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Chemical effects on the soil–plant system in a secondary treated wastewater irrigated coffee plantation—A pilot field study in Brazil

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ABSTRACT

Wastewater reuse in agriculture is recognized worldwide as an alternative water and/or nutrient source. In this study, secondary treated wastewater (STW) from an anaerobic/facultative pond system at the city of Lins (São Paulo State, Brazil) was used over 3 years and 7 months to irrigate coffee (*Coffea arabica* L.). The soil type was Typic Haplustox and the crops were fertilized according to regional agronomical recommendations. Soil and leaf samples from three sampling campaigns were used to study effects on chemical quality parameters, macronutrients and Na within the soil–plant system.

Due to high Na contents of the STW applied, Na concentrations showed increases throughout the soil profile compared to untreated soil conditions. Both, low C/N ratio of STW and fertilizer amendments stimulated soil microbial activity and encouraged nitrification and mineralization of wastewater organic components and soil organic matter (SOM) causing significant decreases of SOM and cation exchange capacity (CEC). Over time exchangeable sodium percentages (ESP) in the topsoil decreased due to Na exchange mainly by Ca and Mg, resulting in increasing exchangeable calcium percentage (ECP) and exchangeable magnesium percentage (EMP) associated with lower soil sodicity. Exchanged Na and available soluble Na from STW led to both elevated ESP at depth by soil migration and high plant uptake. The superficial increase of ECP and EMP favored continuous replenishment of Ca and Mg in the soil solution leading to increasing plant contents over time. The plant Ca, Mg and K contents remained high after fertilization stop and continued STW irrigation. This is expected to be rather a short-lived effect due to a reduction of the essential cation store through constantly provided Na and insufficient supply of essential cations via STW, associated with decrease of SOM and CEC and higher sodicity risk, suggesting the need

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of continued fertilizer use for soil maintenance. On the other hand, the plant contents of P, N and S dropped back to deficient values when irrigated solely with STW mainly due to insufficient replenishment by STW and the anion exchange complex (AEC) indicating moreover the need to continue fertilization to maintain anion levels in soil for optimum plant growth. The study revealed that STW can effectively increase water resources for irrigation, however, innovative and adapted fertilizer/STW management strategies are needed to diminish sodicity risks and to sustain adequate and balanced nutritional conditions in the soil–plant system.

1. Introduction

Increasing population growth and industrialization in the last decades has caused a considerable rise in wastewater generation worldwide. The common practice to cope with the large volume of wastewater is the discharge to surface waters either untreated or after some preliminary treatments (Vazquez-Montiel et al., 1996; Cameron et al., 1997; Biswas et al., 1999). However, the need to preserve existing water resources has led to a re-evaluation of this practice focusing on more environmentally sound methods. Various studies have shown that land application of treated municipal wastewater as water and/or nutrient source for agricultural crop production can represent a sustainable alternative (Day and Tucker, 1959; Quin, 1978; Feigin et al., 1991; Pescod, 1992; Al Salem, 1996; Biswas et al., 1999; Yadav et al., 2002) although this practice is traditionally still affected by problems of public acceptance (Pollice et al., 2004). Nevertheless, Hespanhol (1999) emphasized that the utilization of new water sources is crucial because an increase of sustainable agricultural production may not be attained simply by expansion of cultivated areas.

The latter is of particular interest for coffee production in Brazil. Coffee growing was not dependent on irrigation because the cultivated areas embraced solely regions without water shortage. However, due to coffee expansion beyond those regions, the need of alternative water resources has become a key factor. Additionally, climate change has caused drier conditions in the Brazilian Cerrado and productive areas traditionally without water deficiencies, leading to the fact that irrigation practices had to be expanded into these areas (Matiello et al., 2002).

Although irrigation with wastewater effluents can mitigate the utilization of natural water resources and enables the diversion of nutrients from waterbodies by using soil and plants as natural filters it may also result in environmental problems. Of particular concern are long-term sustainability issues, including nitrate contamination of groundwater, increased salinity and increased soil sodicity with the associated risks of soil structure deteriorations, decrease of soil permeability and reduction of crop yields due to toxic and osmotic effects (Bouwer and Chaney, 1974; Quirk, 1994; Oster, 1994; Bond, 1998; Biswas et al., 1999; Oster and Shainberg, 2001; Halliwell et al., 2001).

This study investigates the feasibility of sustainable utilization of STW in an agricultural ecosystem in Brazil. The main objective was to examine chemical effects after STW irrigation in a fertilized coffee plantation (*Coffea arabica* L.) on tropical soil (Oxisol). Besides selected macronutrients and main chemical parameters emphasis is given to Na as a significant constituent of the STW and its interactions with fertilizer components. To our knowledge, this study represents the first longer-term field approach on municipal wastewater reclamation for irrigation in coffee farming in Brazil.

2. Material and methods

2.1. *Study area*

The wastewater treatment system is operated near the city of Lins (49°50′W, 22°21′S), a city of 70,000 inhabitants in northwestern São Paulo State, Brazil (Fig. 1). The climate is tropical and characterized by a well-defined dry season (winter) from May to August and a wet season (summer) from September to April. The mean annual temperature averages 23 °C with mean annual rainfall of 1257 mm (Ibrahim, 2002).

The experimental area is located adjacent to a wastewater stabilization pond system consisting of three anaerobic ponds (primary treatment), followed by three facultative ponds (secondary treatment), which are producing about 140 L s^{-1} of secondary treated wastewaters. The wastewaters remain in the anaerobic ponds for 5 days and 15 days in the facultative ponds. One component of this system provides the effluent which was used throughout the experiment (Fig. 1). Effluents from the other components are discharged to a nearby river.

The coffee experiment is part of a larger-scale project on agricultural use of STW in crop production including sugarcane, maize, sunflower and bermudagrass (Montes et al., 2004). The soil is a Typic Haplustox (Soil Survey Staff, 1999), sandy clay loam, cropped with *C. arabica* L. The clay mineralogy of the area is predominately quartz and kaolinite and subordinately hematite, magnetite and/or maghemite. The dominance of these minerals commonly found in highly weathered and acid tropical soils, results in a low cation exchange capacity (CEC), according to Soil Survey Staff (1999).

Before installation of the experiment, the area was not cropped. Chemical soil analyses of the initial soil conditions indicated low natural fertility with low P contents, low base saturation (BS) and low CEC. Very low Na concentrations were found along the entire soil profile (Ibrahim, 2002) (Table 1).

2.2. *Crop and irrigation management*

Coffee seedlings were planted in August 2001 at a row spacing of 0.5 m with a distance of 2.7 m between the rows.

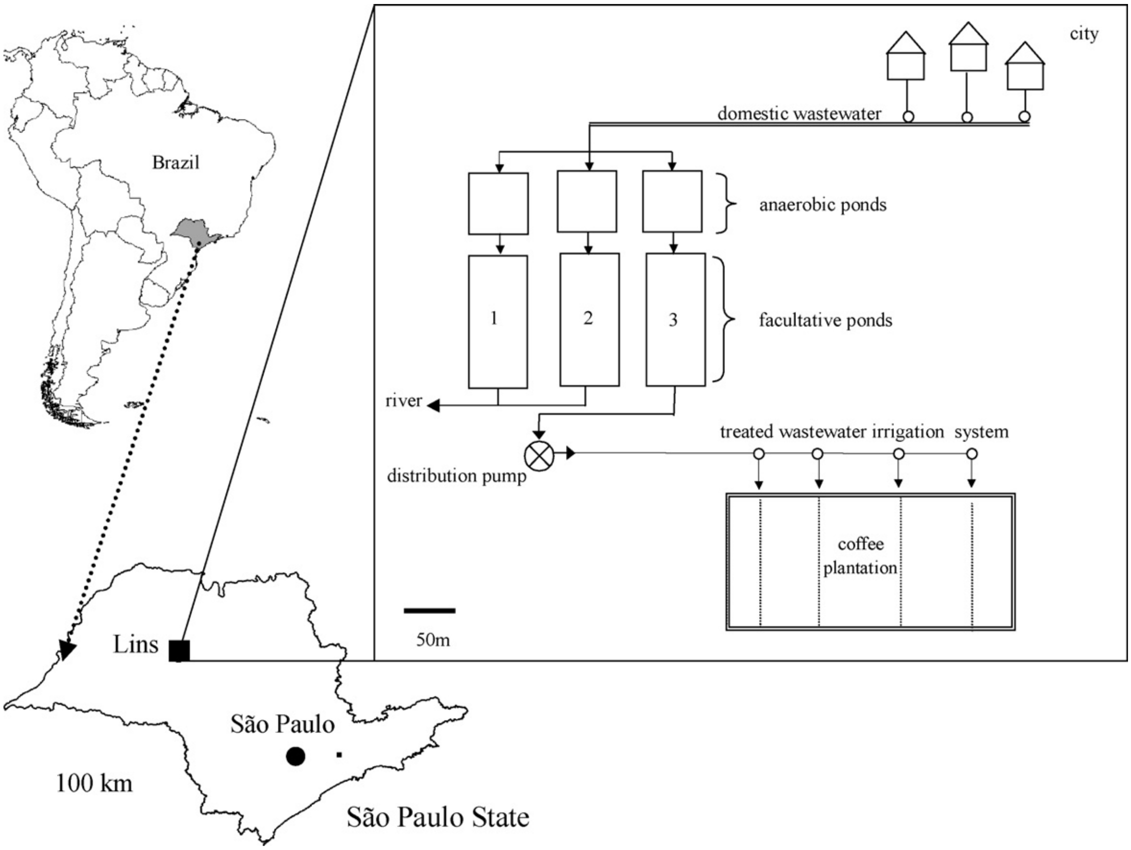

Fig. 1 – Map of the location of the experimental area at Lins, São Paulo State, Brazil, including a scheme of the wastewater treatment facility and the adjacent coffee plantation.

The research plot covers 3000 m^2 with a total of 2144 coffee plants. From September 2001 to September 2004, the area was irrigated with STW and continuously fertilized according to regional recommendations of van Raij et al. (1996). Table 2 shows the total amounts of macronutrients added during the experimental period till September 2004. After this period, fertilization was stopped while STW irrigation continued.

STW application was done by drip irrigation with a mean application rate of 1.3 mm day^{-1} (4778 $m^3\,ha^{-1}\,year^{-1}$) in order to meet the water deficit due to insufficient rainfall and crop evapotranspiration requirements. There were two interruptions of irrigation from July to August 2002 and from June to July 2003, because the coffee crop needs water stress in order to have a uniform flowering and grain maturation. Crop evapotranspiration was estimated from the change in volumetric soil water measured every two days along the crop cycle period. The soil water content was determined and monitored using ceramic cup tensiometers installed at 0–20, 20–40 and 40–60 cm soil layers in the investigated area. The tensiometers indicate the soil water matric potential which is strongly related to the volumetric water content. The relation was determined in the laboratory using the soil water retention curve method according to Camargo et al. (1986), and the data were fit to the Van Genuchten equation (Van Genuchten, 1980) to calculate the actual volumetric water content (θ_i).

The soil water content stored in a given soil depth at a moment "i" (soil water content (SWC_i)) was calculated according to the following equation:

$$SWC_i = (\theta_{fc} - \theta_i) \cdot 10 \cdot z$$

where SWC_i is the soil water content at a moment "i" [mm], θ_{fc} the volumetric soil water content at field capacity [$cm^3\,cm^{-3}$], θ_i the volumetric soil water content at moment "i" [$cm^3\,cm^{-3}$] and z is the soil depth [cm].

Irrigation was done every time the soil water content (SWC_i) dropped below 50% of the maximum soil water content within the top 0–60 cm layer, calculated by the SWC equation and setting $\theta_i = \theta_{fc}$. The value "50%" was used following the crop capacity of water extraction (Allen et al., 1998). The adequacy of the irrigation was determined by verification of the volumetric soil water content remaining between the maximum (θ_{fc}) and the critical (θ_{crit}) values where the critical volumetric soil water content was the value of θ_i corresponding to $SWC_i = 0.5 \times SWC_{max}$.

2.3. *Sampling*

Soil sampling was carried out in July 2002, January 2003 and March 2004. Samples were collected at five sampling sites at 0–10, 10–20, 20–40, 40–60, 90–110 and 180–200 cm depths. Samples were taken in close proximity within five designated

Table 1 – Chemical and physical soil characteristics in the area before the experiment, according to Ibrahim (2002)

Layer (cm)	pH	P (mg kg^{-1})	SOM[a] (g kg^{-1})	Ca (mmol$_c$ kg^{-1})	Mg (mmol$_c$ kg^{-1})	K (mmol$_c$ kg^{-1})	Na (mmol$_c$ kg^{-1})	H + Al (mmol$_c$ kg^{-1})	CEC[b] (mmol$_c$ kg^{-1})	BS[c] (%)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Textural class
0–5	4.9	2	18	10	7	1.9	0.2	34	53.1	36	683	190	127	Loamy sand
5–20	4.1	3	13	7	3	0.9	0.2	30	41.1	27	762	91	147	Sandy clay loam
20–50	4.2	3	10	5	5	0.4	0.3	28	38.7	28	692	102	206	Sandy clay loam
50–100	4.0	2	8	1	1	1.5	0.2	28	31.7	12	699	95	206	Sandy clay loam
100–170	4.1	2	5	1	1	1.9	0.3	20	24.2	17	693	103	204	Sandy clay loam
170–210	4.1	2	5	1	1	1.2	0.3	22	25.5	14	701	100	200	Sandy loam

[a] SOM: soil organic matter.
[b] CEC: cation exchange capacity at pH 7.0.
[c] BS: base saturation.

areas (sub-areas, 12 m^2 each) along the length of the field following a zigzag sampling pattern including edge and centre areas. The same procedure was repeated each year. The individual sampling site in each sub-area was located 30 cm from a dripper. Leaf samples were taken following the method of Malavolta et al. (1997) in March 2003 (3 month after the last fertilization), March 2004 (1 month after the last fertilization) and April 2005 (7 months after last fertilization) (Table 2). Samples were taken from coffee plants located in the same sub-areas where the soil samplings were carried out.

STW samples were taken monthly from the irrigated site directly from the disposal outlet.

2.4. *Preparation and analysis*

After air-drying, the soil samples were sieved at 2 mm. The soil analyses were carried out according to the methods suggested by van Raij et al. (2001). pH was measured in 0.01 mol L^{-1} calcium chloride solution. Total acidity was determined by means of 0.5 mol L^{-1} calcium acetate solution at pH 7.0. Organic matter determination was carried out by Walkley–Black method. The exchangeable cations (Ca, Mg, K) and P were extracted using ion exchange resins. Extraction of Na was carried out using 1.0 mol L^{-1} ammonium acetate solution. Ca and Mg determinations were performed by Atomic Absorption Spectrometry (AAS). Na and K concentrations were determined by Flame Atom Emission Spectrometry (FAES) and P by Molecular Absorption Spectrophotometry.

The leaf samples were cleaned manually by 0.01 mol L^{-1} hydrochloric acid solution and subsequently washed with deionized water. After drying at 50 °C until constant weight, the samples were homogenized. Following digestion in a nitric-perchloric acid, the concentrations of Ca, P, Mg and S were determined by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). Concentrations of Na and K were obtained by FAES. N contents were measured by semi-micro-Kjeldahl.

Physical and chemical analyses of the STW were performed according to APHA (1994).

2.5. *Statistical analyses*

The results of soil and plant analyses were submitted to analyses of variance. The statistical analyses were performed for each parameter in each soil layer and for all years at the same time. Variables showing significant F-test ($P < 0.05$) were submitted to mean comparisons by Tukey test ($P < 0.05$). All statistical analyses were carried out using the SAS program, Version 8.02 (SAS System, 1999).

3. Results

3.1. *Secondary treated wastewater quality*

The quality of the STW at Lins is presented in Table 3. In contrast to commercial fertilizer, the nutrient contents of treated wastewater vary diurnally and seasonally (Hamoda, 1987; Kayombo et al., 2002). Nevertheless, the mean contents obtained in this study are considered to

Table 2 – Total amounts (kg ha^{-1}) of mineral fertilizers applied in different months during the experimental period[a] based on regional recommendations according to van Raij et al. (1996)

Month	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	CaO (kg ha^{-1})	MgO (kg ha^{-1})	S (kg ha^{-1})
September 2001	–	62.2	–	307.5	117.5	38.0
October 2001	34.6	8.6	34.6	–	–	–
January 2002	69.1	173.0	69.1	–	–	–
October 2002	58.4	125.3	90.0	347.3	125.9	218.9
November 2002	50.0	–	–	–	–	–
December 2002	40.0	–	90.0	–	–	–
April 2003	–	173.5	260.9	507.3	201.8	106.1
January 2004	51.0	30.1	60.0	27.9	–	23.6
February 2004	30.1	29.1	90.2	10.9	–	36.1
March 2004	30.7	–	–	–	–	–
April 2004	25.0	–	50.0	–	–	30.0
May 2004	15.3	–	–	–	–	–
September 2004	42.4	–	30.0	–	–	50.9

[a] After September 2004, fertilization was discontinued.

provide a reliable estimate of the STW quality over the experimental period.

According to Feigin et al. (1991), treated wastewater usually has medium to high salinity (measured in electrical conductivity from 0.6 to 1.7 dS m^{-1}). The STW used in this study showed a mean electrical conductivity (EC) = 0.74 dS m^{-1} and can be classified as water with medium salinity typically accompanied by high Na concentrations relative to the other cations Ca and Mg. The ratio of Na to Ca and Mg in irrigation water is quantified by the sodium adsorption ratio (SAR):

$$\mathrm{SAR} = \mathrm{Na}/\sqrt{\mathrm{Ca} + \mathrm{Mg}} \qquad (1)$$

where Na, Ca and Mg is expressed in mmol L^{-1}.

Treated wastewater effluents commonly have a SAR in the range of 4.5–7.9 (Feigin et al., 1991). Because of high Na concentrations with a mean content of 128 mg L^{-1} and relatively low Ca and Mg concentrations, the SAR at Lins shows a mean value of SAR = 10.4 (mmol L^{-1})$^{0.5}$ that can be expected to cause increasing exchangeable sodium percentage (ESP). According to FAO guidelines (Ayers and Westcot, 1985), the STW falls into the slight to moderate category for degree of restriction on use. In order to assess the STW quality for potential water infiltration (permeability) problems, the following equation was used to express the minimum level of electrolytes (threshold concentration (E_T)) in irrigation water required to prevent decline in soil structure (Rengasamy et al., 1984; Quirk, 1994). The equation relates EC to SAR by:

$$E_T = 0.056 \times \mathrm{SAR} + 0.06 \qquad (2)$$

Table 3 – Mean values of quality parameters of the secondary treated wastewater (STW) generated by the Wastewater Treatment Plant at Lins (SP), Brazil

Parameter	STW (mg L^{-1})
Total dissolved salts	689 (621–761)
Biochemical oxygen demand	53.6 (34.4–72.8)
Chemical oxygen demand	220 (172–268)
Carbon/nitrogen ratio (C/N)	2.2 (2.0–2.5)
Alkalinity	396 (289–442)
C-total	62.3 (33.1–87.3)
Dissolved organic carbon (DOC)	19.7 (8.4–45.7)
Total-N	28.8 (13.4–42.2)
NH_4^+-N	24 (15.0–35.7)
NO_3^--N	1.0 (0.03–2.10)
SO_4^{2-}-S	17.1 (3.1–39.1)
Total-P	8.4 (6.5–10.3)
Ca	7.8 (2.7–10.2)
Mg	2.4 (1.4–3.4)
K	12.6 (10.4–15)
Na	128 (112–147)
pH	7.7 (7.5–8.2)
Sodium adsorption ratio (SAR), in (mmol L^{-1})$^{0.5}$	10.4 (8.8–12.9)
Electrical conductivity (EC), in dS m^{-1}	0.74 (0.62–0.85)

Adverse symptoms of sodicity will start to appear if the concentration of electrolyte falls below the Threshold Concentration. In the present study, a threshold concentration of 0.64 dS m^{-1} was calculated compared to a measured EC in the irrigation water of 0.74 dS m^{-1} suggesting that soil structure properties are obviously not negatively affected. Other STW characteristics are high HCO_3^- and NH_4^+-N and low NO_3^--N concentrations. With regard to heavy metals, a characterization of the STW at Lins carried out by Fonseca et al. (2007) showed: (i) Cd, Cr, Ni and Pb concentrations below the detection limits of the analytical method used and (ii) Cu, Fe, Mn and Zn concentrations below the critical/threshold concentrations of irrigation water (Ayers and Westcot, 1985).

3.2. *Chemical soil aspects*

Results of chemical soil parameters in 2002, 2003 and 2004 are shown in Table 4. Generally, STW and fertilization represented the main sources of additional element input.

Soil pH increased with continuous STW and fertilizer application. The differences between the sampling dates were much greater in the surface layers than in lower layers. In the upper soil layer (0–60 cm) in 2002, pH values were significantly lower than in 2004. In deeper layers, pH varied insignificantly over the experimental period.

Table 4 – Chemical soil characteristics at different depths of the samplings carried out in July 2002 (2002), January 2003 (2003) and March 2004 (2004) after secondary treated wastewater irrigation and regional recommended fertilization (van Raij et al., 1996) for coffee

Layer (cm)	K ($mmol_c kg^{-1}$)			Ca ($mmol_c kg^{-1}$)			Mg ($mmol_c kg^{-1}$)			Na ($mmol_c kg^{-1}$)			H + Al ($mmol_c kg^{-1}$)		
	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
0–10	2.8 b[a]	5.0 a	2.5 b	7.6 b	7.8 b	14.9 a	5.6 a	4.0 a	5.4 a	5.1 a	3.4 ab	2.6 b	32.8 a	32.2 a	12.7 b
10–20	2.2 a	2.7 a	2.7 a	8.2 a	9.0 a	11.0 a	5.8 a	4.4 a	5.0 a	2.7 a	2.6 a	3.3 a	30.8 a	30.6 a	13.9 b
20–40	1.9 a	1.4 a	2.5 a	6.2 a	8.0 a	5.9 a	4.4 a	5.2 a	3.6 a	2.0 a	2.5 a	3.3 a	29.2 a	33.4 a	16.0 b
40–60	1.8 a	1.1 a	1.5 a	3.6 a	4.4 a	3.8 a	3.0 a	3.2 a	2.8 a	1.2 a	2.0 a	2.0 a	33.0 a	33.8 a	21.1 b
90–110	1.6 a	1.6 ab	0.7 b	3.4 a	4.0 a	2.1 a	2.6 a	2.0 a	1.4 a	1.2 a	1.3 a	1.1 a	24.4 b	31.8 a	18.9 b
180–200	2.4 a	2.1 a	0.7 b	2.8 a	2.4 a	2.5 a	3.0 a	1.4 b	1.6 ab	0.7 a	1.1 a	0.8 a	20.2 b	26.0 a	15.4 c

Layer (cm)	pH			SOM[b] ($g kg^{-1}$)			P ($mg kg^{-1}$)			CEC[c] ($mmol_c kg^{-1}$)			BS[d] (%)		
	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
0–10	4.2 b	4.8 ab	5.3 a	20.6 a	18.8 a	13.0 b	9.0 b	8.2 b	32.2 a	53.9 a	52.4 a	38.1 b	39.0 b	38.4 b	65.3 a
10–20	4.4 b	4.7 ab	5.2 a	20.2 a	19.2 a	13.0 b	6.6 b	3.0 b	15.0 a	49.7 a	49.3 a	35.9 b	38.4 b	37.0 b	59.6 a
20–40	4.1 b	4.5 ab	4.8 a	16.8 a	17.4 a	10.8 b	5.4 a	1.6 c	4.0 b	43.6 a	50.6 a	31.3 b	32.9 b	33.6 b	48.8 a
40–60	3.9 b	4.1 ab	4.4 a	16.8 a	14.2 a	8.2 b	4.8 a	1.0 c	2.8 b	42.6 a	44.5 a	31.1 b	22.5 a	24.0 a	32.6 a
90–110	4.0 a	4.1 a	4.1 a	13.8 a	11.0 a	6.4 b	4.0 a	1.2 b	1.7 b	33.3 b	40.7 a	24.2 c	27.0 a	21.8 a	21.4 a
180–200	4.1 a	4.2 a	4.2 a	11.8 a	9.2 ab	5.4 b	5.0 a	1.0 b	2.3 b	29.1 b	33.0 a	21.0 c	30.7 a	21.2 a	26.2 a

[a] For each parameter, values in the same row (different years) in each layer with the same letter do not differ by Tukey test ($P < 0.05$).

[b] SOM: soil organic matter.

[c] CEC: cation exchange capacity at pH 7.0.

[d] BS: base saturation.

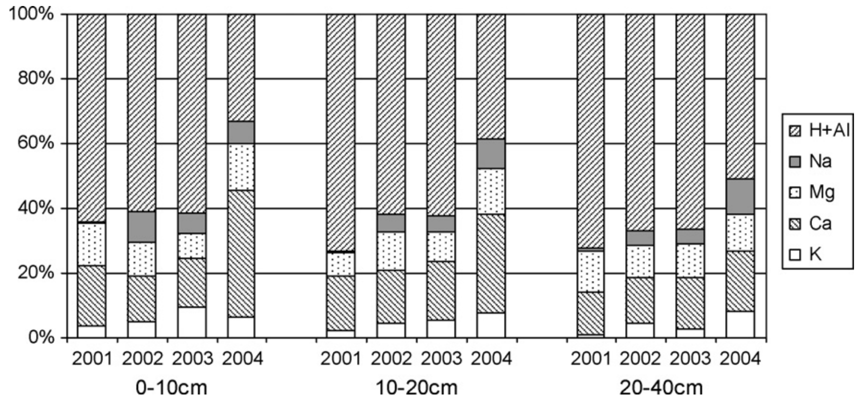

Fig. 2 – Exchangeable calcium, magnesium, potassium, sodium and total acidity (H + Al) percentages (%) of the cation exchange capacity (CEC), in different soil depths (0–10, 10–20 and 20–40 cm) after secondary treated wastewater irrigation and recommended fertilization (van Raij et al., 1996). Soil sampling was carried out in July 2002 (2002), January 2003 (2003) and March 2004 (2004). Results from comparable soil layers before the experimental period are included (2001).

Compared to soil conditions prior to the experiment (Table 1), SOM indicated slightly elevated values in 2002 and 2003 suggesting initial enhancements of SOM after STW application. However, this trend did not continue in 2004. The contents were significantly lower throughout the soil profile suggesting that the decrease of superficial SOM consequently resulted in a lower amount of downward transported carbon.

The P concentrations of the treated soils were substantially higher in the superficial layers at all sampling dates compared to the initial soil conditions (Table 1). Significant increases of P were measured in the surface layers (0–10, 10–20 cm) in 2004 compared to 2002 and 2003. However, in deeper layers (20–200 cm), the P contents were significantly lower in 2003 and 2004 compared to 2002. The lowest P concentrations were determined in 2003 throughout the soil profile.

There were no significant differences in exchangeable Ca contents in the different soil layers between the sampling campaigns except for the 0–10 cm layer in 2004, where the significant higher value indicated Ca enrichment after operation. The exchangeable Mg contents showed generally no alterations in the soil layers during the experimental period.

The K concentration in the surface layer (0–10 cm) in 2003 was significantly higher compared to similar values in 2002 and 2004, likely caused by addition of K fertilizer shortly before the 2003 sampling (Table 2). Mainly insignificant differences were found sub-superficial except for the deepest layers in 2004 with significant lower K concentrations.

Na concentrations in the soil displayed higher values throughout the soil profile compared to the soil before the experimental period (Table 1). The highest Na concentration was found in the 0–10 cm layer in 2002 followed by decreasing values up to a significant lower concentration in 2004. Elevated Na contents were observed in the 10–60 cm layer in 2003 and 2004, however, the differences were not significant. Moreover, the profile average showed the same Na concentration (2.2 $\mathrm{mmol_c\,kg^{-1}}$) throughout the study period from 2002 to 2004.

Cation exchange capacity of soil decreased significantly in 2004 associated with decrease of SOM. In contrast, BS increased significantly in the 0–40 cm layer, while in deeper layers no significant differences were observed. Total acidity (H + Al) showed for the most part significantly lower values in 2004 in all soil layers. Thus, the more years of operation, the more of soil's remaining topsoil CEC was composed of base cations rather than total acidity.

Before the experimental period (2001), the exchangeable cation percentages of the CEC (Fig. 2) were mainly occupied by H + Al, Ca and Mg with low K proportions and negligible Na values in the first three related soil layers. One year after initiation of fertilizer application and STW irrigation in 2002, exchangeable Ca and Mg percentages decreased in the surface layer (0–10 cm) associated with higher exchangeable sodium percentage. Compared to 2003, the Ca and Mg rates in 2004 increased in the surface layer associated with decreasing total acidity and exchangeable K percentage. The ESP remained unchanged despite decreasing exchangeable Na concentrations in 2004 probably caused by the lower CEC which acts as denominator in exchangeable cation percentage calculations. On the other hand, in the 10–20 and 20–40 cm layers ESP increased in 2004, also influenced by the lower CEC (Table 4).

3.3. *Chemical plant aspects*

Macronutrient and Na contents in coffee leaves in March 2003, March 2004 and April 2005 after STW irrigation and recommended fertilization (discontinued in September 2004) are given in Table 5. The N, Ca and Na concentrations were significantly higher in 2004 compared to 2003, while P-contents remained similar. In 2005, the N, P and S contents showed significant decreases, K and Mg increased significantly and Ca and Na concentrations remained at high levels. Especially Na, which is not considered as a nutrient, showed leaf contents in the magnitudes of the macronutrients P, S and Mg. In order to allow a direct evaluation of the plant contents found recommended adequate nutrient ranges for coffee proposed by different authors are included in Table 5.

Table 5 – Macronutrients and Na concentrations in coffee leaves collected in March 2003, March 2004 and April 2005 and recommended adequate values for coffee leaves according to different authors: (A) Willson (1985), (B) Malavolta et al. (1997) and (C) Matiello (1997)

Element	Year			Author		
	2003	2004	2005	A	B	C
N ($g\,kg^{-1}$)	25.8 b[a]	31.2 a	26.1 b	26.0–34.0	29.0–32.0	30.0–35.0
Ca ($g\,kg^{-1}$)	11.6 b	16.3 a	16.1 a	7.5–15.0	13.0–15.0	10.0–15.0
P ($g\,kg^{-1}$)	1.6 a	1.7 a	1.2 b	1.5–2.0	1.6–1.9	1.2–2.0
K ($g\,kg^{-1}$)	21.0 b	22.4 b	26.7 a	21.0–25.0	22.0–25.0	18.0–25.0
Mg ($g\,kg^{-1}$)	2.9 b	3.2 b	3.8 a	2.5–4.0	4.0–4.5	3.5–5.0
S ($g\,kg^{-1}$)	1.8 ab	1.9 a	1.6 b	1.5–2.5	1.5–2.0	1.5–2.0
Na ($g\,kg^{-1}$)	0.8 b	2.2 a	2.4 a	–	–	–

[a] For each element, values in the same row (different years) with the same letter do not differ by Tukey test ($P < 0.05$).

4. Discussion

4.1. Soil–plant interactions

The experimental period was subject to two phases: a longer first phase (September 2001–September 2004) reflecting mainly impacts of a combined STW and fertilizer treatment and a second phase (September 2004–April 2005) with sole STW irrigation. It is suggested that for the STW, high Na supply, low C/N ratio as well as water supply represent the driving variables to the system. The relevant fertilizer components may be outlined as anion/cation supply. Once introduced to the soil, the STW and fertilizer components combined with general environmental factors as, e.g. climate factors and initial soil conditions led to various processes in the soil that may govern the plant response.

4.2. The anions

Because of the low C/N ratio of the treated wastewater applied (Table 3) enhanced nitrification and mineralization rates of wastewater organic components and SOM due to increasing soil microbial activity (Polglase et al., 1995; Speir et al., 1999) were indicated in the present study. Moreover, application of high amounts of conventional fertilizer may stimulate soil microbial growth encouraging nitrification and mineralization (Stevenson, 1986). Additional factors are involved in these processes. For instance, constant wet soil contents throughout the year due to irrigation supports mineralization of SOM (Myers et al., 1982). The local climatic conditions (radiation intensity associated with high soil temperatures, humidity) and adequate soil aeration (Mielniczuk et al., 2003) are factors encouraging SOM decomposition that is directly linked with a decrease of CEC and hence, of soil fertility (van Raij, 1991).

The plants showed inadequate N-concentrations in 2003 (Table 5) suggesting that main portions of mineral-N were unreachable to the plants possibly due to leaching loss to deeper layers by high rainfall in the period. As the experiment continued with constantly increasing N-fertilizer and continuous STW irrigation associated with favorable nitrification conditions, plants took up the redundant mineral-N that may explain the short-run rising of N-concentrations to adequate values in 2004 (Table 5). After fertilization was discontinued in 2004, the renewed fall of the plant nitrogen contents to generally inadequate values in 2005 (Table 5) suggest changes in soil conditions and/or plant specific responses. The results indicate that obviously sole STW irrigation cannot maintain adequate N levels in the plants and that continued supply of N mineral fertilizer is required. Fonseca et al. (2005a) reported similar results for maize under STW irrigation.

Limited P availability in tropical soils represents another important nutritional aspect limiting agricultural production in the tropics. The adequate coffee P contents in 2003 and 2004 (Table 5) were obviously a result of a short-term increase of available P in the soil provided by fertilizer-P (Table 2). The increasing P-availability observed mainly in the topsoil throughout the project phase may be based on various mechanisms: (i) constant increasing supply of fertilizer-P (Table 2) and wastewater-P (Table 3), (ii) mineralization of SOM as an important P-source and (iii) possible P desorption or dissolution due to increasing pH (Table 4).

Despite these favorable conditions for P-uptake, the P-concentrations in leaves decreased significantly to inadequate levels in 2005 (Table 5) after fertilization stop in 2004 presumably in combination with insufficient supply by the anion exchange complex (AEC) and increasing Na concentrations in the soil–plant system. The plant results showed that P-supply by STW irrigation was obviously not sufficient to meet plant requirements and indicate the need to continue P fertilization to maintain soil P levels adequate for optimum plant growth. Similar results for an Oxisol-maize system irrigated with STW were reported by Fonseca et al. (2005a).

Similar to P and N, the leaf S concentrations (Table 5) decreased significantly in 2005 compared to 2004, however, showing still adequate contents at the lower range limits, according to the recommendations given in Table 5. The decline may be caused by the following factors: (i) discontinuation of mineral fertilization in 2004, (ii) reduction of SOM (Table 4) as one of the main S sources in soils (Stevenson, 1986), (iii) increase of P concentration in the topsoil (Table 4) favoring higher adsorption capacity of phosphate to soil colloids followed by desorption of S (van Raij, 1991) and downward transport to soil depths inaccessible to plant roots and (iv) increase of soil pH in the topsoil (Table 4) associated with increase of negative charges on soil colloids favoring repulsion and leaching of sulphate (Singh and Uehara, 1999). The results suggest that without properly managed S supply to the soil sole STW irrigation is not sufficient to sustain plant S-requirements over time (Fonseca et al., 2005b).

Indications of inadequate plant contents may be a result of both deficient nutrient supply from soil and/or plant internal responses caused by harmful elements. In this context, the high Na input via STW reflected by high plant concentrations at magnitudes comparable to macronutrients may interact within plant biogeochemical processes through toxic inhibitions of the protein synthesis that can cause inadequate plant nutrient contents (Marschner, 1995; Subbarao et al., 2003). These aspects have to be considered for future use of STW irrigation on tropical agro-systems.

4.3. *The cations*

The increase of pH in the 0–40 cm layer over time may be attributed to: (i) high wastewater pH (Stewart et al., 1990), (ii) high input of HCO_3^- by STW consuming H^+ and (iii) high base cation inputs by fertilizer and STW elevating concentrations of base cations in soil to a level where Al^{3+} and H^+ are displaced from the exchange sites, leaving H^+ to complex with anions (NO_3^-, SO_4^{2-}) and leach out (Yanai et al., 1996).

The present study showed that the combined STW irrigation/fertilization approach caused reduction of total acidity (H + Al) over time (Falkiner and Smith, 1997; Fonseca et al., 2005b) that is mainly related to decreasing actual acidity (pH), decreasing SOM concentrations and increasing contents of base cations (Table 4).

The cations which make up the base saturation (BS) vary in relative portions depending on the applied amount of fertilizer/STW components and on the element specific conditions as, e.g. valence, size/hydration, specific adsorption and concentration (Loyola Junior and Pavan, 1989; Singh and Uehara, 1999). Likely originated from high fertilizer amounts (220 kg ha^{-1} $year^{-1}$) rather than from STW (37 kg ha^{-1} $year^{-1}$), Ca represents the most abundant base cation in the soil and is therefore composing more of BS, especially in the surface layer (Fig. 2).

On the other hand, the high Na concentration of the STW (Table 2) resulted in a mean annual input of 607 kg ha^{-1} obviously causing the higher ESP from 2002 to 2004 compared to the soil before the experimental period (Fig. 2). Despite the high and continued addition of Na, the levels of exchangeable Na decreased in the topsoil over time. However, the profile average suggested no changes in exchangeable Na levels throughout the study period. Moreover, the increase in ESP of the soil (from 2002 to 2004) particularly in the 10–20 and 20–40 cm layer in 2004 or the constant ESP in the surface layer despite lower Na contents in 2004 compared to 2003 (Fig. 2) suggests rather an effect of the decrease in the CEC of the soil resulting from the decrease in SOM (Table 4). In the equation used to calculate ESP, exchangeable Na is divided by the CEC.

Nevertheless, it is expected that high input of Na by continued STW irrigation will increasingly contribute to the remaining CEC, elevating the risk of soil sodicity over the long term when cation fertilization is discontinued. The present study indicated that during the experimental period the addition of lime and fertilizer could reduce sodification processes in the topsoil due to Na exchange followed by increasing exchangeable calcium percentage (ECP) and exchangeable magnesium percentage (EMP). On the other hand, the exchanged Na and available soluble Na from STW are suggested to enhance ESP in deeper layers by soil migration. Rengasamy and Olsson (1993) pointed out that dependent on the frequency of irrigation and the quantity of ameliorates applied exchangeable Na from the surface may be leached downwards, increasing ESP at depth. Also Woodbury (1993) reported that supply of Ca increases the soil solution electrolyte concentration and displaces Na on the exchange complex going into a soluble form where it may be taken up by plants or leached. The available Na provided by superficial exchange as well as by the constant supply of immediately available soluble Na via STW led to a high intensity of available Na (intensity factor) (Marschner, 1995; Holford, 1997) and may explain the significant increase of plant Na contents. After fertilization was discontinued, Na plant contents increased (Table 5).

The increasing Ca plant contents occurring at the same time (Table 5) should rather be considered in the quantitative than in the intensive dimension which is defined as the capacity of soil to replace solution Ca or other nutrients as they are removed by the crop during its life cycle (quantity factor) (Marschner, 1995; Holford, 1997). Mainly due to fertilization the high amounts of exchangeable Ca in the solid soil phase associated with high ECP in the topsoil favored continuous replenishment of plant available Ca in the soil solution leading to higher uptake rates followed by excessive plant contents (Table 5).

Also Mg and K are interacting in these processes because of relatively high Mg and K supply by liming and fertilization, respectively. The significant increase of the plant K concentrations in 2005 following fertilization stop in 2004 may partly be explained by a K input of 60 kg ha^{-1} $year^{-1}$ by STW irrigation representing approximately 28% of the total K input to the soil–plant system. However, antagonistic effects between K and Na (Marschner, 1995; Malavolta et al., 1997) were not observed in the present study (Table 5).

In contrast to the decrease of N, P and S plant contents after discontinuation of fertilization, the concentrations of essential cations (Ca, Mg and K) remained high in 2005 (Table 5). This indicated a still sufficient supply due to the enhanced BS (Table 4) built up over time by previous fertilization and STW irrigation. However, it is expected to be a rather short-lived effect, due to a reduction of the essential cation store (Ca, Mg, K) through the constantly provided Na input and insufficient supply of essential cations to soil via STW associated with decrease of SOM and CEC. This suggests the need of continued fertilizer use to maintain adequate soil conditions. Although the threshold concentration of irrigation water indicated that soil properties are obviously not negatively affected it can be suggested that without additional and adapted fertilizer supply, sole STW irrigation over time would probably cause both deterioration of soil conditions and unbalanced nutrient conditions in the plant.

Thus, the viability of STW irrigation on coffee cultivated on tropical soils in Brazil depends on the development of agronomical management strategies including adequate and adapted mineral fertilization and, simultaneously, innovative practices to enhance SOM. The latter is crucial because approximately 70% of CEC in the 0–20 cm layer of soils in São Paulo State (Brazil) is influenced by functional groups of SOM (van Raij, 1991). Generally, further research is needed on the overall subject in order to build a well-founded basis for the assessment of STW effects on tropical soils in Brazil.

5. Conclusions

In many studies worldwide, the reuse of treated municipal wastewater as water and nutrient source in agricultural irrigation is introduced as an ecological viable alternative for wastewater destination in the environment (Toze, 2006). However, under the given circumstances, the present study indicated that sole STW irrigation resulted in three main problems which may also apply to other agricultural areas in Brazil with similar soil and climatic conditions: (i) increasing soil sodicity risks, (ii) decrease of soil organic matter accompanied with decreasing CEC and (iii) insufficient and unbalanced nutrient supply to the soil–plant system.

Undoubtedly, agricultural use of STW represents a viable method to preserve existing water sources. However, from the nutritional point of view, we found that sole STW irrigation was not sufficient to supply adequate levels as required by coffee and that continued fertilization is needed to maintain P, N and S levels in the soil for optimum plant growth. On the other hand, a possible reduction of Ca and K fertilizer because of the excessive plant concentrations found would probably impair soil conditions over time due to adverse Na effects on soil via STW irrigation. It can be suggested that with insufficient cation supply by fertilizer, unless otherwise resolved, sodicity will continue causing soil deteriorations. Hence, continued use of fertilizer is still required to maintain soil health despite the supposed cations in the reclaimed water. Thus, recommended agronomical fertilization should be reconsidered and adapted by including the interactions found between STW and fertilizer components in combined STW/fertilizer approaches. Due to economical and ecological reasons future efforts have to be strengthened to develop innovative management strategies for the sustainable use of STW in coffee farming and other cultures in Brazil.

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