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Effects of treated wastewater irrigation on the dissolved and soil organic carbon in Israeli soils

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ABSTRACT

In many arid and semi-arid regions, the demand for drinking water and other domestic uses is constantly growing due to demographic growth and increasing standard of living. Therefore, less freshwater is available for agricultural irrigation and new water sources are needed. Treated wastewater (TWW) already serves as an important water source in Israel since more than 40 years and its usage will further be extended. Related to its high loads with nutrients, salts and organic materials its use as irrigation water can have major effects on the soil physical, chemical and biological properties, in the worst case leading to soil degradation. Additional organic matter reaches the soil with the effluent water and soil microbial activity is stimulated. Soil organic carbon (SOC) seems to accumulate in the topsoil and tends to decrease after long-term irrigation with secondary TWW in the subsoil. The amount of dissolved organic carbon increased and the aromaticity of the organic compounds in the soil percolates decreased over the irrigation period. Priming effects, occurring after stimulation of microbial activity by the addition of easily degradable substances, could be found in the soils and were stronger for subsoil (1 m depth).

Key words | effluent irrigation, Israel, organic carbon, priming effects, TWW

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INTRODUCTION

Increasing evidence of global climatic change could be observed during the last few years. Climatic models predict an increase or decrease in the amount of rainfall or a change in rainfall frequency and distribution (Whetton *et al.* 1993; Timmermann *et al.* 1999; Alpert *et al.* 2004). In semiarid regions like the East-Mediterranean the environment is highly sensitive to different rainfall patterns and the consequent changes in vegetation and soil properties. The global water cycle has strong impact on agriculture practices in regions which are characterized by scarcity of water resources. For agricultural production, the crops need to be irrigated during the dry summer periods. A renewable water source for irrigation is provided by the use of treated wastewater (TWW). This approach is already employed in Israel for more than 40 years and due to a high water demand, the government plans for TWW use at a level of 50 % of the total use in agriculture until 2020 (Israel-Ministry-of-the-Environment 2006). The agricultural land area irrigated with TWW in Israel covered 5.100 ha in 1975, in 1994 already 36,300 ha (Haruvy 2000).

Investigations on the effects of effluent irrigation on soil properties and crop yield was the aim of a number of studies conducted in recent years. A study from Italy was performed by Meli *et al.* (2002) in a citrus orchard which was irrigated with lagoon urban wastewater since 15 years. Chemical and microbiological soil parameters were determined. Mean values of organic matter as soluble carbon during the irrigation season showed always higher amounts in the TWW irrigated soil. Interestingly the values are lowest in both irrigation variants in September at the end of the irrigation season.

Ramirez-Fuentes *et al.* (2002) describes a field site in Mexico which is irrigated since 1886 with domestic and industrial untreated wastewater from Mexico City. A kind of

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primary treatment is only achieved by the flow of water to the field. A significant increase of organic C was found due to length of irrigation. The organic C increased 1.4-fold which amounts on average to 80 mg kg^{-1} soil yr^{-1} in the top 20 cm.

Due to effluent irrigation, changes in soil hydrophobicity occurred in three different soils in an experiment done in Israel (Chen *et al.* 2003). The saturated area and the volumetric water content in the topsoil were smaller with TWW irrigation. Effluent accumulated in small areas and flowed rapidly to deeper horizons so that the water was lost for the vegetation. FTIR and 13C-NMR analysis of natural organic matter (NOM) showed differences in the material composition. This phenomenon was not observed under freshwater irrigation. One reason for it could be a higher amount of the hydrophobic fraction in the organic matter.

As shown in many experiments, the addition of easily degradable substances can cause an increase of the microbial population and the mineralisation of SOM will be enhanced (Kuzyakov *et al.* 2000; De Nobili *et al.* 2001; Hamer and Marschner 2005). Different mechanisms may play an important role in the activation of microorganisms. One possible mechanism, as reviewed by Kuzyakov *et al.* (2000) is co-metabolism. Due to the availability of substrates the previous energy limitation of the microorganisms is abolished. Subsequently they are able to produce more enzymes and possibly energetically more expensive enzymes capable to degrade the soil organic matter. Thus, the activity and the mineralisation of the microorganisms are obviously enhanced. Dissolved organic matter (DOM) may be the most important C source in soils since all microbial uptake mechanisms require an aqueous environment (Metting 1993).

By irrigation with treated wastewater a considerable amount of DOM and POM (particulate organic matter) is added to the soil. Nelson *et al.* (1994) proposed that the amount and composition of DOM in the soil solution strongly influences the microbial activity. If DOM is continuously entering the soil by effluent irrigation it will affect the soil-DOM and the microbial activity to a high extent. Priming effects may have a considerable effect on the carbon budget of soils irrigated with reclaimed wastewater and experiments on this are shown in this study.

Gloaguen *et al.* (2007) studied the soil solution chemistry of a Brazilian Oxisol irrigated with effluent water. An enhanced mineralisation of the DOC could be detected in the soil solutions causing a long-term decrease of DOC. This is explained by a reduction of the SOM due to the intensification of microbial activity.

In this study, we investigated the effects of effluent irrigation on the long-term influence on soil organic carbon content and the amount and quality of dissolved organic matter. Experiments for microbial activity stimulation were performed to demonstrate possible effects of organic matter input.

MATERIAL AND METHODS

Sampling and analysis

The soils were sampled at two sites in Ramat Hakovesh (RH) (field and orchard) and from an orchard at HaMápil (HM) located in the coastal plain of Israel. These three sites served as experimental fields and had therefore controlled conditions of irrigation over 10 and 12 years, respectively. The RH field site was irrigated with TWW for 2 years. In addition, soil sampling was performed in Bazra orchards and Yagur fields. Both sites are farmlands with an irrigation history of about 10 and 40 years, respectively.

Freshwater irrigated soils were taken as controls. The soils were air-dried directly after sampling, mixed and sieved to <2 mm. The total carbon was determined in a C/N-analyzer (Elementar Vario EL) and the inorganic carbon in a C-analyzer (TR 3600 Deltronik) in RH orchard and HM.

The soil characteristics are shown in Table 1.

Soil percolation

Dissolved organic carbon (DOC) was extracted from soils by percolation over a period of 3–4 hours with 1 mM $CaCl_2$ and fitration (0.45 μm). In the percolates, DOC concentration (Dimatec, Germany) and UV-absorption (254 nm) (Lambda 2, Perkin Elmer) were determined. The characterisation of the soil percolates by the specific UV-absorbance at 254 nm ($SUVA_{254}$) indicates the degree of aromaticity of the DOC (Weishaar *et al.* 2003,

Table 1 | Soil characteristics of the freshwater irrigated topsoils (0–10 cm)

Sampling site	Ramat Hakovesh I	Ramat Hakovesh II	HaMápil	Yagur	Bazra
Soil classification (WRB)	Luvisol	Luvisol	Luvisol	Vertisol	Luvisol
Land use	Field	Orchard	Orchard	Field	Orchard
Crop	Corn, Sorghum	Grapefruit	Avocato	Cotton	Grapefruit
pH	7.1	7.2	7.1	7.6	7.7
Sand(%)	60.4	89.4	81.7	27.0	64.7
Clay(%)	23.49	5.7	10.7	39.9	16.9
SOC(%)	0.66	0.85	1.76	0.81	6.17
N(%)	0.06	0.07	0.37	0.20	0.68
C/N ratio	11.3	11.7	4.8	4.1	9.1

Chin 1994, Traina *et al.* 1990). The data was statistically analysed using the Student-Neuwman-Kuels (S-N-K) Test ($p < 0.01$).

Soil incubation

Soil incubations for the determination of soil organic matter (SOM) degradability were carried out with and without the addition of 13.3 μg substrate-C mg^{-1} soil-C of ^{14}C-labelled L-alanine and D-fructose (Amersham Pharmacia Biotech, Little Chalfont, England) mixed with respective unlabelled substrates D-fructose (Acros Organics, New Jersey, USA) and L-alanine (J.T. Baker B.V., Deventer, Netherlands) to obtain the required carbon concentration for the incubation experiment in order to determine the effects of these substrates on microbial activity and C-turnover. These two substrates were chosen as surrogates for easily degradable compounds present in effluent water, and had induced a priming effect in former experiments (Hamer & Marschner 2005). Before incubation the soil was adjusted to 60% water holding capacity and preincubated two weeks at 15°C in the dark. The soils were incubated in a Respicond apparatus (Nordgren Innovations, Bygdeå, Sweden) at 25°C in the dark and the respiration was recorded hourly by the changes of electric conductivity in 10 mL of 0.6 M KOH solution where the CO_2 is trapped (Nordgren 1988). The amount of $^{14}CO_2$ evolved was determined in the KOH by a liquid scintillation counting (Beckmann LS 6000 TA, Fullerton, USA). Differences in PE between freshwater and TWW irrigated soil were statistically defined by using the Student t-Test ($p < 0.05$).

RESULTS AND DISCUSSION

Soil organic carbon

As it can be seen in Figure 1, in the first 20 cm the SOC content is generally similar or higher in the TWW irrigated soils compared to the freshwater controls. A trend of SOC accumulation of the TWW irrigated soil in the topsoil can be pointed out. These results are similar to the results from other studies (Filip *et al.* 1999; Ramirez-Fuentes *et al.* 2002) were after long-term irrigation an accumulation of organic matter could also be seen in the topsoil. In the soil profiles shown in Figure 1a-c the SOC decreased below ~50 cm in the TWW irrigated soils. The SOC content of the HaMápil avocado orchard soil, depicted in Figure 1d, does not show a clear difference between freshwater and effluent irrigated soils in the depth of 100 cm but a decrease of SOC in both irrigation variants which is stronger in the TWW irrigated soil. Based on these different SOC contents in the subsoil of the investigated sites a SOC loss caused by TWW irrigation could be calculated for the soils (Table 2). The calculation with SOC data from Mizra and Wadi Fara are included in the table from other sources.

The loss of organic carbon can be calculated by the assumption of a soil bulk density of 1.25 g cm^{-3}. This value was determined for the soil in HaMápil in 100 cm depth and assumed to be similar in the other soils. Table 2 shows the calculated carbon loss at 100 cm soil depth of five different sites in Israel and one site in the Palestinian Authorities (Wadi Fara). Bazra orchard site is similar to Ramat Hakovesh site concerning the cropping with grapefruit. Also the Mizra

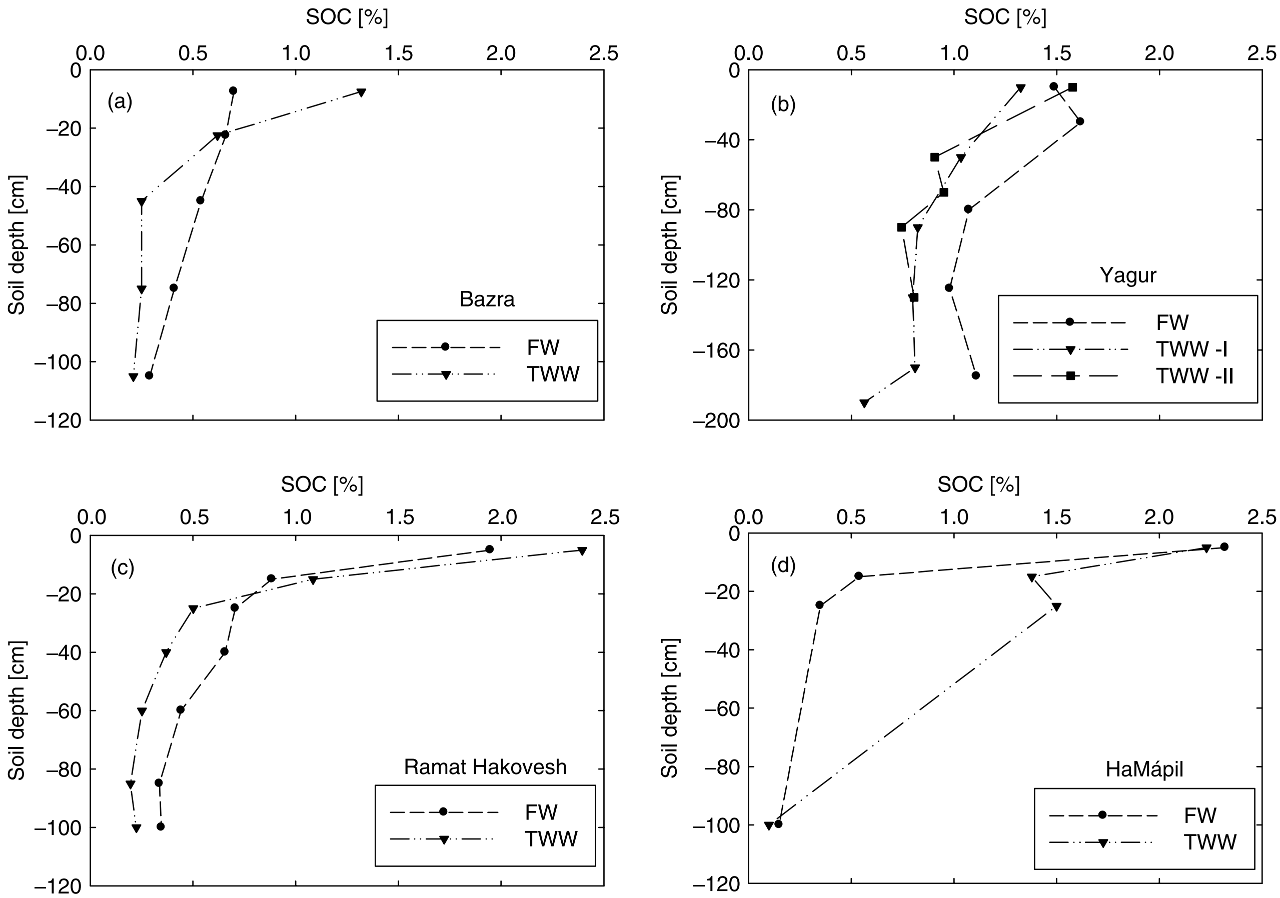

Figure 1 | Soil organic carbon (SOC) content in % of the soil profiles in freshwater (FW) and treated wastewater (TWW) irrigated soils in Bazra (a), Yagur (b), Ramat Hakovesh (c) and HaMápil (HM) site.

site is a grapefruit orchard located in the Yizrel Valley. The loss of SOC is even more pronounced in an area close to Nablus (Wadi Fara) were raw sewage is used for irrigation. In most of the investigated sites a continuous depletion of the SOC in the subsoil of wastewater irrigated fields can be seen but the strongest effect can be noted in the field irrigated with raw sewage. The input of easily degradable organic matter is much higher when wastewater is not treated which might cause a stronger stimulation of microbial activity (Friedel *et al.* 2000).

Table 2 | Calculated organic carbon losses due to TWW irrigation in subsoil (1 m depth) at different sites in Israel and one site in the Palestinian Authorities (Wadi Fara) (referred to the freshwater irrigated soil)

Soil type	Sampling site	Irrigation water quality	SOC loss [t ha^{-1}]	Source
Luvisol	Ramat Hakovesh orchard	Secondary TWW	1.5	Own research
	HaMápil	Secondary TWW	0.6	Own research
	Bazra	Secondary TWW	1.0	Tarchitzky, pers. comm.
Vertisol	Mizra	Secondary TWW	2.1	Tarchitzky, pers. comm.
	Yagur	Secondary TWW	2.5	Jüschke *et al.* (2004)
	Wadi Fara	Raw sewage	4.9	Abu baker, pers. comm.

Table 3 | DOC content and $SUVA_{254}$ of soil percolates from soil samples from RH field (December 2002 and June 2003) topsoil 0–10 cm (letters indicate significant differences (S-N-K, $p < 0.01$) between freshwater and TWW irrigated soils and both month)

	December 2002		June 2003	
Parameter/irrigation	Freshwater irrigated soil	TWW irrigated soil	Freshwater irrigated soil	TWW irrigated soil
DOC content [mg kg^{-1}]	26.40^b	51.25^c	22.21^a	47.52^d
$SUVA_{254}$[$Lmg^{-1} m^{-1}$]	3.7^b	3.7^b	3.6^b	1.9^a

Dissolved organic carbon

In RH field, the DOC content was significantly higher in the TWW irrigated topsoil than in the freshwater irrigated soils in December and June as shown in Table 3. The differences between freshwater and TWW irrigated soils were larger in June than in December. The DOC content in HM orchard topsoil is lower in the TWW irrigated soil in April compared to the freshwater irrigated soil (Table 4). In September the DOC amount increased strongly in the TWW soil while it decreased in the freshwater irrigated soil. This can be due to the current input during the irrigation season between April and October.

Concerning the $SUVA_{254}$ values it can be seen that in the soil percolates from RH field no differences could be detected between both irrigation variants in December, but that the $SUVA_{254}$ decreased strongly after continuous irrigation with TWW in June (Table 3). It is likely that the input of organic material by the TWW influenced the aromaticity of the DOC in the soil solution. As seen in Table 4 the aromaticity of the DOC from the soil percolates from HM soil significantly decreased in both differently irrigated soils. It is notable that the $SUVA_{254}$ of the percolates from the freshwater irrigated soil in April was very high compared to the other values. The TWW irrigation did not seem to have an effect on the $SUVA_{254}$ of the soil solution in the HM sampling site.

Incubation experiments

One possible explanation of the depletion of organic carbon in the subsoil of TWW irrigated soils can be the increase in microbial activity and therefore the enhanced degradation of soil derived organic carbon. Incubation experiments with addition of ^{14}C-labelled substrates were performed, to investigate the stimulation of soil microbial activity by organic matter addition.

Priming effects in the topsoil

The mineralisation of the SOC is enhanced by the addition of substrates in both irrigation variants of RH and HM soil. Priming effects (PE) of the TWW irrigated topsoils from RH (10–20 cm) shown in Table 5 are significantly lower than in the freshwater irrigated soil. In the soil from HM (0–10 cm) these differences are not significant. By irrigation with TWW mainly more complex organic substrates but also proteins, carbohydrates, lignins, different organic acids and amino-acids enter the soil (Feigin *et al.* 1991). According to Fontaine *et al.* (2003) microorganisms which are metabolising according to the K-strategy are more effectively using complex substances and by the release of enzymes contribute stronger to the PE. Therefore, a higher PE in the TWW irrigated soils under field conditions is suggested. Because of lower PE in the TWW soil determined in the experiment, it can be assumed that the available carbon pool in the

Table 4 | DOC content and $SUVA_{254}$ of soil percolates from soil samples from HM (April and September 2004) topsoil 0–10 cm (letters indicate significant differences (S-N-K, $p < 0.01$) between freshwater and TWW irrigated soils and both month)

	April 2004		September 2004	
Parameter/irrigation	Freshwater irrigated soil	TWW irrigated soil	Freshwater irrigated soil	TWW irrigated soil
DOC content [mg kg^{-1}]	35.15^c	30.58^b	15.84^a	38.20^c
$SUVA_{254}$[$Lmg^{-1} m^{-1}$]	4.6^c	3.6^b	3.1^a	3.4^a

Table 5 | Priming effects (%) of RH and HM orchards (asterisks indicate significant differences (t-test $p < 0.01$) between freshwater and effluent irrigated soils)

		Topsoil		Subsoil	
Sampling site	Substrate	Freshwater irrigated soil	TWW irrigated soil	Freshwater irrigated soil	TWW irrigated soil
RH	Alanine	+49	+15***	+26	+40
	Fructose	+42	+19*	+10	+47
HM	Alanine	+32	+11	+233	+145***
	Fructose	+25	+17	+303	+215**

TWW irrigated topsoil is already more exhausted than in the freshwater irrigated soil due to continuously priming in the field. A decrease in the SOC content of these topsoils cannot be stated probably due to the masking by continuously addition of fresh organic material.

Priming effects in the subsoil

In the subsoil from RH no differences of the PE's between freshwater and TWW irrigated soils could be detected. Very high PE's were measured in the HM subsoil with significantly lower values in the TWW irrigated soil (Table 5).

This particular high PE in the HM subsoil can be explained by a large available pool of organic carbon which was accumulated over time. This pool is depleted to a higher extent in the TWW irrigated soil compared to the freshwater irrigated one due to the continuously priming action in the field. This could explain the lower SOC values in soil irrigated with TWW.

Alanine and fructose are generally easily degradable for microorganisms and both substrates show a similar PE. Fructose serves as energy substrate only, alanine also contains nitrogen. Therefore, a comparison of both substrates allows an interpretation of one relevant factor, the N limitation. The results show clearly that obviously no limitation of nitrogen for the degradation of organic material appear referring to the similar levels of the PE without significant differences (t-test $p < 0.05$) between both substrates.

CONCLUSIONS

The organic carbon content of TWW irrigated soils seems to become depleted in the subsoil compared to freshwater irrigated fields. This is in contrast to the topsoils where the content of organic carbon is similar or even higher under effluent irrigation, which could also be found in the literature (Friedel *et al.* 2000, Ramirez-Fuentes *et al.* 2002, Meli *et al.* 2002). The pronounced effect seems to be relevant in deeper soil horizons with continuously input of OM which percolates in the soil. According to our hypothesis the SOC in these horizons gets depleted because of stimulated microbial activity due to substrate inputs from the effluents. The effect has no direct influence on the fertility of the soils in the rooting zone. But, due to enhanced mineralization of organic material a greater amount of CO_2 is released from the soil which changes the C-balance and may therefore contribute to climate change.

This work was the first time that PE could be found under TWW irrigated soils especially subsoils and more research is needed in this field.

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