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Spatial variation of soil water repellency in a commercial orchard irrigated with treated wastewater

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ABSTRACT

The recognition of treated wastewater (TWW) as an alternative water resource is expanding in areas with a shortage of freshwater (FW). While many studies have been devoted to the effects of long-term irrigation with TWW on soil wettability and spatial flow variations in the soil profile, much less attention has been given to the spatial distribution of soil water repellency in the soil surface layer. This is the objective of the current study. Undisturbed soil samples (5 cm thick) were taken at 15-cm intervals parallel to a drip lateral in two adjacent plots of a commercial citrus orchard in central Israel. Each soil sample was sectioned into five consecutive 1-cm layers for which soil water repellency was determined by water drop penetration time method, and soil organic matter by loss-on-ignition method. Geostatistics and multivariate empirical mode decomposition were used to investigate the overall and scale-specific spatial variation of soil water repellency and its dependence on dripper intervals along the lateral. A high degree of soil water repellency with strong spatial variation was found in the surface soil after 4–6 years of TWW irrigation. Weak to moderate spatial dependence of soil water repellency with maximum autocorrelation distance of around 30 cm was discovered by geostatistical analysis. The spatial distribution of soil water repellency was considered to be greatly affected by the location of the drippers, being higher between adjacent drippers and lower underneath them. This soil water repellency distribution is presumed to result from ongoing lateral displacement of the amphiphilic substances in the TWW toward the outer edge of the wetted plume periphery. Multivariate empirical mode decomposition of the overall spatial variation of soil water repellency yielded three scale-specific variations with corresponding characteristic scales of 30 cm, 110 cm and 200 cm. Most of the soil water repellency variation was separated into the 30 cm and 110 cm spatial scales, which were correlated to processes related to the drippers and trees. Replacing TWW with FW for the reclamation of water-repellent soils partially alleviated the intensity of TWW irrigation-induced soil water repellency. Moreover, an inconsistency between the hot spots of water-repellency development between adjacent drippers and the areas that are effectively ameliorated by FW irrigation below the drippers could be developed and affect the spatial distribution of flow pattern in an a priori unpredictable way.

1. Introduction

The scarcity of freshwater (FW) resources is becoming progressively more severe and widespread due to increasing demand by a growing population and dietary changes on the one hand, and the effect of global climate changes on FW availability on the other (Vörösmarty et al., 2000). Water shortages are becoming critical in areas where water reserves are limited, and particularly in arid and semiarid regions where crop production inherently depends on irrigation. A solution that has arisen in the last few decades to alleviate the pressure on FW resources is to use recycled water for irrigation (Toze, 2006; US EPA, 1992).

Reused effluents include treated and untreated sewage effluent, domestic graywater, industrial wastewater and stormwater runoff (Al-Jayyousi, 2003; Gross et al., 2007; Toze, 2006). Although the quality of these effluents differs by their origin and type and level of treatment, they all contain certain amounts of dissolved organic matter, suspend solids, and electrolytes. In addition to conserving FW, the use of effluent for crop irrigation prevents its discharge into natural water bodies and their consequent pollution. Irrigation using treated wastewater (TWW) has been reported to increase soil fertility (Mohammad and Mazahreh, 2003; Yadav et al., 2002), improve soil aggregate stability (Piccolo et al., 1997), and promote soil microbial activity (Meli et al., 2002). In contrast, TWW use increases soil sodicity and salinity (Balks et al.,

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1998; Halliwell et al., 2001; Lado and Ben-Hur, 2009; Bedbabis et al., 2014), may lead to heavy metal and pathogen accumulation in the soil profile (Fazeli et al., 1998; Toze, 2006), soil compaction (Wang et al., 2003), and decreasing soil hydraulic conductivity, which enhances surface runoff and soil erosion (Agassi et al., 2003; Levy et al., 1999; Magesan et al., 1999). The detrimental effects of prolonged TWW irrigation on soil hydrological processes have been mainly attributed to the physical blockage of pores by suspended material (Levy et al., 1999; Lado and Ben-Hur, 2009), swelling dispersion of the clay particles caused by organic acid, and a high concentration of sodium (Halliwell et al., 2001), as well as excessive cell growth of microorganisms and related biofilm structures between soil particles (Magesan et al., 1999).

Recent studies have found that long-term TWW irrigation renders soils water-repellent, leading to spatially uneven distribution of soil water and chemicals (Rahav et al., 2017; Wallach et al., 2005). The decrease in soil wettability hinders spontaneous wetting of the soil for periods ranging from a few seconds to hours (Doerr et al., 2000; Wallach et al., 2005). The hindrance is due to coating of the soil particles with nonpolar aliphatic hydrocarbons and polar substances with an amphiphilic structure (Franco et al., 2000; McIntosh and Horne, 1994). These substances induce an initially high contact angle between the soil particles and incoming water which gradually decreases during their contact time (Bughici and Wallach, 2016). Once the decreasing contact angle reaches a value that enables the water to invade the soil pores, gravity-induced preferential flow pathways (fingers) are formed that induce spatially nonuniform water and chemical distribution in the root zone (Bughici and Wallach, 2016; Leuther et al., 2018; Rahav et al., 2017; Wallach, 2010; Wallach and Jortzick, 2008; Wallach et al., 2013). The uneven water distribution in the soil profile may lead to poor seed germination and plant growth (Wallis and Horne, 1992), and rapid leaching of surface-applied agrochemicals toward the groundwater (Blackwell, 2000; Graber et al., 2009). Moreover, the enhanced surface runoff caused by the hindered wetting and reduced infiltration increases the risk of soil erosion (Benavides-Solorio and MacDonald, 2001; Doerr et al., 2003).

Compared to other aspects of soil water repellency, its spatial variability has received less attention (DeBano, 2000; Regalado and Ritter, 2006). This might be a result of the temporal variation in soil water repellency, in particular via its nonlinear dependence on soil water content (Doerr and Thomas, 2000), in addition to its dependence on the spatial variability of soil texture, soil organic matter (SOM), microtopography (Keizer et al., 2007), lignite content (Gerke et al., 2001), vegetation type and thickness of the litter cover (Buczko and Bens, 2006; Bughici and Wallach, 2016; Lemmnitz et al., 2008). Dekker et al. (2001) found high spatial variability of soil water repellency with soil depth in a grass-covered sand dune. Low spatial variability was found in the surface soil layer of burned and unburned forested land (Doerr et al., 1998). Using geostatistical methods, Regalado and Ritter (2006) quantified the spatial structures of repellency parameters extracted from a repellency–water content relation curve in a forest watershed, and found that the spatial variability of soil water repellency was scale-dependent and could barely be explained by only the spatial structure of SOM. In a TWW-irrigated orchard, high spatial variability of soil water repellency was reported both laterally and vertically in the top soil layers (Wallach et al., 2005).

The objectives of the current research were: (i) to study the spatial distribution of soil water repellency along the soil surface layer in a commercial orchard that had been irrigated with TWW, and in part of it, the TWW had been replaced after 4 years with FW; (ii) to determine the dominant spatial scales for soil water repellency variation and its relationship with relevant affecting factors; (iii) to relate the spatial soil water repellency distribution to drip irrigation that is commonly used with TWW and other geometrical characteristics in the orchard.

2. Materials and methods

2.1. Study site and field sampling

The study was carried out in a commercial TWW-irrigated citrus orchard located in Sitriya, in central Israel. The site is in a semiarid Mediterranean climate, with average annual rainfall of ~550 mm during the winter months (November to March) and a dry summer. The soil in the plot is a Luvisols (Singer, 2007) of loamy sand in texture (80.1% ± 2.4 sand, 8.8% ± 1.7 silt and 11.1% ± 1.3 clay, based on 64 soil samples taken in the fall 2014 sampling campaign), with an average pH of 7.2 (± 0.4). The average bulk density of the topsoil is 1.24 g cm^{-3}, ranging from 0.84 g cm^{-3} to 1.58 g cm^{-3}.

'Star Ruby' grapefruit trees were planted in the orchard in 1992 at 2 × 6 m spacing. The plot was irrigated with FW up until 2008, when secondary TWW from the 'Ayalon' sewage-treatment plant replaced the FW. In 2012, for the purpose of research on the effect of TWW irrigation on water and chemical distribution in the soil profile (Rahav et al., 2017), an experimental orchard area of 1500 m^2 with relatively flat topography was divided into plots; in some of them, TWW irrigation was continued and in others, irrigation was switched back to FW from the local groundwater. The orchard was irrigated daily during the irrigation season using one surface drip line along each tree row, located ~0.3 m from the tree trunk. Drippers, each with a discharge rate of 3.8 L h^{-1}, were spaced at 0.75 m along the drip line, to achieve an overlap between the wetted diameters at the soil surface around each dripper (noted as continuous wetted strip). The trees were irrigated once a day, 6 days a week. The average seasonal irrigation amount was approximately 700 mm. The irrigation system, amounts of water and fertilizer applied, and irrigation frequencies in both treatments were identical. Different liquid fertilizers ('Idit', 'Sarit' and ammonium nitrate solution, 21%, ICL Fertilizers, Israel) were injected into the irrigation water in the same manner for both TWW and FW throughout the irrigation seasons during the study period.

Twenty-one undisturbed soil samples were taken by pressing a sharpened stainless-steel cylinder of 5 cm inner diameter and 5 cm height (total volume of 100 cm^3) (Eijkelkamp, Netherlands) into the soil surface. Soil samples were taken at 15-cm intervals along a 300-cm long transect parallel to the drip lines. The transect was 10 cm and 30 cm away from the drip line and tree trunk, respectively. Dry leaves, stems and other vegetal residue on the soil surface were gently removed by hand prior to sampling. After lifting the cylinders out of the soil, their upper and lower faces were sealed with fitted plastic caps to prevent water loss from the soil samples. The soil samples were stored in the laboratory in special aluminum cases that were resistant to humidity and heat (Eijkelkamp, Netherlands) until soil water repellency determination. Given that soil water repellency depends on soil water content (de Jonge et al., 1999), the cylinders were placed in a 55 °C oven for 48 h to eliminate the effect of variations in soil water content on the soil water repellency measurement. Following a cooling period, the caps were removed and the soil water repellency of the soil surface was determined by water drop penetration time (WDPT) test.

2.2. Characterizing soil water repellency

Soil water repellency was measured by the time that it takes for a water drop to penetrate the soil surface (WDPT method) (DeBano, 2000). Three 50-μL drops of distilled water were placed on the surface of the soil samples, and the time elapsed to drop absorption was determined. The average time for the three drops was reported as the WDPT. Water drops penetrating the soil maintained a well-defined, spherical shape and were easily removed with a spatula. To investigate the variation in soil water repellency with depth in the soil surface layer, the WDPT test was conducted for five consecutive 1-cm layers in each cylinder. A wooden disc of 4.9 cm diameter and 1 cm thickness was inserted into the bottom of the cylinder, to push the soil sample

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