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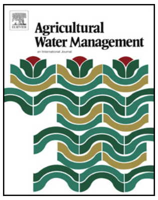

Soil moisture sensor calibration, actual evapotranspiration, and crop coefficients for drip irrigated greenhouse chile peppers

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ABSTRACT

Limited water supplies in arid regions put constraints on agriculture. In arid New Mexico, greenhouse chile pepper production has the potential for water and nutrient savings. The objectives of this study were to (1) compare two capacitance sensors – (Hydra probes and 5TM) and one TDR CS616 sensor, (2) compute actual evapotranspiration (ETa) for drip-irrigated chile peppers for three water treatments, and (3) develop new crop coefficients (K_c) for the three growing seasons in a greenhouse study. Three water treatments were (1) control where water was applied near the surface using two drip emitters, (2) partial root zone drying vertical (PRDv) where subsurface irrigation was applied at 20 cm depth from soil surface, and (3) partial root zone drying compartment (PRDc) where roots were divided into two compartments and irrigation were switched between compartments after 15 days. Sensor-generated volumetric water contents (θ) were correlated with the gravimetrically determined θ, and the new calibration coefficients improved the precision of θ estimates. From 2011 onward, irrigation amounts were adjusted to minimize deep percolation, and about 30% less water was applied in 2014 as compared to the 2011 growing season but no significant differences were observed in transpiration rate and leaf temperature. The ratio of intercellular to ambient CO_2 concentrations (Ci/Ca) was significantly correlated to transpiration rate and vapor pressure deficit in 2014 ($P < 0.05$). ETa obtained from water balance and reference ET (ETr) from Penman-Monteith developed the K_c for drip-irrigated greenhouse chile peppers for three growing seasons. The maximum values of K_c were about 1.4 during 2013 and 1.2 during 2014. The 2011 growing season was shorter and the maximum K_c were closer to one. Crop coefficients for greenhouse grown chile peppers varied with growing seasons and irrigation treatment. Irrigation scheduling can be done based on the soil moisture or K_c for the known growing season. This study demonstrated the water saving potential of PRD.

1. Introduction

Southern New Mexico is characterized by a semiarid to arid climate with an average of 3700 h of annual sunshine, high annual and diurnal temperatures, low relative humidity, and low average annual precipitation of 20–22 cm (Norman, 2000). Agriculture in arid regions primarily relies on irrigation and puts more constraints on the fresh surface and groundwater resources. Although New Mexico's aquifers have about 2.46 billion ha-m volume of fresh water, it is non-uniformly distributed. About 75% of the water is saline and cannot be used directly for irrigation (U.S. Geological Survey, 1988). Surface water availability in southern New Mexico is becoming increasingly limited, and environmental conditions are forcing the implementation of water management strategies for the sustainability of agriculture and food security in the region.

Irrigation scheduling can be done using a combination of soil, plant, and climate data (Deb et al., 2013). Nondestructive continuous soil water monitoring using time domain reflectometry (TDR) or capacitance-based sensors (Baumhardt et al., 2000), periodic monitoring of stem or leaf water potential using pressure bombs (Deb et al., 2013), and evapotranspiration (ET) estimates (Sammis et al., 2012) are used to schedule irrigation. These methods can optimize irrigation scheduling of crops and prevent water wastage and groundwater contamination due to nutrient leaching (Cepuder and Shukla 2002; Sharma et al., 2012).

Computing water balance within a soil system is very complex because soil water movement is a multidirectional process

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(Jackson, 1992; Maroux and Lafolie, 1998). The soil water balance method can be used to estimate actual ET (ETa) or deep percolation as an alternative to the expensive lysimeter method (Ochoa et al., 2007; Deb et al., 2012). However, the accuracy of data depends on the sensor quality to measure soil water contents (Burrough, 1989). Therefore, soil- and site-specific calibrations for soil water sensors are recommended (Topp et al., 1980; Evett and Parkin 2005).

Chile peppers, an important cash crop for New Mexico, are warm-season crops, sensitive to freezing temperatures at any growth stage, and require temperatures above 24 °C and 10 °C during the day and night, respectively (Bosland and Votava, 2012). There is a possibility of year-round chile pepper production in greenhouses using drip irrigation system. Crops grown in a greenhouse are managed differently than those grown outside, the microclimate inside the greenhouse is different than the outside, and crop coefficient (K_c) values determined outside cannot be used for greenhouse crops. Furrow irrigated chile peppers in New Mexico require about 100–120 cm of water and about 315 kg N ha^{-1} of URAN during growth period of about 150 days (Sharma et al., 2012). Drip irrigated chile peppers are reported to require about 95 cm of water (Wierenga, 1983). Greenhouse grown chile peppers in New Mexico are primarily surface irrigated, however, drip irrigation is used on a small scale. Because water is an increasingly scarce commodity in New Mexico, greenhouse production of chile peppers has the potential to apply water- and nutrient-saving strategies. Therefore, the objectives of this study were to compare three soil moisture content sensors; estimate chile pepper ETa; and determine K_c values for efficient irrigation scheduling of drip-irrigated greenhouse chile peppers.

2. Materials and methods

2.1. Study site and greenhouse

This study was carried out in greenhouses located at New Mexico State University, Las Cruces, New Mexico (32.2830°N latitude, 106.7480°W longitude; elevation 1186 m). The climate of the area is arid with mean annual temperature and precipitation of 15.83 °C and 21.6 cm, respectively (Norman, 2000; Sharma et al., 2015). The total area of the greenhouse is approximately 260 m^2. The greenhouse is constructed with reinforced aluminum frame encased with single frame, corrugated, and oriented east to west. It has a double layer of polycarbonate copolymer sheets for insulation, a evaporative cooler and an exhaust on opposite ends, and heaters. A 70% shade-cloth is placed over the roof from May to early October to reduce the heat load in the greenhouse. Temperature inside the greenhouse is controlled by an automatic control system and the minimum and maximum cutoff temperatures are 26 °C and 30 °C.

2.2. Time domain reflectometry CS616 sensors

TDR CS616 sensors that measured diurnal variation of soil water content for actual ETa estimation using water balance consisted of two parallel rods attached at the probe head (300 mm long × 3.2 mm diameter) with 32 mm spacing. Voltage impulses are generated and reflected within the head and output is calculated based on reflections per second (frequency), which depends upon the dielectric permittivity (ε) of the medium surrounding the probe. Because there is a big difference between the dielectric permittivity of air ($\varepsilon = 1$), soil (2.4–3.5), and water (80), travel times of the electromagnetic wave through soil vary with the soil water content (Chandler et al., 2004). The sensor output reports the dielectric constant (τ) and is given as $(la\ l^{-1})^2$, where la is the measured or apparent distance from the beginning to the end of the wave guide, and l is the real or physical lengths. The volumetric soil water content (θ) is obtained using the following second order quadratic equation (Campbell Scientific Inc, 2014; Shukla, 2014):

$$\theta = A + B\tau + C\tau^2 \quad (1)$$

where A is −0.0663, B is −0.0063, and C is 0.0007.

2.3. Capacitance-based sensors

Stevens Hydra probe (SDI-12) and Decagon 5TM are capacitance-based sensors that estimate the θ by measuring ε and both also measure soil temperature. Furthermore, Hydra probes can measure bulk soil electrical conductivity (EC). Hydra probes and 5TM sensors are much smaller than TDR CS616 sensors. Hydra probe consists of four metal prongs, and each prong is 4.5 cm long and 0.3 cm wide. The 5TM sensor has three prongs, and each prong is 10 cm long and 3.2 cm wide. Deviation in calibration of a sensor occurs due to changes in soil texture, soil physical and chemical properties, soil temperature, and soil salinity. Calibration equations for Hydra sensors are given below (Stevens Water Monitoring System Inc, 2007):

$$\theta = A + B\varepsilon^{1/2} \quad (2)$$

$$\theta = A + B\varepsilon + C\varepsilon^2 + D\varepsilon^3 \quad (3)$$

where A–D are calibration constants and their values vary with soil texture (Bellingham, 2007). Like TDR sensors, soil-specific calibration was also suggested for capacitance-based sensors (Seyfried et al., 2005). 5TM sensors use the following Topp's equation to calculate θ from ε (Topp et al., 1980).

$$\theta = A + B\varepsilon + C\varepsilon^2 + D\varepsilon^3 \quad (4)$$

where coefficient A is -5.3×10^{-2}, B is 2.92×10^{-2}, C is -5.5×10^{-4}, and D is 4.3×10^{-6} (Bellingham, 2007).

2.4. Soil media for calibration and growth experiments

Soil for sensor calibration as well as for growth experiments during 2011 through 2014 consisted of 1:1:1 mixture by volume of sand, loam, and peat moss. Soil was first sterilized in a PRO-GROW electric soil sterilizer at 60 °C for 30 min and then cooled down to air temperature before packing in the containers. All containers used were of the same size with a 26 cm diameter and 70 cm depth. Packing was done manually in 5 cm depth increments to obtain a homogeneous soil profile with an overall bulk density of 1.01 ± 0.02 g cm^{-3}. The bottom of each container was perforated, and perforations were covered with squared iron mesh (5 mm × 5 mm) to prevent soil loss. Red lava rocks were placed on top of the mesh to ensure free drainage. There were three containers for sensor calibration, nine more for conducting growth experiments, and three more containers were used as border pots.

2.5. Calibration of soil moisture sensors

Measurement of soil water content is important for scheduling irrigation as well as conducting water balance analysis, therefore three different sensors were tested to find the one that could be used consistently. The sensor calibration was conducted in three separate pots not used for chile pepper growth experiments. CS616 sensors were installed in the containers at an angle of about 25° and at depths of 0–15 and 15–30 cm from the soil surface. Hydra probes were installed vertically at 0–15 and 15–30 cm depths, and 5TM sensors at 0–15 cm depth only. Two Hydra probes and two 5TM sensors were installed at each depth, but only one CS616 sensor was installed at each depth. All data were recorded at 10 min intervals using a CR10X data logger. Each container during sensor calibration was irrigated from the top using two drip emitters. To

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