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Long term irrigation with treated wastewater (TWW) and soil sodification

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Use of treated wastewater (TWW) for irrigation has grown noticeably in recent years, especially in arid and semi-arid regions. The sodium adsorption ratio (SAR) in TWW is considerably higher than that in its fresh water of origin. Recently, there is evidence showing that subsurface (depth >30 cm) exchangeable sodium percentage (ESP) levels in Israeli orchards may reach 6–9 which is higher than expected following long-term irrigation with TWW having SAR <5. Our objectives were to (i) determine the ESP in soil profiles of orchards exposed to irrigation with TWW, and (ii) examine the relationships between the SAR of the irrigation water, the SAR of the soil solution and the ESP of the studied soils. Soil samples were taken from different depths (up to 120 cm) in orchards grown on two different soil types that had been irrigated for >10 years with TWW. In each soil sample non-adjusted SAR and adjusted SAR (SARadj) of the saturated paste and ESP were determined. In all sampled sites except one, accumulation of adsorbed sodium in the soil subsurface was noted. The obtained ESP levels were higher than those expected based on the SAR of the TWW. A satisfactory agreement was noted between ESP data and the non-adjusted SAR and SARadj of the soil solution. These observations suggest that a chemical equilibrium exists between the soil exchange phase and the soil solution and that the properties of the latter were not always dictated by those of the irrigation water.

1. Introduction

Use of treated wastewater (TWW), i.e., sewage water originating mainly from domestic sources that has been subjected to a number of treatment processes making it suitable for the irrigation of arable land, in agriculture has grown considerably in recent years, especially in areas suffering from shortage in fresh water (FW) (e.g., arid and semi-arid regions). For instance, in Israel ~50% of the water used for irrigation is TWW. With this increased necessity to use TWW, farmers are faced with unique and unfamiliar problems, among which is the possible degradation in soil structure and stability (Levy & Assouline, 2011). Probable risks for adverse changes in the structure and stability of soils and their hydraulic properties following irrigation with TWW, relative to irrigation with FW, may stem from the higher levels of salinity and sodicity, with the latter being expressed in terms of sodium adsorption ratio (SAR):

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$$SAR = \frac{(Na^+)}{((Ca^{2+}+Mg^{2+})/2)^{0.5}} \quad \left[(mmol_c\ l^{-1})^{0.5}\right] \tag{1}$$

where (Na^+), (Ca^{2+}) and (Mg^{2+}) are $mmol_c\ l^{-1}$ concentrations. In Israel, the electrolyte concentration in TWW is 16–20 $mmol_c\ l^{-1}$, being approximately twice that found in FW (Feigin, Ravina, & Shalhevet, 1991). Subsequently the SAR of the TWW may reach levels of 4–5 compared with SAR of only ~2 in FW (National Wastewater Effluent Irrigation Survey, 2006).

Hence, in comparison to irrigation with FW, long term irrigation with TWW could lead to a substantial increase in soil sodicity expressed in terms of exchangeable sodium percentage (ESP). This, in turn, may enhance soil sensitivity to clay swelling and dispersion and aggregate breakdown through slaking or the impact of water drops of high kinetic energy (e.g., rain or overhead sprinkler irrigation systems). These processes, which negatively affect soil-structure stability, are expected to occur mainly in winter (rather than during the irrigation season), because then the soil is leached with rainwater (i.e., water with very low electrolyte concentration) and the sensitivity of the soil clay to swelling and dispersion is much higher (Shainberg & Letey, 1984), as is the susceptibility of aggregates to slaking (Levy, Mamedov, & Goldstein, 2003).

Despite its importance, the relationship between the SAR of the irrigation water and soil ESP is not satisfactorily understood. As a first approximation, it is common to estimate the ESP of the soil by using the empirical equation proposed by the US Salinity Laboratory Staff (1954) that relates the SAR of the irrigation water or of the soil saturation extract to the ESP of the soil as follows:

$$ESP\ (\%) = \frac{100(-0.0126 + 0.01475 \cdot SAR)}{1 + (-0.0126 + 0.01475 \cdot SAR)} \tag{2}$$

This empirical method has gained worldwide popularity because of its simplicity and has been extensively used even in recent years (e.g., Chhabra, 2005; Faulkner, Wilson, Solman, & Alexander, 2001; Ganjegunte & Vance, 2006). Based on this relationship, long term irrigation with water having SAR commonly found in TWW (3–5) is expected, under equilibrium conditions, to lead to an ESP in the range of 4–6. It should be noted, that some studies have reported that water flow in the soil can already be harmed with this ESP range (Assouline & Narkis, 2011; Mace and Amerhein, 2001). In addition, when the concentrations of Ca^{2+} and HCO_3^- ions in the irrigation water and the soil solution are high, some of the Ca ions can precipitate as calcium carbonate (lime). Hence, the effective concentration of calcium ions (Ca_{eq}) which affects the SAR in this system is lower than the total concentration of the Ca ions. Consequently the actual SAR would be higher. There is, therefore, the need to use an adjusted SAR (SAR_{adj}) (Suarez, 1980), which takes into consideration the effects of the concentration and ratio of Ca^{2+} and HCO_3^- ions in the soil solution/irrigation water on the SAR, in order to more accurately predict the risk to soil sodification following irrigation with a given water quality.

Some indications have emerged in Israel in recent years (e.g., reports by Assouline & Narkis, 2013; Zilberstaine, Lowengart, Lahav, Keren, & Chen, 2007), suggesting that, compared to irrigation with FW, crop production, particularly orchard crops grown on clay soils, is harmed by irrigation with TWW. The reasons for the apparent deleterious effects of TWW on crop production are yet to be elucidated. Moreover, analyses of soil samples taken from orchards (with and without adversely affected yields), that had been irrigated with TWW having SAR of 3–4, have shown a buildup of an undesired ESP level of >6 at a soil depth >30 cm. Such ESP levels were higher than expected based on the SAR-ESP relation developed by the US Salinity Laboratory Staff (1954). We hypothesise that the aforementioned observed deviation of the ESP may stem from: (i) under estimation of the SAR due to overlooking the ionic strength and the electrolyte composition of the irrigation water, thus ignoring the possible formation of complexes between the divalent cations and organic or inorganic ligands (Halliwell, Barlow, & Nash, 2001); (ii) non-validity of the SAR-ESP relation developed by the US Salinity Laboratory Staff (1954) for the conditions prevailing in the soils of Israel, and (iii) the absence of equilibrium in the soil profile between the SAR of the irrigation water, the SAR of the soil solution and the soil ESP, which could lead to greater than expected sodium adsorption to the soil (Sposito & Mattigod, 1977). The objectives of our study were therefore: (i) to characterise the ESP in the soil profile of orchards that had been subjected to many years of irrigation with TWW, and (ii) to carefully evaluate the relations among the SAR of the irrigation water, that of the soil solution and the ESP of the soil in those orchards.

2. Materials and methods

2.1. Soil samples

Soil samples were collected from two different orchards in Israel. In each orchard, samples were collected from four depths (0–30, 30–60, 60–90 and 90–120 cm) near the emitter ("in row") and midway (3 m) between two neighbouring irrigation lines ("between rows") as follows: (i) Samples of a sand/loamy sand (Typic Haploxeralf) were collected in an experimental avocado orchard, drip irrigated, with one emitter line per row of trees, in Hama'apil in the central coastal plain (average annual precipitation – 774 mm, average annual amount of irrigation- 657 mm); samples from four replicate plots (one from each plot) were collected in June 2012 (summer sampling; 3 months into the irrigation season) "in-row" and "between rows" in plots irrigated either by FW or TWW for 10 years. (ii) Samples of a sandy clay (Chromic Haploxerert) were collected in an experimental vineyard at Lachish experimental station in the Pleshet plains (average annual precipitation – 325 mm, average annual amount of irrigation – 884 mm); samples from four replicate plots (one from each plot) were collected in November 2012 (autumn sampling; at the end of the irrigation season and prior to rain) "in-row" and "between rows" in plots irrigated either by FW or TWW for 12 years. The collected soil samples were brought to the laboratory, air-dried and crushed to pass through a 2-mm sieve. Some basic properties of the soils are presented in Table 1. It should be emphasised that in Hama'apil the texture of the soil (sand) in plots 1 and 2 was considerably different from that (loamy sand) in plots 3 and 4 (Table 1).