Solute Dynamics
in
Advanced Fertigated Horticulture

Submitted by

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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.