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A field-modeling study for assessing temporal variations of soil-water-crop interactions under water-saving irrigation strategies

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ABSTRACT

Simulation models are useful tools that may help to improve our understanding of soil-water-plant interactions under innovative water-saving irrigation strategies. In this study, the HYDRUS-2D model was applied to evaluate the influence of deficit irrigation (DI) and partial root-zone drying (PRD) on maize water extractions during two cropping cycles of 2010 and 2011. The model was calibrated and validated using measured soil water content data (expressed as equivalent water depths). Reliable estimates of soil water content were provided by HYDRUS-2D, with root mean square error and mean bias error values of 2.3–5.11 and 1.63–4.93 mm, respectively. Root water uptake and maize grain yields were reduced by 13.2–28.8% and 13.6–52.8%, respectively, under different water-saving irrigation treatments compared to full irrigation. However, different root and water repartitions in the PRD treatment with a 25% reduction in the irrigation depth (PRD_{75}) improved soil water utilization and consequently, crop growth. Increased root water uptake (2.2–4.4 times higher than in other treatments) from the 60–100 cm soil depth in the PRD_{75} treatment maintained a favorable daily evapotranspiration rate, resulting in no significant reduction in maize grain yield compared to full irrigation. Consequently, a 15.7–85% increase in water use efficiency for maize cultivation under PRD_{75} ensured 25% water savings without threatening food security in the study area. It can be concluded that HYDRUS-2D can be successfully used to optimize water management under local water-stress conditions.

1. Introduction

The reduction in fresh water resources due to climate change and rapid growth of the world's population often leads to severe competition between industrial, municipal, and environmental users of water (Alberto et al., 2014). Agriculture is the biggest fresh water user all over the world and commands over 70% of the world's freshwater withdrawals (OECD, 2010). Indeed, to feed the growing worldwide population and banish hunger from the world, food and animal feed production will need to be significantly increased (Darzi-Naftchali and Shahnazari, 2014), requiring the allocation of even more fresh water to agriculture. Consequently, irrigated agriculture has been widely developed over the past few decades. Nevertheless, since sustainable agriculture needs to be achieved with limited fresh water resources, exposing plants to water stress will become unavoidable.

Under such circumstances, deficit irrigation (DI) has been developed as a water-saving irrigation strategy where crops receive less irrigation water during their growing season. However, although adapting DI may be a rational decision under an existing water crisis (Karandish et al., 2015), it may lead to a significant yield loss (Payero et al., 2006) that may threaten food security. Therefore, it is essential to find an efficient water saving method to sustain local social and economic developments. During recent decades, an efficient irrigation method named partial root-zone drying (PRD) has been developed (Dry and Loveys, 1998). In this method, one half of the root zone is irrigated while the other half is allowed to dry out. The irrigated and dry sides are periodically switched. It has been reported that this water-saving irrigation method can reduce irrigation amounts without reducing crop yield and hence can increase water and nutrient use efficiencies (Kang and Zhang, 2004; Shao et al., 2008; Karandish and Shahnazari, In press).

Nevertheless, some researchers have demonstrated that reducing the amount of irrigation water under PRD should be done with special caution because the resulting water stress may affect crop

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yields if it is higher than the plants' tolerance. Liu et al. (2006) reported that although a 25% reduction in irrigation water during a potato growth season significantly increased the irrigation water use efficiency (IWUE), a further 45% reduction led to a significant decrease in yield and IWUE. Similar results were reported by Karandish and Shahnazari (In press) for maize. These results could be associated with a linear relationship between root water uptake and yield under water stress conditions (Traore et al., 2000). Many researchers reported that the effects of water stress on yield depend on how significantly the stress affects the crop evapotranspiration (Payero et al., 2006; Klocke et al., 2004; Stone, 2003). Therefore, a better understanding of daily soil-water-plant interactions may help to improve the water use efficiency under water-saving irrigation strategies, since such knowledge may lead to finding optimal levels of the water stress, preventing significant yield losses and producing optimal irrigation scheduling.

These goals could be achieved using laborious and time-consuming, and therefore expensive, field investigations. As a result, direct measurements of soil water dynamics and soil-water-plant interactions under PRD have rarely been carried out. Previous research has focused mainly on PRD effects on yield and crop physiological responses (Kang and Zhang, 2004; Shao et al., 2008; Karandish and Shahnazari, In press). Modeling could be an alternative tool to identify optimal conditions for applying PRD, especially when the project is economically or technically impossible to be carried out in the field (Li and Liu, 2011).

Among the different available models, HYDRUS-2D (Šimůnek et al., 2008, 2016) has been extensively and successfully used to simulate daily soil water dynamics under many different conditions (e.g., Cote et al., 2003; Gärdenäs et al., 2005; Ajdary et al., 2007; Doltra and Munoz, 2010). However, a review of the literature indicates that no research has been done on evaluating HYDRUS-2D for PRD conditions, especially for PRD involving surface drip irrigation (SDI). Meanwhile, SDI is becoming a widely accepted irrigation method that minimizes leaching and improves water and fertilizer use efficiencies due to its advantage of applying water in precise amounts and at exact locations throughout the field (Bar-Yosef and Sheikholslami, 1976).

PRD-SDI is expected to be an efficient irrigation strategy for many crops because it has both the advantages of PRD and SDI. However, there is a lack of knowledge about soil-water-plant interactions under PRD-SDI and therefore a need to identify the optimal management for this irrigation strategy. To address this issue, a two-year field investigation was carried out in a maize field equipped with an SDI system under full irrigation and both DI-SDI and PRD-SDI strategies to evaluate the following objectives: (i) to calibrate and validate HYDRUS-2D for simulating various soil water balance components; (ii) to describe daily variations of soil water balance components; and (iii) to compare soil-water-plant interactions and evaluate the most water efficient irrigation strategy within the study area.

2. Materials and methods

2.1. Field trial

A two-year field investigation was carried out in a 15 × 55 m maize field at the Sari Agricultural Sciences and Natural Resources University (SANRU: 36.3°N, 53.04°E; 15 m below sea level). Climatic variables during the study period (i.e., maize growing seasons of 2010 and 2011) are displayed in Fig. 1, which shows daily recorded weather data collected at the weather station near the experimental field. Daily mean air temperatures (*T*) in 2010 were between 0.1 and 7.8 °C higher than in 2011. Both vapor pressure deficits (*VPD*) and net radiations (R_n) followed the same seasonal trend as temperatures. During more than 66% of days in 2010, R_n was between about 0.3 and 56.8% higher than in 2011. Total precipitations of 8 and 40 mm were recorded during the entire growing seasons of 2010 and 2011, respectively. There was no rainfall 55 and 45 days after planting (DAP) in 2010 and 2011, respectively. Selected soil physical properties for the study area are summarized in Table 1.

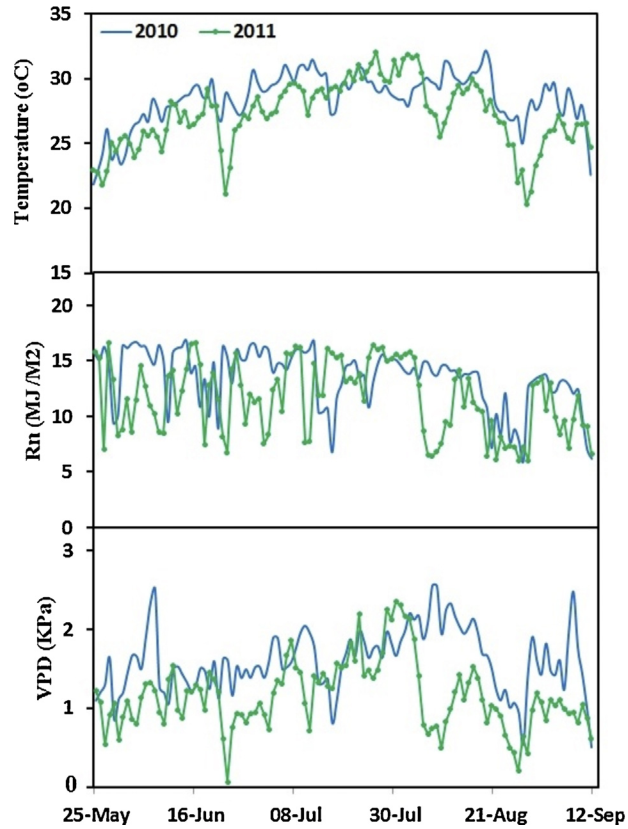

Fig. 1. Daily mean temperatures (a), net radiations (R_n) (b), and vapor pressure deficits (*VPD*) (c). during two growing seasons of 2010 and 2011.

A complete block design with five SDI treatments [full irrigation (FI), two partial root-zone drying (PRD) treatments (PRD_{75} and PRD_{55}), and two deficit irrigation (DI) treatments (DI_{75} and DI_{55})] in three replicates was used in the field trial. The surface drip irrigation system was installed before sowing. Drip lines with emitters 20 cm apart and an emitter discharge rate of 2 L h^{-1} were placed on the soil surface 75 cm apart (Fig. 2a).

Thereafter, for each treatment, five 100 cm long TDR probes (Trime FM; IMKO; Germany) were installed as illustrated in Fig. 2b (i.e., 25 TDR probes were installed in the study area; 5 probes × 5 treatments). TDR probes were used at least two times a day to measure soil water contents (SWCs) at depths of every 5 cm (i.e., at measuring points displayed in Fig. 2b) during both growing seasons. Overall, SWCs were measured at each measuring time in 100 points for each treatment. Moreover, information about the movement of the wetting front during irrigation events was collected at least 10 times in each treatment by measuring SWCs one hour before, and immediately and 2, 6, 12, 24, 48, 72, and 96 h after the irrigation events in the 2010 growing season. To measure retention curves, soil samples were taken every 20 cm to a depth of 80 cm for each treatment in three replicates. SWCs at 11 different pressure heads were measured in the laboratory at each sample using a pressure plate apparatus.

The single-cross, hybrid maize 704 was then planted 5 cm deep; parallel to and between the drip lines on May 26 (in both 2010 and 2011), at 75 × 20 cm row and crop spacings (Fig. 2a). The experi-