Journal of Hydrology 522 (2015) 285–294

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

An index for plant water deficit based on root-weighted soil water content

Jianchu Shi [a,b,c], Sen Li [a,b,c], Qiang Zuo [a,b,c,*], Alon Ben-Gal [d]

[a] Department of Soil and Water Sciences, China Agricultural University, Beijing 100193, China
[b] Key Laboratory of Plant–Soil Interactions, Ministry of Education, Beijing 100193, China
[c] Key Laboratory of Arable Land Conservation (North China), Ministry of Agriculture, Beijing 100193, China
[d] Soil, Water and Environmental Sciences, Agricultural Research Organization, Gilat Research Center, Mobile Post Negev 85280, Israel

ARTICLE INFO

Article history:
Received 6 August 2014
Received in revised form 16 December 2014
Accepted 17 December 2014
Available online 6 January 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Juan V. Giraldez, Associate Editor

Keywords:
Plant water deficit index
Root distribution
Soil water distribution
Centralized signal
Irrigation scheduling

SUMMARY

Governed by atmospheric demand, soil water conditions and plant characteristics, plant water status is dynamic, complex, and fundamental to efficient agricultural water management. To explore a centralized signal for the evaluation of plant water status based on soil water status, two greenhouse experiments investigating the effect of the relative distribution between soil water and roots on wheat and rice were conducted. Due to the significant offset between the distributions of soil water and roots, wheat receiving subsurface irrigation suffered more from drought than wheat under surface irrigation, even when the arithmetic averaged soil water content (SWC) in the root zone was higher. A significant relationship was found between the plant water deficit index (PWDI) and the root-weighted (rather than the arithmetic) average SWC over root zone. The traditional soil-based approach for the estimation of PWDI was improved by replacing the arithmetic averaged SWC with the root-weighted SWC to take the effect of the relative distribution between soil water and roots into consideration. These results should be beneficial for scheduling irrigation, as well as for evaluating plant water consumption and root density profile.

1. Introduction

Increasing worldwide population and shortage of water make efficient use of water for agricultural crops imperative. Water movement within the soil–plant–atmosphere continuum (SPAC) is driven by potential gradients, first from soil into roots (absorption), subsequently into leaves, and finally to atmosphere (transpiration). Plant water status is central to water flow in SPAC as the "bridge" between water supply and water demand, and thus an exact and timely evaluation of plant water status is critical for efficient irrigation scheduling (Jones, 2004). Plant water deficit occurs when root water uptake (RWU) cannot support atmospheric demand for transpiration. Plant water deficit index (PWDI), a dimensionless coefficient used to quantify the extent of water deficit, has been defined as the ratio of water deficit to water demand (Thornthwaite, 1948; Woli et al., 2012):

$$\mathrm{PWDI} = \frac{T_p - T_a}{T_p} = 1 - \frac{T_a}{T_p} \tag{1}$$

where T_a and T_p are actual and potential transpiration rates, respectively, cm d^{-1}. Calculating the "theoretical" PWDI with Eq. (1) is extremely challenging, especially under field conditions, since plant actual and potential transpiration rates are affected by many complicated factors and are difficult to determine.

Two alternative approaches to estimate PWDI have been adopted in practice for irrigation scheduling. The first approach is based on plant water stress response, namely plant-based approach (PA). The PA, usually delineated by plant stress sensing parameters such as tissue water potential, plant growth rate or

Abbreviations: PWDI, plant water deficit index; SWC, soil water content; RLD, root length density; NRLD, normalized root length density; RWU, root water uptake; SPAC, soil–plant–atmosphere continuum; DAP, days after planting; SA, soil-based approach; PA, plant-based approach; TH, high water supply via traditional surface irrigation; TL, low water supply via traditional surface irrigation; SH, high water supply via subsurface irrigation; SL, low water supply via subsurface irrigation; SD, statistical distribution; LD, linear distribution; UD, uniform distribution; TPRPS, traditional paddy rice production system; GCRPS, ground cover rice production system.

* Corresponding author at: Department of Soil and Water Sciences, China Agricultural University, Beijing 100193, China. Tel.: +86 10 62732504; fax: +86 10 62733596.

E-mail addresses: shijianchu@cau.edu.cn (J. Shi), lisen0802@163.com (S. Li), qiangzuo@cau.edu.cn (Q. Zuo), bengal@volcani.agri.gov.il (A. Ben-Gal).

http://dx.doi.org/10.1016/j.jhydrol.2014.12.045
0022-1694/

some other index of physiological response, has been increasingly adopted due to the natural and close relationship between plant water status and physiological response (Gardner et al., 1992; Jones, 2004). For example, plant canopy temperature, supported by the rapid development of infrared thermometers and remote infrared sensors, has been extensively applied to reflect plant water status (Idso et al., 1981; Testi et al., 2008). Nevertheless, application of a PA faces a number of practical difficulties (Colaizzi et al., 2003; Jones, 2004; Testi et al., 2008; Agam et al., 2013). Firstly, major issues remain concerning the mechanisms of the complex and transient physiological processes of plants, and therefore in determining rational plant-specific thresholds for irrigation. Secondly, without additional information regarding soil water, this approach can indicate only when, but not how much, to irrigate. Thirdly, equipment for measuring plant physiological parameters tends to be prohibitively expensive, and measurements for stress index determination are usually limited by meteorological conditions. Lastly, irrigation scheduling, formulated according to plant stress sensing, relies on the crop being under some level of stress prior to trigger an irrigation event, and is not appropriate for cases when zero stress is desired.

The second approach to estimate PWDI is based on root zone soil water status, namely soil-based approach (SA). Until now, a traditional SA is still typically employed in practical irrigation management, where the ratio of the actual transpiration rate to the potential (the relative transpiration rate) is described as a function of the arithmetic averaged soil water content (SWC) or its derivatives (e.g. the total available soil water, and the fraction of soil water depletion) in a root zone (Jensen et al., 1970; Stegman, 1983; Topp and Davis, 1985; Penning de Vries et al., 1989; Stričević and Čaki, 1997; Colaizzi et al., 2003; Hoppula and Salo, 2007; Muñoz-Carpena et al., 2008; Woli et al., 2012):

$$\mathrm{PWDI} = 1 - \gamma(\overline{\theta}) \tag{2}$$

where $\overline{\theta}$ is the arithmetic averaged SWC in a root zone, $\mathrm{cm^3\,cm^{-3}}$; $\gamma(\overline{\theta})$ is a dimensionless soil water stress response function described by either SWC or soil matric potential (the current study employs SWC). Measured SWC at a specific position has also been used to substitute the root zone arithmetic average to trigger irrigation (Dabach et al., 2013).

Even though the traditional SA has been validated under many specific situations, its main problem is that plant water status under any particular climate condition responds directly to changes in the rate of water flow via SPAC rather than the amount of water in root zone (Jones, 2004; Woli et al., 2012). In SPAC, soil water must first move to the location of growing roots before it can be absorbed. The relative position of water to roots should significantly impact its availability to RWU by changing the resistance and distance of soil water movement (Gardner, 1960). The nearer soil water is to roots, the easier for it to be absorbed because of the increased hydraulic conductivity and more effective hydraulic contact between soil and roots (Jarvis, 1989; Simunek and Hopmans, 2009). In other words, if more water is located where more roots grow, or, if water distribution is similar to root distribution, soil water will be more readily absorbed to enhance plant water status. Water far from roots or distributed disproportionally would be "ineffective" or even "unavailable" for RWU (Zuo et al., 2006).

The effect of the relative distribution relationship between soil water and roots on plant transpiration has in fact been taken into account previously in macroscopic RWU models (Feddes et al., 1976, 1978; Wu et al., 1999). Accordingly, the traditional SA is improved to (Jarvis, 1989; Simunek and Hopmans, 2009):

$$\mathrm{PWDI} = 1 - \sum_{i=1}^{k} \gamma(\theta_i) R_i \tag{3}$$

where i is the number of soil layer from soil surface to rooting depth, named as the 1^{th}, $2^{\mathrm{th}}, \ldots, k^{\mathrm{th}}$ soil layer in turn; θ_i is the SWC in the i^{th} soil layer, $\mathrm{cm^3\,cm^{-3}}$; and R_i is the proportion of the total root length in the i^{th} soil layer. Eq. (3) indicates that PWDI is influenced by the relative distribution patterns between water and roots, and might be different even when total soil water and root length in the root zone are the same. Practically, Eq. (3) is rarely applied in irrigation scheduling, despite its superiority to Eq. (2). The lack of adoption is likely at least partially due to the difficulty involved in acquiring reliable root length information in the field. This could be rectified by recent studies showing that the distribution of normalized root length density (NRLD) for a number of specific crop plants (e.g. wheat, cotton, maize, or beans) could be statistically described using a general function of NRLD vs. normalized root depth, independent of environmental conditions (Wu et al., 1999; Zuo et al., 2006, 2013).

The decentralized form of Eq. (3) might be another reason for its scarce application, since the root-weighted soil water stress response functions in various soil layers are integrated without interdependence. Effort has been made to investigate centralized signals other than the arithmetic averaged SWC to represent actual root zone soil water status and thus to estimate PWDI. For example, de Jong van Lier et al. (2008) used maximum soil water supply as a centralized signal defined by matric flux potential. Couvreur et al. (2012) took root-weighted soil water potential as a centralized signal while analyzing a root system hydraulics model. Although based on solid theoretical foundations, these approaches are practically limited due to the required data, such as detailed hydraulic and morphological parameters for soil or roots.

The objective of this study was to find and develop a reliable and accessible centralized signal to improve the traditional SA for the estimation of PWDI, by investigating and quantifying the effect of the relative distribution of water and roots on plant water status.

2. Materials and methods

2.1. Estimating PWDI on root-weighted soil water content

The volume of water absorbed by roots from a unit soil volume during a unit time, namely the RWU rate (S, $\mathrm{cm^3\,cm^{-3}\,d^{-1}}$), can be simulated as (Feddes et al., 1976, 1978):

$$S(z) = \gamma(\theta) S_{\max}(z) \tag{4}$$

where z is the depth from soil surface, cm; and $S_{\max}(z)$ is the maximal RWU rate under optimal water condition, $\mathrm{cm^3\,cm^{-3}\,d^{-1}}$, assumed to be proportional to root length density (RLD) as (Feddes et al., 1976, 1978; Wu et al., 1999):

$$S_{\max}(z) = \frac{T_p L_{nrd}(z_r)}{L_r} \tag{5}$$

in which

$$L_{nrd}(z_r) = \frac{L_d(z_r)}{\int_0^1 L_d(z_r)\mathrm{d}z_r}$$

where L_r is rooting depth, cm; z_r is normalized depth ranging from 0 at soil surface to 1 at rooting depth, $z_r = z/L_r$; $L_d(z_r)$ is the RLD at z_r, representing the length of roots in a unit soil volume, $\mathrm{cm\,cm^{-3}}$; $L_{nrd}(z_r)$ is the NRLD at z_r.

Plant actual transpiration rate can be approximated by the integration of the RWU rates over root zone (Wu et al., 1999):