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Research Paper

Root-weighted soil water status for plant water deficit index based irrigation scheduling

Xun Wu[a], Wenjing Zhang[a], Wen Liu[a], Qiang Zuo[a], Jianchu Shi[a,*], Xudong Yan[b], Hongfei Zhang[b], Xuzhang Xue[c], Lichun Wang[c], Mo Zhang[a], Alon Ben-Gal[d]

[a] *College of Resources and Environmental Sciences, China Agricultural University, Key Laboratory of Plant-Soil Interactions, Ministry of Education, and Key Laboratory of Arable Land Conservation (North China), Ministry of Agriculture, Beijing 100193, China*
[b] *Land Management Center of Inner Mongolia Autonomous Region, Hohhot, 010020, China*
[c] *National Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China*
[d] *Soil, Water and Environmental Sciences, Agricultural Research Organization, Gilat Research Center, Mobile Post Negev, 85280, Israel*

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ABSTRACT

Indices based on plant water stress or deficit have been extensively employed to aid irrigation scheduling. The objective of this study was to validate a recently proposed approach to estimate plant water deficit index (PWDI) based on root-weighted soil water status and to investigate its effects on irrigation scheduling, plant growth and yield, water consumption and use efficiency when applied to trigger irrigation. A lysimetric experiment and a field experiment were conducted in 2015 and 2016, in which different climatic zones (Beijing and Inner Mongolia), crop species (winter wheat and spring maize), soil types (loam and sandy), PWDI estimation approaches (traditional based on arithmetic average soil water status and root-weighted), irrigation methods (surface and drip irrigation) and levels (full and deficit) were involved. Although both PWDI estimations failed to capture the sharply changing theoretical values resulting from transient fluctuations of weather conditions or irrigation events, the root-weighted approach (RWA) was found to be more reliable than the traditional approach based on arithmetic average soil water status. More precisely timed irrigation scheduling by the RWA resulted in higher irrigation frequency and quantity, and thus higher aboveground biomass, leaf area, grain yield, and transpiration mostly without significant decrease in water use efficiency. Further improvement is necessary to consider the effects of plant recovery from water stress after re-watering, weather conditions, and choice of soil water stress response function on RWA based irrigation scheduling.

1. Introduction

Water scarcity (spatial or temporal imbalance of water availability) is a primary limiting factor for agricultural production, and thus irrigation is important for sustainable agriculture, especially in arid and semiarid regions (Yazar et al., 1999). Exactness in irrigation scheduling is necessary to optimize water productivity (maximum yield with minimum resource consumption) and is dependent on accurate and timely evaluation of plant water requirements. Plant water stress or deficit indices are popularly used in irrigation scheduling in order to promote water productivity. A plant water deficit index (PWDI) uses an estimation of water available for uptake to indicate need to irrigate, defined as the ratio of water deficit to water demand (Thornthwaite, 1948; Woli et al., 2012; Shi et al., 2015):

$$\mathrm{PWDI} = \frac{t_p - t_a}{t_p} = 1 - \frac{t_a}{t_p} \qquad (1)$$

where t_a and t_p are the actual and potential transpiration rates (mm d^{-1}), respectively, and t_a/t_p is the relative transpiration rate. In addition to transpiration, other physiological indicators such as leaf stomatal conductance (Gollan et al., 1985), leaf water potential (Muchow and Sinclair, 1991) and canopy temperature (Idso et al., 1981; Jackson et al., 1981) can also be used to evaluate plant water

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* Corresponding author.
E-mail addresses: wuxun232425@163.com (X. Wu), sxxyzwj@163.com (W. Zhang), 15600661006@163.com (W. Liu), qiangzuo@cau.edu.cn (Q. Zuo), shijianchu@cau.edu.cn (J. Shi), y13847161881@126.com (X. Yan), 494734716@qq.com (H. Zhang), xuexz@nercita.org.cn (X. Xue), wanglc@nercita.org.cn (L. Wang), 1098243485@qq.com (M. Zhang), bengal@volcani.agri.gov.il (A. Ben-Gal).

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status or stress. The application of such physiological indicators faces some inevitable difficulties in both theory and practice (Shi et al., 2015). Firstly, determination of rational plant-specific thresholds for irrigation scheduling is challenging due to complex and transient plant physiological processes. Secondly, irrigation is often delayed when plant physiological stress is found. Thirdly, additional information regarding soil water content has to be supplied for a rational estimation of irrigation quantity. Lastly, physiological measurements are often limited by meteorological conditions and expensive equipment.

Measuring or calculating root-zone soil water status has been suggested as a simple method for estimation of PWDI. Traditionally, this approach considers only the effects of soil water content on plant water status, usually described by an arithmetic average of soil water contents at various depths (Hoppula and Salo, 2007; Muñoz-Carpena et al., 2008; Woli et al., 2012) or by a representative value determined at a given depth (Dabach et al., 2013). However, recent studies based on field and soil column experiments, as well as numerical simulations, indicated that matching theoretical PWDI values with those estimated by this approach was limited to cases of uniform soil water or root distribution (Shi et al., 2015). Besides soil water content, the relative position of soil water to roots was found to significantly impact its availability to root uptake, and the nearer soil water to roots, the easier for it to be taken up (Gardner, 1960; Jarvis, 1989; Zuo et al., 2006). Shi et al. (2015) put forward a root-weighted approach (RWA) utilizing a normalized root length density distribution to calculate the weighted average of soil water content over the root zone, instead of the traditional approach (TRA) considering only the arithmetic average of root-zone soil water content. In a uniform soil column experiment with winter wheat cultivated in greenhouse, PWDI estimated with RWA (PWDI-RWA) improved agreement with theoretical values under various soil water distribution situations in comparison to TRA (PWDI-TRA) (Shi et al., 2015).

When PWDI is taken as an indicator to initiate irrigation, its dynamics become the critical factor impacting water application and its repercussions including crop growth and yield (Nielsen, 1990). The TRA has been shown to benefit irrigation and is popularly employed for practical irrigation management. Although RWA has been shown superior in estimating PWDI under specific conditions, it requires further validation before application under more complicated field conditions. Open questions regarding its relevance or sensitivity to crop type, soil texture, climatic condition and irrigation method are yet to be answered. Furthermore, more attention should be paid on the effects of RWA on irrigation scheduling, crop growth and yield, water consumption and use efficiency, especially in comparison to TRA. Taking TRA as a control, two experiments in lysimeters and under field conditions were conducted in 2015 and 2016 to evaluate RWA and to investigate its effects on irrigation scheduling, plant growth and yield, water consumption and use efficiency when applied to trigger irrigation with various PWDI thresholds. The experiments spanned two of each variable: climatic condition, crop species, soil type, irrigation method and level.

2. Materials and methods

2.1. Lysimetric experiment in Beijing

2.1.1. Experimental conditions and treatments

An experiment (Exp. 1) was conducted from September 2015 to June 2016 at the National Experimental Station for Precision Agriculture (40° 10′ 31″ N, 116° 26′ 10″ E, and altitude 50.1 m) in Changping District, Beijing, China, located in a warm temperate continental monsoon climate zone with annual mean precipitation of 500–600 mm (Yang et al., 2014). In this region, supplemental irrigation is necessary for agricultural production of crops including winter wheat (Zhang et al., 1999).

On 29 September 2015, winter wheat seeds (*Triticum aestivum* L. *Nongda* 212) were sown in 6 weighing lysimeters (230 cm high × 75 cm wide × 100 cm long, 0.05 mm precision) at a density of 6.7×10^6 plants ha^{-1}. Winter wheat was also planted around the lysimeters at the same density to eliminate any oasis effect. Basal fertilizers (organic fertilizer 2×10^4 kg ha^{-1}, urea 450 kg ha^{-1}, diammonium phosphate 450 kg ha^{-1}, potassium sulfate 300 kg ha^{-1} and zinc sulfate 15 kg ha^{-1}) were supplied before sowing, and 227 kg ha^{-1} urea were top-dressed on 17 April 2016 (201 days after sowing, DAS). Three distinct loamy soil layers from the surface to 230 cm depth in the lysimeters are described in Table 1. Soil water retention was measured by a pressure membrane plate (Soil Moisture Equipment Co., USA) and described with the closed form of van Genuchten (1980). Field water capacity was chosen corresponding to soil matric potential of −300 cm (Romano and Santini, 2002). Saturated hydraulic conductivity was determined with a disc infiltrometer under a positive head (Perroux and White, 1988). Air temperature, relative humidity, solar radiation, wind velocity and precipitation were automatically recorded at 30 min intervals at an agro-meteorological station (WeatherHawk 500, Campbell Scientific, USA) located adjacent to the lysimeter field.

From sowing to 6 April 2016 (190 DAS), all the lysimeters were managed uniformly with 80.8 mm irrigation (30 mm at overwintering stage and 50.8 mm at turning green stage) in addition to 52.6 mm precipitation occurring during this period (Table 2). Subsequently, precipitation was completely prevented by a movable rain-shelter, and one full irrigation treatment (RWA0.02, in which RWA indicates the PWDI estimation approach applied for irrigation scheduling and the number 0.02 indicates the PWDI threshold to trigger irrigation) and two deficit irrigation treatments (RWA0.4 and TRA0.4) were used to schedule surface irrigation. Since only 6 lysimeters were available, the 3 treatments (RWA0.02, TRA0.4 and RWA0.4) could be evaluated with only two replicates. Under each treatment, irrigation was discontinued for 15 days before harvest, independent of the estimated PWDI.

2.1.2. Plant sampling and measurements

One access tube (160 cm in length and 5 cm in diameter) was fixed at the center of each lysimeter and a portable soil moisture

Table 1

Soil properties: texture (content of sand, silt, and clay), bulk density (ρ), saturated water content (θ_s), residual water content (θ_r), field water capacity (θ_f), saturated hydraulic conductivity (K_s), and the fitting parameters to van Genuchten's (1980) soil water retention curve (α and n) in Exp. 1 and Exp. 2.

Experiments	Depth (cm)	Texture	Sand (%)	Silt (%)	Clay (%)	ρ (g cm^{-3})	θ_s (cm^3 cm^{-3})	θ_r (cm^3 cm^{-3})	θ_f (cm^3 cm^{-3})	K_s (cm d^{-1})	α (cm^{-1})	n
Exp. 1	0–30	loam	49.44	45.04	5.52	1.43	0.495	0.029	0.316	5.13	0.014	1.315
	30–80	loam	34.82	44.20	20.98	1.40	0.541	0.068	0.394	1.86	0.013	1.245
	80–230	loam	31.92	49.90	18.18	1.56	0.548	0.060	0.410	0.12	0.020	1.177
Exp. 2	0–30	sandy	77.39	9.42	13.19	1.53	0.510	0.010	0.172	37.24	0.022	1.555
	30–70	sandy	72.98	13.44	13.58	1.60	0.560	0.010	0.212	16.37	0.022	1.493
	70–150	sandy	80.02	7.44	12.54	1.68	0.526	0.010	0.221	16.31	0.017	1.500