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Evaluation of urea–ammonium–nitrate fertigation with drip irrigation using numerical modeling

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ABSTRACT

Microirrigation with fertigation provides an effective and cost-efficient way to supply water and nutrients to crops. However, less-than-optimum management of microirrigation systems may cause inefficient water and nutrient use, thereby diminishing expected yield benefits and contributing to ground water pollution if water and nitrogen applications are excessive. The quality of soils, ground, and surface waters is specifically vulnerable in climatic regions where agricultural production occurs mostly by irrigation such as in California. Robust guidelines for managing microirrigation systems are needed so that the principles of sustainable agriculture are satisfied. The main objective of this research was to use an adapted version of the HYDRUS-2D computer model to develop irrigation and fertigation management tools that maximize production, yet minimize adverse environmental effects. This software package can simulate the transient two-dimensional or axisymmetrical three-dimensional movement of water and nutrients in soils. In addition, the model allows for specification of root water and nitrate uptake, affecting the spatial distribution of water and nitrate availability between irrigation cycles. Recently, we analyzed four different microirrigation systems in combination with five different fertigation strategies for various soil types using a nitrate-only fertilizer, clearly demonstrating the effect of fertigation strategy on the nitrate distribution in the soil profile and on nitrate leaching. In the present study, the HYDRUS-2D model was used to model the distribution of soil nitrogen and nitrate leaching using a urea–ammonium–nitrate fertilizer, commonly used for fertigation under drip irrigation. In addition, the distribution of phosphorus and potassium was modeled. Model simulations are presented for surface drip and subsurface drip tape, each associated with a typical crop in California.

1. Introduction

Microirrigation with fertigation provides an effective and cost-efficient way to supply water and nutrients to crops (Bar-Yosef, 1999). However, less-than-optimum management of microirrigation systems resulting in excessive water and nitrogen applications may result in inefficient water and nutrient use, thereby diminishing expected yield benefits and contributing to ground water pollution. The quality of soils, ground, and surface waters is specifically vulnerable in climatic regions where agricultural production occurs mostly by irrigation, such as in California. Liquid nitrogen (N) fertigation, using mixtures of urea, ammonium, and nitrate compounds, is widely used with microirrigation. Robust guidelines for managing microirrigation systems are needed so that the principles of sustainable agriculture are satisfied.

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The mathematical formulation with corresponding analytical solutions of transient transport in soils to include transformation of ammonia and nitrate for steady state water flow was presented by Misra et al. (1974). Wagenet et al. (1977) extended the theory to include urea transport, determining the control of soil oxygen concentration, and initial urea concentration on urea hydrolysis. The various N transformation processes in soils occur mostly by microbial processes that are predicted by first-order reaction kinetics, but are complex because of their coupled nature and their control by soil environmental conditions such as soil water and temperature. Nitrogen transport and transformations with transient water flow to include plant uptake, nitrification, denitrification, immobilization, mineralization, and ionic exchange was modeled for the first time by Selim and Iskandar (1981) by simultaneously solving the transport equations for the different N species with the purpose to evaluate nitrogen fate for a wide range of nitrification rate, ammonium retardation and N-uptake values. Other one-dimensional models, that were specifically developed for N-transport in soils, include the simulation model by Tanji et al. (1981), DAISY (Hansen et al., 1990), LEACHN (Hutson and Wagenet, 1991), COUP (Jansson and Karlberg, 2001), and the lumped parameter model LPM (Ling and El-Kadi, 1998).

While high field-scale uniformity is possible under microirrigation, the distribution of both water and nitrate about the drip line is very nonuniform. Both soil water content and chemical concentration will be the highest near the drip line after application, but water and chemicals will redistribute thereafter as controlled by soil physical properties. Because of the typical nonuniform wetting patterns, it is essential to use multi-dimensional modeling to develop optimal fertigation practices for optimum nutrient use efficiency. In the absence of experimental data, we can use mathematical solutions of the governing multi-dimensional water and nutrient transport equations to evaluate the multi-dimensional aspects of nitrate fertigation. Yet, few computer simulation models have the capability to analyze water flow and nutrient transport in multiple spatial dimensions, with the exception of HYDRUS-2D (Somma et al., 1998; Šimůnek et al., 1999; Cote et al., 2003) and FUSSIM2 (Heinen, 2001). The HYDRUS model allows for specification of root water and nitrate uptake, affecting the spatial distribution of water and nitrate availability between irrigation cycles. As documented by Weinbaum et al. (1992) and later by Hopmans and Bristow (2002), few studies evaluated the interrelationships between rates and spatial distribution of N application, root distribution and growth, and total plant uptake. Most recently, a first step in this general direction was achieved by Gärdenäs et al. (2005), where four different microirrigation systems were analyzed in combination with five different fertigation strategies for various soil types, clearly demonstrating the effects of root distribution and fertigation strategy on the uniformity of water and nutrients around drip lines and their effects on water drainage and associated nitrate leaching.

In concept, the rhizosphere dynamics of water and nutrient uptake is very complex, and may have to consider differentiation between passive and active nutrient uptake, while including N mineralization (Bar-Yosef, 1999), denitrification and rhizosphere acidity (Pierre and Banwart, 1973). In order to not be overcome by these many complications of which the relative magnitude and relevance is yet to be determined, this study makes the typical assumption that root uptake of ammonium and nitrate is strictly passive and assumes that the other listed mechanisms are not occurring.

The main objective of this study was to use a state-of-the-art modeling tool to evaluate irrigation and fertigation practices. For that purpose we applied the HYDRUS-2D model (Šimůnek et al., 1999) to evaluate the control of fertigation strategy with microirrigation on both the movement and fate of a liquid urea–ammonium–nitrate fertilizer, mixed with phosphorus and potassium in the irrigation water for two commonly used microirrigation systems.

2. Materials and methods

The modeling of water flow and fertigation scenarios was conducted using an adapted version of the computer simulation model HYDRUS-2D (Šimůnek et al., 1999). This software package can simulate the transient two-dimensional or axisymmetrical three-dimensional movement of water and nutrients in soils. In addition, the model allows for specification of root water and nitrate uptake, affecting the spatial distribution of water and nitrate availability between irrigation cycles. The database of the model contains the values of the parameters specifying the hydraulic properties for the various soil types that are required for the simulation model. For each soil type and emitter type, the spatial patterns of water content and nitrate concentration were determined for various fertigation strategies. These strategies included different nutrient injection durations, different injection times relative to the irrigation set time, and different concentrations. Model simulations will be presented for two different pressurized irrigation systems, each associated with a typical crop and representing two commonly used microirrigation systems in California: surface drip (DRIP; grape) and subsurface drip tape (SUBTAPE; processing tomatoes).

2.1. *Modeling domain and nitrogen reactions*

The irrigation layouts for the two selected microirrigation systems with characteristic dimensions, including emitter and irrigation line spacing, are presented in Fig. 1, whereas relevant irrigation application and model parameters are presented in Table 1. DRIP (Fig. 1A) is considered a point source so that axisymmetric-radial geometry is assumed, whereas the SUBTAPE (Fig. 1B) layout was simulated using the line-source model with a rectangular geometry, because of the multiple outlets along the tape. The model domain for these microirrigation system layouts represents the area explored by roots, based on field measurements and experience (Bassoi et al., 2003; May and Hanson, 2005). More detailed information about the simulation model and model parameters can be found in Gärdenäs et al. (2005).

Irrigation water concentrations of phosphorus and potassium were 1.0 M L^{-3}, while applied irrigation water concentrations for urea, ammonium, and nitrate were 0.5, 0.25, and 0.25 M L^{-3}, respectively, with nitrogen concentrations corresponding to the proportion of nitrogen in the fertilizer solution