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Scheduling irrigation using an approach based on the van Genuchten model

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ABSTRACT

Crop irrigation which results in high water use efficiencies typically uses science-based irrigation scheduling tools to determine irrigation application timing and quantities. Although a large variety of sensors are available for measuring soil moisture status, there are a few easy-to-use irrigation scheduling tools which provide a yes/no irrigation decision or recommend how much water should be applied to return the soil profile to an optimal soil moisture condition. The work described here developed a method which uses soil water tension data from soil moisture sensors and the van Genuchten model to provide irrigation scheduling recommendations. The strength of the method is that it can use data readily available from USDA-NRCS soil surveys to predict soil water retention curves and calculate the volumetric water content and soil water tension of a soil at field capacity. Those parameters are then used to translate measured soil water tension into irrigation recommendations which are specific to the soil moisture status of the soil. The method was validated by comparing its results to other published methods and with continuous soil water tension data with multiple wetting and drying cycles from six fields in southern Georgia, USA. Finally, the model was incorporated into a web-based irrigation scheduling tool and used in conjunction with a wireless soil moisture sensing system to schedule irrigation in a large commercial field during 2015. By the van Genuchten model, we used about two thirds of the irrigation water and produced about the same yields as a commonly used yes/no irrigation decision tool. The presented method can be used to build resiliency to climate variability because it provides growers with data which they can use to make informed decisions about managing their water resources.

1. Introduction

Agricultural irrigation is vital to food production in many parts of the globe and a critical tool for ensuring food security. Irrigation not only serves to reduce risk of crop loss but also to build resiliency to climate variability and yield stability in food production systems. Irrigated agriculture provides 40% of the world's food while being used on only 18% of the cultivated land (FAO, 2015). The United Nations Food and Agricultural Organization estimates that the world currently consumes about 70% of available fresh water for irrigation (FAO, 2015). In the United States, irrigation withdrawals were estimated at 435 million m^3 per day in 2010 and accounted for 38% of total freshwater withdrawals (Maupin et al., 2014). In light of projected food needs of a growing world population, significant improvements in agricultural water use efficiency (WUE) leading to more crop per drop should be a high priority across multiple disciplines of science.

Irrigation which results in high WUE typically uses science-based irrigation scheduling tools to determine irrigation application timing and quantities. A large number of techniques and tools have been developed to assist growers to estimate when and how much water to apply to crops. Yet data recently released by the 2013 USDA National Agricultural Statistical Service Farm and Ranch Irrigation Survey indicated that more than 72% of irrigated farms still rely either on a fixed schedule or on visual symptoms of plant stress such as wilting. Only 28% use any type of science-based irrigation scheduling tools and even fewer (12%) use irrigation scheduling methods such as soil moisture sensors or web-based tools that address conditions specific to their farms (NASS, 2013). Typically, farmers will apply a standard amount (for example, 25 mm or

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1 in.) at each irrigation event. As a result, both the timing and depths of irrigation may be inappropriate and may lead to yield, nutrient, and soil losses. The extent to which improper timing of irrigation can result in yield losses has been documented for many crops. For example, Vories et al. (2006) found that improper timing of irrigation in cotton can result in yield losses of USD 370 ha^{-1} to USD 1850 ha^{-1}. Sensors have been used to collect data for irrigation scheduling using several methods including sap flow, canopy temperature, and soil moisture measurements (Jones, 2004; O'Shaughnessy and Evett, 2010). In this paper we will focus on irrigation scheduling using soil water potential measurements.

1.1. Estimating field capacity

Knowing the range of plant available soil water content (AWC) is necessary to avoid crop water stress. The dry end of this range is at permanent willing point (PWP) and the wet end is at field capacity (FC). FC is generally described as the point at which gravitational water flow has ceased after rain or irrigation (Nemes et al., 2011) and is also defined as having a soil water potential in the range of −5 to −33 kPa (Tolk, 2003). PWP is generally defined as the soil water content at which plants irreversibly wilt and fail to recover and is also defined as having a soil water potential of −1500 kPa (Tolk, 2003). Soil water tension (SWT) is equal to the modulus of the soil water potential (Shock et al., 2013) and for simplicity will be used throughout the remainder of this paper instead of soil water potential.

For agronomic crops, soil water depletion down to 35–65% of AWC is often used as the threshold for initiating irrigation and the exact threshold varies between soil types and crop species (Alan et al., 1998; Girona et al., 2002; Irmak et al., 2014). Frequently the goal of irrigation events is to return the soil profile to FC (Irmak et al., 2014; Zotarelli et al., 2009). For proper irrigation controlling, it is particularly important to have a good estimate of FC otherwise irrigation events may result in the under- or over-application of water.

FC is notoriously difficult to measure *in situ* and the results are often not repeatable. Field experiments (e.g., Brito et al., 2011; de Jong van Lier and Wendroth, 2015) using the method of fluxed-based estimation and simulation studies (e.g., Twarakavi et al., 2009) show that it may take several days for a saturated soil profile to reach FC. For example, Brito et al. (2011) observed that it took 52–205 h to reach FC (defined as the soil water content at a flux rate of 0.01 mm d^{-1}) and that time was a function of soil texture and profile depth. In another study, drainage reached a flux rate of 0.01 mm d^{-1} after 83 h for sand and 303 h for clay (Twarakavi et al., 2009). Thus, *in situ* measurements are labor and time consuming. Lab measurements of FC usually determine the soil volumetric water content (VWC) at a SWT of 33 kPa (Majumdar, 2013; Rawls et al., 1982; Saxton and Rawls, 2006). However, this threshold is somewhat arbitrary and does not represent soils of different textures and with different horizons. FC should be defined for each specific soil and not by a universal SWT value (Nemes et al., 2011; Zacharias and Bohne, 2008) and its estimation should rather be flux- than SWT-based. For example, a SWT of 33 kPa is an underestimation of the *in situ* soil water content at FC in coarse-textured soils. FC is usually determined for the 12 USDA textural classes (Nemes et al., 2011; Twarakavi et al., 2009) overlooking some of the characteristics that individual soils within a certain textural class possess and their impact on FC. For instance, different percentages of silt and clay lead to variation in FC even within sandy soils (Zettl et al., 2011). It is thus imperative to further improve approaches to estimate soil-specific FC and SWT at FC.

1.2. Soil water retention curves

The transpiration requirements of plants result in tension being transmitted to the roots to extract water from the soil (Muñoz-Carpena et al., 2005; Shock et al., 2013), also known as the soil-plant-atmosphere continuum. As a measure of the energy status of soil water, SWT has been widely used in irrigation management and irrigation scheduling thresholds are often suggested in terms of SWT rather than VWC.

Soil matric sensors measure directly the tension required by plants to extract water from the soil (Thompson et al., 2007; Vellidis et al., 2008; Shock et al., 2013; Irmak et al., 2014). For effective irrigation scheduling, SWT thresholds must be converted to soil-specific irrigation volumes which replenish soil moisture but do not add excessive irrigation water which would result in water moving below the root zone causing leaching of nutrients and other crop inputs. To estimate this optimal irrigation amount, it is necessary to convert measured SWT to VWC and to also know the VWC of the soil at FC and PWP.

Soil water retention curves (SWRC) characterize the relationship between SWT and VWC and by those curves it is possible to describe the respective amounts of recharge and depletion of soil water between FC and PWP. SWRC can be utilized to translate SWT into VWC but the curves are difficult and time consuming to create experimentally and consequently generic curves found in the literature are frequently used (Fredlund and Xing, 1994; Rajkai et al., 2004; Ghanbarian-Alavijeh et al., 2010). A prerequisite for their use is to evaluate their accuracy in describing the changes in soil water status observed under field conditions.

1.3. Objectives

The goal of this study was to develop techniques for using SWRC to estimate optimal irrigation amounts from measured soil water tension by applying the van Genuchten (1980) model. The specific objectives of this research were to: (1) propose a new method of calculating FC using the van Genuchten model; (2) evaluate the accuracy of the van Genuchten model in converting SWT into VWC under field conditions; and (3) develop irrigation scheduling recommendations from the calculated VWCs.

2. Methods

2.1. The van Genuchten model

The van Genuchten model has been widely used to describe water retention behavior of soils. The model describes this relationship in a continuous function. Through the capillary rise equation SWT can be converted to an equivalent pore diameter, and the first derivative of SWRC reflects the pore size distribution of a soil. In the transition from saturated to increasingly unsaturated conditions, at first, the larger pores and subsequently pores with decreasing equivalent diameter are drained. The water in the larger pores is only weakly held by capillary forces, and with decreasing pore diameter, the water is retained with increasing SWT. Therefore, given the same cross sectional area of water-filled pore space, water in large pores flows much faster than in a bundle of smaller pores, we may conceptually link the segments of the SWRC to different rates of water transport. Large soil pores that are known to drain rapidly after long rain periods cover the range between water saturation and an inflection point of the SWRC. This range is also known for relatively small SWT changes with decreasing VWC. Between the inflection point and the PWP, soil water is held in smaller pores. In this range, SWT changes increasingly rapidly with each unit of soil water content decrease. The inflection point of SWRC segre-