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EFFECTS OF IRRIGATION WITH DEPURATED LIVESTOCK EFFLUENTS ON SOILS. A CASE STUDY FROM CENTRAL ITALY

EFFETS SUR LES SOLS DE L'IRRIGATION AVEC DES EFFLUENTS ZOOTECHNIQUES ÉPURÉS. ÉTUDE DE CAS EN ITALIE CENTRALE

EFFETTI SUL SUOLO DELL'IRRIGAZIONE CON EFFLUENTI ZOOTECNICI DEPURATI. UN CASO STUDIO PER L'ITALIA CENTRALE

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Abstract

The work deals with the qualitative modifications of a Calcaric fluvisol after irrigation with fresh water and depurated pig-slurry effluents (aerobic and anaerobic treatment, and phytodepuration with a reed bed system). The accumulation of nutrients (nitrogen and phosphorus) and heavy metals (Cd, Co, Cr, Cu, Ni, Pb, Zn) as total and as bio-available forms in the soil was evaluated, together with soil aggregate stability index, hydraulic conductivity of the saturated soil and the *in situ* infiltration rate. The experimental field was divided into three plots, and cultivated with silage maize for three years (2003-2005). Results showed that the irrigation with depurated and phytodepurated effluents produced significant changes in the soil chemical properties controlling soil permeability, and influenced the bio-available fraction of heavy metals.
Key-words: *pig-slurry effluents; nutritive elements; heavy metals; soil aggregate stability; hydraulic conductivity; in situ infiltration rate*

Résumé

L'étude s'intéresse aux transformations qualitatives d'un Calcaric Fluvisol après irrigation avec de l'eau douce et des effluents de porcherie purifiés (traitements aérobie et anaérobie, phyto-épuration avec un système de roselière). On a évalué l'accumulation d'éléments (azote et phosphore) et de métaux lourds (Cd, Co, Cr, Cu, Ni, Pb, Zn) sous formes totale et biodisponible dans le sol, aussi bien que l'index de stabilité de structure des agrégats, la conductivité hydraulique du sol saturé et le taux d'infiltration in situ. Le champ expérimental a été partagé en trois parcelles et cultivé avec du maïs pendant trois ans (2003-2005). Les résultats montrent que l'irrigation avec les effluents purifiés et phyto-epurés a induit des changements significatifs dans les propriétés chimiques du sol qui en régulent la perméabilité et y a modifié la fraction des métaux lourds bio-disponibles.
Mots-clés: *effluents de porcherie; éléments nutritifs; métaux lourds;stabilité des agrégats du sol; conductivité hydraulique; taux d'infiltration in situ*

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Riassunto

Il lavoro descrive le modifiche qualitative di un Calcaric fluvisol a seguito dell'irrigazione con acqua dolce ed effluenti suinicoli depurati (trattamento aerobico ed anaerobico, e fitodepurazione a flusso verticale). É stato valutato l'accumulo nel suolo di elementi nutritivi (azoto e fosforo) e di metalli pesanti (Cd, Co, Cr, Cu, Ni, Pb, Zn) in forma totale e biodisponibile, l'indice di stabilità di struttura degli aggregati, la conducibilità idraulica del suolo saturo e la velocità di infiltrazione in *situ*. Il campo sperimentale è stato diviso in tre parcelle e coltivato a mais per tre anni (2003-2005). I risultati mostrano che l'irrigazione con effluenti depurati e fitodepurati ha indotto variazioni significative nelle proprietà chimiche del suolo che ne regolano la permeabilità ed ha modificato la frazione bio-disponibile dei metalli pesanti.
Parole chiave: *reflui suinicoli; elementi nutritivi; metalli pesanti; stabilità degli aggregati; conducibilità idraulica; velocità di infiltrazione in situ*

Introduction

The improvement in crop management and the rise in crop yields has increased the requirement of water for irrigation, and the interest in reusing wastewater for irrigation (Mohammad and Mazareh, 2003; AQUAREC Project, 2006). Treated effluents contain essential plant nutrients such as nitrogen, phosphorous, potassium and micronutrients (Fonseca *et al*., 2005a). With careful planning and management, the use of effluents for irrigation can be beneficial to the environment, and help to recycle nutrients and water (WHO, 2006). Proper consideration must be given to the possible negative long-term effects on soils and plants due to the high levels of salts, toxic ions, heavy metals, and organic residues, since their accumulation in water and soil poses a threat to agricultural production and the environment, affecting soil fertility, crop productivity, plants quality and foodstuffs (Hassanli *et al*., 2008). Moreover, in arid and semi-arid climates the irrigation water can evaporate increasing soil salinity (Tanji and Kielen, 2002), and a good drainage is important to avoid the rise of the water table and to prevent its salinization.

The objective of the present study was to compare the change in the basic soil physicochemical properties in response to irrigation with fresh water and pig-slurry effluents treated with different depurative processes. The accumulation of nutrients (nitrogen and phosphorus) and heavy metals (Cd, Co, Cr, Cu, Ni, Pb and Zn) as total and bio-available forms were evaluated, together with soil aggregate stability index, hydraulic conductivity of the saturated soil and the *in situ* infiltration rate.

Materials and methods

An experimental field in Bettona (Perugia, Central Italy) was cultivated with silage maize for three years (2003-2005); during winter the field was left fallow. Three different plots (280 m^2 each) were irrigated with: i) the effluent from a pig-slurry aerobic and anaerobic depuration plant (W); ii) the effluent from a phytodepurative vertical flow reed-bed system (P), established in 2004; and iii) fresh water as a control (C). During the three years, each plot was irrigated with 220, 257 and 257 mm of water (Cingolani *et al*., 2006; Delicato et *al*., 2006; Piccini et *al*., 2006). Plot C was fertilized with 244 kg ha^{-1} of nitrogen (72 from biammonic phosphate in pre-sowing, and 172 from urea as top dressing), and 184 kg ha^{-1} phosphorous (in pre-sowing).

Five soil samples from the topsoil (0-40 cm) were collected in each plot before and after each cultivation cycle. Soil chemical and physical analyses were performed according to the standard methods (SSSA, 1986; 1996; MiPA, 1997; MiPAF, 2000). We discuss the effects of irrigation on pH, the electrical conductivity ECe of the saturation extract, exchangeable cations, total nitrogen, available phosphorus and heavy metals (Cd, Co, Cr, Cu, Ni, Pb and Zn) in their total and bio-available form, by DTPA extraction (Lindsay and Norwell, 1978). Further analyses included particle size distribution, water retention curve, total and active $CaCO_3$, organic carbon, soil aggregate stability index and hydraulic conductivity of the saturated soil, and the *in situ* infiltration rate. Water samples were analyzed weekly according to the standard methods (APHA, 1995; MiPAF, 2001): electrical conductivity, pH, Ca, Mg, Na and K, CO_3 and HCO_3, Cl, NH_4, NO_2 and NO_3 nitrogen, phosphorus, metals (Cd, Co, Cr, Cu, Ni, Pb and Zn), and the sodium adsorption ratio (S.A.R.). Analysis of variance (ANOVA) was used to assess the effect of each treatment. Statistical analyses were performed with SPSS® 15.0.

Results and discussion

The main characteristics of the irrigation waters are summarized in Table 1.

Both effluents showed a high content of suspended solids (S.S.) not removed by the depurative processes (the mean value in plot W is 589 $mg·L^{-1}$ and 189 $mg·L^{-1}$ in plot P), thus also the effluents solid fraction was analysed (Cingolani et *al*., 2006; Piccini and Mecella, 2006). The water used in the control plot had neutral reaction (pH=7.3) and low ECw (0.52 $dS·m^{-1}$). Heavy metals**,** N-NH_4 and phosphorus were nearly absent, and S.A.R. was quite low (0.6). The two effluents were alkaline (pH = 8.2-8.5), with a higher N-NH_4 level (178-273 $mg·L^{-1}$) compared to N-NO_3 concentration (~4-27 $mg·L^{-1}$), index of inefficient treatment and incomplete nitrification. Phosphorus in effluents (~5.6 $mg·L^{-1}$) was much higher in comparison with the control water (0.02 $mg·L^{-1}$), as well N-NH_4 and N-NO_3. Suspended solids of effluents contained 585-1387 $mg·L^{-1}$ of N-NH_4, 45-181 $mg·L^{-1}$ of N-NO_3, 709-1344 $mg·L^{-1}$ of P. Concentrations of heavy metals in the depurated effluents were higher than in the fresh water**,** but below the recommended maximum levels for irrigation (Ayers and Westcot, 1985). Their concentrations were much higher in the suspended solids, particularly Zn (19.6-23.7 $mg·L^{-1}$), Cu (3.5-7.5 $mg·L^{-1}$), and Ni (2.2-3.2 $mg·L^{-1}$). ECw (3.8 vs. 6.0 $dS·m^{-1}$), N-NH_4 (178 vs. 273 $mg·L^{-1}$), and the heavy metals content were significantly lowered by the phytodepurative process.

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Table 1 - *Characteristics of the irrigation water* (nd = *not detectable)*

		C		W		P	
		Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
ECw	$dS \cdot m^{-1}$	0.52	0.15	6.02	2.50	3.79	2.05
pH		7.3	0.2	8.5	0.2	8.2	0.2
Ca^{2+}	$meq \cdot L^{-1}$	4.47	2.38	1.75	1.70	0.72	0.51
Mg^{2+}	$meq \cdot L^{-1}$	1.73	0.44	1.44	0.57	1.64	0.58
Na^{+}	$meq \cdot L^{-1}$	1.12	0.35	8.99	4.27	5.64	2.87
K^{+}	$meq \cdot L^{-1}$	0.03	0.02	16.18	9.41	10.73	7.95
CO_3^{2-}	$meq \cdot L^{-1}$	0.90	0.47	33.88	24.40	14.45	12.57
HCO_3^{-}	$meq \cdot L^{-1}$	2.84	1.26	35.87	27.78	19.10	13.48
Cl^{-}	$meq \cdot L^{-1}$	1.15	0.29	18.30	7.95	16.14	6.47
Suspended solids (S.S.)	$mg \cdot L^{-1}$	7	4	589	706	189	206
$N\text{-}NH_4$	$mg \cdot L^{-1}$	0.5	0.7	273.0	70.4	178.6	84.6
$N\text{-}NH_4$ (S.S.)	$mg \cdot L^{-1}$	-		1387	400	585	469
$N\text{-}NO_3$	$mg \cdot L^{-1}$	7.7	4.7	3.7	9.8	27.6	26.2
$N\text{-}NO_3$ (S.S.)	$mg \cdot L^{-1}$	-		45.4	55.3	181.1	196.5
$N\text{-}NO_2$	$mg \cdot L^{-1}$	0.13	0.19	0.68	1.02	5.59	6.77
P	$mg \cdot L^{-1}$	0.02	0.03	5.57	4.20	5.60	2.86
P (S.S.)	$mg \cdot L^{-1}$	-		1.344	1.003	709	683
Cu	$mg \cdot L^{-1}$	nd		0.13	0.20	0.05	0.03
Cu (S.S.)	$mg \cdot L^{-1}$	-		7.50	11.81	3.53	5.88
Ni	$mg \cdot L^{-1}$	nd		0.05	0.13	0.03	0.01
Ni (S.S.)	$mg \cdot L^{-1}$	-		2.23	1.79	3.18	3.23
Pb	$mg \cdot L^{-1}$	0.00	0.01	0.00	0.01	0.01	0.01
Pb (S.S.)	$mg \cdot L^{-1}$	-		0.38	0.50	0.62	1.07
Zn	$mg \cdot L^{-1}$	0.01	0.03	0.42	0.59	0.09	0.11
Zn (S.S.)	$mg \cdot L^{-1}$	-		23.70	42.32	19.59	32.21
Cd	$mg \cdot L^{-1}$	nd		0.00	0.01	nd	
Cd (S.S.)	$mg \cdot L^{-1}$	-		0.04	0.06	0.04	0.06
Co	$mg \cdot L^{-1}$	nd		0.01	0.01	0.01	0.01
Co (S.S.)	$mg \cdot L^{-1}$	-		0.10	0.10	0.12	0.09
Cr	$mg \cdot L^{-1}$	0.01	0.01	0.02	0.02	0.01	0.01
Cr (S.S.)	$mg \cdot L^{-1}$	-		0.91	1.43	2.40	5.73
S.A.R	$mg \cdot L^{-1}$	0.6		7.1		5.2	

Soil chemical and physical characteristics are shown in Table 2 (Piccini et *al*., 2006).

The soil was classified as Calcaric Fluvisol (FAO, 2006), and had a silty-loam texture with a stable clotted structure, a moderate hydraulic conductivity (HC = 11-18 mm h^{-1}), a sub-alkaline reaction (pH = 7.8-8.2), no exceeding soluble salts, a balanced exchangeable complex.

Table 2 – *Initial soil characteristics (topsoil)*

Plot		C		W		P	
		Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
Sand	%	21.2	4.1	17.6	2.7	21.0	2.8
Silt	%	57.0	6.2	60.2	1.6	55.0	2.5
Clay	%	21.8	3.0	22.2	1.8	24.0	1.5
Water retention curve							
-10kPa	% d.w.	30.6	1.2	30.9	0.6	31.2	2.7
-33kPa	% d.w.	23.4	0.6	24.9	0.7	24.6	2.0
-100kPa	% d.w.	19.1	1.1	20.8	1.2	20.3	1.9
-1500kPa	% d.w.	12.7	3.0	13.1	0.7	14.9	0.7
H.C.	mm h^{-1}	11.0	4.4	12.5	2.0	18.8	8.9
ECe	$dS \cdot m^{-1}$	1.0	0.2	1.3	0.1	1.4	0.5
$pH_{1:2.5}$		8.2	0.1	8.1	0.1	7.8	0.3
Total $CaCO_3$	%	30.3	1.7	31.6	1.4	29.9	1.2
Active $CaCO_3$	%	9.7	0.8	10.9	1.3	4.9	0.7
C.E.C.	$cmol_{(+)}\ kg^{-1}$	12.42	1.68	14.90	0.75	10.71	2.32
Na^+	$cmol_{(+)}\ kg^{-1}$	0.22	0.07	0.27	0.04	0.24	0.02
K^+	$cmol_{(+)}\ kg^{-1}$	0.49	0.07	0.52	0.07	0.42	0.03
Ca^{2+}	$cmol_{(+)}\ kg^{-1}$	9.98	1.23	12.01	0.75	6.00	1.23
Mg^{2+}	$cmol_{(+)}\ kg^{-1}$	1.72	0.70	2.06	0.22	4.04	2.38
E.S.P.	%	1.9	0.8	1.8	0.5	2.3	0.4
Organic C	%	0.82	0.15	1.16	0.26	1.33	0.45
P_2O_5	$mg \cdot kg^{-1}$	75.4	52.1	12.2	16.7	85.8	64.3
Total N	‰	0.74	0.31	0.58	0.33	0.60	0.34

Plot	Period	ECe dS m^{-1}	pH (1:2.5)	E.S.P. %	P_2O_5 mg kg^{-1}	Min. N mg kg^{-1}
C	2003 apr	1.00	8.2	1.89	75.4	10.2
	2003 sep	0.85	8.3	1.44	56.2	56.4*
	2004 apr	1.07	8.1	1.57	44.1	20.2
	2004 sep	1.11	7.8	2.03	114.2*	62.4*
	2005 apr	0.90	8.2	1.77	56.7	12.2
	2005 sep	1.14[a]	8.0[a]	1.93[a]	117.5*[a]	49.2*[a]
W	2003 apr	1.29	8.1	1.81*	12.2	60.4
	2003 sep	4.87*	7.8	4.68	74.4	120.4*
	2004 apr	1.51	8.0	4.46	30.7	81.0
	2004 sep	2.23	7.9	4.43	128.1*	186.9*
	2005 apr	1.18	8.3	2.42	129.8*	34.1
	2005 sep	2.60[b]	7.9[a]	6.55*[b]	68.5[b]	113.8*[b]
P	2004 apr	1.37	7.8	2.31	85.8	30.4
	2004 sep	2.11	7.8	3.79	150.4*	107.2*

Table 3

Mean values of the main chemical soil parameters.

*Within the same treatment means with * are significantly different ($p<0.05$)*
In September 2005 means with different letters are significantly different ($p<0.05$)

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	2005 apr	1.09	7.8	1.45	57.4	10.2
	2005 sep	2.32[b]	7.8[a]	3.12[a]	190.2*[a]	39.5[a]

The irrigation with phytodepurated and non-phytodepurated effluents added a considerable amount of soluble salts to the soil, and ECe increased with time markedly in plot W (1.3-4.9 dS m^{-1}) during the first year (Table 3), since the winter rainfall was probably insufficient to maintain a low salinity in the arable layer. The soil pH was not significantly affected by the depurated effluents (pH = 7.8-8.3), due to soil buffering capacity (Fonseca et al. 2005b). The increase in exchangeable sodium percentage (ESP) was notable during the first year particularly in plot W (from 1.8% to 4.7%), constant during the second year (about 4.4 %), and again consistent during the third year (up to 6%). No significant variation occurred in the control.

Phosphorus and $N\text{-}NH_3$+$N\text{-}NH_4$ concentrations showed a high variability within and among the plots, with a general increase during the growing season and a decrease in winter (Table 3). The increase was always significant for nitrogen within each plot. In plot C, 10.2 vs. 56.4 mg kg^{-1} in 2003, 20.2 vs. 62.4 mg kg^{-1} in 2004, and 12.2 vs. 49.2 mg kg^{-1} in 2005. In this case, the increase was due to the fertilization inputs. In plot W, 60.4 vs. 120.4 mg kg^{-1} in 2003, 81.0 vs. 186.9 mg kg^{-1} in 2004, and 34.1 vs. 113.8 mg kg^{-1} in 2005. Plot W was significantly different from plots C and P, due to the higher inputs from the suspended solids (see Table 1).

Table 4a - *Mean values of soil Cd, Co, Cr and Cu (mg kg^{-1}). Within the same treatment means with * are significantly different ($p<0.05$). In September 2005 means with different letters are significantly different ($p<0.05$).*

Plots	Period	Tot Cd	Av Cd	Tot Co	Av Co	Tot Cr	Av Cr	Tot Cu	Av Cu
C	2003 apr	0	0	11.4	0	63.8	0	48.6	4.0
	2003 sep	0.2	0	12.0	0	71.8	0	47.0	4.2
	2004 apr	0.5	0	10.8	0	72.6	0	36.8	4.8
	2004 sep	0	0	9.5	0	54.7	0	48.2	3.7
	2005 apr	0.2	0	11.4	0	65.6	0	36.0	3.7
	2005 sep	1.0[a]	0	11.3[a]	0	60.7[a]	0	56.8[a]	4.5[a]
W	2003 apr	0	0	11.6	0	75.0	0	31.4	2.7
	2003 sep	0	0	12.2	0	65.6	0	38.6	3.8
	2004 apr	0.9	0	10.9	0	67.0	0	35.9	3.8
	2004 sep	0.9	0	10.1	0	68.2	0	49.7	6.0*
	2005 apr	0	0	11.6	0	68.2	0	38.2	3.8
	2005 sep	1.0[a]	0	12.1[a]	0	51.5[a]	0	55.9*[a]	6.2[b]
P	2004 apr	0.6	0.1	11.4	0	67.0	0	62.8	6.5
	2004 sep	0	0	9.6	0	59.6	0	58.1	7.7
	2005 apr	0	0	11.0	0	62.4	0	64.2	7.2
	2005 sep	0.1[b]	0	9.8[a]	0	72.6[b]	0	68.4[a]	4.7[a]

Table 4b - *Mean values of soil Ni, Pb and Zn (mg kg^{-1}). Within the same treatment means with * are significantly different (p<0.05). In September 2005 means with different letters are significantly different (p<0.05)*

Plot	Period	Tot Ni	Av Ni	Tot Pb	Av Pb	Tot Zn	Av Zn
C	2003 apr	44.2	0.3	13.6	0.8	68.4	1.2
	2003 sep	45.0	0.4	14.0	1.0	74.2	1.8
	2004 apr	49.7	0.4	14.6	1.1	74.8	1.8
	2004 sep	49.2	0.5	14.7	0.8	77.3	2.2
	2005 apr	48.2	0.4	14.4	1.0	71.2	2.4
	2005 sep	42.7[a]	0.3[a]	13.0[a]	1.0[a]	73.4[a]	3.6[a]
W	2003 apr	49.6	0.5	13.2	0.8	65.8	0.7*
	2003 sep	45.2	0.7	13.8	1.1	69.4	2.8
	2004 apr	48.8	0.7	14.0	1.1	73.9	2.1
	2004 sep	55.5	0.6	14.6	0.8	90.0	3.4
	2005 apr	75.4	0.5	14.8	0.9	88.8	3.8
	2005 sep	57.2[a]	0.4[a]	14.4[b]	1.4*[b]	94.4[a]	3.6[a]
P	2004 apr	46.3*	0.5	16.7	1.0	74.6	1.3
	2004 sep	63.7	0.8	16.7	1.0	83.0	2.5
	2005 apr	68.2	0.5	13.9	0.9	75.8	3.9
	2005 sep	59.4[a]	0.3[a]	12.6[a]	0.7[a]	81.8[a]	5.3*[a]

The concentrations of total Cd, Cr, Ni, and Pb were not significantly affected by the irrigation treatment (Table 4a-4b), but Ni showed an increasing trend in plot P, and Cd was significantly different in comparison to plots C and W. Total and bio-available forms of Cu showed a sharp increase in plot W, no accumulation in plots C and P. DTPA extractable Ni (Table 4b) did not accumulate in the soil, while Pb significantly increased in plot W (1.4 mg kg^{-1}). Total Zn slightly accumulated in plot W (65.8-94.4 mg kg^{-1}), but the differences were not statistically significant. Available Zn was initially significantly lower in plot W in comparison with the final value (0.7 vs 3.6 mg kg^{-1}); Zn accumulation was significantly higher and in plot P (1.3 vs. 5.3 mg kg^{-1}), but at the end of the experiment the values in the three plots were not statistically different (3.6-5.3 mg kg^{-1}).

Soil structure is detrimentally affected by sodium, due to its ability to disperse the soil, resulting in reduced infiltration rates of water and air. The aggregate stability index (A.S.I.), the hydraulic conductivity of saturated soil (H.C.) and the *in situ* infiltration rate (I.R.) showed significant decreases in plot W, particularly evident in 2005 (Table 5). A.S.I. decreased from 37.2 to 22.5, H.C. from 12.5 to 4.7 mm h^{-1} and I.R. from 14 to 4 cm d^{-1}, in agreement with the higher Na content and S.A.R. of the effluent (see Table 1).

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Plot	Period	A.S.I.	H.C. mm h^{-1}	I.R. cm d^{-1}
C	2003 apr	28.0	11.0	16
	2003 sep	31.1	20.6	15
	2004 apr	35.0	20.1	17
	2004 sep	39.3	25.0	17
	2005 apr	39.9	14.4	14
	2005 sep	32.4^{a}	17.0^{a}	12^{a}
W	2003 apr	37.2	12.5	14
	2003 sep	46.6	13.9	18
	2004 apr	49.2	21.0	13
	2004 sep	45.0	20.3	17
	2005 apr	27.6*	6.8*	12
	2005 sep	22.5*^{a}	4.7*^{b}	4*^{b}
P	2004 apr	31.8	18.8	13
	2004 sep	35.4	28.7	10
	2005 apr	34.5	22.7	14
	2005 sep	30.6^{a}	20.4^{a}	12^{a}

Table 5

Mean values of soil physical properties.

*Within the same treatment means with * are significantly different ($p<0.05$) In September 2005 means with different letters are significantly different ($p<0.05$).*

Conclusions

The irrigation with depurated effluents induced some variations in the soil chemical properties controlling permeability conditions, since significantly increased the ESP and to a lower extent soil salinity. Moreover, irrigation affected the bio-available fraction of micronutrients and heavy metals moving them towards more bio-available forms, with a significant increase in Zn concentration.

The use of phytodepurated effluents did not result in substantial modifications of the soil content of macro and micronutrients and of heavy metals. In the considered pedoclimatic conditions the use of depurated and phytodepurated effluents should be limited in time, and the leaching requirement should be considered in irrigation management. Three years is a short period to give a correct interpretation: anyhow, long term supply of depurated effluents may lead to nutrient imbalances, toxicity problems by heavy metals, soil degradation and decrease of soil productivity. In the long-term, the dynamics of nitrogen and sodium, and the possible accumulation of heavy metals in soil and plants would require further observations and a periodic monitoring of soil and crops.

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