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Evaluation of subsurface drip irrigation design and management parameters for alfalfa

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ABSTRACT

Alfalfa is one of the most cultivated crops in the US, and is being used as livestock feed for the dairy, beef, and horse industries. About nine percent of that is grown in California, yet there is an increasing concern about the large amounts of irrigation water required to attain maximum yield. We introduce a conceptual framework to assist in the design and management of subsurface drip irrigation systems for alfalfa that maximize yield, while minimizing deep percolation water losses to groundwater. Our approach combines the strengths of numerical modeling using HYDRUS-2D with nonlinear optimization using AMALGAM and Pareto front analysis. The HYDRUS-2D model is used to simulate spatial and temporal distributions of soil moisture content, root water uptake, and deep drainage in response to drip-line installation depth and distance, emitter discharge, irrigation duration and frequency. This model is coupled with the AMALGAM optimization algorithm to explore tradeoffs between water application, irrigation system parameters, and crop transpiration (T_a), to evaluate best management practices for subsurface drip irrigation systems in alfalfa. Through analysis of various examples, we provide a framework that seeks optimal design and management practices for different root distribution and soil textures.

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1. Introduction

Alfalfa is one of the most widely cultivated crops in the world, and is used as livestock feed for the dairy, beef, and horse industries (Breazeale et al., 2000). The United States is the world's largest producer of alfalfa, with an annual value of about one billion dollars. About nine percent of all alfalfa produced in the United States is grown in California, with an average acreage of 360,000 ha (900,000 acres, Alfalfa's commodity fact sheet, 2011).

Because of California's semi-arid climate, irrigation is necessary to attain high yields. In California, about 1.2 billion m^3 of water is used to irrigate alfalfa each year, which is about 20% of California's developed water supply (Natural Resources Defense Council, 2001; Putnam et al., 2001). These large amounts of required irrigation water have encouraged the development and application of efficient irrigation systems. Hutmacher et al. (2001) reported a 20% increase in water use efficiency for alfalfa by using subsurface drip irrigation (SDI) rather than furrow irrigation. Another comparison between SDI and flood irrigation by Godoy et al. (2003) demonstrated that subsurface irrigation significantly improved the yield by about 25%, while using about 40% less water than flood irrigation. The study by Alam et al. (2002) showed that a well-designed SDI system can potentially decrease the volume of applied water by about 22%, while increasing the yield by 7%, compared to using a center pivot sprinkler system.

Alfalfa, a perennial crop, is harvested between 3 and 11 times throughout the year, depending on soil, irrigation practice, and climatic conditions. One of the biggest challenges in alfalfa production is the selection of irrigation design and management practices that maximize yield (and thus income), while simultaneously minimizing water losses. In addition, at harvesting times the soil surface should be sufficiently dry so that machinery can drive over the field without creating stressed root zone soil moisture conditions, allowing for quick re-growth of the cut alfalfa. In addition, the nonlinearity of soil–water–plant relationship makes it particularly difficult to find irrigation systems and strategies that maximize yield while simultaneously minimizing water losses. For all these reasons the optimal irrigation system and design practices are not immediately obvious for most climatic and soil conditions. A subsurface drip system, however, is ideally suited as it directly supplies water to the rooting zone at high frequency, allowing control of surface soil moisture required, for dry soil surface conditions prior

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Nomenclature

- AW_{max} maximum possible applied water [$L^3\,L^{-2}$]
- D drip-line depth [L]
- DP deep percolation [$L^3\,L^{-2}$]
- DP_{max} maximum possible deep percolation [$L^3\,L^{-2}$]
- ET_a actual evapotranspiration [LT^{-1}]
- ET_o reference evapotranspiration [LT^{-1}]
- ET_p potential evapotranspiration [LT^{-1}]
- f irrigation frequency [T^{-1}]
- FE finite elements
- h soil water pressure head [L]
- h_1, h_2, h_3, and h_4 parameters of Feddes uptake reduction function [L]
- ID irrigation duration [T]
- $I1$ optimization scenario such that $\omega_D = \omega_L = \omega_{AW} = \omega_{DP} = 1$
- $I2$ optimization scenario such that $\omega_D = 0$ and $\omega_L = \omega_{AW} = \omega_{DP} = 1$
- $I3$ optimization scenario such that $\omega_D = \omega_{DP} = 0$ and $\omega_L = \omega_{AW} = 1$
- ISA irrigation scheduling Alfalfa model
- $K(h)$ unsaturated hydraulic conductivity [LT^{-1}]
- K_c crop coefficient
- K_s saturated hydraulic conductivity [$L\,T^{-1}$]
- L drip-line distance [L]
- l shape parameter in the van Genuchten soil hydraulic functions
- L_x width of the soil surface associated with transpiration [L]
- m shape parameter in the van Genuchten soil hydraulic functions, $m = 1 - 1/n$
- N number of irrigation events
- n shape parameter in the van Genuchten soil hydraulic functions
- OF_i objective function (i)
- Q drip-line discharge [$L^3\,L^{-1}\,T^{-1}$]
- q drip-line discharge [$L^3\,L^{-2}\,T^{-1}$]
- $R1$ optimization scenario using uniform root distribution
- $R2$ optimization scenario using linear root distribution
- $S(x,z)$ sink term [$L^3\,L^{-3}\,T^{-1}$]
- SDI subsurface drip irrigation
- S_e effective saturation
- S_p potential root water uptake [$L^3\,L^{-3}\,T^{-1}$]
- t time [T]
- $T1$ optimization scenario using clay-loam soil
- $T2$ optimization scenario using loam soil
- $T3$ optimization scenario using sandy-loam soil
- T_a actual plant transpiration [LT^{-1}]
- T_p potential plant transpiration [LT^{-1}]
- x horizontal spatial coordinate [L]
- z vertical spatial coordinate [L]
- $\alpha(h)$ Feddes' uptake reduction function
- α_{VG} shape parameter in the van Genuchten soil hydraulic functions
- $\beta(x,z)$ normalized root density for any coordinate in the two-dimensional soil domain [L^2]
- θ volumetric water content [$L^3\,L^{-3}$]
- θ_r residual water content [$L^3\,L^{-3}$]
- θ_s saturated water content [$L^3\,L^{-3}$]
- Ω root zone area [L^2]
- ω_D, ω_L, ω_{AW}, ω_{DP} weighting factors for D, L, AW, and DP in objective functions

to alfalfa cutting. We use detailed numerical soil water flow modeling with HYDRUS-2D (Šimůnek et al., 2008), combined with a multi-criteria optimization framework to determine optimal irrigation water management strategies for subsurface drip irrigation of alfalfa.

Past sensitivity analysis (Gärdenäs et al., 2005) has shown that the root distribution exerts strong influence on subsurface drip irrigation design and management practices, as water uptake by plant roots determines spatial and temporal patterns in soil water availability. Whereas various past studies investigated root distributions of alfalfa (Abdul-Jabbar et al., 1982; Meinzer, 1927), we know of no studies that evaluate the effects of SDI on alfalfa root distribution.

The ever increasing pace of computational power along with significant advances in numerical modeling of soil–plant–water relationships enables the application of numerical vadose zone simulation models for analyses of micro-irrigation systems involving a wide range of crops. The HYDRUS-2D (Šimůnek et al., 2006, 2008) model has been widely used for this purpose, including for SDI (Gärdenäs et al., 2005; Hanson et al., 2006; Skaggs et al., 2006; Hanson et al., 2008). The effect of different irrigation design variables such as drip-line distance and drip-line installation depth can be readily simulated by such a modeling system for a range of soil types. Whereas these design parameters are relevant to water availability for crops and soil types, drip-line depth and distance also have economic consequences as they essentially determine irrigation system costs. Other factors to consider are leaching losses, rodent damage, and requirement of soil dryness before harvesting.

In this study, we present a general purpose multi-criteria optimization framework to help in the design of optimal subsurface drip irrigation systems for alfalfa. Instead of providing specific irrigation system and water application recommendations, we present a flexible optimization tool that allows definition of a range of objective functions to be minimized, using multiple criteria and weights. Our approach combines the strengths of numerical vadose zone modeling using HYDRUS-2D with the AMALGAM evolutionary search (Vrugt and Robinson, 2007) and Pareto front (Wöhling et al., 2008) algorithms, to provide water application strategies that maximize yield and minimize water loss for a range of irrigation system designs. In particular, we seek to optimize drip-line installation depth and distance, irrigation duration, and irrigation frequency, while maximizing root water uptake and minimizing irrigation water losses by leaching. In addition, our analysis is especially designed to ensure sufficiently dry soil surfaces at harvesting times. These optimal parameters are determined for different root distribution (uniform and linear), and soil types (sandy loam, loam, and clay loam). We realize that economics of irrigation system and water costs should also be considered, however, we do not consider these factors in the present analysis, as dollar values can be easily included in the formulation of the objective functions when available.

2. Materials and methods

A schematic of the followed computational procedures to arrive at the final set of optimal design and decision parameters is shown in the flow chart of Fig. 1. The main computational loop is defined by the AMALGAM evolutionary search algorithm (Vrugt and Robinson, 2007), selecting specific values of drip-line installation depth (D) and distance (L), irrigation duration (ID) and frequency (f) from