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Structure and hydraulic properties in soils under long-term irrigation with treated wastewater

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ABSTRACT

Secondary treated wastewater, a commonly used water resource in agriculture in (semi-)arid areas, often contains salts, sodium, and organic matter which may affect soil structure and hydraulic properties. The main objective of this study was to jointly analyse the effects of long-term irrigation with treated wastewater on physicochemical soil characteristics, soil structure, and soil water dynamics in undisturbed soils. X-ray microtomography was used to determine changes in macro-porosity ($> 19\,\mu m$), pore size distribution, and pore connectivity of a sandy clay loam and a loamy sand. Differences in the pore network among soils irrigated with treated wastewater, fresh water that replaced treated wastewater, and non-irrigated control plots could be explained by changes in textural composition, soil physicochemical parameters, and hydraulic properties. In this study we showed that irrigation led to the development of a connected macro-pore network, independent of the studied water quality. The leaching of silt and clay particles in the sandy soil due to treated wastewater irrigation resulted in an increase of pores $< 130\,\mu m$. While this change in texture reduced water retention, the unsaturated hydraulic conductivity was diminished by physicochemical alteration, i.e. induced water repellency and clay mineral swelling. Overall, the fine textured sandy clay loam was much more resistant to soil alteration by treated wastewater irrigation than the loamy sand.

1. Introduction

The utilization of treated wastewater (TWW) has become an important source of irrigation water in many countries, primarily in arid and semiarid areas where water scarcity is severe. In Israel, already 75 % of wastewater is treated and re-used for irrigation, covering 50 % of the water consumption in agriculture (OECD, 2015). Compared to fresh water (FW), TWW is generally characterized by a higher load of dissolved organic matter, suspended solids, sodium adsorption ratio, and considerable levels of salinity. Therefore, irrigation with TWW can increase salinity and sodicity of soils at depths down to 1.5 m (Lado and Ben-Hur, 2009; Levy, 2011; Bedbabis et al., 2014), accompanied with clay migration due to dispersion of clay minerals in the top soil (Bardhan et al., 2016). The latter can enhance soil sealing, reduce infiltration, increase soil loss in sandy soils, and enhance slaking in clay soils (Lado et al., 2005).

At the same time, higher loads of organic matter in the effluents are reported to result in inconsistent effects on the carbon concentrations of the topsoil. While in some soils the organic carbon concentrations were increased (Jueschke et al., 2008), in others the effect was marginal (Lado et al., 2012) or it was reduced by priming effects due to the stimulation of microbial activity (Adrover et al., 2012). It is well known that soil structure is to a large extent formed by soil biota (Oades, 1993) and that the quality and quantity of organic matter in irrigation water can shape the structure of soil biological communities (Adrover et al., 2012; Frenk et al., 2014; Ibekwe et al., 2018). Hence, organic compounds introduced through TWW irrigation are expected to affect soil structure and thereby soil water dynamics.

Lado and Ben-Hur (2009) and Levy (2011) reported that TWW irrigation decreased soil structural stability and significantly altered soil pore architecture. This resulted in a reduction in saturated hydraulic conductivity in clay and loamy soils due to clogging of the pores with suspended solids while sandy soils were not affected. Bardhan et al. (2016) reported that the conductivity of clay soil was reduced in a water potential range of 0 down to -100 hPa, suggesting that the volume fraction of macro- and meso-pores were affected by pore narrowing through dissolved organic matter that may have led to enhanced clay swelling. Halliwell et al. (2001) hypothesized that changes in the

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pore system of the soil due to TWW seem to be the dominant factor for the reduction in soil hydraulic conductivity. Moreover, it has been shown that TWW contains hydrophobic compounds which can cause water repellency and can effect soil water dynamics such as reduced infiltration capacity, overland flow, formation of preferential flow path, and reduced water retention (Bauters et al., 2000; Diamantopoulos et al., 2013; Wallach and Jortzick, 2008). For the loamy sand soil discussed in this paper, an impact of reduced wettabiliy on the stability of water infiltration and the occurrence of preferential flow has been confirmed by heterogeneous water distributions in the field (Rahav et al., 2017) and infiltration experiments in undisturbed soil columns (Leuther et al., 2018).

The main objective of this study was to jointly analyse the effects of long-term irrigation with TWW on soil structure and soil water dynamics in undisturbed soils which integrates effects of changes in microbial communities, clay mineral swelling and dispersion, clogging of pores, and induced water repellency by loads of organics, suspended solids, and sodium. We used X-ray microtomography to determine the undisturbed macro-pore network of a sandy clay loam and a loamy sand irrigated with TWW for more than 7 years. The measurements were concentrated on the topsoil, assuming that this is the most affected region under drip irrigation (Assouline and Narkis, 2011; Elifantz et al., 2011; Wallach et al., 2005). Furthermore, we determined differences in soil texture and physicochemical characteristics to analyse how TWW irrigation potentially had changed clay content, and analysed the effect on soil hydraulic properties as integrative soil characteristics reflecting changes in soil wettability, soil texture, and soil structure.

2. Materials & methods

2.1. Study sites and soil sampling

The topsoils of two commercial orchards located in the coastal plain of Israel were investigated. The region is dominated by Lovisols (Singer, 2007) of a sandy texture and has two pronounced climate seasons, a hot and dry summer where orchards are irrigated, and a rainy winter without irrigation. At the study sites, water was applied via drip irrigation and the amount was adjusted to the daily evapotranspiration rates, approximately 700 mm per dry season. Soil cultivation was mainly inorganic fertilization without any tillage. To capture seasonal dynamics due to the irrigation schemes, the sampling was carried out in October 2015 and February 2016. We investigated the top soil (0 to 200 mm depth) of a loamy sand close to Rehovot (31°53’59.0”N, 34°51’00.0”E), denoted in the following as S, and a sandy clay loam close to Hadera (32°24’48.0”N, 34°58’02.3”E), denoted as L.

For the S-site, the water management was changed from fresh water (FW) to secondary treated wastewater irrigation (TWW) in 2008. In 2012, single plots of a block design experiment were converted back to FW irrigation for soil reclamation (Rahav et al., 2017). For the L-site, farmers have used secondary treated wastewater for more than 30 years. Soil samples were randomly taken within the wet soil along the dripper lines (FW and TWW) and between the tree rows beyond the reach of irrigation water (NoI) as a control for untreated soil. The study sites enclosed an area of 4500 m^2 at the S-site and of 1500 m^2 at the L-site. The chemical properties of the different water treatments are given in Table 1.

Table 1
Irrigation water characteristics (EC = electrical conductivity, SAR = sodium absorption ratio) for the two study sites (S = loamy sand, L = sandy clay loam, FW = fresh water, TWW = treated wastewater): mean values based on two measurements in 2014 and 2015 (S-site adapted from Rahav et al., 2017).

Site	pH	EC	SAR	*Na*	*Ca*	*Mg*
		[dS m^{-1}]	[$(meq/L)^{0.5}$]	[mg L^{-1}]	[mg L^{-1}]	[mg L^{-1}]
S-FW		0.77	1.73	65.32	61.00	28.31
S-TWW	7.2	1.65	4.61	164.68	61.80	21.02
L-TWW	7.4	1.32	3.96	153.00	85.00	16.80
	Cl [mg L^{-1}]	NO_3-N [mg L^{-1}]	NH_4-N [mg L^{-1}]	SO_4 [mg L^{-1}]	*P* [mg L^{-1}]	*K* [mg L^{-1}]
S-FW	108.20	$<$ 1.50	0.63	253.92	$<$ 0.01	3.58
S-TWW	231.60	$<$ 1.50	53.82	487.20	7.38	26.00
L-TWW	175.50	2.26	8.32	369.50	5.20	22.10

Cylindrical polycarbonate containers with a wall thickness of 3 mm and an outer diameter of 100 mm were used for soil sampling. These had a height of either 100 mm or 200 mm, depending on the feasibility of undisturbed sampling in the presence of woody roots below the trees. Soil samples were excavated by using a sampling device for undisturbed soil cores manufactured by UGT GmbH, Germany (Kuka et al., 2013). The method is adapted from an excavation technology for large soil monoliths, where surrounding soil is pre-cut and continuously removed by a rotating cutting sleeve. While slowly penetrating the soil, the remaining, undisturbed soil core is taken in by a sampling cylinder placed inside the sleeve. All samples were immediately covered with a lid, stored in plastic bags to keep them field moist, carefully packed and shipped to Germany. Overall, 17 soil cores (3 S-FW, 4 S-NoI, 3 S-TWW, 7 L-TWW) were taken in October 2015 and 26 soil cores (6 S-FW, 2 S-NoI, 6 S-TWW, 5 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 measure soil water repellency.

2.2. Soil properties

The total carbon (C) and nitrogen (N) concentrations in air dried soil were measured for each sample. To exclude a possible impact of carbonates on the measured C values, the soil was tested for lime content via hydrochlorid acid (10%) with a negative result (Jahn et al., 2006). C and N were determined by elemental analysis using gas chromatography (Vario EL Cube, Elementar). Three replicates per sample were ground, weighed (60 mg) and burned at 950 °C.

Particle size distribution in mineral soil was analysed by sedimentation following DIN ISO 11277 (2002). Samples had been dried in an oven at 105 °C, and separated from carbonates and organic substances before sedimentation.

Three different parameters were determined to describe changes in soil chemical properties by TWW irrigation: acidity (pH), electrical conductivity (EC), and sodium adsorption ratio (SAR) following the protocol described by Rowell (1994). Oven dried soil samples were mixed and sub-samples of 10 g were suspended in 25 mL distilled water and shaken for 15 min to measure soil pH_{H2O} in a 1:2.5 suspension with a pH meter. The pH was recorded after 1 min time of stabilization. Afterwards, 25 mL more distilled water was added, the reagent was shaken for 30 min, and the EC was measured in the supernatant of the 1:5 suspension. By multiplication with a factor of 6.4, the measured value was converted to EC of a saturation extract, the reference water content to describe soil salinity (Rowell, 1994). After filtering the extraction (Whatman No.1), Na^+, Ca^{2+}, and Mg^{2+}-ion concentrations were analysed via ion chromatography (DIONEX Aquion, Thermo Fisher). The SAR was determined via

$$SAR = \frac{Na^+}{\sqrt{\frac{(Ca^{2+} + Mg^{2+})}{2}}}, \qquad (1)$$

all concentrations were expressed in millimol per kilogram.

Soil water repellency at soil surface was determined by two methods, the water drop penetration time test (WDPT) (Doerr, 1998) and the sesille drop contact angle (CA) (Bachmann et al., 2000). Therefore, additional soil samples were placed in an oven at 50 °C until a reference water content corresponding to that of air dried soil was reached. The WDPT was determined by placing three drops of 50 µL