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Small scale stratification of microbial activity parameters in Mediterranean soils under freshwater and treated wastewater irrigation

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ABSTRACT

Using treated wastewater for agricultural irrigation is a common practice in many water-scarce countries. Apart from the beneficial effects associated with the nutrient load and organic substrates, some negative effects on soil properties, such as increased water repellency or priming effects have been observed. The objective of this study was to determine if negative effects are associated with differences in microbial activity parameters. Soil samples were collected from three sites in Israel (IL) and Palestine (PA): (i) a lysimeter experiment near Lachish (IL) with three soils irrigated with four different water qualities; (ii) a long-term field experiment in a citrus orchard (Batsra, IL) irrigated with fresh water (FW) and treated wastewater (TWW), and (iii) an arable field experiment with also FW and TWW irrigation (Gaza, PA). Samples were collected from 0 to 5 (top-crust) and 5–20 mm (sub-crust) and analyzed for biological and chemical properties.

The results show little influence of water quality on the tested parameters. Only total phosphorus content in soils was enhanced due to TWW irrigation at all sites. Soil organic carbon showed a trend to lower contents under TWW irrigation compared to FW irrigation. Microbial biomass showed no significant influences of irrigation water quality while enzyme activities were higher in FW irrigated soils compared to TWW at Gaza. Instead, depth stratification within the top 20 mm was very pronounced at all sites, independent of irrigation water quality. Associated with a 13–34% higher SOC content in the top-crust, microbial biomass, basal respiration and enzyme activities were greatly elevated compared to the underlying sub-crust. At the arable sites (Lachish, Gaza), amino-peptidases dominated in the top-crusts while β-glucosidase activity dominated in the orchard soil (Batsra) independent of irrigation water qualities. These differences are attributed to the occurrence of phototrophic N-fixing organisms (i.e. cyanobacteria, lichens) on the surface of the lysimeter and Gaza soils.

Overall, no significant effect of TWW irrigation on the microbial activity within the C-, N-, P-, and S-cycle was observed in this study. Instead, soil crusts formed on light-exposed soil surfaces are characterized by high microbial activity forming a hotspot of fertility which should be protected to maintain soil functionality.

1. Introduction

Many countries in the Middle East are threatened by water scarcity requiring alternative strategies of water usage. In Israel, agricultural irrigation consumes 43% of the water resources and therefore needs to be optimized with respect to efficiency and alternative sources (Israel Water Authority, 2012). As a consequence, fresh water is increasingly replaced by treated wastewater, reaching about 38% of the irrigation water in 2010 (Israel Water Authority, 2012). In the Gaza strip 70% of the treated wastewater flows into the Mediterranean Sea, 25% infiltrate into the ground water and only a small amount is used for irrigation of agricultural fields (Shomar et al., 2010). Therefore there is a high potential for enhancing the percentage of wastewater used for agricultural irrigation (Fatta et al., 2004; Arlosoroff, 2006; The World Bank, 2010).

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Apart from the benefit of replacing scarce freshwater resources, irrigation with TWW also provides mineral nutrients and organic matter thus enhancing the nutrient availability and soil fertility (Friedel et al., 2000; Chen et al., 2008; Jueschke et al., 2008). However, depending on wastewater quality and source, salts, heavy metals or other contaminants may be added to the soil causing salt or metal contamination stress to soil organisms and plants (Chen et al., 2008). Further, treated wastewater irrigation holds a risk for human health by introducing pathogens like *Escherichia coli* into the soil or to the cultivated crop. Therefore, irrigation with (treated) wastewater is generally restricted to crops not intended for direct human consumption (Blumenthal et al., 2000).

A further problem reported by several authors is the development of hydrophobic soil crusts under TWW irrigation which decrease the infiltration potential of water during the irrigation season (Wallach et al., 2005; Tarchitzky et al., 2007; Chen and Tarchitzky, 2010; Nadav et al., 2011). The reasons for this phenomenon are not fully understood. The main causes appear to be an accumulation of amphiphilic and aliphatic compounds added with the organic matter in TWW (Tarchitzky et al., 2007; Nadav et al., 2011). Additionally, microbial growth particularly of basidiomycete fungi building up hydrophobic mycelium can enhance soil hydrophobicity on soil surfaces (Bond and Harris, 1964). Therefore, this study focuses on the characterization of the top millimeters of soil impacted by irrigation water. The top millimeters of soil are not only influenced by the input of organic matter (OM), nutrients, salts and heavy metals through wastewater irrigation but are also subject to harsh environmental conditions with extreme temperatures and a change of drying and re-wetting periods (Gundlapally and Garcia-Pichel, 2006; Miralles et al., 2012). Microorganisms adapted to desiccation and high radiation dominant in semi-arid and arid areas can form so called biological soil crusts (BSC) with the dominance of phototrophic organisms as cyanobacteria, mosses and lichens (Miralles et al., 2012). In a laboratory experiment Soule et al. (2013) detected that the cyanobacteria *Nostoc punctiforme* ATCC 29133 react on UVA stress with an up-regulation of genes encoding antioxidant enzymes and producing scytonemin. A special microbial community developing on bare arid soils has been termed as "mantle of soil fertility" (Garcia-Pichel et al., 2003) because some microorganisms forming these crusts can fix atmospheric N_2 in their thick-walled cells, e.g. *Anabaena*, *Microcoleus* (Belnap, 2001, 2002). Between 5 and 70% of the fixed nitrogen can be released into the deeper soil used by heterotrophic organisms or plants (Evans and Ehleringer, 1993; Belnap, 2002). Further, BSC promote soil stability, retain soil moisture, lead to an increase of organic C and prevent soil erosion (Gundlapally and Garcia-Pichel, 2006; Chaudhary et al., 2009; Zaady et al., 2010). There are many investigations of biological soil crusts dealing with the effect of climate properties on the biogeochemical processes (Zwikel et al., 2007; Miralles et al., 2012; Marusenko et al., 2013), the different microbial community composition (Castillo-Monroy et al., 2011) or analyzing the ecosystem services of BSC (Thomas et al., 2011). But little is known about the interactions of soil crust microorganisms and TWW irrigation and the consequences for C-, N-, P-, and S-turnover. For our study, we assumed that I) TWW irrigation enhances SOC and nutrient contents in the soils; II) increased TWW-borne SOC and nutrient inputs stimulate microbial biomass and activity as well as enzyme activities and affect enzyme activity patterns III) the stratification of microbial biomass and enzyme activity is stronger developed in TWW irrigated soils. In order to test these hypotheses, we collected top-crust (0–5 mm) and sub-crust (5–20 mm) soil samples from three field experimental sites in Israel and Palestine and characterized them in regarding basic soil parameters, microbial biomass and microbial as well as enzyme activities.

2. Materials and methods

2.1. Experimental sites

Three long-term field experimental sites variations in irrigation water quality (freshwater, treated wastewater), land use (arable, orchard) and soil texture (sandy, loamy) were selected. The lysimeter experimental site in Lachish near Kiryat Gat, Israel was established in 2007 by the Hebrew University of Jerusalem. There, 42 lysimeters were built with one meter height and 80 cm diameter and filled with 3 loess-derived soils from the Negev (Nir Oz, Ein Hashlosha, Saad), differing in clay content (high: 31%, medium: 13% and low: 7%). The irrigation of the lysimeters with four different water qualities was conducted through circular tubes providing 7 drippers each with a nominal discharge of 1.6 l h^{-1}. For further details regarding the lysimeter design see Nadav et al. (2011). The water used was obtained from the treatment plant of Kiryat Gat and was composed of domestic and industrial wastewater which underwent a secondary treatment before it was transferred to the research site. Here the secondary treated wastewater (TWW) was used as one of three additional treatments (Table 4). For the production of other water qualities the secondary treated wastewater was further processed by tertiary treatment (T-TWW) and by ultra-filtration (UF-TWW) at the research site. Fresh water (FW) was used as a control irrigation treatment with the addition of a dose of two liters of a 5:3:8 (%N:%P_2O_5:%K_2O) liquid fertilizer per cubic meter of water. An irrigation dose of 2000 m^3 ha^{-1} was applied, resulting in a nutrient application of 238 kg ha^{-1} nitrogen, 62 kg ha^{-1} phosphorus and 314 kg ha^{-1} potassium, and micronutrients. For more details of the wastewater treatment processes see Nadav et al. (2011). The different water treatments influenced the water qualities and resulted in highest water quality with ultra-filtration and tertiary treatment (Table 1). In comparison to TWW these treatments lead to less input of salts and a reduced sodium absorption ratio (SAR) while the biological oxygen demand (BOD) and the chemical oxygen demand (COD) are not differing as much (Table 1). All treatments were replicated three times and distributed randomly in the field. While six lysimeters were not cultivars, crops were grown in 36 lysimeters in a sequence of wheat–peanut–pepper–wheat–pepper–Chinese cabbage. Chinese cabbage was the crop cultivated and harvested before soil sampling in March 2011. Before each crop was planted, the soil was mixed to a depth of 20 cm to imitate soil tillage.

The second site Batsra is located in the coastal plain about 30 km north of Tel Aviv (IL) with an average annual rainfall of 580 mm. The site is under commercial agricultural use and was separated into one part irrigated with secondary treated wastewater (TWW) and another part with fresh water irrigation (FW) since 1976. In

Table 1
Properties of irrigation water in 2011 for the lysimeter site with fresh water (FW), ultra filtrated (UF), tertiary treated (T) and secondary treated (S) wastewater. Batsra site with FW and treated wastewater (secondary TWW) and Gaza site.

Parameter	Lysimeter				Batsra		Gaza	
	FW	UF	T	S	FW	TWW	FW	TWW
pH	7.6	7.8	8.2	8.7	7.5	7.7	8.2	8.4
EC (dSm^{-1})	0.7	2.0	1.9	2.1	1.1	1.3	2.4	2.2
Chloride (mg l^{-1})	94	188	189	266	146	195	505	305
Bicarbonate	146	573	567	628	305	378	n.d.	n.d.
SAR (mEq l^{-1})	1.6	5.8	6.0	8.0	1.67	2.8	1.9	3.3
BOD (mg l^{-1})	–	8.1	18	16	–	10	–	96
COD (mg l^{-1})	–	55	63	55	–	25	–	242

n.d. = not detected.