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Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree

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ABSTRACT

Adoption of high input irrigation management systems for South Australian horticultural crops seeks to provide greater control over timing of irrigation and fertilizer applications. The HYDRUS 2D/3D model was used to simulate water movement in the soil under an orange tree planted in a field lysimeter supplied with 68.6 mm of irrigation water over 29 days. Simulated volumetric water contents statistically matched those measured using a capacitance soil water probe. Statistical measures (*MAE*, *RMSE*, t_{cal}) indicating the correspondence between measured and simulated moisture content were within the acceptable range. The modelling efficiency (*E*) and the relative efficiency (*RE*) were in the satisfactory range, except *RE* at day 19. Simulated daily and cumulative drainage fluxes also matched measured values well. Cumulative drainage flux was 48.9% of applied water, indicating large water losses even under controlled water applications. High drainage losses were due to light texture of the soil and high rainfall (70 mm) during the experimental period. Simulated root water uptake was 40% of applied water.

The calibrated HYDRUS model was also used to evaluate several scenarios involving nitrate fertigation. The numerical analysis of NO_3-N dynamics showed that 25.5% of applied fertilizer was taken up by the orange tree within 15 days of fertigation commencement. The rest of the applied NO_3-N (74.5%) remained in the soil, available for uptake, but was also vulnerable to leaching later in the growing season. The seasonal simulation revealed that NO_3-N leaching accounted for 50.2% of nitrogen applied as fertilizer, and plant N recovery amounted to 42.1%. The scenario analysis further revealed that timing of a nitrogen application in an irrigation event had little impact on its uptake by citrus in the lysimeter. However, slightly higher NO_3-N uptake efficiency occurred when fertigation was applied late in the daily irrigation schedule, or was spread out across all irrigation pulses, rather than being applied early or in the middle. Modelling also revealed that pulsing of irrigation had little impact on nitrate leaching and plant uptake. Applying less irrigation (50% or 75% of ET_C) resulted in higher nitrate uptake efficiency. This study showed that timing of water and fertilizer applications to an orange crop can be better regulated to enhance the efficiency of applied inputs under lysimeter conditions.

1. Introduction

High frequency irrigation systems involve fastidious planning and complex designs, so that timely and accurate additions of water and fertilizer can result in sustainable irrigation. At the same time these production systems are becoming more intensive, in an effort to optimise the return on expensive and scarce resources such as water and nutrients. Advanced fertigation systems combine drip irrigation and fertilizer application to deliver water and nutrients directly to the roots of crops, with the aim of synchronising the applications with crop demands (Assouline, 2002), and maintaining the desired concentration and distribution of ions and water in the soil (Bar-Yosef, 1999). Hence a clear understanding of water dynamics in the soil is important for the design, operation, and management of irrigation and fertigation under drip irrigation (Li et al., 2004). However, there is a need to evaluate the performance of these systems, because considerable localised leaching can occur near the driplines, even under deficit irrigation conditions (Hanson et al., 2008). The loss of nutrients, particularly nitrogen, from irrigation systems can be expensive and pose a serious threat to receiving water bodies (Van der Laan et al., 2010).

Citrus is one of the important horticultural crops being grown under advanced fertigation systems in Australia. Fertigation delivers nutrients in a soluble form with irrigation water directly into

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the root-zone, thus providing ideal conditions for rapid uptake of water and nutrients. Scholberg et al. (2002) demonstrated that more frequent applications of a dilute N solution to citrus seedlings doubled nitrogen uptake efficiency compared with less frequent applications of a more concentrated nutrient solution. Delivery of N through fertigation reduces N losses in the soil-plant system by ammonia volatilisation and nitrate leaching (Alva et al., 2008). However, poor irrigation management, i.e., an application of water in excess of crop requirements, plus the storage capacity of the soil within the rooting depth, can contribute to leaching of water and nutrients below the rootzone. Therefore, optimal irrigation scheduling is important to maximise the uptake efficiencies of water and nutrients (Alva et al., 2005).

Most of the citrus production along the Murray River corridor is on sandy soils, which are highly vulnerable to rapid leaching of water and nutrients. Nitrogen is the key limiting nutrient and is therefore a main component of fertigation. An increasing use of nitrogenous fertilizers and their subsequent leaching as nitrate from the rootzone of cropping systems is recognised as a potential source of groundwater contamination, because the harvested crop seldom takes up more than 25–70% of the total applied fertilizer (Allison, 1996). Several researchers have reported substantial leaching (6–45%) of applied N under citrus cultivation in field conditions (Wang and Alva, 1996; Paramasivam et al., 2002; Sluggett, 2010). Similarly, in lysimeter experiments, Boaretto et al. (2010) showed 36% recovery of applied nitrogen by orange trees, while Jiang and Xia (2008) reported N leaching of 70% of the initial N value, and found denitrification and leaching to be the main processes for the loss of N. These studies suggest that knowledge of the nitrogen balance in cropping systems is essential for designing and managing drip irrigation systems and achieving high efficiency of N fertilizer use, thereby limiting the export of this nutrient as a pollutant to downstream water systems.

Quantifying water and nitrogen (N) losses below the root zone is highly challenging due to uncertainties associated with estimating drainage fluxes and solute concentrations in the leachate, even under well-controlled experimental conditions (Van der Laan et al., 2010). Moreover, direct field measurements of simultaneous migration of water and nitrogen under drip irrigation is laborious, time-consuming and expensive (Bar-Yosef and Sheikholslami, 1976; Kachanoski et al., 1994). Hence simulation models have become valuable research tools for studying the complex and interactive processes of water and solute transport through the soil profile, as well as the effects of management practices on crop yields and on the environment (Pang and Letey, 1998; Li et al., 2003). In fact, models have proved to be particularly useful for describing and predicting transport processes, simulating conditions which are economically or technically impossible to carry out in field experiments (Li and Liu, 2011).

Several models have been developed to simulate flow and transport processes, nutrient uptake and biological transformations of nutrients in the soil (Subbaiah, 2011). HYDRUS 2D/3D (Šimůnek et al., 2008, 2011) has been used extensively for evaluating the effects of soil hydraulic properties, soil layering, dripper discharge rates, irrigation frequency and quality, timing of nutrient applications on wetting patterns and solute distribution (e.g., Cote et al., 2003; Gärdenäs et al., 2005; Assouline et al., 2006; Hanson et al., 2006; Ajdary et al., 2007; Patel and Rajput, 2008; Šimůnek and Hopmans, 2009; Phogat et al., 2009, 2010, 2012, 2013; Li and Liu, 2011; Ramos et al., 2012) because it has the capability to analyse water flow and nutrient transport in multiple spatial dimensions (Cote et al., 2003).

In the absence of experimental data we can use multidimensional models solving water flow and nutrient transport equations to evaluate the multi-dimensional aspect of nitrate movement under fertigation (Cote et al., 2003; Gärdenäs et al., 2005; Hanson et al., 2006). However, earlier simulation studies have reported contradictory results on nitrate distribution in soils. For example, Cote et al. (2003) reported that nitrate application at the beginning of an irrigation cycle reduced the risk of leaching compared to fertigation at the end of the irrigation cycle. On the other hand, Hanson et al. (2006) reported that fertigation at the end of an irrigation cycle resulted in a higher nitrogen use efficiency compared to fertigation at the beginning or middle of an irrigation cycle. These studies very well outlined the importance of numerical modelling in the design and management of irrigation and fertigation systems, especially when there is a lack of experimental data on nutrient transport in soils. However, there is still a need to verify the fate of nitrate in soils with horticultural crops and modern irrigation systems.

Fig. 1. Drainage pipes and a filter sock placed at the bottom of the lysimeter.

Therefore, a lysimeter was established to observe water movement and drainage under drip irrigated navel orange, and to calibrate the HYDRUS 2D/3D model against collected experimental data. The model was then used, in the absence of experimental data on nitrate, to develop various modelling scenarios to assess the fate of nitrate for different irrigation and fertigation schemes.

2. Materials and methods

2.1. Lysimeter setup

The study was conducted on a weighing lysimeter assembled and installed at the Loxton Research Centre of the South Australian Research and Development Institute. The lysimeter consisted of a PVC tank (1 m diameter × 1.2 m height) located on 1.2 m × 1.2 m pallet scales fitted with 4 × 1 tonne load-cells, and connected to a computerised logging system which logged readings hourly. A specially designed drainage system placed at the bottom of the lysimeter consisted of radially running drainage pipes, which were connected to a pair of parallel pipes, which facilitated a rapid exit of drainage water from the lysimeter (Fig. 1). These pipes were covered in a drainage sock and buried in a 25-cm layer of coarse washed river sand at the base of the lysimeter, which ensured easy flushing of water through the drainage pipe. A layer of geo-textile material was placed over the top of the sand layer to prevent roots growing down into it, as this layer was intended to be only a drainage layer.

A healthy young citrus tree (about 3 years old) was excavated from an orchard at the Loxton Research Centre and transplanted into the lysimeter. A soil profile approximately 85 cm deep was transferred to the tank with the tree and saturated to remove air pockets and to facilitate settling. The final soil surface was around 10 cm below the rim of the tank. Soil samples were collected from