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Development of an irrigation scheduling software based on model predicted crop water stress

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ABSTRACT

Modern irrigation scheduling methods are generally based on sensor-monitored soil moisture regimes rather than crop water stress. Crop water stress is difficult to measure in real-time, but can be computed using agricultural system models. In this study, an irrigation scheduling method and its facilitate software based on RZWQM2 model (Root Zone Water Quality Model) predicted crop water stress were developed and evaluated. The timing of irrigation was based on the occurrence of model-simulated water stress, while the depth of irrigation was based on the fraction of the soil moisture deficit (K) needed to replenish the soil water content (θ) at any given time to field capacity (θ_{fc}), *i.e.*, from θ_{t_0} to $\theta_{t_0} + K(\theta_{fc}-\theta_{t_0})$. The predicted water stress for different K values was tested based on RZWQM2 scenarios calibrated against data collected in a drip-irrigated corn (*Zea mays* L.) field near Greeley, Colorado, USA between 2008 and 2010, and in a sprinkler irrigated soybean [*Glycine* max (L.) Merr.] field in Noxubee, Mississippi, USA in 2014. For the Colorado site, the simulated full irrigation ($K = 1$) using this newly developed water stress-based irrigation approach saved 30.5%, 17.3% and 7.1% in total irrigation depth in successive years, whereas higher frequency with 60–90% of full irrigation at each event ($0.6 \le K \le 0.9$) provided water savings of as much as 35%, 30%, and 16%, respectively. The water stress-based irrigation scheme showed that crop yield was not affected, with a negligible change about 0.03–3.81% decrease. These water savings were a result of the water stress-based irrigation regime maintaining sufficient water to meet crop root water uptake requirements without constantly fully rehydrating the soil, thereby minimizing evaporation from the soil surface and soil water storage after grain filling. For the Mississippi site, this newly developed water stress-based irrigation software could improve crop yield by 291 kg ha^{-1} though consume 3.43 cm more water than field irrigation regime. Similarly, high frequency irrigation (lower K) under water stress-based regime resulted in higher water use efficiency. This study suggested that the water stress-based irrigation scheme could save water use and maintain crop yield in semi-arid region, while in humid region it could increase crop yield while consume more water. Further work is needed to install this system in an irrigated field and test its performance under different climate and soil conditions.

1. Introduction

Irrigation is particularly critical for agricultural production in arid and semi-arid agricultural areas where water resources are scarce. Smart irrigation is known as an important part of precision agriculture nowadays, where a well-scheduled and well-dosed irrigation regime is essential, as by applying the right amount of water at the right time one avoids plant demand being either exceeded or not met, resulting in reduced crop yield. If plant water demand is significantly exceeded by the quantity of water applied, the excessive water can carry pollutants off-site through either percolation or runoff (Annandale et al., 2011; English et al., 2002; Singh, 2010).

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Nomenclature

ψ_m	soil tension
θ	soil water content
θ_{fc}	θ across the root zone at field capacity
θ_{wp}	θ across the root zone at permanent wilting point
θ_{LL}	θ across the root zone at lowest limit determined by management allowable depletion (MAD)
θ_{t_0}	θ across the root zone on the day of irrigation ($cm^3\,cm^{-3}$)
K	the proportion of the $\theta_{fc}-\theta_{t_0}$ deficit which is replenished
N	the number of soil layer at the deepest simulated rooting depth on the day of irrigation (t_0) ($cm^3\,cm^{-3}$)
D_i	depth of ith layer (cm)
IR_{t_0}	required irrigation water supply calculated on the day of irrigation (t_0) under water stress based scheduling method (cm)
P_{t_0+4d}	cumulative precipitation expected for the day of irrigation (t_0) and the four subsequent days (cm)
D_s	deep seepage (cm)
ET_a	actual evapotranspiration (cm)
E_a	actual evaporation (cm)
T_a	actual transpiration (cm)
I	cumulative depth of irrigation from onset to end (cm)
P	cumulated precipitation from onset to end (cm)
R	runoff (cm)
SWS_o	soil water storage at the onset of concerned crop growth stage (cm)
SWS_e	soil water storage at the end of concerned crop growth stage (cm)
$\overline{SWS}$	average soil water storage over the period from onset to end (cm)
ΔI	irrigation water savings percentage comparing to field ET-WB treatments (%)
T_p^{SW}	Shuttleworth-Wallace potential transpiration (cm)
n	numbers of irrigation events

The four main methods of irrigation scheduling rely on: (i) evapotranspiration (ET) and water balance (ET-WB), (ii) soil tension (ψ_m) or soil moisture (θ) across the rooting depth, (iii) measurements of plant stress, and (iv) simulation models. In the first method, an estimate of ET coupled with the water balance equation allows a calculation of the soil water deficit, which is then compared with the readily available water (RAW). Triggered when the water depletion exceeds the RAW, individual irrigation events commonly return θ to field capacity (θ_{fc}). When correctly applied, ET-based irrigation scheduling practices have a long history of conserving water and maintaining crop yield and quality (Davis et al., 2009; McCready and Dukes, 2011; McCready et al., 2009). ET-based method is relatively easy to implement because of the easier achieved parameters. For some crops, smartphone apps or tools for ET-based irrigation scheduling have been developed and delivered equal or better yields with significantly less water than some irrigation systems (Bartlett et al., 2015; Migliaccio et al., 2016; Vellidis et al., 2014, 2015). However, possible errors in estimating crop coefficients (K_c), reference ET, and field features (*e.g.*, soil properties and site-specific rainfall) can result in this irrigation scheduling method failing to provide water savings (Devitt et al., 2008; McCready et al., 2009) or provide sufficient irrigation (Davis and Dukes, 2010; Gowda et al., 2007).

Irrigation scheduling methods based on ψ_m or θ are usually implemented through automatic irrigation controllers or systems which sense and maintain the soil's moisture status at certain depths (Hedley and Yule, 2009; Nemali and van Iersel, 2006). The determination of a lower limit or threshold of ψ_m or θ for different crops is essential to successfully apply this irrigation scheduling method and requires additional field studies (Hoppula and Salo, 2006; Migliaccio et al., 2010; Thompson et al., 2007a, b). Smart sensor arrays have been used to facilitate in-field spatial soil variability solutions (Dursun and Ozden, 2011; Gutierrez et al., 2014; Vellidis et al., 2008). With good management, θ-based methods are an effective way to schedule irrigation, conserve water and maintain crop yield (Cardenas-Lailhacar and Dukes, 2010; Haley and Dukes, 2012; Zotarelli et al., 2010). However, both ET-based and θ-based scheduling methods focus directly or indirectly on θ, which is not a direct indicator of crop water stress. If crop demand is very low due to high humidity, low radiation or cool temperatures, the crop may not suffer from water stress under a low θ.

Alternatively, irrigation schedules can be developed by directly estimating plant water stress (*e.g.*, dendrometry, fruit gauges, tissue water content sensors, as well as measures of growth, sap flow and stomatal conductance) (Jones, 2004; Steppe et al., 2008). Canopy temperature, measured by infrared thermometry or thermography, is one of the most widely used of such indicators (Bellvert et al., 2016; Emekli et al., 2007; Moller et al., 2007; O'Shaughnessy et al., 2011). Irrigation is then triggered at either a threshold time (O'Shaughnessy and Evett, 2010; O'Shaughnessy et al., 2012) or a canopy-temperature-derived crop water stress index (Alderfasi and Nielsen, 2001; Gontia and Tiwari, 2008; Idso et al., 1981; Jackson et al., 1981; Yuan et al., 2004). However, this scheduling method is constrained by the high variation of plant stress-related measurements due to the change in weather variables.

With a better understanding of the soil-plant-atmosphere continuum and the interactions between plants and the environment, irrigation scheduling has becoming more complex. Recently, models and tools have been used to facilitate irrigation scheduling: *e.g.*, CROPWAT (Augustin et al., 2015), SWAT (Maier and Dietrich, 2016), SIMERAW# (Mancosu et al., 2015), AquaCrop (Linker et al., 2016), DAISY (Seidel et al., 2016), as well as simple mathematical models (Lopes et al., 2016). However, with most of these irrigation scheduling methods it may prove difficult to predict plant water stress under different weather and soil conditions or select appropriate irrigation management responses. These methods except model-based method, mostly based on single indicator (soil water content/potential, a certain crop response), manage irrigations according to the thresholds of the indicator, without considering the crop responses under variable managements, soil and atmosphere conditions comprehensively. Model-based methods are more dependable as they estimate the crop responses with multiple factors. Some methods, in providing inaccurate irrigation timing and quantity recommendations, may result in excessive water apply and/or crop water stress during a growing season and therefore waste water and/or reduce crop yield. For example, when water stress was estimated later than the actual occurrence of water stress, the crop yield may decrease; on the other hand, when the soil water deficit was overestimated, more irrigation water could be applied than the soil water holding capacity, and thus result deep seepage and runoff.

A model effective in simulating comprehensive crop responses to atmospheric and soil conditions and managing crop water stress and growth under variable managements (Ma et al., 2012a, 2012b; Saseendran et al., 2015), Root Zone Water Quality Model (RZWQM2; Ahuja et al., 2000) can provide, after calibration, a more accurate daily assessment of crop growth status comparing to the models mentioned above. In a recent study, Qi et al. (2016) showed that RZWQM2 model, integrated with SHAW model (Simultaneous Heat and Water model; Flerchinger and Saxton, 1989), was able to predict the response of corn (*Zea mays* L.) yield to water stress satisfactorily according to widely used statistics (e.g. NSE > 0.5, $-15\% <$ PBIAS $< 15\%$, RSR < 0.7). Above study provided an inspiration of developing an accurate irrigation scheduling approach based on RZWQM2 predicted daily water stresses in advance using the forecasted weather information at local