SOIL EXCHANGEABLE CATIONS, SUGARCANE PRODUCTION AND NUTRIENT UPTAKE AFTER WASTEWATER IRRIGATION

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ABSTRACT: Wastewater irrigation may benefit agricultural crops with water and essential nutrients (mainly nitrogen), also affecting soil chemistry. The effects of effluent irrigation on yield, stalk nutrient uptake and on soil chemistry over 16 months were studied in a sugarcane (*Saccharum* spp.) crop growing on an Oxisol in Lins, State of São Paulo, Brazil. Irrigated plots received 50% of the recommended mineral-N fertilization and 100, 125, 150 or 200% of the crop water demand, while control plots received neither additional N nor water. The high sodium content of effluent resulted in Na inputs as high as 6.2 t ha^{-1}, along with 1497 kg N ha^{-1} and 628 kg K ha^{-1}. All the effluent plots except the T125 treatment had higher yields (up to 247 t ha^{-1}) than the control (153 t ha^{-1}). Significant amounts of N (up to 597 kg ha^{-1}) and K (up to 546 kg ha^{-1}) were exported by the plant harvest. Additions of nutrients and Na via irrigation were not compensated by stalk growth, causing a low recovery of N, P, Ca, Na, and showing the relative over N fertilization of the crop. Changes in soil pH, H + Al, Ca, Mg and K were small, whereas Na accumulated over time with irrigation. The treated wastewater irrigation is expected to gain increased importance, requiring careful considerations involving the adequate balance between nutritional inputs via irrigation and optimal plant productivity requirements.

Key words: *Saccharum* spp., water reuse, land disposal, nutrient cycling

CÁTIONS TROCÁVEIS DO SOLO, PRODUÇÃO E EXTRAÇÃO DE NUTRIENTES PELA CANA-DE-AÇÚCAR APÓS IRRIGAÇÃO COM ÁGUA RESIDUÁRIA

RESUMO: A irrigação com águas residuárias pode beneficiar as culturas agrícolas com água e nutrientes essenciais (especialmente nitrogênio), afetando também a química do solo. Os efeitos da irrigação por 16 meses com efluente de esgoto na produtividade, extração de nutrientes pelo colmo, e nos atributos químicos do solo, foram estudados em um Latossolo cultivado com cana-de-açúcar (*Saccharum* spp.), situado em Lins, São Paulo. As parcelas irrigadas receberam 50% do N mineral recomendado e 100, 125, 150 ou 200% da demanda hídrica da cultura, enquanto o controle não recebeu N mineral e nem água. As elevadas concentrações de sódio do efluente ocasionaram um aporte de Na de até 6,2 t ha^{-1}, juntamente com até 1497 kg N ha^{-1} e 628 kg K ha^{-1}. Todas as parcelas irrigadas, com exceção do T125, apresentaram maior produtividade (até 247 t ha^{-1}) do que o controle (153 t ha^{-1}). Quantidades expressivas de N (até 597 kg ha^{-1}) e de K (até 546 kg ha^{-1}) foram exportadas através da colheita da cultura. As adições de nutrientes e de Na via irrigação não foram compensadas pelo crescimento da planta, ocasionando uma baixa recuperação de N, P, Ca e Na, evidenciando uma excessiva fertilização da planta (N). Alterações no solo de pH, H + Al, Ca, Mg e K, foram de pequena magnitude, enquanto houve acúmulo de Na trocável ao longo do tempo nos tratamentos irrigados. A irrigação com águas residuárias deverá adquirir importância crescente, exigindo atenção detalhada ao balanço entre o aporte de nutrientes via irrigação e as quantidades requeridas para a otimização da produtividade da cultura.

Palavras-chave: *Saccharum* spp., reuso de água, disposição agrícola, ciclagem de nutrientes

INTRODUCTION

Population growth and urban sprawl are increasing the demand for good quality municipal waters and pressuring many Brazilian municipalities to adequately treat their wastewater. As a consequence, domestic wastewater treatment plants (WWTPs), especially stabilization ponds, are increasingly adopted in many small to medium cities in São Paulo State. Agricultural land has been considered as an interesting and practical alternative to the disposal of treated wastewater, avoiding discharge to natural waterways, and the associated risks of eutrophication (Feigin et al., 1991). Agriculture can readily use the water and plant nutrients from the wastewater, but this may cause some potential problems, including nitrates and salts leaching to the groundwater or accumulation of sodium, salts, pathogens and trace contaminants in the soil (Bond, 1998). In most cases, irrigation of crops with treated domestic wastewaters alters soil chemistry, causing: (i) slight decrease on soil acidity; (ii) marked increases in Na concentrations and exchangeable sodium percentage (ESP); (iii) mixed effects on soil K and Mg and; (iv) increase in exchangeable Ca (Fonseca et al., 2007).

São Paulo State has approximately 60% of the Brazil's sugarcane production (FNP Cosultoria & Comércio, 2006), with the crop mainly dependent on rain to meet plant water needs. Production is increasing due to the importance of ethanol for fuel in the national and international markets. In this context, the use of wastewater for irrigation might assist this crop agro-industry expansion.

The main objective of the present study was to evaluate the effects of secondary-treated wastewater on soil chemistry, plant productivity and nutrients uptake in a sugar crop wastewater irrigated during 16 months.

MATERIAL AND METHODS

Study area

The experimental field of 7.500 m^2 was located in Lins, State of São Paulo, Brazil (49°50' W; 22°21' S; average altitude: 440 m), beside a WWTP. The plant treats the wastewater by three anaerobic ponds (primary treatment) followed by three facultative ponds (secondary treatment), also known as the Australian system. The region has a tropical wet climate, with annual rainfall from 1,100 to 1,300 mm. The clayey sand texture local soil was classified as Typic Haplustox (Latossolo Vermelho Distrófico Típico by Brazilian classification), cropped with 'RB 72454' sugarcane (*Saccharum* spp.) variety. Total rainfall during experiment was 1,292 mm.

Crop and irrigation management

Before planting, the site was cultivated with *Crotalaria juncea*. Sugarcane was planted in March 2005, with 1.4 m between the rows. Fertilization followed regional recommendations of Raij et al. (1996): Plots received 15 kg ha^{-1} of N (ammonium nitrate), except the control; 52 kg ha^{-1} of P (simple superphosphate), and 66 kg ha^{-1} of K (potassium chloride), manually distributed along the furrows at planting. The crop was irrigated from May 2005 to August 2006, with the crop harvest in the end of September 2006.

The crop was watered by drip irrigation giving 3.8 L h^{-1}. Irrigation management was based on the critical volumetric water content in the 0–60 cm layer. The matrix potential (Ψ_m) was monitored every 2 days by tensiometers installed at 0–20, 20–40 and 40–60 cm layers. The Ψ_m values obtained together with the local water retention curve data were fit to the Genutchen equation (Genutchen, 1980) to calculate the volumetric water content. Plants were irrigated when Ψ_m was less than –40 kPa, corresponding to a volumetric water content of approximately 60% of the available water capacity in the top 0–60 cm layer. Once the need for irrigation was defined, wastewater was applied at the same time for all irrigated treatments. When compared to T100, at higher irrigation rates (T125, T150 and T200), the time of application was proportional to the extra volume applied.

The experiment was arranged in a split plot design, with irrigation rates as the main plots and sampling time as the split plot, and five treatments and four blocks. Treatments were: (i) Control, with no irrigation and no addition of mineral-N fertilizer; (ii) T100–T200, addition of 50% of the recommended mineral-N fertilization and irrigation with 100, 125, 150, or 200% of the crop water demand. Each plot was 280 m^2 (40 m × 7 m) and 126 m^2 excluding borders.

The specific design of the present research, involving irrigations rates ranging from 100 to 200% of the crop water needs, was intended to apply "two opposite philosophies" of land application: one disposing the maximum amount of effluent in the smallest possible area (wastewater applications higher than 100%): other disposing according to the plant water demand (T100) and represents wastewater agricultural use with the primary objective to enhance agricultural production, avoiding the loss of nutrients and the potential for pollution.

Sampling, preparation and analysis

Soil sampling was carried out in February 2005 (before planting), December 2005 (eight months of irrigation) and September 2006 (after sugarcane harvest and 16 months of irrigation). Samples were collected at 0–10, 10–20, 20–40, 40–60, 60–80 and 80–100 cm depths. Determinations of pH and H + Al were carried out as described by Raij et al. (2001), whereas Ca, Mg, K, Al, and Na were determined according to the methods of Embrapa (1999). After air-drying and sieving (2 mm), the pH was determined in a 0.01 mol $CaCl_2$ L^{-1} solution. Exchangeable Ca, Mg, and Al were extracted with a 1 mol KCl L^{-1} while H + Al with a 0.5 mol calcium acetate (pH 7.0) L^{-1}. The concentrations of Al and H + Al were determined by titration using a standard 0.025 mol NaOH L^{-1} solution. Exchangeable Ca and Mg were determined by Atomic Absorption Spectrometry (AAS). Na and K were determined in soil extracts obtained with Mehlich-1 solution, following readings by Flame Emission Photometry (FEP).

Stalk samples were collected after harvest to quantify their nutrient uptake. Samples were pounded, dried and ground in a Willey-type mill. The concentrations of N, P, Ca, Mg, K and Na were determined according to Malavolta et al. (1997). Nitrogen was determined by sulfuric acid digestion and the semi-micro-Kjeldahl method. After nitric/ perchloric acid digestion, Ca and Mg were measured by AAS; P by Colorimetry; and K and Na by FEP.

Wastewater was collected 12 times during the experiment directly from the outlet of the drip irrigation system, and analyzed according to APHA (1999).

Statistical analyses

Soil and plant data were submitted to analysis of variance. The analysis presented a uniform covariant matrix, a necessary condition to carry out univariate statistical analysis for a complete block design, considering time (sampling date) as subplot. The variables which showed significant F test ($p < 0.05$) were submitted to mean comparisons using Tukey's test ($p < 0.05$). All statistical analyses were carried out using the SAS program, version 9.1.

RESULTS AND DISCUSSION

Quality of Irrigation Water

Water chemistry varied throughout the seasons (Table 1). The main changes occurred for N, Ca, Na and K, with lower concentrations during the rainy summer due to a dilution effect. In comparison to the reference values, the water had a high sodium adsorption ratio (SAR), low salinity, and low concentration of P, Ca and Mg (Table 1). Average values of pH, N, Na, K, and B were within commonly reported ranges for this type of water. The wastewater was not necessarily suitable for crop optimal production, with seven units of Na added for each unit of N (Table 1).

Table 2 presents some general guidelines adapted from Pescod (1992) for irrigation water quality, based mainly on salinity, sodicity and specific ion toxicity hazards. These guidelines do not take into account some important differences between sites, such as: climate, soil type, salinity tolerance of the cultivated crop, and different crop management practices. However, the present classification is still valid as it emphasizes the long-term influence of water quality on crops, soils and farm management (Ayers & Westcot, 1985).

Table 1 - Seasonal and mean values (n = 12) of water quality in the experiment.

Constituent	Water					Reference Values[a]	Source
	Spring	Summer	Autumn	Winter	Average		
pH	7.7	8.0	7.5	7.7	7.7	6.5 to 8.4	Pescod (1992)
EC[b] (dS m^{-1})	0.8	0.9	0.9	0.8	0.8	1.0 to 3.1	Pescod (1992)
Total N[c] (mg L^{-1})	28.7	28.3	27.5	33.1	29.4	10 to 50	Feigin et al. (1991)
$H_2PO_4^-$ P(mg L^{-1})	1.9	3.9	2.2	1.9	2.5	4.2 to 9.7	Bouwer & Chaney (1974)
Ca (mg L^{-1})	7.6	6.5	7.6	8.2	7.5	20 to 120	Feigin et al. (1991)
Mg (mg L^{-1})	1.2	2.0	2.2	1.8	1.8	10 to 50	Feigin et al. (1991)
K (mg L^{-1})	13.4	10.8	11.2	14.0	12.3	10 to 40	Feigin et al. (1991)
Na (mg L^{-1})	130	111	109	135	121	50 to 250	Feigin et al. (1991)
Al (mg L^{-1})	0.01	0.01	0.01	0.01	0.01	-	-
B (mg L^{-1})	0.1	0.1	0.2	0.2	0.1	0 to 1	Feigin et al. (1991)
Cl^- (mg L^{-1})	58	67	67	74	66	40 to 200	Feigin et al. (1991)
SAR[d] $(mmol\ L^{-1})^{0.5}$	11.6	9.7	8.9	11.1	10.3	4.5 to 7.9	Feigin et al. (1991)

[a]Reference concentrations for the water constituents generally reported by different authors. [b]EC: electrical conductivity. [c]Total N = (N in the particulate matter + NH_4^+-N + NO_3^--N + NO_2^--N). [d]SAR: Sodium adsorption rate $= Na/\sqrt{Ca+Mg}$, where Na, Ca and Mg concentrations are given in mmol L^{-1}.

According to the classification of Pescod (1992) the salinity of the water was low and not likely to affect most agricultural crops. Sugarcane, as a moderate salinity tolerant crop, is not expected to be affected by ECs below 1.0 dS m^{-1} (Maas, 1984).

The effects of effluent on soil water infiltration and permeability can be evaluated using EC and SAR (Table 2). Both SAR and EC were moderate (Table 1), with some restriction for crop production. High SAR values can be expected to cause increasing exchangeable sodium percentage (ESP), enhancing the risk of sodification associated with soil structure degradation (Balks et al., 1998).

High concentrations of Na indicate a moderate to severe restriction. Significant Na concentrations, together with high SAR, low EC and low Ca:Mg ratios are the main factors limiting the use of wastewater in agriculture (Fonseca, 2005). In contrast, concentrations of B and Cl^- were not restrictive, and pH values were within the safe range.

Irrigation provided additional N, P, Ca, Mg and K for crop growth, but also potentially harmful Na (Table 3). Secondary-treated waste water is more alkaline than other irrigation waters, and the continuous addition of HCO_3^- and CO_3^{-2} ions can intensify the negative effects of Na due to the formation of Ca and Mg precipitates (Feigin et al., 1991).

Table 2 - Classification of water quality for irrigation, adapted from Pescod (1992).

Possible Limiting Factors	Degree of Restriction on Use		
	None	Slight to Moderate	Severe
Salinity			
EC (dS m^{-1})	< 0.7	0.7 to 3.0	> 3.0
Infiltration		and EC (dS m^{-1})	
SAR = 0 to 3	> 0.7	0.7 to 2.0	< 0.2
3 to 6	> 1.2	1.2 to 0.3	< 0.3
6 to 12	> 1.9	1.9 to 0.5	< 0.5
12 to 20	> 2.9	2.9 to 1.3	< 1.3
20 to 40	> 5.0	5.0 to 2.9	< 2.9
Specific Toxicity			
Sprinkler Irrigation - Na (mg L^{-1})	< 69	> 69	-
Surface Irrigation - SAR (mmol $L^{-1})^{0.5}$	< 3.0	3 to 9	> 9.0
Cl (mg L^{-1})			
Surface Irrigation	< 142	142 to 355	> 355
Sprinkler irrigation	< 106	> 106	
B (mg L^{-1})	< 0.7	0.7 to 3.0	> 3.0
pH		Normal Range 6.5 - 8.4	

Table 3 - The effect of treated wastewater irrigation on the input of different nutrients and Na to the soil during the experiment.

Constituent	Treatments			
	T100	T125	T150	T200
	kg ha^{-1}			
Total N	742	938	1127	1497
$H_2PO_4^-$-P	62	78	94	125
Ca	189	239	287	382
Mg	45	56	68	90
K	311	393	473	628
Na	3056	3860	4638	6163
B	3.5	4.5	5.4	7.1
Al	0.22	0.28	0.34	0.45
Total Irrigation - (mm)	2524	3189	3832	5092

T100–T200: Secondary-treated wastewater irrigation with 100, 125, 150 and 200% of plant water demand.

Plant Productivity and Nutrients Uptake

All the plots irrigated with wastewater, except the T125 treatment, had yields higher than the control without irrigation (Figure 1).

The wastewater plots received water and extra nutrients as compared with the control plots. Since all the treatments had similar concentrations of nutrients in the stalks (Table 4), it appears that the higher yields under irrigation were mainly due to the applied water. Productivity in T125 was not different when compared to the control, even though it was more than 40 t ha^{-1} higher. It is possible that some other factors reduced the potential productivity of the T125 plots.

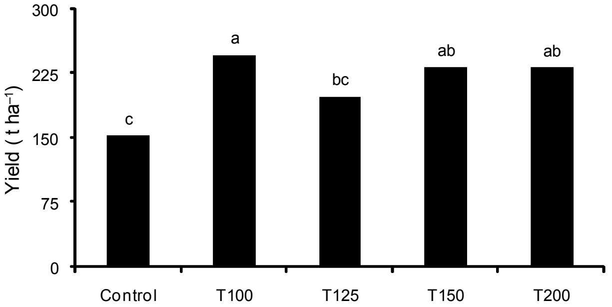

Figure 1 - Effects of treated wastewater irrigation on the sugarcane first cycle yield. Control: No irrigation and N mineral fertilization; T100–T200: Secondary-treated wastewater irrigation with 100, 125, 150, and 200% of plant water demand. Means followed by different letters are different (p = 0.05).

Average sugar cane yields of the first cut of the plant cycle in Brazil in 2005/2006 were 108 t ha^{-1} (FNP Cosultoria & Comércio, 2006). In a field experiment using subterranean drip irrigation, Aguiar (2006) reported increased crop longevity and average yields of 155 t ha^{-1} over 8 cycles. Our data suggest that yields of 175–250 t ha^{-1} are possible with irrigation with wastewater and good management, at least over the short term of the first cut.

The effects of irrigation on stalk nutrient concentrations were found to be not significant (N, P, K and Mg) or inconsistent (Ca and Na) (Table 4). Concentrations of N and K were high compared with standard values, whereas those for Ca and Mg were lower. Sugarcane extracts significant amounts of nutrients, such as N and K, depending on soil type, cultivars, and climatic conditions (Demattê, 2005).

High additions of N and Na to the soil can be counterbalanced to some extent by plant growth and harvest. However, this effect is generally insufficient in reducing significantly a soil element excessive accumulation, especially of Na (Tillman & Surapaneni, 2002). Elevated N additions by wastewater (Table 3), mainly at the highest irrigation rates, were also not fully

Table 4 - Effects of treated wastewater irrigation on the concentration of nutrients and Na in the stalks, and the uptake and recovery of nutrients and Na in the stalks.

Treatments	Stalk nutrient concentration (kg t^{-1})					
	N	P	Ca	Mg	K	Na
Control	2.26 a	0.17 a	0.09 b	0.15 a	2.00 a	1.14 a
T100	2.16 a	0.18 a	0.15 a	0.19 a	2.21 a	0.55 b
T125	2.33 a	0.18 a	0.10 ab	0.19 a	2.23 a	0.61 b
T150	2.25 a	0.20 a	0.12 ab	0. 19 a	2.06 a	0.68 ab
T200	2.57 a	0.21 a	0.12 ab	0.20 a	1.98 a	0.74 ab
	Reference Values (kg t^{-1} stalks^{-1}) Demattê, 2005					
	0.90 to 1.32	0.08 to 0.30	0.5 to 0.67	0.33 to 0.51	0.99 to 1.49	-
	Stalks nutrient uptake (kg ha^{-1})					
Control	345	26	14	23	306	174
T100	534	44	37	47	546	136
T125	463	36	20	38	443	121
T150	524	47	28	44	479	158
T200	597	49	28	46	460	172
	Recovery of nutrients and Na (kg ha^{-1} in stalks/kg ha^{-1} applied via irrigation)					
T100	0.72	0.72	0.20	1.04	1.76	0.04
T125	0.49	0.46	0.08	0.67	1.13	0.03
T150	0.46	0.50	0.10	0.65	1.01	0.03
T200	0.40	0.39	0.07	0.52	0.73	0.03

T100–T200: Secondary-treated wastewater irrigation with 100, 125, 150 and 200% of plant water demand. Means followed by different letters are different (p = 0.05).

Table 5 - Main soil chemical characteristics before irrigation (Feb/05) and after 8 (Dec/05) and 16 (Sep/06) months of sugarcane irrigation with effluent at different depths.

Depth (cm)	pH $CaCl_2$			H + Al (mmol$_c$ kg^{-1})			Ca (mmol$_c$ kg^{-1})			Mg (mmol$_c$ kg^{-1})			K (mmol$_c$ kg^{-1})			Na (mmol$_c$ kg^{-1})		
0-10	Feb/05	Dec/05	Sep/06	Feb/05	Dec/05	Sep/06	Feb/05	Dec/05	Sep/06	Feb/05	Dec/05	Sep/06	Feb/05	Dec/05	Sep/06	Feb/05	Dec/05	Sep/06
Control	5.0 a	4.7 a	4.6 aB	17.2 a	17.5 a	20.1 aA	11.4 a	11.8 a	9.1 aA	2.5 a	4.5 a	3.5 aA	3.4 a	2.3 a	2.3 aA	1.1 a	0.4 a	0.4 aB
T100	5.0 a	5.0 a	5.5 aA	15.3 a	16.7 a	14.5 aA	12.2 a	13.5 a	10.6 aA	3.0 b	6.2 a	3.8 abA	3.8 a	1.7 b	1.6 bA	0.6 c	3.0 b	5.9 aA
T125	5.1 a	5.2 a	5.7 aA	14.7 a	14.5 a	13.7 aA	11.3 a	11.9 a	11.4 aA	4.0 a	6.0 a	5.2 aA	2.4 a	1.7 a	2.0 aA	0.3 c	2.8 b	4.6 aA
T150	4.8 a	4.8 a	5.5 aA	15.8 a	14.8 a	13.5 aA	11.8 a	13.1 a	11.3 aA	2.9 a	5.1 a	4.3 aA	2.4 a	1.4 a	1.8 aA	0.7 c	3.0 b	4.6 aA
T200	5.6 a	5.4 a	5.8 aA	14.1 a	13.9 a	13.5 aA	16.8 a	15.6 a	12.2 aA	4.9 a	7.6 a	5.0 aA	3.2 a	1.4 b	2.0 abA	1.1 c	3.9 b	5.4 aA
10-20																		
Control	5.1 a	4.8 a	5.0 aB	19.8 a	17.3 a	17.6 aA	13.3 a	13.9 a	11.8 aA	2.8 a	5.4 a	3.7 aA	2.5 a	1.2 b	1.1 bA	2.1 a	1.4 a	1.1 aC
T100	5.2 a	5.1 a	5.6 aAB	13.5 a	18.0 a	13.1 aA	11.8 ab	14.3 a	10.3 bA	3.1 a	5.8 a	3.3 aA	2.8 a	0.9 b	0.7 bA	1.4 b	3.6 b	9.5 aA
T125	5.2 a	4.9 a	5.5 aAB	16.7 a	17.1 a	15.1 aA	11.9 a	11.8 a	10.1 aA	4.2 a	6.7 a	4.4 aA	2.0 a	0.6 b	0.8 bA	0.4 c	3.1 b	5.6 aB
T150	5.0 a	4.9 a	5.5 aAB	15.3 a	15.5 a	13.3 aA	11.9 a	11.4 a	10.7 aA	3.1 a	4.8 a	3.6 aA	2.4 a	0.8 b	0.9 bA	1.5 b	3.6 b	6.4 aB
T200	5.7 a	5.4 a	5.8 aA	9.5 a	13.8 a	12.2 aA	16.9 a	13.8 ab	11.9 bA	4.6 a	7.0 a	4.8 aA	2.4 a	0.8 b	0.8 bA	1.9 b	4.2 b	6.8 aB
20-40																		
Control	4.6 a	4.6 a	4.5 aB	19.6 a	20.8 a	22.8 aA	7.1 a	8.2 a	5.1 aA	2.5 a	4.9 a	2.7 aA	1.6 a	0.6 b	0.6 bA	3.3 a	2.6 a	2.3 aB
T100	5.0 a	4.8 a	5.4 aA	15.7 ab	23.3 a	14.0 bB	12.2 a	9.7 a	8.7 aA	3.8 a	5.4 a	3.3 aA	1.5 a	0.5 b	0.5 bA	3.0 b	3.3 b	6.9 aA
T125	4.6 a	4.9 a	4.9 aAB	18.5 a	18.2 a	19.9 aAB	8.7 a	10.1 a	6.8 aA	3.3 b	6.7 a	3.5 bA	2.2 a	0.4 b	0.7 bA	0.4 c	3.1 b	6.1 aA
T150	4.8 b	4.8 ab	5.4 aA	15.1 a	15.6 a	14.7 aAB	9.5 a	10.8 a	8.6 aA	3.2 a	5.3 a	3.7 aA	1.7 a	0.4 b	0.6 bA	2.6 b	3.5 b	7.4 aA
T200	5.6 a	5.3 a	5.3 aA	10.3 a	14.3 a	13.2 aB	13.6 a	11.7 ab	8.1 bA	5.0 a	6.6 a	3.8 aA	1.8 a	0.8 b	0.6 bA	3.3 b	4.3 ab	6.1 aA
40-60																		
Control	4.3 a	4.2 a	4.0 aB	25.6 a	21.9 ab	18.2 bA	3.9 a	4.3 a	2.6 aB	1.3 a	3.0 a	1.3 aA	1.2 a	0.5 a	0.8 aA	3.6 a	3.0 a	3.5 aC
T100	4.5 a	4.4 a	4.6 aA	20.6 ab	25.7 a	14.9 bA	5.6 a	6.1 a	6.0 aAB	1.8 b	3.8 a	2.0 abA	1.2 a	0.3 b	0.7 abA	3.6 b	3.7 b	5.1 aB
T125	4.5 a	4.2 a	4.3 aAB	25.0 a	26.4 a	17.2 bA	6.4 a	5.3 a	5.5 aAB	2.2 a	3.1 a	2.2 aA	1.8 a	0.4 b	0.8 bA	0.5 c	2.8 b	4.8 aB
T150	4.6 a	4.3 a	4.7 aA	22.4 a	18.4 ab	15.1 bA	6.2 a	5.8 a	7.3 aA	2.4 a	4.2 a	2.7 aA	1.0 a	0.3 a	0.7 aA	2.5 c	4.1 b	5.4 aAB
T200	4.8 a	4.7 a	4.8 aA	15.4 a	19.2 a	15.7 aA	8.8 a	7.4 a	6.9 aA	3.6 ab	5.2 a	2.9 bA	1.0 a	0.6 a	1.0 aA	3.7 b	4.4 b	6.4 aA
80-100																		
Control	4.3 a	4.0 a	4.0 aC	18.4 a	25.4 a	21.1 aA	7.6 a	3.0 b	2.0 bB	1.9 a	1.5 a	0.5 aB	1.1 a	0.8 a	0.7 aA	2.9 a	2.7 a	1.9 aD
T100	4.3 a	4.3 a	4.4 aBC	16.2 b	24.9 a	15.2 bAB	7.0 a	5.1 a	5.2 aA	1.5 a	2.8 a	1.3 aAB	1.4 a	0.7 a	0.7 aA	3.2 a	3.8 a	4.1 aBC
T125	4.4 a	4.3 a	4.4 aAB	18.2 a	22.7 a	16.7 aAB	6.8 a	5.3 a	4.5 aAB	2.4 a	3.5 a	1.4 aAB	1.5 a	0.6 b	0.5 bA	0.5 b	2.8 a	3.7 aC
T150	4.4 a	4.4 a	4.6 aAB	17.4 ab	22.7 a	14.1 bAB	5.1 a	4.7 a	4.8 aAB	1.8 a	3.4 a	2.2 aAB	0.9 a	0.6 a	0.9 aA	1.6 c	3.3 b	5.2 aAB
T200	4.7 a	4.5 a	4.8 aA	15.1 a	20.7 a	13.0 aB	6.4 a	4.5 ab	3.2 bAB	2.7 a	3.2 a	3.0 aA	1.1 a	0.6 a	1.3 aA	3.4 b	4.1 b	5.8 aA

Control: no mineral N fertilization and no secondary-treated wastewater irrigation (STWW). T100-T200: STWW irrigation with 100, 125, 150 and 200% of the crop water demand. For each parameter, small equal letters in the same row (different sampling data) do not differ by the Tukey test ($p = 0.05$). In the columns, equal capital letters (different treatments) do not differ by the Tukey test ($p = 0.05$)

compensated by plant growth, causing a low recovery of the extra N applied via irrigation and resulting in a relative N overfertilization of the crop (Table 4).

Soil exchangeable cations

Soil pH at the start of the experiment was similar in the different plots (Table 5). Later on, irrigated treatments had higher pH values than the control at all layers, especially T200, but with little differences between each other. Small pH changes were also observed by Smith et al. (1996) in a 17-year experiment with a secondary effluent in Australia. Higher pHs under wastewater irrigation are related to the effluent alkalinity, addition of exchangeable cations and anions to the soil, and changes in N cycling production of OH^- ions due to enhanced denitrification or nitrate reduction (Fonseca, 2005). These small changes in pH are not likely to directly affect crop production. There were small differences in potential acidity (H + Al) below 20 cm (Table 5). Irrigated treatments had lower values than the control. Differences in pHs discussed above may explain the higher or smaller neutralization of soil potential acidity. Decreases in exchangeable Ca were observed mainly for T200 over time at most soil depths (Table 5). Irrigated treatments had higher concentrations of Ca than the control at 40–60 cm and 80–100 cm (Table 5). Although the effluent was a significant source of Ca to the crop, providing up to 380 kg ha^{-1} against a maximum uptake by the stalks of 37 kg Ca ha^{-1}, Ca did not accumulate in the exchangeable complex (Table 5). On the other hand, Falkiner & Smith (1997) reported increased exchangeable calcium concentrations with effluent Ca additions of 230 kg Ca ha^{-1} each year in a slow growing *Pinus radiata* plantation.

There were no differences in exchangeable Mg between sampling dates or between treatments at the last sampling date (Table 5). Reports for soil exchangeable Mg after effluent irrigation range from increases (Falkiner & Smith, 1997), decreases (Wang et al., 2003) or inexpressive changes (Fonseca, 2005). These responses are possibly related to variations in soil natural fertility, concentrations of the nutrient in the wastewater and also to the local characteristics of production systems, with less intensive systems expected to cause increases in exchangeable Mg and more intensive systems a decrease (Leal, 2007; Fonseca, 2005). Moreover, in the present case, little changes were expected, once Mg additional input by effluent irrigation was relatively low.

Irrigation added up to 628 kg K ha^{-1} to soil. However, there were only small changes as compared with the control plots (Table 5). Soil K concentrations from 0–40 cm decreased in all treatments when compared with initial conditions. The Na in the effluent can possibly displace K and cause it to leach through the soil profile. Mixed effects for soil K concentrations under effluent irrigation have been reported (Fonseca et al., 2007). In the present case, it is assumed that most of the K applied was absorbed by the crop, with a maximum uptake in the stalk of 546 kg ha^{-1}.

Effluent irrigation increased soil Na concentrations throughout the profile when compared with initial values and also with the control plots (Table 5). Compared with other cations, Na has a lower affinity for the exchangeable soil complex, remaining mainly in soil solution where it can be leached. Thus the Na applied in the effluent easily moved to the subsoil. Increases in exchangeable Na after wastewater irrigation are reported widely in both agricultural and forest soils, in short and long term investigations (Fonseca et al., 2007; Toze, 2006). Bond (1998) considers that increased sodicity, together with high nitrate concentrations and salinity, are the main factors affecting the sustainability of effluent irrigation.

CONCLUSIONS

Irrigation with treated wastewater increased sugarcane yield. However, applications of wastewater above 100% of plant water demand led to no benefits in terms of crop yield and, moreover, caused problems with Na accumulation in the soil and potential ones for N offsite. Changes in pH and other soil exchangeable cations were of small magnitude among the treatments and over time.

Irrigation is expected to be of future importance for sugarcane cropping. The use of wastewater for irrigation purpose will require careful management and adequate technical guidelines. Once agronomic restrictions concerning optimal crop production requirements are observed, alterations provided by wastewater irrigation seem to be manageable.

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