulfanilic acid to form an intermediate diazonium salt which couples to gentisic acid to form an amber-coloured product. The intensity of the colour was measured using a HACH DR 850 colorimeter (HACH, 2005). The colorimeter was initially calibrated to a standard solution of 15 mg/L $NO3^{-1}$-N to ensure measurement accuracy.

Deep drainage and nitrate leaching calculation

The method used to assess deep drainage involves using tensiometers to measure the difference in matric potential (*p*) between the 0.9 and 1.2 m depth and then determine the water flux using the Darcy's flux equation:

$$Jw = -K(p)\left(\frac{d(p)}{dz} - 1\right)\Delta t$$

K(*p*) is the unsaturated hydraulic conductivity (cm/day), *d(p)* is the difference in pressure between 0.9 and 1.2 m depth, *dz* is the distance between the tensiometers (0.3 m) and Δ*t* is the time period that drainage was calculated for. The negative sign accounts for the direction of flow being opposite to the direction of increasing head.

The unsaturated hydraulic conductivity for different soil pressure heads was estimated using measured saturated hydraulic conductivity (*Ks*), the average matric potential (*p*) and fitting parameters (*a, n and m*) from van Genuchten (1980):

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

Ks was measured in the field using a Guelph Permeameter, which measures the steady state inflitration of water from a ponded well into the surrounding soil. For a more detailed description of the method refer to Bosch and West (1998). The fitting parameters from van Genuchten (1980) in Table 1 were estimated using the Rosetta model (Schaap, 2003). The fitting parameters were estimated using the percent sand, silt, clay and bulk density of the soil. There is uncertanty in the *K(p)* value due to the use of textual data to infer hydraulic parameters. This data forms part of a long term study and will be improved as more information is collected. Soil cores have been collected and are being used to develop a soil water release curve for this site which will eliminate the need to use the Rosetta model to estimate the parameters.

Table 1: Soil hydraulic parameters

a (cm^{-1})	n	m	*Ks* (cm/day)

0.0323	2.0653	0.5158	150

The nitrate leaching losses below the root zone was estimated using the concentration of NO_3-N in the SWE at 1.5 m depth for the AFS site and 0.9 m for the NOVA site. At this depth there is little root activity and therefore it is assumed that this nitrate is lost to the plant and is subject to leaching. It was assumed that there was minimal denitrification due to the sandy soil conditions making anoxic conditions highly unlikely (Alva et al., 2006). The nitrate leaching (*NL*) was calculated from the relationship between drainage water (*Jw*) and nitrate concentration at 1.5 m depth (C_{150}):

$$NL = JwC_{150}$$

Alva et al. (2006) also used this method to estimate nitrate leaching but commented that the actual quantity of NO_3-N leached was underestimated due to the infrequent sampling of nitrate (every two weeks). To avoid this uncertainty we increased the frequency of soil water sampling events and used continuous real time measurement of soil water matric potential to measure the total amount of drainage water.

Fertigation and weather data

Irrigation and fertigation records were collected from the Dareton Research and Advisory Station. Weather data, including rainfall were collected from an automated weather station located within the Dareton research farm. Potential evapotranspiration (ETo) was calculated using FAO 24 method (Doorenbos and Pruitt, 1977).

Results and Discussion

Water and fertiliser use by AFS, CFS and Sprinkler systems

Between Sep 06 and Aug 07, water usage by AFS was 4.4 ML ha^{-1} compared to 1.76 ML ha^{-1} for CFS and approximately 12 ML ha^{-1} for NOVA. Fertilizer usage data during the same period is given below in Table 2.

Table 2: Fertiliser use for the three trial sites (kg ha^{-1} yr^{-1})

Treatments	**N**	P	K
AFS	164	36.5	225.3
CFS	95.5	22.7	42.7
Sprinkler	115 (32 Foliar)	0	0 (33 foliar)
Mature tree Standard	110	50	50

Nitrate leaching and deep drainage below the root zone

Deep drainage was calculated by using the equations described above, where soil matric potentials were measured from 0.9 and 1.2 m tensiometers situated just below the root zone. At the AFS site the tensiometers were installed on 30th of Aug 2007 whereas at the NOVA site the tensiometers were installed on the 20th Nov 2004.

NOVA mini deep drainage and nitrate leaching

The methodology to estimate deep drainage and nitrate leaching was first tested on the NOVA site simply because this site was established in 2004. In order to capture a month of peak fertigation (summer) and a winter low activity month, September 2006 and January 2007 data was analysed. Although, peak winter is in June and July, unfortunately the tensiometers failed in May 2006 and were only back in operation in August 2006. Hence Sept was chosen as the winter low activity month.

The nitrate-N concentrations in the soil solution at various depths for September 2006 and January 2007 from the NOVA site are shown in Figure 1. During September the NO_3-N concentration at all depths increased from below 10 mg/L to as high as 35 mg/L in top layer. During the month as the fertilizer moved through the soil profile, the NO_3-N exceeded the environmental guidelines of 10 mg/L at 0.9 m depth, just below the root zone. Contrastingly, the nitrate concentrations at 0.9 m depth in January remained at levels well above 10mg/L NO_3-N.

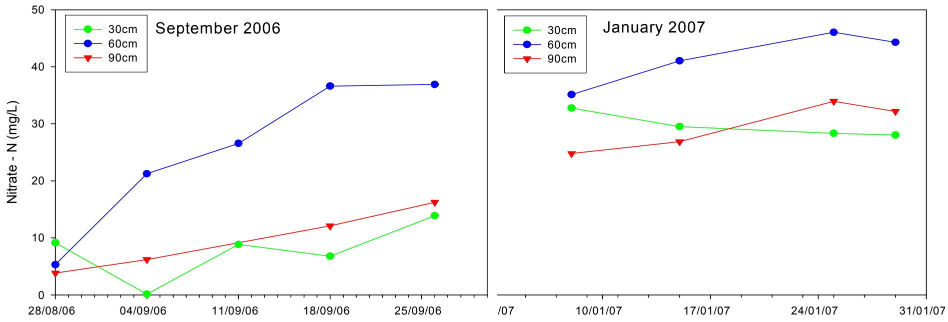


Figure 1: Soil solution Nitrate-N concentration for Sept 2006 and Jan 2007 at the NOVA site.

The cumulative drainage and nitrate leaching along with irrigation and drainage volumes for September 2006 and January 2007 are shown in Figure 2. In September there was one small rainfall event and three irrigations all below or near 20 mm. In contrast in January there were four irrigation and three rainfall events, 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 volume 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 September and January was 1.2 and 12 kg NO_3-N ha^{-1}, respectively. The higher nitrate concentration at 0.9 m combined with the higher LF in January as compared to September explains the ten fold increase in nitrate leaching. At 0.9 m there are still roots that are able to extract water and nutrients and therefore the nitrate leaching is going to be overestimated.

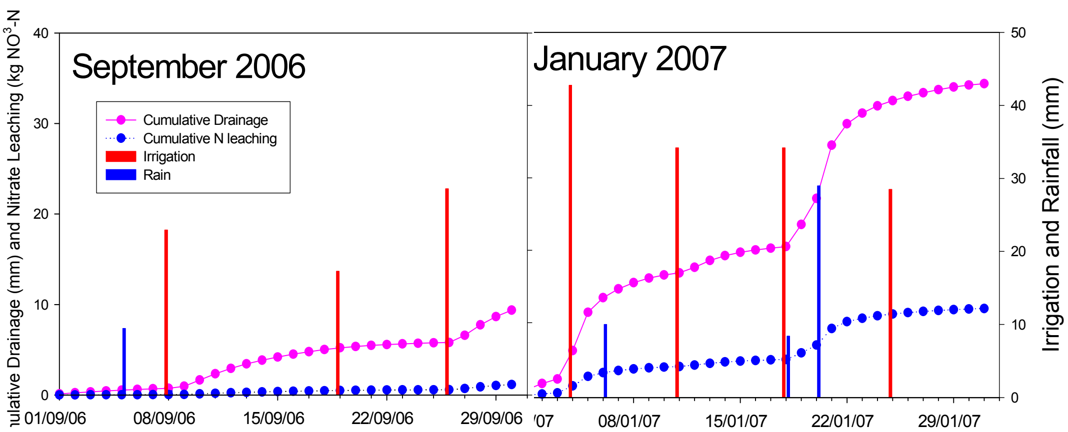


Figure 2: Comparison between cumulative drainage and nitrate leaching for September (2006) and January (2007) for NOVA.

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

AFS deep drainage and nitrate leaching

Soil pore water from the AFS site was sampled weekly with sampling commencing on the 28th of August 2006 and continuing through to the 10th of Dec 2007. Soil profile NO_3-N concentration at 1.5 m depth over this period is shown in Figure 3. Irrigation, rainfall, ETo and nitrogen input through fertigation are also shown in Figure 3.

A number of different types of fertilizers were used including ammonium nitrate and mono ammonium phosphate up until the 9th of April 2007 and then ammonium sulphate, magnesium nitrate, potassium nitrate and mono ammonium phosphate after the 27th of August 2007. Any nitrate present at 100 cm or below was assumed to be lost to leaching. The line at the 10 mg/L NO_3-N mark indicates the maximum concentration before there is a greater risk of groundwater contamination.

The data shows that generally the NO_3-N is below 10 mg/L during the initial stages of the two fertigation seasons as well as during the winter period of no fertigation (between 9th March and 27th August). However, by late November the nitrate levels at 1.5 m had begun to record more than 10 mg/L NO_3-N. The second season showed an interesting trend where the nitrate concentration at depth was related to the amount of fertilizer applied. The data showed that initially a large amount of fertilizer was applied starting on the 27th of August. The first sign of elevated nitrate levels at 1.5 m depth was observed on 22nd October indicating that it took nearly two months for nitrate to reach this depth. The nitrate concentration peaked on the 1st January 2007 where it recorded 41 mg/L NO_3-N. At these high concentrations any excess water drained through the bottom of the root zone will leach this nitrate, potentially causing environmental damage. The irrigation would also play a significant role in increasing the depth of nitrate with the wetting front. Any optimization 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 taking up. This combined with refined fertilizer management would ensure that nitrate does not exceed the threshold level which will optimize the fertilizer efficiency and reduce the threat to the environment.

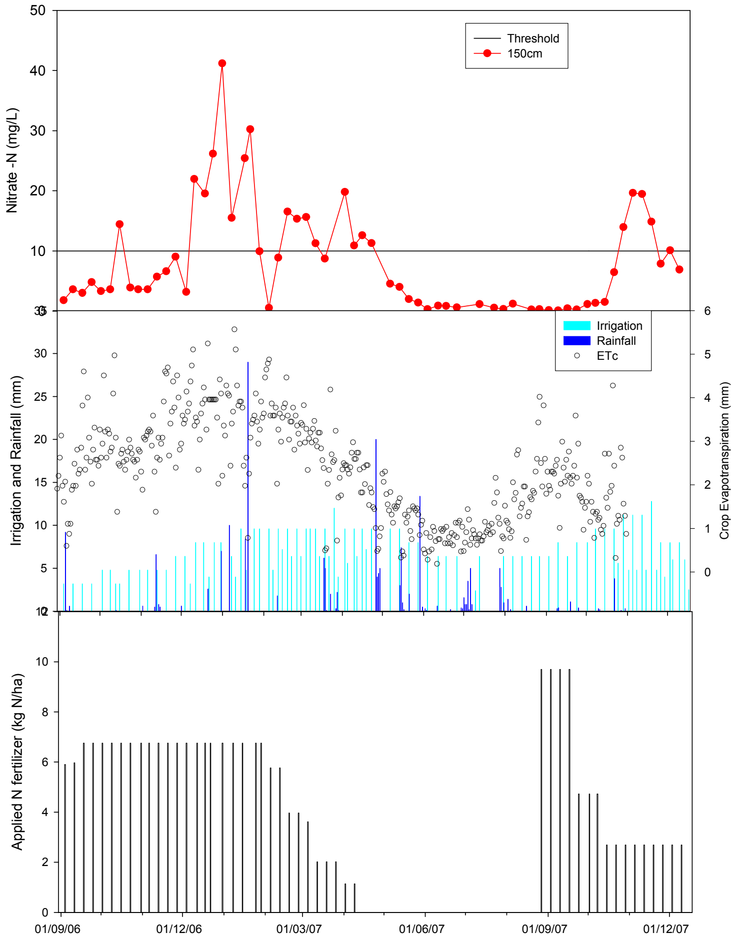


Figure 3: Soil solution Nitrate-N concentrations in relation to water and fertilizer application at the AFS site.

Figure 4 shows the change in matric potential from the tensiometers between the 30th August and 18th December 2007. The data shows that wetting fronts frequently reached the 0.9 and 1.3 m depths. Unlike the sprinkler irrigated NOVA site, AFS site received drip irrigation and therefore the wetting pattern was expected to be non-uniform. This made it more difficult to determine the deep drainage flux and nitrate leaching from one point scale measurement within the three dimensional wetted zone.

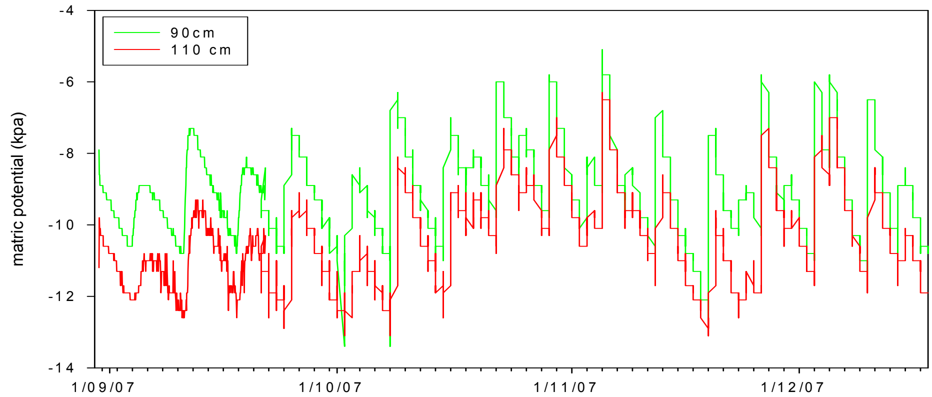


Figure 4: Log Tensiometer derived matric potential readings at 90 and 120 cm depths from AFS site.

To resolve this soil sampling was conducted one day after an irrigation of 12 mm to try and determine the shape of the wetted zone by sampling in a grid pattern (data not shown). The water content did not change substantially along the drip line but showed a sausage wetting shape similar to that reported by Assouline (2002). Therefore, the AFS site was conceptualised as a tube of wetted zone along the drip line with decreasing water away from the dripper into the row. Because of difficulty of determining the width of the bottom boundary of wetted zone subject to deep drainage, four different drainage widths were used, including 1.25, 0.8, 0.6 and 0.4 m across the row, which related to a fractional area subject to draining of 0.25, 0.16, 0.12 and 0.08.

Between 30th August and 12th December 2007 the total amount of water applied was 205 mm and the drainage calculated over the entire row length was 315 mm. Table 3 shows four different drainage scenarios. The calculated drainage ranged from 25 to 79 mm depending on the assumed bottom wetting areas for deep drainage. The calculated LF varied between 10 and 32%. The nitrate leaching was low throughout with a range of 1.9 to 6 kg NO_3-N ha^{-1}.

Table 3: Calculated deep drainage and nitrate leaching at AFS between 30 Aug 07 to 18 Dec 07 for a range of bottom boundary fractions associated with deep drainage.

Fraction of row width associated with deep drainage	Deep Drainage from bottom boundary (mm)	Nitrate Leaching (kg $NO3^{-1}$-N ha^{-1})	Leaching Fraction (%)
0.25	78.6	6	32.2
0.16	50.3	3.9	20.6
0.12	37.7	2.9	15.5
0.08	25.2	1.9	10.3

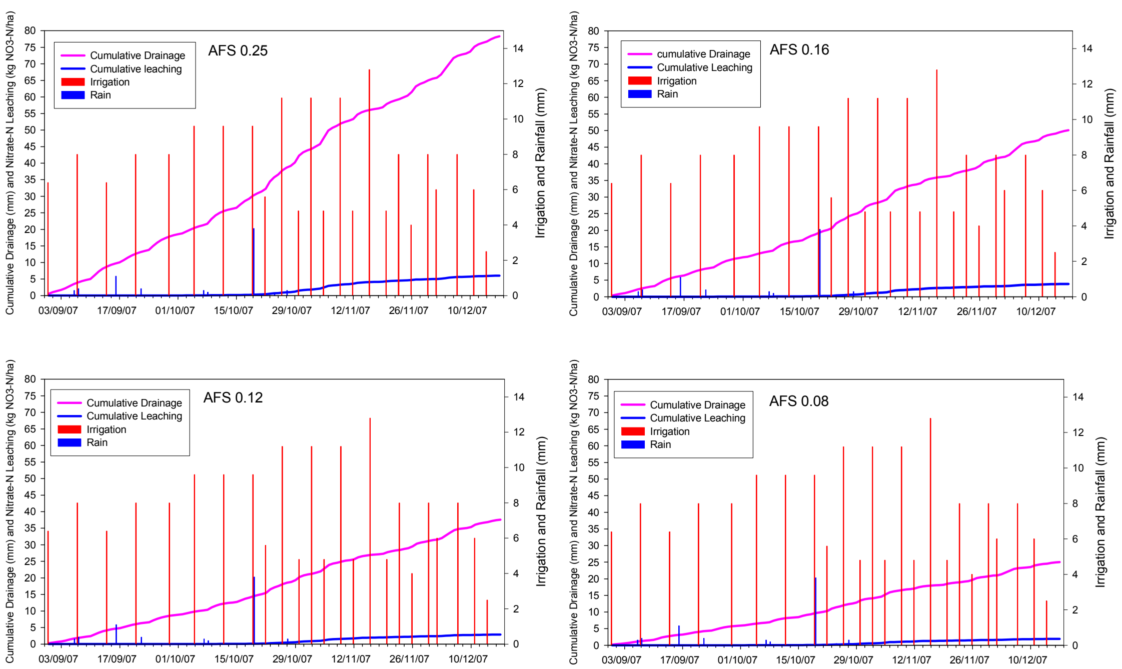


Figure 7: Cumulative drainage, nitrate leaching, irrigation and rainfall at AFS for the period between 30/8/07 to 18/12/07. The different numbers represent the width of the bottom draining boundary relative to the entire width of the tree row.

This data set for drainage and leaching at AFS only represents the beginning of the fertigation season. It has been shown that the highest nitrate concentrations at 1.5m depth occur during the summer and therefore at the end of the current season the total drainage and leaching is hypothesised to be much higher. The width of the bottom boundary associated with drainage is uncertain but had to be estimated owing to the use of point source data to characterise a three dimensional system. The next step is to use the field data to run and calibrate an unsaturated hydraulic model to determine the actual deep drainage and nitrate leaching. HYDRUS 2/3D has been chosen as the numerical model for this task (Simunek et al., 1999).

Conclusion

The study used tensiometers and ceramic cup soil water samplers at two different depths below the root zone to calculate deep drainage and nitrate leaching for an AF citrus trial site in the Sunraysia Region. The results showed that drainage was between 25 and 78 mm and nitrate leaching was between 1.9 and 6 NO_3-N ha^{-1} for the period between 30th of August to the 18th of December 2007. This time period represents the beginning of the fertigation season. The results showed that for the previous year the nitrate concentration in the 1.5 m SoluSAMPLER was regularly over the 10 mg/L NO_3-N ha^{-1} threshold between November and March and therefore by the end of the current season it is predicted that the nitrate leaching will be much higher. The range of drainage and nitrate leaching is due to the uncertainty regarding the width of the bottom of the root zone associated with leaching. This problem stems from the fact that point source data is being used to try and characterise the three dimensional wetted zone. Extensive spatial sampling to determine the extent of the deep drainage across the row is economically unviable and for this reason a numerical model is being developed to simulate the citrus root zone. The mature tree comparison between September 2006 and January 2007 showed the drainage and nitrate leaching was much higher in January as compared to September. This method of assessing deep drainage and nitrate leaching has been shown to be a viable option for assessing the environmental impacts of AF, due to nitrate leaching and will help in optimizing fertilizer use in citrus production.

Acknowledgements

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