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Actively heated fiber optics method to monitor three-dimensional wetting patterns under drip irrigation

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ABSTRACT

Monitoring dynamics in wetting patterns under drip irrigation is important to optimize the frequency and duration of irrigation, the emitter discharge rate and the spacing. However, difficulties in measurement of soil water content (SWC) at high spatial and temporal resolution and in three-dimensions (3D) restricts direct monitoring around drip emitters. Indirect methods such as actively heated fiber optics (AHFO) has shown the potential to measure SWC at sub-meter intervals. Therefore, the objective of this study was to examine the feasibility of the AHFO method to monitor 3D spatial and temporal variations in wetting patterns under a single drip emitter. Heat pulses of three minutes duration were applied at a rate of 20 $\mathrm{W m^{-1}}$ through a helically wrapped fiber optic cable in a soil column before, during, and after irrigation. A distributed temperature sensing (DTS) instrument was used to estimate the cumulative temperature increase (T_{cum}) at locations along the cable. An indirect relationship between T_{cum} and SWC was developed and validated using the SWC measurements determined by the gravimetric method. Data from the network of 3D points (from fiber optic cable) were used to generate 3D surfaces of SWC. In comparison with the gravimetric method, AHFO showed predictive accuracies; root mean squared error (RMSE) of 0.03 $\mathrm{m^3 m^{-3}}$ for SWC < 0.05 $\mathrm{m^3 m^{-3}}$ (N = 17), 0.03 $\mathrm{m^3 m^{-3}}$ for SWC 0.05–0.3 $\mathrm{m^3 m^{-3}}$ (N = 19) and, 0.05 $\mathrm{m^3 m^{-3}}$ for SWC > 0.3 $\mathrm{m^3 m^{-3}}$ (N = 6). The time evolution of the 3D SWC helped to identify wetting bulb formation, movement of the wetting front and changes in the dimensions (wetted radius and depth) of wetting bulbs. This study showed not only the potential of AHFO to help design drip emitters but also the ability to provide high resolution SWC information to improve water movement models in the future.

1. Introduction

Increasing threats of freshwater shortages due to the diversion of water towards per capita profitable industrial use and more frequent and severe droughts from changing climate have stimulated research into water-saving irrigation strategies aiming to produce 'more crop per drop' (Cervi et al., 2018; Koutroulis et al., 2018; Morison et al., 2008). Current trends of the research from surface to drip irrigation have improved irrigation water productivity, plant quality and, crop yield (Martínez-Gimeno et al., 2018; Paris et al., 2018; Wang et al., 2018). Drip irrigation has increasingly been used to supply water, fertilizers, and pesticides to a wide range of vegetables, field crops, and fruit trees due to its ability to enable highly localized application (Xue et al., 2017; Yang et al., 2017).

Drip systems can achieve higher irrigation efficiency (70–90%) than surface irrigation (40–50%) when designed well and operated correctly (Postel, 2000). Knowledge of wetting patterns under a single emitter are important in designing, managing, and operating drip irrigation systems. The wetted radius (WR) and the wetted depth (WD) are the two important dimensions of wetting patterns under drip irrigation. The WD should coincide with the depth of the active root system which depends on the crop species (Coelho and Or, 1999) while the WR is dependent on the spacing between emitters and lines (Zur, 1996). Changes of wetting patterns during and after irrigation can be obtained by direct measurement using installed soil water sensors in the soil or through simulation models such as Hydrus 2-D ((Šimůnek et al., 2016) and WetUp (Cook et al., 2003). There are a considerable number of studies that have used modeling to quantify the soil water content (SWC) distributions in surface (e.g. Al-Ogaidi et al., 2016; Han et al., 2015; Lazarovitch et al., 2007; Li et al., 2015; Moncef and Khemaies, 2016; Simionesei et al., 2016) and subsurface (e.g. Elmaloglou and Diamantopoulos, 2009; Ismail et al., 2006; Kandelous and Simunek,

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2010; Lazarovitch et al., 2007) drip irrigation, however, its application in *in-situ* soils is somewhat limited by difficulty of parameterizing spatial–temporal variation in soil properties and limited ability to simulate preferential flow processes (Šimůnek et al., 2003). Further, studies have also used direct measurements. Among these, Hanson et al. (2003) and Badr and Abuarab (2013) used neutron scattering to monitor soil water distribution patterns under surface and subsurface irrigation systems. However, the neutron probe measures soil water at coarse spatial resolutions under a drip emitter due to the large sphere of measurement and often fail to accurately represent the wetting patterns at single drip emitter scale. Disturbed gravimetric soil samples (Al-Mefleh and Abu-Zreig, 2013; Kumar et al., 2015) and point based SWC measurement sensors such as TDR (da Silva et al., 2009; dos Santos et al., 2016), capacitance probes (Fernández-Gálvez and Simmonds, 2006), and tension meters (Wang et al., 2006) have also been used to characterize the spatial and temporal dynamics of wetting patterns under irrigation. However, most of these studies have allowed to characterize wetting patterns dynamics in two-dimensional (2D) due to lack spatially dense SWC measurements around the drip emitters while three-dimensional (3D) wetting patterns could provide more insights into the changes of WR and WD in heterogeneous soils. Installation feasibility, cost and between-sensor variability, sensitivity to salinity (e.g. capacitance & TDR probes) restrict the use of point-based sensors at high densities around a drip emitter, consequently it affects the accurate characterization of wetting patterns under drip irrigation. However, Fuentes (2005) and Dalton et al. (2015) used soil water measurements from a radial distribution of capacitance probes to develop 3D/2D maps of wetting patterns under drip irrigation and this study evidenced the potential of using such 3D/2D maps to evaluate various irrigation schedules and compare the performance of different irrigation systems.

Despite the point–based soil water sensors, A few minimally invasive geophysical methods have been used to characterize and map the spatial and temporal dynamics of wetting patterns under drip irrigation. The methods include; electromagnetic induction sensors (EM) (Coppola et al., 2016; Misra and Padhi, 2014), ground penetrating radar (GPR) (Saito and Kitahara, 2012; Satriani et al., 2015), and electrical resistivity imaging (ERI) (Consoli et al., 2017; Puy et al., 2017). Despite their potential to characterize the spatial and temporal dynamics of wetting patterns, both methods are hampered by highly conductive soils (Algeo et al., 2016) and the poor correlation between the soil water and electrical resistivity at single emitter scale (Hardie et al., 2018). Therefore, it is necessary to explore alternative soil water sensing techniques which could provide spatially dense soil water measurements at single drip emitter to field scales, to better characterize the wetting patterns.

Distributed temperature sensing (DTS) systems are optoelectronic devices which are capable of measuring temperature both in space and time along a fiber optic cable. DTS systems have gained research interest in environmental temperature sensing due to their ability to measure temperature at sub-meter intervals along a fiber optic cable to a distance > 10,000 m and at high frequency (Selker et al., 2006a, 2006b; Tyler et al., 2008, 2009; Westhoff et al., 2007). DTS observed temperatures can be used to estimate soil thermal properties using the principles of heat pulse probe methods (Weiss, 2003) and subsequently SWC. When a line source of energy (heat pulse) is sent to a probe, the resulting temperature change (thermal response) of the probe principally depends on the water content of the soil in addition to the soil mineralogy and bulk density (Bristow et al., 1994, 1993). A DTS system resembles a single probe heat pulse sensor where the fiber optic cable serves as the probe and the optoelectronic device (within the DTS) records temperature along the fiber optic cable. A heat pulse can be generated by actively heating the fiber optic cable (AHFO) and the thermal response can be related to the water content in soil.

The AHFO method has been used to study the subsurface water movement but these earlier studies were restricted to the identification of dry, wet and saturated soil (Perzlmaier et al., 2004, 2006; Weiss, 2003;) and small changes were not detected at levels > 6% volumetric water contents (Weiss, 2003). Sayde et al. (2010) expanded the method by using the cumulative temperature increase (T_{cum}) as the thermal response and reported more accurate SWC measurements over a wide range. Further application of this method can also be found in field (Sayde et al., 2014) and laboratory (Gil-Rodríguez et al., 2013) studies. However, all these studies have mainly focused on the feasibility of 2D spatial (width and depth) SWC measurements, while the method has the potential to extend into 3D spatial (width, depth and length) SWC measurements (e.g. helically wrapping the fiber optic cable (laboratory) or developing 3D grids (field) to study soil water movements in 3D. Three-dimensional monitoring of the variations of SWC is important for understanding rainfall or irrigation water infiltration, redistribution of water within the root zone and, transport of nutrients. This is especially necessary for heterogeneous media such as soil where soil water shows great variations in both the vertical and in the horizontal directions (Flury et al., 1994; Dekker and Ritsema, 1994). The AHFO method can provide a dense array of radially distributed SWC measurements under a drip emitter and would be useful to develop detailed 3D maps of soil water distributions through time with minimal soil disturbance. Therefore, the objective of this study was to examine the feasibility of AHFO method to monitor 3D spatial and temporal variations in wetting patterns under a single drip emitter. Overall, the results of this study will indicate, if the AHFO method is a feasible tool to monitor 3D spatial and temporal variations in wetting patterns at a single drip emitter scale.

2. Materials and methods

2.1. Distributed temperature sensing system

A distributed temperature sensing, DTS (Linear Pro series, AP Sensing, Germany), consisting of two channels with a maximum measurement range of 4 km (using laser transmission) was used in this study. The spatial resolution (integrated length over which a single value of the temperature is recorded by the DTS) was 0.5 m and spatial sampling interval (the minimum spatial distance between two consecutive measurement points in the measured temperature profile) was 0.25 m. The fiber optic cable (BRUsteel, Brugg Cable, Switzerland) consisted of a stainless steel loose tube containing four multimode 50 μm cores and 125 μm cladding fibers surrounded by stainless steel strands which was further enclosed in a protective nylon jacket (Fig. 1a). The external cable diameter was 3.8 mm. A laser pulse, generated by the DTS instrument, travelling along the fiber optic cable, results in backscattered Raman Stokes and anti-Stokes photons due to collisions with electrons in the core of the glass fiber. The DTS estimates the temperature using the ratio of Stokes to anti-Stokes and the elapsed time between the laser pulse and the observed returned light. Detailed information on the principle of temperature measurement using DTS is well documented by Kurashima et al. (1990) and Tyler et al. (2009), while its application for environmental temperature monitoring can be found in Selker et al. (2006a, 2006b).

2.2. Construction of soil column

A soil column was built in a plastic barrel (height of 0.85 m and diameter of 0.6 m) and was stationed in the soil science laboratory of McGill University in 2015. A Plexiglas base with small perforations (0.005 m in diameter) was constructed at a height of 0.15 m from the bottom of the column. Inside the column, the fiber optic cable (length 44.5 m) was coiled in two concentric helixes with radii of 0.10 and 0.20 m (Fig. 1b) and spacing of 0.025 m between the turns forming a 3D network of 178 measurement points. Ten fiberglass rods (0.005 m diameter) resting at the Plexiglas base supported the helixes. The measurement point network provided 3D spatial SWC measurements