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Quantitative analysis of wetting front instabilities in soil caused by treated waste water irrigation

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ABSTRACT

Irrigation with treated waste water (TWW) is a common practice in agriculture, mainly in arid and semiarid areas as it provides a sustainable water resource available at all-season in general and at freshwater shortage in particular. However, TWW still contains abundant organic material which is known to decrease soil wettability, which in turn may promote flow instabilities that lead to the formation of preferential flow paths. We investigate the impact of long-term TWW irrigation on water wettability and infiltration into undisturbed soil cores from two commercially used orchards in Israel. Changes of water content during infiltration were quantitatively analysed by X-ray radiography. One orchard (sandy clay loam) had been irrigated with TWW for more than thirty years. In the other orchard (loamy sand) irrigation had been changed from freshwater to TWW in 2008 and switched back in some experimental plots to freshwater in 2012. Undisturbed soil cores were taken at the end of the dry and the rainy season to investigate the seasonal effect on water repellency and on infiltration dynamics in the laboratory. The irrigation experiments were done on field moist samples. A test series with different initial water contents was run to detect the influence on water movement at different wettabilities. In this study we show that the infiltration front stability is dependent on the history of waste water irrigation at the respective site and on the initial water content.

1. Introduction

Crop irrigation with treated waste water has become a common practice in arid and semiarid areas to deal with water scarcity and to reduce the usage of fresh water. In Israel, the reuse of former waste water already provides more than 50% of total water consumption by agriculture (OECD, 2015). Besides the advantages as a sustainable water resource and recycling of nutrients, it has been observed that TWW irrigation may have critical impact on soil hydrological properties mainly induced by the load of organic compounds (DeBano, 1981; Doerr et al., 2000; Wallach et al., 2005). A reduced affinity of soil to water, so called soil water repellency, may lead to reduced infiltration capacities, intensify overland flow, and formation of preferential flow paths that render the spatial wetting pattern uneven (Rahav et al., 2017). Previous studies have shown these effects as a result of forest fires, decomposing of litter from plants rich in lipids and waxes, root exudates, fungal hyphae, and the usage of irrigation water of poor quality (Bughici and Wallach, 2016; Dekker and Ritsema, 2000; Horne and McIntosh, 2000; Lado and Ben-Hur, 2009; Zavala et al., 2009), concluding that mainly hydrophobic organics influences soil hydraulic properties. The occurrence of water repellency is induced by hydrophobic molecules coating mineral surfaces and by the presence of hydrophobic particles in the pore space (Doerr et al., 2000). The hydrophobic effect of amphipathic coatings depends on soil water content as their non-polar hydrocarbon chains are changing the orientation during drying. Hydrophobicity of soil can become a persistent attribute over time when supply is larger than degradation or leaching of these substances. The occurrence of water repellency and their affect on soil water dynamics is still not fully understood (Doerr et al., 2007). One reason is that the detection of wetting front characteristics and, furthermore, quantifying preferential flow in undisturbed soils is a challenge (Allaire et al., 2009). Therefore, infiltration studies in the past were mainly carried out by using flat, quasi two-dimensional Hele-Shaw cells (Carrillo et al., 2000; Rye and Smettem, 2017; Wallach and Jortzick, 2008; Wang et al., 2000; Xiong et al., 2012), by detecting wetting pattern of soil profiles and transects (Dekker and Ritsema, 1994; Kobayashi and Shimizu, 2007; Lipsius and Mooney, 2006), or by solute transport experiments (Clothier et al., 2000). The impact of water repellency on the wetting behaviour of the soil and the occurrence of preferential flow is already described, but is mainly limited to

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two-dimensional detection of a three-dimensional process, to a single scenario in the field by destroying the structure, or to point measurements. Rahav et al. (2017) have shown the occurrence of uneven wetting and preferential flow on the field scale via non-invasive ERT-measurements. A new approach developed by Weller et al. (2017) enables a direct, non-destructive quantification of water infiltration into undisturbed soil cores via X-ray radiography without the usage of chemical tracers. Compared to X-ray computer tomography image recoding takes only seconds, this enables the detection of fast moving water fronts. The results are 2D projections of mean changes in water content along the beam line, i.e. the horizontal sample depth. The objective of this study was to use this method to investigate influences of long-term TWW irrigation on the stability of infiltration fronts in undisturbed, cylindrical soil cores under different moisture conditions and, therefore, simulate diverse irrigation strategies. Furthermore, we included seasonal dynamics and soil textural differences to test for persistence of repellency, and the effect of reclaiming of water repellent soil by fresh water irrigation.

2. Materials & methods

2.1. Study sites and soil sampling

The study sites were located in Israel's coastal plain which is dominated by brown-red (degrading) sandy soils and marked by two pronounced climate seasons, a hot and dry summer where orchards are irrigated, and a rainy winter without irrigation. The first sampling location was close to Rehovot, where soil texture is loamy sand (denoted in the following as S). Here, three different treatments of irrigation were investigated: fresh water (FW), treated waste water (TWW), and no irrigation (NoI). Bulk density and carbon content were different in the irrigated parts ($\rho_b = 1.31$ g cm^{-3}, $C = 1.2\%$) compared to the non-irrigated part ($\rho_b = 1.64$ g cm^{-3},$C = 0.6\%$), shown in Table 1. Soil pH under TWW irrigation ($pH = 5.7$) was reduced compared to NoI ($pH = 7.4$) and FW irrigation ($pH = 7.2$). The second location was close to Hadera, where sandy clay loam (denoted in the following as L) was the predominant soil texture. At this site, no freshwater irrigation was available, only treated waste water (TWW) and no irrigation (NoI). Bulk density $\rho_b = 1.48$ g cm^{-3} and soil $pH = 7.4$ were independent of the irrigation regime. The carbon content under NoI $C = 1.7\%$ was higher than under TWW irrigation $C = 0.8\%$ (Table 1). At both study sites, citrus fruit (grapefruit in Rehovot and mandarin in Hadera) were produced. Soil cultivation was mainly reduced to inorganic fertilization without any tillage. In Rehovot, the water management was changed from fresh water to secondary treated waste water irrigation in 2008. In 2012, single plots of a block design experiment were converted to ground water irrigation for soil reclamation (Rahav et al., 2017). In Hadera, farmers have used secondary treated waste water for more than 30 years. At both study sites, the amount of irrigation was adjusted to the daily evapotranspiration rates. The first sampling was done at the end of dry season (October 2015), when soils were irrigated with the different treatments for seven months. The second campaign was scheduled in February 2016, after four months of the rainy season without irrigation. The samples were taken within the wet soil along the dripper lines (FW and TWW) and between the tree rows beyond the reach of irrigation water (NoI). Soil cores were sampled from the topsoil (0 mm to 200 mm depth) by using a custom-made drill (UGT GmbH, Germany) for undisturbed sampling of cylindrical soil cores (Kuka et al., 2013). The sample cylinders were made of polycarbonate with a wall thickness of 3 mm and an outer diameter of 100 mm. Depending on the difficulty to take undisturbed samples below the trees we used columns of different height, 100 mm and 200 mm. The samples were immediately stored in plastic bags to keep them field moist, carefully packed and shipped to Germany. Overall, 13 minimally disturbed soil cores (2 S-FW, 4 S-NoI, 2 S-TWW, 5 L-TWW) were taken in October 2015 and 23 (5 S-FW, 1 S-NoI, 6 S-TWW, 4 L-TWW, 7 L-NoI) in February 2016. Additional 77 undisturbed samples (50 mm in diameter and 50 mm in height) were taken from the topsoil in the vicinity of larger soil cores to test the soil for water repellency.

Table 1
Site conditions: texture (FAO, LS = loamy sand, SCL = sandy clay loam), grain size distribution, bulk density, soil pH$_{H_2O}$, and carbon content (C).

Treatment	Texture	Sand	Silt	Clay	Bulk density	pH	C
S-NoI	LS	81.4%	7.8%	10.8%	1.64 g cm^{-3}	7.4	0.6%
S-FW	LS	80.7%	8.5%	11.1%	1.31 g cm^{-3}	7.2	1.2%
S-TWW	LS	86.2%	5.9%	7.9%	1.32 g cm^{-3}	5.7	1.2%
L-NoI	SCL	63.4%	14.3%	22.3%	1.48 g cm^{-3}	7.5	1.7%
L-TWW	SCL	65.5%	12.6%	21.8%	1.48 g cm^{-3}	7.4	0.8%

2.2. Soil water repellency

The persistence and intensity of soil water repellency was characterized by two methods, the water drop penetration time test (WDPT) (Doerr, 1998; Letey et al., 2000) and the sessile drop contact angle (CA) (Bachmann et al., 2000). The small (50 mm in diameter) undisturbed soil samples were placed in an oven at 50 ° C until a reference water content corresponding to that of air dried soil was reached. WDPT and CA were measured for the upper 50 mm of the soil in an interval of 10 mm following Bughici and Wallach (2016). The WDPT was determined by placing three drops of 50 µL distilled water on the soil surface and recording the required time for their complete infiltration. The average time was used to classify their water repellency (Bisdom et al., 1993): class I, not water repellent (infiltration within 5 s); class II, slightly water repellent ($5 < \text{WDPT} \leq 60$ s); class III, strongly water repellent ($60 < \text{WDPT} \leq 600$ s); class IV, severely water repellent ($600 < \text{WDPT} \leq 3600$ s); class V, extremely water repellent ($\text{WDPT} > 3600$ s). The initial contact angle and its variation in time was measured with a goniometer (EasyDrop DSA20E, KRÜSS GmbH, Germany) for a flat surface of air dried, sieved soil (< 50 µm) from every 10 mm layer. The soil was glued to a double-sided tape attached to a pathology slide to form a flat single layer of soil particles and a drop volume of 15 µL was placed on the single particle layer. The change in drop shape was translated to a change in CA by the Easy Drop Software. The decrease in CA during the contact time $\phi(t)$ of the liquid with soil particles can be influenced by conformational changes, hydration, or rearrangement of organic molecules, coating soil-particle surfaces as a result of contact with water (Graber et al., 2007). Double-exponential-decrease functions were fitted to describe the dynamics of changing CA (Eq. (1)), as an additional quantification of water repellency persistence.

$$\phi(t) = a{*}e^{-b*t} + c{*}e^{-d*t} \tag{1}$$

where b, and d represents the rate at which the CA ($a + c$) varies with time (t). The sum of parameter a and c at time point zero is the initial CA, and their ratio describes the relevant dominance of the tailing.

2.3. Infiltration experiments

The detection of infiltration fronts in the larger cylindrical, undisturbed soil cores followed the approach developed by Weller et al. (2017). 36 samples were tested for their infiltration characteristics while they were still field moist. Afterwards, a test series with 12 loamy sand samples (6 TWW and 6 FW) at reduced initial soil water content was investigated. Therefore, soil cores were dried in an oven at 50 ° C for three and for seven days. All irrigation experiments were performed inside an X-ray microtomograph (Nikon Metrology X-Tek XCT 225) with the same irrigation rate (Fig. 1 a). A peristaltic pump provided a constant flux of $j = 8$ mm h^{-1} which was equally distributed over the soil surface by an irrigation device with 21 needles installed on top of the sample. The applied flux correspond to the irrigation rate of one