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Determination of lower limits for irrigation management using in situ assessments of apparent crop water uptake made with volumetric soil water content sensors

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ABSTRACT

In situ approaches for determining lower limit (threshold, refill) values for irrigation management using continuously monitored data from volumetric soil water content (SWC) sensors were evaluated. Four indices were derived from SWC data: (i) apparent daily crop water uptake (ADCWU), the reduction in SWC during daylight periods; (ii) daily soil water loss (DSWL), the reduction in SWC during 24 h periods; (iii) previous overnight redistribution (POR), overnight drainage; and (iv) ADCWU normalised for reference evapotranspiration (ADCWU:ET_o). Indices were calculated for 0–20 and 20–40 cm soil depths in four drying cycles applied to melon and to autumn and spring tomato crops. In each drying cycle, there were well-watered and un-watered irrigation treatments. In drying soil, values of ADCWU and DSWL followed a decay curve with three phases: (1) of rapid decline when drainage occurred; (2) of a much slower decline, after drainage ceased, with smaller values influenced by climatic factors; and (3) of constantly very low values not influenced by climate. The actual commencement of crop water stress was indicated by the first statistically significant difference in midday Ψ_{leaf} between un-watered and well-watered plants. A protocol was developed to identify commencement of crop water stress using ADCWU or DSWL in un-watered plants. POR was used to identify cessation of internal drainage. Then, the first reduction in ADCWU or DSWL while climatic variables (solar radiation, VPD) indicated a constant or increasing atmospheric evaporative demand was considered an ‘‘indication’’ of crop water stress, the second such reduction as ‘‘confirmation’’. In the four cycles studied, ‘‘indications’’ of crop water stress using both ADCWU and DSWL for 0–20 cm soil were 1 (twice), 2 and 6 d after commencement of water stress. When there was not appreciable climatic variation during phase 2, ADCWU and DSWL detected crop water stress within 1–2 d of Ψ_{leaf}. Generally, climate-mediated fluctuations in ADCWU and DSWL during phase 2 delayed identification of the commencement of water stress. Normalising ADCWU for ET_o reduced effects of climatic fluctuation. Using a 25% relative reduction in ADCWU:ET_o as a threshold, this parameter was more sensitive than ADCWU or DSWL using the proposed protocols for detecting commencement of water stress. ‘‘Breaking points’’ in the rate of reduction of SWC, and variations in stem diameter were also compared for detecting commencement of crop water stress. This study suggested that reductions in SWC in drying soil can be used to identify lower limits for irrigation management using SWC sensors, and that stable climatic conditions are required to optimise these approaches.

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1. Introduction

With growing demand for limited fresh water resources, and increasing societal pressure to reduce negative environmental effects, irrigation farmers are increasingly required to optimise on-farm irrigation efficiency (Gardner, 1993; Fereres et al., 2003). Recent technological advances have contributed to the development of a range of sensors that permit continuous on-farm monitoring of soil water status. Soil water sensors provide farmers with the potential to accurately meet the specific crop water requirements of individual crops.

Soil water sensors measure either soil matric potential (SMP) or volumetric soil water content (SWC). The use of soil water sensors for irrigation management, whether measuring SMP or SWC, requires that soil water be maintained within upper and lower limits (Campbell and Campbell, 1982), also referred to, respectively, as full and refill points (Campbell and Campbell, 1982). Commonly, the upper limit approximates "field capacity" (FC) and the lower limit, often referred to as "threshold", is somewhat above where a crop commences to experience water stress (Campbell and Campbell, 1982). Maintaining soil water within this range ensures that the crop maintains adequate water status and appreciable drainage is avoided (Campbell and Campbell, 1982).

Irrigation scheduling using SMP measurement is well-established; standard values are readily-available for individual crop species with consideration of crop phenology, atmospheric evaporative demand and soil texture (e.g. Taylor, 1965; Hanson et al., 2000). Soil matric potential is simpler to use for irrigation management than SWC (Campbell and Campbell, 1982; Thompson et al., 2007a); however, current SMP sensors have technical limitations that limit their working range or their accuracy in rapidly drying soils (Campbell and Campbell, 1982; Thompson et al., 2006).

Multiple depth capacitance (MDC) sensors that continuously measure SWC at different depths, providing data on soil water content and dynamics throughout the root zone, are being used for on-farm irrigation scheduling (Starr and Paltineanu, 2002; Fares and Polyakov, 2006). A number of scientific studies have described their application to irrigation scheduling (Roberson et al., 1996; Fares and Alva, 2000a,b; Hanson et al., 2000; Fares and Polyakov, 2006). To define upper limit SWC values using FC, laboratory determined (Fares and Alva, 2000a) and in situ field determined values (Cassel and Nielsen, 1986; Starr and Paltineanu, 1998a) have been used. For defining lower limit SWC values, combined use of the concepts of "allowable depletion" (AD) and "available water content" (AWC) has been done (Fares and Alva, 2000a; Fares and Polyakov, 2006). Available water content being the amount of water in the soil root zone between FC and "permanent wilting point" (PWP), and AD being the permissible reduction in AWC before irrigation is required (Doorenbos and Kassam, 1979; Allen et al., 1998). When using the combined AD/AWC approach, standard AD values are available (Doorenbos and Kassam, 1979; Allen et al., 1998; Hanson et al., 2000).

There are several practical disadvantages associated with the on-farm use of AWC with fixed AD values, using SWC sensors. Relevant values of FC and PWP may not be available, and laboratory-determined values may not reflect field conditions (Cassel and Nielsen, 1986; Thompson et al., 2007a). On-farm in situ determinations can be made for FC (Cassel and Nielsen, 1986), but are impractical for PWP. The use of AD requires that soil depth be specified; however, the rooting depth selected strongly influences the calculation of the lower limit SWC value (Girona et al., 2002; Thompson et al., 2007a). In a given farming situation, the rooting depth may be unknown, and rooting depth can change with crop growth (Sadras and Milroy, 1996). The AD/AWC approach requires quantitative measurement of SWC; therefore accurate sensor calibration is essential. However, numerous studies have demonstrated that site-specific calibrations are required for quantitative measurement with MDC sensors (Mead et al., 1995; Morgan et al., 1999; Hanson and Peters, 2000; Girona et al., 2002; Leib et al., 2003; Thompson et al., 2007a), which is impractical for on-farm applications. Furthermore, the AD/AWC approach with SWC sensors is most suitable where irrigation application is relatively homogenous; its use is less straightforward for heterogeneous water application such as with drip irrigation. General sources of inaccuracy associated with the AD/AWC approach for irrigation scheduling or modelling studies have been identified by Sadras and Milroy (1996), Sinclair et al. (1998) and Girona et al. (2002).

An alternative approach to combined AD/AWC, for the use SWC sensors for on-farm irrigation management is the in situ determination of upper and lower limits based on the interpretation of soil water dynamics. This approach dispenses with requirements for (a) accurate quantitative calibration, (b) pre-defined values of FC and PWP, (c) the use of standard AD values, and (d) estimates of rooting depth. Dynamic approaches enable upper and lower limits of SWC to be defined for the unique characteristics of individual crops and fields. These approaches are suitable for heterogeneous irrigation applications because they can be used to characterise upper and lower limits for selected key locations within the root system. In situ determination of apparent FC as the upper limit of SWC can be made using the cessation of drainage from the root zone after irrigation (Starr and Paltineanu, 1998a,b); data of drainage beneath the root zone can assist in these assessments (Fares and Alva, 2000b). A suggested approach for defining lower limit SWC values is to firstly identify the SWC at which "commencement of stress" occurs, and then to select a slightly higher value.

Commonly, in drying soil, SWC reduces in a step-like manner with sharp reductions during daylight periods because of crop water uptake, and relatively constant SWC during overnight periods when little or no drainage occurs (Starr and Paltineanu, 1998a,b). As soil progressively dries, day-time reductions in SWC get progressively smaller (Starr and Paltineanu, 1998a,b; Goldhamer et al., 1999; Girona et al., 2002). Starr and Paltineanu (1998a,b) commented that the transition from adequate to insufficient soil water supply for crop growth occurred during the progressive reduction in the rate of daily water loss. They suggested that the decline in SWC in drying soil occurred in two phases: (i) a relatively rapid phase, and (ii) a subsequent slower phase, when soil water was strongly limiting crop water uptake. These authors termed the transition between the two phases as the "breaking point" and suggested that it could be used to identify the commencement of crop water stress. Very few studies have related the progressive decline in day-time reduction of SWC,