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Treated wastewater irrigation: Soil variables and grapefruit tree performance

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ABSTRACT

Soil degradation and declining tree performance following long term irrigation with treated wastewater (TWW) have been reported recently in orchards grown on clay soils. In an attempt to reverse this situation our research objectives were to quantify the effects of replacing TWW irrigation with fresh water (FW) on water uptake, water and mineral status, growth and yield of citrus trees in relation to soil physical and chemical properties. A field experiment was carried out in a commercial grapefruit orchard in a clay soil with a history of TWW irrigation. Changing irrigation water quality from TWW to FW significantly decreased soil solution electrical conductivity (EC), Na and Cl concentration, sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP) and improved aggregate stability (AS) of the soil. The concentrations of Na and Cl in leaves and roots were lower in FW-irrigated trees than in TWW-irrigated ones. Fruit yield, shoot and root growth, leaf area, water status and water uptake were all significantly and favorably affected by replacing TWW with FW. Although fruit yield increased by replacing TWW with FW irrigation, it was not significantly associated with any single or group of the studied soil attributes. However, in a stepwise regression analysis a correlation was established between fruit yield and leaf Cl and soil AS. Our findings indicate that the negative effects of irrigation with TWW are (i) through damage to soil structure leading to reduced water uptake and (ii) via accumulation of Na and Cl in roots and leaves of grapefruits to toxic levels. The positive effects of alternating poor quality water (TWW) with water of high quality (FW) occur in a relatively short time span, i.e. several months to two years, thus promoting the viability of this management practice.

1. Introduction

Irrigation with treated wastewater (TWW) is an attractive option for expanding agriculture when fresh water is scarce and/or limited, eg. in arid and semi-arid regions (Dobrowolski et al., 2008). Irrigation with TWW also contributes nutrients that partially replace fertilization (Fares and Alva, 1999; Hadas and Kislev, 2010). Many publications reported that irrigation with TWW had no detrimental effects on tree growth and productivity (Bielorai et al., 1978; Reboll et al., 2000; Parsons et al., 2001; Morgan et al., 2008). However, recent studies reported damage to plantations and gradual yield decreases (up to about 75%; Noshadi et al., 2013b) and recommended investigation prior to the further application of TWW in orchards (Noshadi et al., 2013b; Assouline et al., 2015; Yang et al., 2010; Pedrero et al., 2013).

The main causes proposed for the negative effects of TWW on soil and crops are (i) osmotic effects on the water potential of the soil and plants (Carden et al., 2003), (ii) toxic effects when ions, eg. Na (sodium), Cl (Chloride), and Boron (B), reach threshold levels (Aucejo et al., 1995; Noshadi et al., 2013a), and (iii) deterioration of the soil physical and hydraulic properties such as hydraulic conductivity and aggregate stability due to high sodium adsorption ratio [SAR] and exchangeable sodium percentage [ESP], and consequences in the rooting zone (Levy and Assouline, 2010; Noshadi et al., 2013b; Assouline et al., 2015; Assouline and Narkis, 2013; Schacht and Marschner, 2015; Bardhan et al., 2016).

Long term irrigation with relatively saline TWW (threshold EC

Abbreviations: AS, aggregate stability; BOD, biochemical oxidation demand; COD, chemical oxidation demand; DOM, dissolved organic matter; EC, electrical conductivity; ESP, exchangeable sodium percentage; FW, fresh water; PC, principal component; PCCA, principal component and classification analysis; SAR, sodium adsorption ratio; TSS, total suspended solids; TWW, treated waste water; Ψ_{stem}, stem water potential

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2 dS m^{-1}) leads to changes in the chemical properties of soil and increasing concentrations of ions in the soil solution, especially in clay soils (Lado et al., 2012). This increases the osmotic potential of the TWW, the soil water potential and the osmotic gradient between the soil solution and the plant, reducing water uptake by plants and root activity (Assouline et al., 2015). The main toxic effects stem from high concentrations of the most common ions, Na and Cl, and from some trace ions like B (Ben-Hur, 2004). For many years B was a major threat to citrus orchards irrigated with TWW in Israel, but in the past decade new regulations have led to a large reduction in the median B concentration in TWW from 0.4 to 0.17 mg l^{-1} (Tarchitzky et al., 2004).

The effects of salinity and high SAR on the physical properties of the soil are amplified in fine-textured soils due to the adsorption of Na to clay minerals leading to clay swelling, particle dispersion, altered soil structure, water retention, and clogging of water conducting pores (Levy and Assouline, 2010; Assouline et al., 2015). Recently it was suggested that during irrigation with TWW, the effect of the presence of dissolved organic matter in the TWW was equivalent to an increase in SAR of two to three units (Suarez and Gonzalez-Rubio, 2017). Several studies further suggested that long term irrigation with TWW affected structural porosity by modification of the composition of the dissolved organic matter (Bardhan et al., 2016) and/or by clogging of soil pores by dispersed organic particles (Levy et al., 1999). These processes may reduce the hydraulic conductivity (Assouline and Narkis, 2013; Lado et al., 2012, Assouline et al., 2015; Schacht and Marschner, 2015; Suarez and Gonzalez-Rubio, 2017), aeration (Assouline et al., 2015), root growth, plant water uptake and performance of plants in clay soils (Bravdo et al., 1992; Li et al., 2006).

Although many studies have shown the advantages (Maurer et al., 1995; Pedrero et al., 2015; Parsons et al., 2001; Zekri and Koo, 1993) and disadvantages (Araújo et al., 2001; Bielorai et al., 1978; Morgan et al., 2008; Parsons et al., 2001; Pedrero et al., 2010; Pedrero et al., 2013; Zekri and Koo, 1993) of using TWW for citrus orchard irrigation, few studies focused on the effects of winter rainfall on soil recovery (Assouline and Narkis, 2013; Bhardwaj et al., 2007). We are not aware of previous studies of soil-tree response to irrigation with FW following long term irrigation with TWW, except for an observation that reported positive influences of replacing TWW with FW in citrus orchards (Azenkot et al., 2005). We hypothesized that damage to the soil-tree system following long term TWW irrigation is reversible, and the questions are to what extent and how fast the soil-tree system will recover following replacement of TWW with FW. We propose to test our hypothesis in the same orchard where a preliminary study compared soil properties in irrigated rows with those in the unirrigated area between rows (Bardhan et al., 2016). They reported a significant reduction in the saturated and unsaturated (at low metric water potential) hydraulic conductivity of the TWW-irrigated soil.

The research objectives were to quantify the effects of replacing TWW irrigation with FW on water uptake, plant water and mineral status, growth and yield of citrus trees in relation to soil physical and chemical properties.

2. Materials and methods

2.1. Experimental site, plant material and design

A field study was conducted in a commercial fruit bearing orchard of Ruby Red grapefruit *(Citrus paradisi Macf.)* on *C. volcameriana* rootstock planted at 5 × 4 m spacing at Kibbutz Mizra in the Izra'el Valley, Israel (32°40′N 35°37′E 83 m asl). Climate is typical Mediterranean with a long dry season requiring irrigation, and a rainy period (with mean precipitation of 570 mm) in the winter (November-March) (Fig. 1). Soil was clay Chromic Haploxerert. Soil properties, determined at the beginning of the experiment in 2012 before starting the FW irrigation treatment, are listed in Table 1. The clay size particle fraction was high, 690 g kg^{-1}, whereas the sand fraction was much lower, 160 g kg^{-1}. The

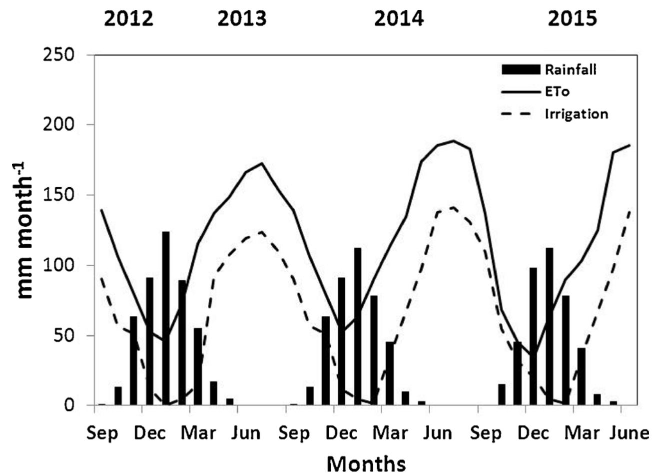

Fig. 1. Crop reference evapotranspiration (ET_0, solid line), rainfall (Vertical bars) and irrigation (dotted line) in mm. Values are monthly average data from September 2012 to June 2015.

carbonate content was considerable, about 10%, leading to pH above 7.0 and probably a high buffer capacity for pH. The CEC was high, in agreement with the clay content. ESP was high, probably due to the long term irrigation with TWW containing relatively high SAR.

The orchard had a history of irrigation with treated wastewater from 1986 until 1991, followed by 10 years of experiments with two water sources, FW and TWW (Lado et al., 2012), which led to significant yield decline and severe damage of trees including mortality of a few trees. From 2001 to 2004 different management treatments or remediation of the orchard were examined (Azenkot et al., 2005).

The trees were uprooted and rain-fed annual crops were grown during the next 4 years, and then the current orchard was planted in 2007 and irrigated with TWW. Each tree row was irrigated with a set of two drip line laterals, located along both sides of the trees, 0.5 m apart; each lateral consisted of a set of drippers with emitter discharge of 1.6 L h^{-1} (Amnon Drip, Naan Dan Jain, Israel), 0.5 m apart. The experimental orchard was divided into six blocks, each with one plot for each treatment in a random arrangement. Each plot was 3 rows of 5 trees, the central 3 trees in the median row were monitored as treatment trees, and 12 were border trees. Treatments were secondary treated domestic TWW and fresh water (FW) and the differential irrigation treatments started in May 2013, after the end of the rainfall season (Fig. 1). Meteorological data were collected from an automatic weather station (Campbell Scientific Inc., Logan UT) sited in the experimental field. Air temperature (T_{air}), solar radiation (R_s), vapor pressure deficit (VPD), relative humidity (RH) and wind speed were measured (Fig. 1). Irrigation doses were scheduled on the basis of weekly ETc estimated as crop reference evapotranspiration (ET_o), calculated using the Penman–Monteith equation (Allen et al., 1998). The total annual dose was 550–650 mm. Treatments and yield monitoring lasted four years and other detailed measurements were made during 2 years after starting irrigation with FW.

2.2. Chemical characterization of irrigation water

Water samples were taken from irrigation drippers and from main taps bimonthly during the irrigation season. Samples were analyzed for pH (pH meter), NH_4-N and NO_3-N with an auto analyzer (QUICKCHEM, Lachat Instruments, Milwaukee, WIS, USA), Na and K with a flame photometer (M410, Sherwood, Scientific Ltd, Cambridge-CB1), Ca and Mg concentrations were determined with an atomic absorption spectrometer (AA 800, Perkin Elmer, Norwalk, CT, USA) and the concentrations of Fe and B were determined by inductively coupled plasma (ICP-ICAP 6500 DUO Thermo, England). Electrical conductivity (EC)