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Research Paper

Soil and irrigation heterogeneity effects on drainage amount and concentration in lysimeters: A numerical study

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ABSTRACT

Water and solute fluxes measured from lysimeters located in the field can be used to estimate evapotranspiration, for irrigation scheduling and in solute leaching management. System-imposed heterogeneities are expected to affect the variability of the measured fluxes, and therefore the uncertainty of data obtained using lysimeters. In this study, local heterogeneities in soil hydraulic conductivity and dripper discharge rate were studied and their effect on drainage amount and concentration assessed. Three-dimensional simulations were performed with HYDRUS (2D/3D) with 100 simulations per treatment. The effect of three levels of soil and irrigation heterogeneities was studied for lysimeters of two different sizes (1 m^2 and 0.5 m^2). Additionally, three leaching fraction levels and water uptake reduction due to solute stress were evaluated. Coefficient of variations of the drainage amount and solute concentrations were evaluated for the different scenarios. Irrigation heterogeneity caused higher variability in drainage amount while soil heterogeneity caused higher variability in drainage concentration. The larger the lysimeter, or the higher the leaching fraction, the lower the variability for both drainage concentration and amount. Combined soil and irrigation heterogeneities produced no synergistic effect, suggesting that the variability measured in lysimeters was governed by the factor that caused the highest variability. When water uptake reduction due to salinity was considered, the same trends were observed. The results from this study can help to decide if to use either drainage concentration or amount values, for saline water irrigation management using lysimeters, according to the soil or irrigation heterogeneity levels.

1. Introduction

Lysimeters are widely used for closing water balances by monitoring drainage amount and water storage in the soil profile. Lysimeters are also used as management tools for fertigation scheduling (Ruiz-Peñalver et al., 2015) and salt leaching (Tripler et al., 2012) by monitoring drainage solute concentration and loads. Systems of lysimeters are a good compromise between point measurements with sensors in the soil or plant (water content and salinity, sap flow, etc) and large scale measurements of ET based on near or remote sensing (energy balance, vegetation indices, Bowen ratio, scintillometers, etc) (Skaggs et al., 2012, 2013). When properly calibrated and well representative of the surrounding field, in situ lysimeters have been shown to be easy to operate and perform with relatively small measurement errors (Allen et al., 2011), compared to alternative methods.

The accuracy of lysimeters is often defined as the resolution and precision of the scale or load cell used in the setup (Howell et al., 1991). However, the overall accuracy of water and solute balances measured using lysimeters will depend on the representativeness of the lysimeter in comparison to the field (Evett et al., 2012). This representativeness is defined mainly, but not exclusively, by the similarity of the plants inside and outside of the lysimeter and it is influenced by: edge effects, boundary conditions, soil properties, fetch and lysimeter surface area (Allen et al., 2011; Evett et al., 2015). In addition, the uncertainty of output values measured in a lysimeter will be affected by heterogeneities imposed by the system such as micro-meteorological conditions, plant response, irrigation method and soil hydraulic properties. Heterogeneous atmospheric conditions in greenhouses was the motivation for a rotating lysimeter system proposed by Lazarovitch et al. (2006a). Recently, Hagenau et al. (2015) demonstrated how

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Table 1
Scenarios of lysimeter area, heterogeneity and leaching fraction levels and water or osmotic stresses.

		Heterogeneity level			
Scenario #	Lysimeter size m^2	Drippers discharge rate CV	Soil hydraulic conductivity CV	Leaching fraction	Water or osmotic stress
1	0.5	–	0.25	0.43	Water
2	0.5	–	0.5	0.43	Water
3	0.5	–	1	0.43	Water
4	1	–	0.25	0.43	Water
5	1	–	0.5	0.43	Water
6	1	–	1	0.43	Water
7	0.5	0.02	–	0.43	Water
8	0.5	0.044	–	0.43	Water
9	0.5	0.09	–	0.43	Water
10	1	0.02	–	0.43	Water
11	1	0.044	–	0.43	Water
12	1	0.09	–	0.43	Water
13	0.5	0.044	0.5	0.43	Water
14	0.5	0.044	–	0.2	Water
15	0.5	0.044	–	0.33	Water
16	0.5	–	0.5	0.2	Water
17	0.5	–	0.5	0.33	Water
18	0.5	0.044	–	0.2	Water + osmotic
19	0.5	0.044	–	0.43	Water + osmotic
20	0.5	–	0.5	0.2	Water + osmotic
21	0.5	–	0.5	0.43	Water + osmotic
22	0.5	0.044	0.5	0.43	Water + osmotic

two identical lysimeters were effected significantly by slightly different surrounding conditions in the field.

It is well known that soil heterogeneity will affect the results of measurements (Weihermüller et al., 2006). However, understanding the effect of the type or magnitude of the heterogeneity on water flow and solute transport at different scales still remains a challenge. In general, increased soil heterogeneity causes increased solute dispersion and spreading due to variability in pore water velocity (Mousavi Nezhad et al., 2011; Russo, 1998). Abdou and Flury (2004) studied the effect of different spatially structured soil heterogeneities on water flow and solute transport in free-drainage (h = 0 cm at the lower boundary condition) lysimeters and found that breakthrough of a non-reactive solute was faster in the field in comparison to lysimeters for vertically structured soils. These previous studies, however, do not explain how different levels of soil heterogeneity affect the uncertainty or variability of the results measured in the lysimeters themselves.

Irrigation uniformity has been widely studied (Guan et al., 2013; Lazarovitch et al., 2006b; Li, 1998; Or and Hanks, 1992; Pang et al., 1997; Russo, 1986; Solomon, 1984; Warrick and Gardner, 1983; Wu and Barragan, 2000; Zhao et al., 2012). Most studies focus on the effect of the water application uniformity on yield or soil water content and look for an optimum between irrigation water amount and uniformity. For sprinkler irrigation systems, soil water content uniformity was shown to be higher than the imposed irrigation uniformity (Li, 1998). Similarly, crop yield was found to have higher uniformity than the irrigation imposed uniformity for drip irrigated corn (Or and Hanks, 1992). It is possible to compensate for low uniformity by increasing the irrigation amount (Letey et al., 1984), but this will translate into lower water use efficiency, economical losses, groundwater pollution, waterlogging or salinity problems. It is therefore advisable that uniformity due to its repercussions on crops, water management, and the environment, play a role in irrigation system design (Wu and Barragan, 2000). In addition, dripper clogging can be a major issue affecting irrigation uniformity within or between seasons (Bounoua et al., 2016).

The primary objective of this study was to investigate the influence of local heterogeneities in soil hydraulic conductivity and irrigation discharge rate, individually and combined, on the variability of drainage amount and solute concentration obtained from lysimeters. Additional objectives included quantification of the effects of lysimeter size, leaching fraction, and ET reduction due to salinity on the generated variabilities of drainage amount and concentration.

2. Methods

2.1. Heterogeneity analyses

The effect of heterogeneity stemming from soil hydraulic conductivity and dripper discharge rate on drainage amount and chloride concentration was studied. One hundred numerical simulations were performed for each scenario that consisted of a different combination of: soil hydraulic conductivity or dripper discharge rate heterogeneity, lysimeter size, leaching fraction level and salinity stress. A summary of the 22 unique scenarios is presented in Table 1. Irrigation and soil heterogeneity levels (3 for each) are expressed as the coefficient of variation (CV) values used to generate each simulation (Sections 2.3 and 2.4). Lysimeter size, expressed as surface areas (0.5 m^2 and 1 m^2) was chosen so as to be relevant when different drippers discharge heterogeneity levels were applied. Further explanation on how the irrigation heterogeneity was applied is found in Section 2.3. Drainage results were evaluated every 4 days in order to reduce the noise consequential to daily variability in ET (Fig. 2). A total of 2200 simulations were run, each with an average running time of 8.5 h. Some of the simulations were run on an Intel Core i7-6700 CPU 3.4 GHz with16 GB of memory while others on an Intel Core i5-4570 CPU 3.2 GHz with 8 GB of memory.

2.2. Numerical simulations

Lysimeters with two surface areas (1 m × 1 m and 0.5 m × 1 m) and a depth of 0.6 m were simulated using HYDRUS (2D/3D) (Šimůnek et al., 2016). This model represents the most used and most accessible simulation tool for three dimensional water flow and solute transport in soils (Dudley et al., 2008). The 1 m^2 lysimeters were defined by 18 equally spaced horizontal planes and discretized using an unstructured finite element mesh, resulting in a total of 18,078 nodes and 52,224 three-dimensional tetrahedral elements (Fig. 1). The 0.5 m^2 lysimeters were defined by 21 equally spaced horizontal planes with a finite element mesh having 14,156 nodes and 40,080 three-dimensional tetrahedral elements. The soil hydraulic and transport properties were as defined in Raij et al.