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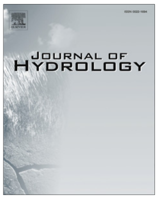

A method for estimating soil water diffusivity from moisture profiles and its application across an experimental catchment

A. Espejo [a], J.V. Giráldez [a,b,*], K. Vanderlinden [d], E.V. Taguas [c], A. Pedrera [d]

[a] University of Cordoba, Dept. of Agronomy, da Vinci Bldg., Cra. Madrid km 396, 14071 Cordoba, Spain
[b] Institute for Sustainable Agriculture, CSIC, Dept. of Agronomy, Alameda del Obispo, Apdo. 3048, 14080 Cordoba, Spain
[c] University of Cordoba, Dept. of Agricultural Engineering, da Vinci Bldg., Cra. Madrid km 396, 14071 Cordoba, Spain
[d] IFAPA, Las Torres-Tomejil Center, Cra. Sevilla-Cazalla km 12.2, Alcalá del Río, Seville, Spain

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SUMMARY

Despite the well-accepted value of soil hydraulic properties for describing and modeling matter and energy fluxes in the unsaturated zone, their accurate measurement across scales is still a daunting task. The increasing availability of continuous soil water content measurements at discrete points in space, as provided by sensor networks, offers still unexplored possibilities for evaluating soil physical properties across landscapes. In this study, we propose a new method, based on the Bruce and Klute equation, to estimate effective soil water diffusivity from soil water profile data observed during continuous desiccation periods. An analytical expression is proposed for the diffusion-soil water relationship, assuming an exponential relationship between soil water content and the Boltzmann variable. The method has been evaluated using soil water profile data observed at inter-row and under canopy locations across a rainfed olive orchard in SW Spain. The spatial variability of the effective soil water diffusivity across the orchard was estimated. Different soil conditions under the tree canopies as compared to inter-row areas resulted in significantly different effective diffusivity relationships, reflecting the effect of trees on soil physical properties and water dynamics across olive orchards. The proposed method offers a suitable alternative to traditional laboratory methods and can be easily extended to estimate soil hydraulic conductivity and water retention curves.

1. Introduction

Soil hydraulic properties are important indicators for assessing soil functioning and are essential for modeling matter and energy fluxes in the unsaturated zone. However, laboratory measurements of these properties are generally time-consuming, expensive and labor-intensive. Since measurements are made on small soil cores, the results often lack representativeness for field-scale applications.

The increasing use of soil water content (SWC) sensor networks offers as yet unexplored possibilities for estimating effective soil physical properties across landscapes (Martinez et al., 2013). Such networks are generally established to provide detailed measurements of the soil water dynamics across a range of scales (Vereecken et al., 2008). Though still limited in its spatial resolution, SWC sensor networks deliver quasi-continuous information on the temporal dynamics of SWC at discrete points in space. In this work, we have extended a traditional laboratory method for estimating soil water diffusivity (Bruce and Klute, 1956) in order for it to be used with field-measured SWC data obtained during a continuous drying period, as an alternative to laboratory measurements of soil physical properties. To our knowledge, the method has so far not been used under such conditions.

Based on the diffusion theory Matano proposed in 1933 (Crank, 1956, Section 11.62) a method for estimating the diffusivity coefficient, which was adopted later in soil science by Bruce and Klute (1956) for the evaluation of soil water diffusivity, $D(\theta)$, where θ is the volumetric water content, from horizontal absorption experiments, when the gradient of the gravitational component of soil water potential is negligible. In this case, space and time coordinates can be combined with the Boltzmann transform which converts the Richards' equation for horizontal water flow into an

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Abbreviations: SWC, soil water content; IR, inter row areas; UC, under canopy areas.

* Corresponding author at: University of Cordoba, Dept. of Agronomy, da Vinci Bldg., Cra. Madrid km 396, 14071 Cordoba, Spain. Tel.: +34 957 212241; fax: +34 957 212097.

E-mail address: ag1gicej@uco.es (J.V. Giráldez).

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ordinary differential equation. The original method of Bruce and Klute (1956) required water content and horizontal distance measurements of the wetting front from the water inlet at fixed times. Whisler et al. (1968) broadened the method for water content measurements at fixed positions along the horizontal soil column. Selim et al. (1970) confirmed the validity of both methods for estimating the soil diffusivity, $D(\theta)$. The Bruce and Klute (1956) method for horizontal flow, was extended by Turner and Parlange (1975) to account for radial flow from a line source.

In order to account for the experimentally observed relationship between the water content, θ, and the Boltzmann variable, η, several approaches have been suggested. One of them is the use of explicit $D(\theta)$ functions such as those proposed by Gardner and Mayhugh (1958), Ahuja and Swartzendruber (1972), Miller and Bresler (1977) and Brutsaert (1979). Alternatively, Cassel et al. (1968) fitted continuous functions to the $\theta(\eta)$ data for evaluation of the Bruce and Klute (1956) equation. Clothier et al. (1983) adopted a more elegant approach choosing fit functions, for which an analytical diffusivity expression can be obtained. Such relationships have also been proposed by McBride and Horton (1985), Shao and Horton (1998), Evangelides et al. (2005, 2010). Clothier and Wooding (1983) and Clothier et al. (1983) analyzed the shortcomings of the method to accurately determine the diffusivity for soil conditions near saturation, as a result of inaccuracies in the measured data and the improper values of the water retention curve slope in this moisture range.

Other solutions for the horizontal adsorption problem were presented by Shao and Horton (1996), Wang et al. (2004), Prevedello et al. (2008) and Barry et al. (2010). The Bruce and Klute (1956) method has also been extended to estimate unsaturated hydraulic conductivity, $K(\theta)$, and water retention curves, $\psi(\theta)$. Shao and Horton (1998) proposed an integral method for estimating soil hydraulic properties based on horizontal absorption experiments. Wang et al. (2002) and Ma et al. (2009, 2010) developed analytical methods to determine Brooks and Corey model parameters.

All these methods were applied to soil samples under laboratory conditions. Nevertheless, the use of soil moisture probes allows the extension of the method to estimate effective hydraulic properties in experimental plots or watersheds, overcoming scale and representativeness problems of laboratory results. Gardner (1970) proposed a field method to estimate $D(\theta)$ from successive tensiometer readings at a specific depth during drainage of a soil profile, more specifically using the rate of decrease of the matric component of soil water potential with time and the hydraulic gradient. Clothier and White (1981) lengthened the Bruce and Klute (1956) method for field measurements under infiltration.

The objectives of this work were (1) to develop a method for estimating the soil water diffusivity from field-measured moisture data during a desiccation period, and (2), to assess the influence of olive trees on soil hydraulic properties across an experimental catchment. An analytical solution has been provided for soil water diffusivity, assuming that the evolution of the soil water profile with time can be described by an exponential relationship.

2. Materials and methods

2.1. Setenil catchment

The Setenil microcatchment (36.88°N, 5.13°W) is situated in the Northern part of the province of Cadiz, Spain (Fig. 1). The drainage area is 6.7 ha, with a mean slope of 10% and an average elevation above sea level of 782 m. Trees were planted on a 7 × 7 m grid in 1995, except for an area of 1.4 ha in the southeastern part of the catchment, where trees were planted in 2007 (Fig. 1). The climate is subhumid Mediterranean with an Atlantic influence and an annual average rainfall of 1100 mm concentrated mainly in the September–May period. The summer is dry and hot, with frequent spells of dry, hot east winds.

The soil subgroup is an intergrade between Lithic and TypicRhodoxeralf (García del Barrio et al., 1971; Soil Survey Staff, 1999). The textural class is sandy, with mean values of 74% sand, 6% silt and 20% clay overlying a hardened bedrock layer consisting of calcarenites, which limits soil depth from 0.05 to 1.20 m. The average organic matter content is close to 1.0% in the upper soil horizon.

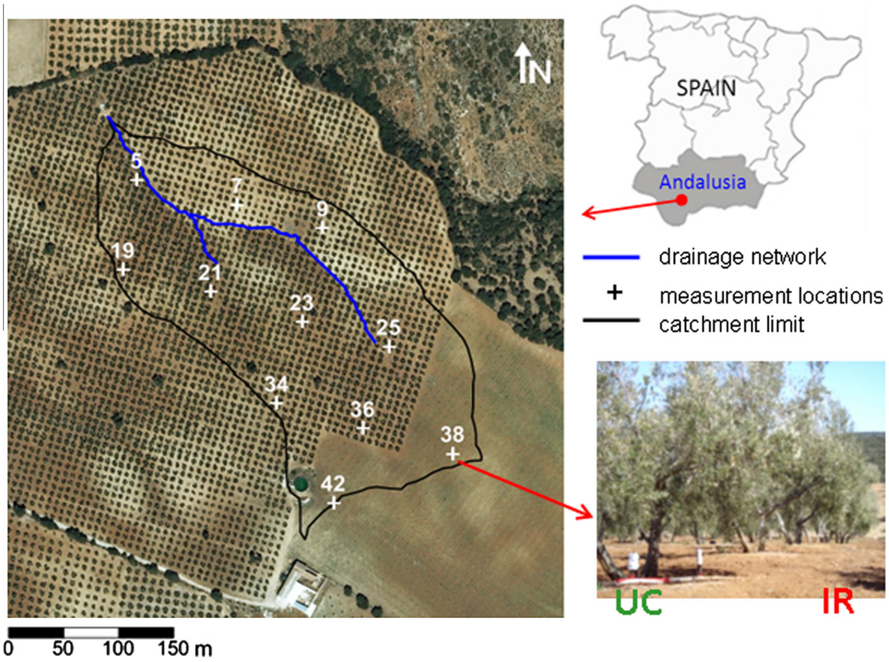

Fig. 1. Location of the experimental catchment and position of the 11 measurement points within the catchment. At each point, profile measurements of water content were made at the inter-row area (IR) and under the olive canopy (UC).