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Numerical calculation of soil water potential in an irrigated 'conference' pear orchard

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ABSTRACT

Irrigation in Belgian 'Conference' pear orchards is often managed by soil water potential (Ψ_{soil}) sensors. The most widespread sensor among fruit growers in Belgium is the Watermark sensor (Irrometer Co., USA). To gain better insight into the use of the Watermark soil sensor for irrigation scheduling in pear orchards the water extraction pattern of the 'Conference' pear trees was acquired by a numerical calculation of Ψ_{soil} in three experimental plots. A reasonable accordance between calculated and measured Ψ_{soil} was observed with $R^2 = 0.56$ and RMSE = 13.4 kPa over 1320 observations. Furthermore the sensitivity of the numerical calculation to the selected root distribution was shown. The Ψ_{soil} calculation with the root distribution parameterized by site specific fine root length observations gave satisfactory results for all plots, in contrast to Ψ_{soil} calculation based on other root distributions.

1. Introduction

In Belgium 'Conference' pear tree (*Pyrus Communis*, cv. 'Conference') is irrigated to maintain a high fruit yield in dry years (Janssens et al., 2011). Belgium is situated in the temperate climate zone with a relatively low average evapotranspiration and a high but variable rainfall from bloom (first half of April) to harvest (first half of September). Irrigation in the orchards is supplied by drip irrigation on a weed free strip under the canopy of the trees. Irrigation scheduling in the orchards is often managed by soil water potential (Ψ_{soil}) sensors. The sensor the most widespread among fruit growers in Belgium is the Watermark sensor (Irrometer Co., USA). This sensor is an electrical resistance sensor with two electrodes embedded in a granular matrix. The granular matrix is a gypsum tablet increased in polyvinyl chloride plastic fill. The use of the sensor entails some limitations (Scanlon et al., 2002): The relation between water content and matrix potential in the sensor is hysteric (Bourget et al., 1958; Whaylley et al., 2001); errors may occur during rapid drying or rewetting of the soil (McCan et al., 1992) and the maximal pressure head that can be measured is −10 kPa which is the air entry pressure value of the sensor. Errors due to the hysteric response of the sensor can be minimized by calibration based on the specific drying or wetting curves form the soil or by creating a sensor with a ceramic-based porous matrix (Whaylley et al., 2001). A comparative study between various soil moisture sensors indicates that the accuracy of the sensor is comparable to the widely spread frequency domain reflectometer (FDR), time domain reflectometer (TDR) and gypsum block but lower than the neutron probe (Leib et al., 2003). Due to the low cost and ease of operation the Watermark sensors are useful as a qualitative indicator for matrix potential and therefore suitable for irrigation scheduling on commercial farms (Jabro et al., 2009; Thompson et al., 2006).

Since drip irrigation causes rapid and variable changes in Ψ_{soil} distribution knowledge of soil water dynamics in the root zone of pear orchards permits better insight into the use of the Watermark soil sensor. Root water extraction patterns have been calculated previously in various fruit crops e.g. apple (Arbat et al., 2008; Besharat et al., 2010; Gong et al., 2006; Green and Clothier, 1999; Green et al., 2003) almond (Phogat et al., 2012; Vrugt et al., 2001a,b), grape (Zhou et al., 2007), orange (Consoli et al., 2014) and pear (Yao et al., 2011). In almost all these studies the numerical calculations have been compared with FDR, TDR or neutron probe recordings of soil water content. The question remains to what extent Ψ_{soil} observations, achieved with Watermarks

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sensors, can be related to numerical calculations of water extraction patterns.

Root water uptake patterns of trees can be calculated numerically using a sink term presented by Feddes et al. (1978). This sink term includes functions which account for crop transpiration, response to water stress and the root distribution of the crop:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}\right)-K(h)\right]-S(x,z,t) \quad (1)$$

$$S(x,z,t)=T_p\beta(x,z)\alpha(h,x,z) \quad (2)$$

where, θ is the volumetric water content, h (m) is hydraulic head, t is the time, x, z is the position, K (m d^{-1}) is the hydraulic conductivity. S (d^{-1}) is the sink term depending on potential transpiration rate (T_p) (m d^{-1}), a normalized root distribution function $\beta(x, z)$ (m^{-1}) and a dimensionless water stress response function $\alpha(h, x, z)$.

The numerical calculation of Eq. (1) can be executed with HYDRUS (Simunek et al., 2006). HYDRUS is designed to describe water movement in the vadose zone and has a broad range of applications. HYDRUS is often used to study irrigation design and root water uptake patterns (Arbat et al., 2008; Phogat et al., 2012; Vrugt et al., 2001a,b; Yao et al., 2011; Zhou et al., 2007). Input parameters needed for the numerical calculation are soil hydraulic properties, rainfall, irrigation rate, evaporation, transpiration of the tree and root distribution of the tree. Soil hydraulic properties, $\theta(h)$ and $K(h)$ relationships, can be measured in the field, laboratory or derived from pedotransferfunctions such as ROSETTA (Schaap et al., 2001) which is embedded in the HYDRUS software. Rocha et al. (2006) pointed out that especially the shape of the water retention curve, θ_{sat} and K_{sat} have a big influence on the HYDRUS calculation. Rainfall and irrigation can be measured on site, transpiration of the tree can be measured by sap flow gauges or derived from reference evapotranspiration (ET_o) with crop coefficients (Allen et al., 1998). Root distribution of the tree is probably one of the parameters that is the most difficult to obtain. In this case root distribution may be crucial since it can be expected to play a major role in the water extraction pattern of the tree. Previously root distributions for numerical calculations have been derived from observed root length densities (Gong et al., 2006; Green and Clothier, 1999; Green et al., 2003; Yao et al., 2011; Zhou et al., 2007), derived from literature (Phogat et al., 2012), assumed to decrease linearly with depth (Arbat et al., 2008) or derived from soil moisture observations using inverse modelling techniques (Besharat et al., 2010; Vrugt et al., 2001a,b). This raises the question which procedure is most suited for a reliable calculation of Ψ_{soil} distribution in the Conference pear orchards.

First objective of this study is to evaluate to what extent Ψ_{soil} observations obtained with Watermark sensors in irrigated pear orchards can be related to numerical calculations of Ψ_{soil} distribution. Secondly the sensitivity of the HYDRUS calculation to the implemented root distribution is investigated.

2. Materials and methods

2.1. Plant material and site description

The experiment was conducted in an orchard planted with Conference pear trees on a Quince Adams rootstock, situated in Belgium, Sint-Truiden (50°45′59.46″N, 5° 9′24.68″E). Belgium is situated in a temperate climate zone with frequent rainfall events and a relatively low evapotranspiration during the growing season. Average rainfall in Belgium during the growing season from April to August is 67 mm/month, average reference evapotranspiration (ETo) is 85 mm/month. However in 48% of the years between 1959 and 2012, rain deficits of 60 mm/month occurred. The trees were planted in 1996 with a planting distance of 3.5 m by 1.5 m. The average tree height was 3.5 m. The trees were trained in a free spindle system. The orchard was situated on a uniform silt loam textured soil. The organic carbon content in the upper soil layer (0–23 cm) was 1.1%. Rainfall was recorded on site; ET_o was calculated using the Penman–Montheith equation (Allen et al., 1998) based on data recorded in a regional weather station at 20 km from the site. In the orchard a drip irrigation system was installed with line drippers every 20 cm with a discharge rate of 2 L/h. Distance between the line drippers and the trunk was 35 cm. Management practices such as pruning, disease control, fertilization and mulching were carried out in the same way as in a commercial orchard. The EC of the irrigation water was 0.87 dS m^{-1} at 25 °C.

2.2. Soil water potential (Ψ_{soil}) observations

Three plots (plot A, B and C) in the centre of the orchard were selected for the experiment. Every plot consisted of four trees with in the centre one tree around which Watermark sensors were installed (Fig. 1). Sensors were installed on six positions perpendicular to the tree line. The numerical Ψ_{soil} calculations were executed in 2D in the plane XZ, with X being the horizontal coordinate perpendicular to the tree line and Z being the vertical coordinate. The calculation of Ψ_{soil} in 2D is a simplification of the reality but was done to ease the computation time. Previously the calculation of water distribution after drip irrigation, with the drippers in line, has been calculated successfully in 2D in a plane perpendicular to the drip line (Skaggs et al., 2004; Zhou et al., 2007). All sensors were installed at a depth of 30 cm in search of a gradient in Ψ_{soil} independent from suction due to gravity. It is expected that root concentration is highest in the soil layers close to 30 cm depth. Installing more sensors in the root zone would possibly disturb the soil too much for a representative experiment. To supply information on water content in the deeper soil layers gravimetric soil moisture samples were taken at a depth of 30–60 cm, at reasonable distance from the sensors to prevent further soil disturbance. The Watermark sensors were connected to a data logger which recorded Ψ_{soil} every 4 h. The standard manufacturer calibration was used to compute Ψ_{soil} from the electrical resistance measured by the sensors. In every plot the sensors were brand new and used for the first time. Sensors were installed 1 day before the start of the observation period according to manufactory guidelines. In plot A Ψ_{soil} was recorded in 2009 while in plot B and C Ψ_{soil} was recorded in 2011. In the irrigated plots irrigation was scheduled using the Watermark sensors. Irrigation was initiated when Ψ_{soil} decreased to −40 kPa, the irrigation dose ranged between 1 and 3 mm/day.

2.2.1.1. Plot A Ψ_{soil} observed in 2009 in an irrigated plot

In plot A Ψ_{soil} was observed between 04/06/2009 and 15/08/2009. Sensors were only installed at positions 2, 3, 4 and 5 according to Fig. 1. Total irrigation amount during this period was 77 mm, 132 mm rainfall was recorded and total ET_o during this period was 255 mm.

2.2.1.2. Plot B Ψ_{soil} observed in 2011 in an irrigated plot

In plot B Ψ_{soil} was observed between 20/04/2011 and 15/07/2011. Sensors were installed at positions 1, 2, 3, 4, 5 and 6 according to Fig. 1. Total irrigation amount during this period was 45 mm, 112 mm rainfall was recorded and total ET_o during this period was 300 mm.

2.2.1.3. Plot C Ψsoil observed in 2011 in a non irrigated plot

Similar to plot B Ψ_{soil} was observed between 20/04/2011 and 15/07/2011. Sensors were installed at positions 1, 2, 3, 4,