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A split-pot experiment with sorghum to test a root water uptake partitioning model

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ABSTRACT

Correct modeling of root water uptake partitioning over depth is a relevant issue in hydrological and crop growth models. We describe an experiment performed in split-pot lysimeters with sorghum plants. Both compartments were submitted to different irrigation cycles resulting in contrasting water contents. Observations of root water extraction were compared to matric flux potential based model predictions. Following model prediction, plants should prefer water uptake from wetter compartments according to the respective matric flux potential of both compartments, the root matric flux potential, and a root length density related parameter. In order to obtain reasonable agreement between model and experimental results, a correction factor had to be included accounting for heterogeneity of root length density and root activity as well as imperfect soil-root contact. Including this correction factor, model predictions of root water extraction were in reasonable agreement with observations. Release of water from roots to soil was observed on several occasions during the experiment, but model predictions it suggested a higher frequency and intensity than observed. This is probably due to not considering internal root system resistances, thus overestimating the ease with which roots can act as conductors of water.
KEYWORDS: Root water uptake, split pot, root length density, matric flux potential

1. INTRODUCTION

Information about root water uptake partitioning over depth is important for hydrological and crop growth modeling. Under wet conditions when root water extraction is at its maximum (potential) rate and transpiration equals potential transpiration T_p, experimental results show that this partitioning is highly correlated to root length per unit volume of soil. Under drier conditions when actual transpiration is lower than T_p, root water extraction has been observed to be proportional to root length density as well as to the soil water potential (Novák, 1987).

The relation between relative transpiration and soil hydraulic conditions (the transpiration reduction function) is commonly described by empirical piecewise linear reduction functions like the one proposed by Feddes et al. (1978). When more than one rooted soil layer is present, uptake per layer is calculated by multiplying the maximum root water uptake by the value of the transpiration reduction function in that layer. There is an ongoing discussion about whether and how plants compensate the reduced water uptake from drier soil layers by enhanced uptake from wetter ones (e.g. Li et al. 2001). The problem was addressed in a physically based model by De Jong Van Lier et al. (2008) including root length density as well as a composite soil physical characteristic, the matric flux potential of the respective soil layers. In this paper we describe an experiment performed in a split-pot lysimeter to test this model.

2. MATERIALS AND METHODS

2.1. Model description

To estimate root water extraction, the rooted soil volume is divided in subvolumes considered to be homogeneous in terms of root density, hydraulic properties and water content. Defining matric flux potential (M, m^2 d^{-1}) as the integral of hydraulic conductivity over pressure head, according to De Jong van Lier et al. (2008) the root water extraction per unit volume of soil from each of these homogeneous subvolumes S_v (m^3 m^{-3} d^{-1}) is given by:

$$S_v = \rho_v \left(\overline{M}_v - M_{0,v} \right) \tag{1}$$

where $\overline{M}_v$ (m^2 d^{-1}) and $M_{0,v}$ (m^2 d^{-1}) are the matric flux potential corresponding to the average water content in the subvolume and at the root surface, respectively, and ρ_v (m^{-2}) is defined as:

$$\rho_v = \frac{4}{r_0^{\,2} - a^2 r_m^{\,2} + 2\left(r_m^{\,2} + r_0^{\,2}\right)\ln \frac{a r_m}{r_0}} \tag{2}$$

In eq. [2], r_0 (m) is the root radius, a is a physical factor defined by De Jong van Lier et al. (2006) and found to be equal to approximately 0.53, and r_m (m) is the mean half distance between roots.

On deducing Equation [1] and the parameter ρ_v (eq. [2]), roots were supposed to be homogeneously distributed in the soil, i.e., each root of length L exploits a soil volume equal to the volume of a cylinder with radius r_m and height L. Moreover, all roots were considered to have the same extraction activity and efficiency (equal root water potential, no internal resistance to flow, equally perfect root-soil contact). These factors converge to a higher predicted water extraction by this hypothetical root system than by the real one. To account for this, an empirical factor f was inserted in eq. [1], making it:

$$S_v = f \rho_v \left(\overline{M}_v - M_{0,v} \right) \tag{3}$$

Factors ρ_v and $\overline{M}_v$ from eq. [3] can be determined experimentally, but root water potential $M_{0,v}$ cannot be measured. However, its value can be estimated from measured values of S_v and assuming $M_{0,v}$ to be equal in the entire root system. By comparing S_v from Eq. [3] to observed values of root water extraction, f can be estimated by minimizing the sum of square errors between observations and predictions.

2.2. Lysimeter experiment

To test the model described by eq. [3], a split-pot experiment with sorghum plants was performed. Four lysimeters with surface area of 0.60 x 0.25 m and depth of approximately 0.4 m were constructed from iron plates. The lysimeters were divided internally into two compartments with a surface area of 0.25 x 0.3 m. The compartments were filled with material from the surface layer of a medium textured soil (0.76 kg kg^{-1} sand, 0.04 kg kg^{-1} silt and 0.20 kg kg^{-1} clay) to a depth of 0.37 m. TDR waveguides were installed at depths of 0.08 m, 0.18 m and 0.28 m in each compartment, and a tensiometer was installed at the depth of 0.05-0.10 m for irrigation control.

Sorghum plants were sown in pots on February 25, 2008. Twenty days after germination two of the plants were transplanted to each lysimeter, on top of the metal division and with the roots split over the two sides. Evaporation was inhibited by a layer of coarse sand on top of the soil surface. Soil water potential was kept around -2 m. The application of water stress to one or both compartments of the lysimeters started 71 days after seeding and consisted of 4 phases (I: 7-25/May, irrigation of compartment B only; II: 26/May – 5/June, no irrigation; III: 6-14/June irrigation of compartment A only; IV: 15-22/June, no irrigation). During this period, TDR readings were performed three times per day, at 8am, 1pm and 6pm, approximately. Readings were transformed in water contents and averaged over one day and over the three reading depths in the compartments. In this way, 9 TDR readings resulted in one space-time averaged water content per compartment per day. During phases I and III, irrigation was performed whenever the tensiometer in the respective compartment indicated a pressure head of -2 m or more negative. At the end of the experiment roots were separated from soil by watering on a sieve. Roots were dried for 48 hours at 65 °C, after which dry root mass was determined. Using r_0 = 0.0003 m and a root density of 500 kg m^{-3}, values of r_m (eq. [2]) were calculated for each compartment.

2.3. Soil hydraulic properties

The soil water retention curve was determined in three samples by standard methodology on suction funnels for the less negative pressure heads (-0.1, -0.2 e -0.4 m) and on pressure plates for the more negative ones (-1, -3, -5, -10, -50 e -150 m). The Van Genuchten (1980) θ-h equation was fitted to the data (θ_r = 0.0646 m^3 m^{-3}; θ_s = 0.4542 m^3 m^{-3}; α = 2.7457 m^{-1}; n = 1.5268). Hydraulic conductivity K (m d^{-1}) as a function of pressure head was determined by the Wind (1968) evaporation method. The following equation was fitted to the data:

$$K = K_s; \quad |h| < |h_b| \qquad\qquad K = K_s\left(\frac{|h_b|}{|h|}\right)^b; \quad |h| \geq |h_b| \tag{4}$$

Fitting resulted in hydraulic conductivity of the saturated soil K_s = 0.06454 m d^{-1}, bubble pressure h_b (m) = -0.4211 m and shape factor b = 2.9995. Integration of Eq. [4] over pressure head allowed calculating the matric flux potential M as a function of h.

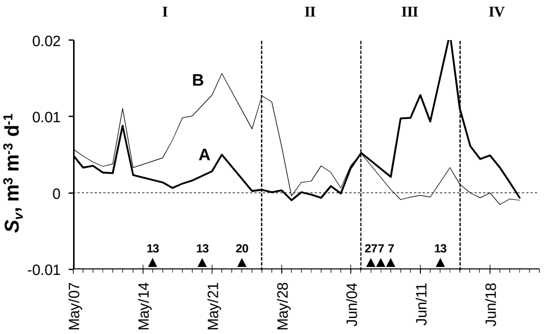
3. RESULTS AND DISCUSSION

Root analysis of all compartments resulted in an average observed root length density of 0.238 cm cm^{-3}. As results from the 4 lysimeters were similar, we will focus here on one of the lysimeters only. During the first days of phase I, before the first irrigation of compartment B, root water extraction S_v was similar in both compartments (Figure 1 left). From the first irrigation until the end of phase I, root water extraction from the irrigated compartment B can be seen to exceed the extraction from compartment A. From the last irrigation in phase I on, and during phase II, extraction was initially more intense from the (wetter) compartment B. About one week after the last irrigation in phase I, soil water contents, matric flux potentials and extraction rates in both compartments become similar.

An interesting aspect to be observed is the release of water by the root system to the soil (negative values of extraction). The phenomenon of water release by roots has been reported in literature mainly for tree species but also for annual crops (Dirksen and Raats 1985; Wan et al. 2000). For the specific case of sorghum plants, Xu and Bland (1993) detected release of water from roots to soil when the pressure head difference was greater than 550 kPa.

Comparison of observed to simulated extraction rates from all lysimeters and compartments allowed to determine that f = 0.0147 resulted in the lowest RMSE. In a split-pot experiment described by Herkelrath et al. (1977), a reasonable fit between theory and experiment could only be obtained by assuming a rooting density a 100 times smaller than that experimentally measured, which is similar to the value of f found in our experiment.

Figure 1 (right) shows simulated versus observed extraction rates obtained using the value of f. The RMSE is high considering many of the data points to refer to simulated values in the same order of magnitude. However, it should be remembered that the RMSE is strongly affected by outlying values like the several mismatching data points with experimentally observed extraction close to zero and simulated values much higher or lower.



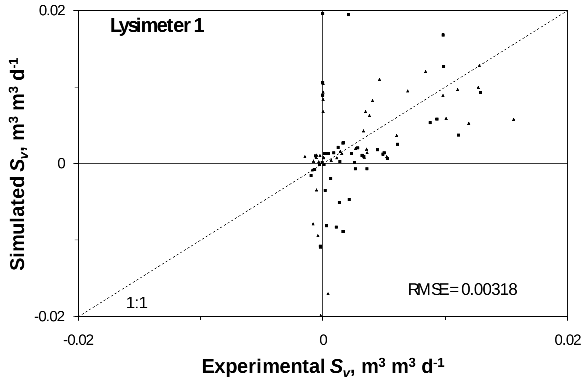


Figure 1. Root water extraction per compartment during experimental phase I, II, III and IV; triangles indicate irrigations, in mm (left) and simulated versus observed extraction rates (right) for one of the lysimeters.

4. CONCLUSIONS

Root water extraction data obtained from a split-pot lysimeter experiment with sorghum plants in a medium textured soil allowed observations of water uptake partition between compartments with contrasting water contents to be compared to model prediction. To obtain agreement between model and experimental results, a correction factor had to be included accounting for heterogeneity of root length density and root activity as well as imperfect soil-root contact. Release of water from roots to soil was observed on several occasions during the experiment, but model predictions suggested a higher frequency and intensity than that observed. This is probably caused by not taking internal root system resistances into account, thus overestimating the ease with which roots act as conductors of water.

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