Impact of pig slurry on soil properties, water salinization, nitrate leaching and crop yield in a four-year experiment in Central Spain

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Abstract. The repeated application of pig slurry to agricultural soils may result in an accumulation of salts and a risk of aquifer pollution due to nitrate leaching and salinization. Under Mediterranean conditions, a field experiment on a sandy loam soil (Typic Xerofluvent) was performed with maize (*Zea mays*) in 1998, 1999 and 2001 to study the effects of applying optimal (P1) and excessive rates (P3) of pig slurry on soil salinization, nitrate leaching and groundwater pollution. The rate of pig slurry was established considering the optimal N rate for maize in this soil (170, 162 and 176 kg N ha⁻¹ for 1998, 1999 and 2001, respectively). Pig slurry treatments were compared to an optimal N rate supplied as urea (U) and a control treatment without N fertilizer (P0). The composition of the slurries showed great variability between years. Mean NO₃⁻ leaching losses from 1998 to 2001 were 329, 215, 173 and 78 kg N ha⁻¹ for P3, P1, U and P0 treatments, respectively. The amount of total dissolved salts (TDS) added to the soil in slurry application between 1998 and 2001 was 2019 kg TDS ha⁻¹ for the P1 treatment and 6058 kg TDS ha⁻¹ for the P3 treatment. As a consequence, the electrical conductivity (EC) of the slurry-treated soils was greater than that of the control soil. The EC correlated significantly with the sodium concentration of the soil solution. Over the entire experimental period, 2653, 2202 and 2110 kg Na ha⁻¹ entered the aquifer from the P3, P1 and P0 treatments, respectively. The P3 treatment did not significantly increase grain production in 1999 and 2001 compared with that achieved with the optimal N rate treatment (P1). This behaviour shows the importance of establishing application guidelines for pig slurry that will reduce the risk of soil and groundwater pollution.

Keywords: Irrigation, leaching, maize, nitrate, pig slurry, soil salinity, aquifer pollution

INTRODUCTION

The soils of Mediterranean countries are often relatively infertile, low in organic matter (frequently <2%), and at risk of erosion (Ferrer & Sanz 1983). The application of livestock waste is therefore usually beneficial. As the second largest pig producer in the European Union (EU), Spain generates 2×10^{10} kg yr⁻¹ of pig slurry, over half of which is used directly as fertilizer (Chávez & Babot 2001). Given its high water content, pig slurry use is generally limited to areas close to where it was produced. Unfortunately, this use is often indiscriminate, with no regard for optimum levels of application; it can lead to serious pollution problems in areas where excess slurry is applied (European Community 1991). The emissions of ammonia (NH₃),

nitrous oxide (N₂O) and nitric oxide (NO) and the leaching of nitrate (NO₃⁻) after slurry application represent serious environmental problems; slurry applications to land have also been held responsible for contamination of surface waters with coliform bacteria (Vinten *et al.* 2002).

Nitrate leaching is normally intensified by excessive rainfall or irrigation, as well as by use of N fertilization that is surplus to crop requirements (Díez *et al.* 1997, 2000). Recent studies have shown the importance of slurry application for optimizing maize grain production while minimizing NO₃⁻ pollution (Díez *et al.* 2001; Al-Kaisi & Waskom 2002). However, application guidelines are difficult to establish given the variable composition of slurries, which depend on several factors, such as age and feed of animals and different cleaning systems. The amount of available soil N (Sánchez *et al.* 1998), the slurry N content and the N requirement of the crop must be known for the optimum application rate to be estimated (Díez *et al.* 2000).

Large applications of liquid animal manures, which often have a high salt content due to the addition of salt to the diet, can increase soil salinity and the Na⁺ content of

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the soil solution and groundwater. Hao & Chang (2003) have studied this risk with cattle manure. Soil salinity is one of the most important factors reducing soil quality and productivity (Shortall & Liebhardt 1975). Salinization usually occurs over the first few days following slurry application (Díez *et al.* 2001), but it decreases thereafter because of rainfall and irrigation.

Currently, the EU is attempting to deal with the problems of organic wastes by identifying the risks and benefits associated with their agricultural use (European Community 2001). These efforts also include a proposal to modify directive 86/278/EEC (Joint Research Centre 2001). If successful, this problem can be tackled on a more scientific basis.

The aim of this work was to evaluate the effects of applying optimal and excessive rates of pig slurry on soil and groundwater salinization, nitrate leaching and the yield of a maize crop, in an irrigated Mediterranean soil.

MATERIALS AND METHODS

Experimental site

The experimental site was located at La Poveda Field Station in Arganda del Rey (Madrid) (40°19'N, 3°19'W) in the middle of the Jarama river basin. The soil is a Typic Xerofluvent (Soil Survey Staff 1998), which is a sandy loam that becomes progressively more sandy with depth to a gravel layer located at 1.5–2.2 m. The mean water-storage capacity of the soil profile (0–2 m) was estimated at 309 ± 33 mm, while that for the top 0.5 m was 154 ± 21 mm, as measured by time domain reflectometry. Some physicochemical characteristics of the top 0–50 cm are shown in Table 1. Other characteristics of the soil and the methods of soil analysis have been previously described (Díez *et al.* 2001). The water-table fluctuated from 4 to 4.5 m below the soil surface, depending on rainfall and river discharge. The highest temperatures at the Field Station during the maize crop were between 12 and 37 °C in 1998, 14 and 39 °C in 1999, and 14 and 37 °C in 2001, while the lowest temperatures were between 4 and 19 °C in 1998, 5 and 28 °C in 1999, and 4 and 21 °C in 2001. The rainfall mean in the region is 460 mm yr^{-1} .

Experimental design, field instrumentation and crops

Maize was grown at the experimental site in 1998, 1999 and 2001. In 2000, however, barley was grown to avoid the problems caused by cultivating the same crop for too many consecutive seasons. Four treatments were applied each year to triplicate plots (9.9×11.1 m): an optimal rate of urea (U), an optimal rate of pig slurry (P1), a three times the optimal rate of pig slurry (P3), and a control with no N

fertilizer (P0). Based on electro-ultrafiltration soil analysis (EUF) results and according to criteria established by Sánchez *et al.* (1998), the optimal N rates (Table 2) for the maize crop were 170, 162 and 176 kg N ha^{-1} in 1998, 1999 and 2001, respectively. For the barley in 2000, the optimal rate was 120 kg N ha^{-1} . These rates were lower than those applied by farmers from this area (300 kg N ha^{-1} for maize and 150 kg N ha^{-1} for barley). Optimal N rates (U and P1) were calculated using the expression:

$$\text{Optimal N rate} = (\text{N uptake by aboveground crop} - \text{available soil N}) / \text{N efficiency} \quad (1)$$

Where available, soil N was calculated by soil analysis before sowing (Sánchez *et al.* 1998). N efficiency had previously been estimated to be from 0.7 to 0.8 for this crop (Díez *et al.* 2000). The amount of pig slurry applied (Table 2) to the P1 plots was calculated considering the N content of pig slurry (Table 3).

The pig slurry was collected from different farms each year at discharge points and kept in storage tanks. Table 3 shows the characteristics of representative slurry samples taken at regular intervals (every 5 min) during application. A portion (50 mL) of each sample was first homogenized by shaking for 10 min, then analysed following the protocol of Díez *et al.* (2001).

The slurry was applied to the soil through a band spreader connected to a tanker, following the local technique. Applications were made at the beginning of April for the

Table 2. Pig slurry applied to maize based on optimal N requirements in each year.

	1998	1999	2001
Available N (kg N ha^{-1}) ^a	111	114	107
Optimal rate N (kg N ha^{-1}) ^b	170	162	176
Slurry Kjeldahl N (mg N L^{-1})	3130	2700	4834
Pig slurry rate ($\text{m}^3 \text{ ha}^{-1}$) ^c	54.3	60.0	35.2

^a Available N was calculated by means of soil analysis at 30 cm by the EUF method before sowing time, previously calibrated by N balance (Sánchez *et al.* 1998), which includes mineral N plus potentially mineralizable N.

^b Optimal N rates were calculated using the expression given in equation (1) (Sánchez *et al.* 1998).

^c values

These were obtained by calculating the quantity of pig slurry necessary to obtain the optimal N rate, considering the Kjeldahl-N content and available N in the soil.

Table 3. Physicochemical characteristics of pig slurry.^a

	1998	1999	2001
Density (g L^{-1})	1.02 ± 0.002	1.01 ± 0.003	1.02 ± 0.002
Dry matter (%)	8.50 ± 1.3	0.56 ± 0.4	1.60 ± 0.7
Organic matter (% DM)	74.0 ± 8.1	60.4 ± 6.5	59.0 ± 4.2
Conductivity (mS cm^{-1})	20.0 ± 1.2	6.4 ± 0.7	22.1 ± 1.8
NO_3^- -N (mg L^{-1})	4.5 ± 0.2	1.6 ± 0.1	1.6 ± 0.2
NH_4^+ -N (mg L^{-1})	2264 ± 34	344 ± 41	3792 ± 37
Kjeldahl-N (mg N L^{-1})	3130 ± 28	2700 ± 31	4834 ± 38
Organic-N (mg N L^{-1})	862	2355	1040
K (mg K L^{-1})	2108 ± 5	294 ± 8	920 ± 12
P (mg N L^{-1})	105 ± 7	164 ± 8	270 ± 11
Na (mg L^{-1})	304 ± 9	204 ± 13	330 ± 18

^a Values are given as means of 20 subsamples $\pm$ standard deviation.

Table 1. Physicochemical characteristics of the sandy loam soil at 0–50 cm depth.

pH _{H2O}	8.1
Organic matter (g kg^{-1})	14.0
CaCO_3 (g kg^{-1})	34.0
Bulk density (t m^{-3})	1.47

maize crop. The soil was then worked with a rotocultivator to incorporate the slurry into the soil (0–5 cm). P1 and P3 doses were applied in one single application. The urea was incorporated in June.

After slurry application and ploughing, maize (*Zea mays* L. cv. Juanita) was sown at the end of April each year (1998, 1999 and 2001). The rows were 75 cm apart and the plant density 75 000 plants ha⁻¹. During seedbed preparation, superphosphate (18% P₂O₅) and K₂SO₄ (50% K₂O) were applied at 50 kg P₂O₅ ha⁻¹ and 121 kg K₂O ha⁻¹. The maize was cultivated following usual practices (including ploughing, weed-killer treatments, etc.), and was harvested in October when the grain was mature. Barley (*Hordeum vulgare* L. cv. Nevada) was sown in November 1999 at a density of 160 kg ha⁻¹. The crop was harvested on 20 June 2000.

The water used throughout the experiment was taken from an irrigation ditch from the Jarama River. This water was sampled 33 times. The mean quality components of the irrigation water were: NO₃⁻, 5.1 ± 0.5 mg N L⁻¹; Na, 90 ± 16 mg L⁻¹; total solids, 650 ± 50 mg L⁻¹; electrical conductivity (EC), 1.0 ± 0.1 dS m⁻¹; sodium adsorption ratio (SAR), 1.55 and pH 7.6 ± 0.2. The groundwater contained: NO₃⁻, 2.7 ± 1.0 mg N L⁻¹ and Na⁺, 70 ± 25 mg L⁻¹.

An overhead mobile-line sprinkler system was used to irrigate the crops. Irrigation started 5 days before the end of June and continued to the end of August. The maize was watered every 7–10 days following the schedule used by the majority growers in the area. (Some 70–80% of the water applied is used by the crop under these conditions.) Rainfall and total irrigation inputs are shown in Table 4. The quantity of applied irrigation was that recommended by the advisory services of the area, based on a potential evapotranspiration (ET₀) of 500–520 mm for the dry season (Instituto Técnico Agronómico Provincial 1998). Irrigation water was applied on seven occasions (mean 61 mm) during the dry season of 1998, eight occasions (mean 69 mm) in 1999 and eight (mean 77 mm) in 2001.

Sampling

Samples of the soil solution from the ceramic cups were extracted 33 times throughout the experiment. A vacuum of -80 kPa was applied to the tubes and maintained for a period of 7–10 days. After this period, water samples were extracted using air pressure, and NO₃⁻, Na⁺ and EC determined, the latter being measured to estimate salt concentration (g L⁻¹) (Caballero *et al.* 2001).

Table 4. Water inputs, output and balance during the crop-growing periods.

Year	Rainfall (mm)	Irrigation (mm)	Evapotranspiration (ET) ^a (mm)	Drainage ^a (mm)	Water balance
1998	106.0	428	426	83	26
1999	163.4	554	603	138	-24
2001	130.0	619	660	132	-43

^a Calculated from field tensiometers and TDR data described by Román *et al.* (1996) based on water flow direction and water balance between layers.

For the salt leaching study, two ceramic cups were used in each plot to obtain soil solution samples at a depth of 1.4 m (Díez *et al.* 2001). It was assumed that water reaching this depth near the gravel layer would quickly leach into the groundwater (mean depth 4 m) because of the high hydraulic conductivity (Smith & Mullins 1991). During drainage periods, NO₃⁻ and Na⁺ leaching were calculated weekly by multiplying the weekly drainage by the corresponding NO₃⁻ and Na⁺ concentrations at 1.4 m at each sampling event (Díez *et al.* 1997). Errors in the estimation of drainage volume are discussed by Román *et al.* (1999). NO₃⁻ concentration was determined using a Technicon AAI Autoanalyzer (Technicon Hispania) employing the N1 naphthylethylenediamine method, Na⁺ was determined by atomic absorption spectrophotometry (Perkin-Elmer 403, Perkin-Elmer Hispania), and EC by a Crison 525 conductivity meter.

Plants were harvested from 5 m of two adjacent rows in the middle of each plot and their aboveground biomass determined. Ten of the harvested plants were randomly selected. The stalk, leaves, bracts, cob and grain were separated and weighed, oven-dried for 24 h at 60 °C followed by a further 2 h at 80 °C, and weighed again to determine their dry matter (DM) content. The harvest index (HI) was calculated as the grain weight over the aboveground biomass (percentage). Grain yield (kg ha⁻¹) was calculated and plant N content determined as described in Díez *et al.* (2001).

Monitoring soil water content, hydraulic head and drainage

Time domain reflectometry (TDR) probes (at a maximum depth of 2 m) and vertical tensiometers (capable of measuring water pressures of 0–80 kPa) were installed according to the method described by Díez *et al.* (2001) in the four central plots of the 12 used in the experiment. Soil water potential gradients (the relationship between the hydraulic head [*h*] and the soil depth) were used to determine water movement through the soil. Four water flow patterns were identified during the course of the work, and six patterns of water-balance partitioning were reported (see Román *et al.* 1996). Water storage, estimated from the volumetric water content (θ , TDR), and the hydraulic head were determined before and after each irrigation session during growth periods. Data provided by the instruments in the middle four plots plus the water flow direction and water balance in each soil layer (Table 4) were used to calculate the drainage (*D*) and evapotranspiration (*ET*) rate of each plot weekly during the growing season, according to the method of Roman *et al.* (1996). Each of the 12 plots was provided with four extraction tubes (63 mm i.d.; one at a depth of 0.5 m, one at 0.9 m, and two at 1.4 m) attached to porous ceramic cups to collect soil solution samples.

Statistical analysis

Statistical analysis was performed using STATGRAPHICS PLUS 5.1 software (Manugistics 2000). Analysis of variance, according multivariate models, was used to study the differences between data sets, agronomic data (plant dry matter at harvest, grain yield and plant N content) and soil solution data (EC, NO₃⁻ and Na⁺ concentrations). Differences between treatments and soil depths were analysed and

compared using the Duncan Test. Significance was set at $P < 0.05$.

RESULTS AND DISCUSSION

The physicochemical characteristics (Table 3) of the slurries showed great variability between years, especially in dry matter (from 0.56 to 8.50%) due to different storage systems (pit in 1998 and lagoon in 1999 and 2001), $\text{NH}_4^+\text{-N}$ (from 0.34 to 3.7 g L^{-1}), Kjeldahl-N (from 2.70 to 4.83 g L^{-1}), $\text{NO}_3^- \text{-N}$ (from 1.6 to 4.5 mg L^{-1}), and organic-N (from 0.86 to 2.35 g L^{-1}). Since the application rate was calculated taking into account the available N content of the soil, the N content of the slurries and the amount of N needed by the crop, the volumes applied were different each year (Table 2).

Nitrate leaching

Amounts of between 428 and 619 mm of irrigation water were applied to the maize, depending on the soil water reserve (Table 4). Mean drainage losses were 82, 138 and 131 mm during 1998, 1999 and 2001, respectively, representing an overall mean drainage loss of 22% of the irrigation water applied (Table 4). Drainage during the barley crop was low (33 mm) because it was not irrigated. However, drainage for the entire year of 2000 was 204 mm due to autumn (post-barley crop) rainfall.

Table 5 shows that soil solution NO_3^- concentrations increased significantly with increasing N application, regardless of N source. N concentrations were similar at a depth of 50 cm in the U and P1 treatments where the total N applied was the same. Over the course of the experiment there were no appreciable changes in NO_3^- concentration between the drainage (after rainfall and irrigation) and non-drainage periods. Great spatial variability in NO_3^- concentrations was observed between samplings of each plot and also between plots, confirming the results of Kengni *et al.* (1994), Bruckler *et al.* (1997) and Díez *et al.* (2001) (Table 4).

Nitrate concentrations of the soil solution at 1.4 m (Table 5) were used to study the possibility of groundwater contamination. Cumulative NO_3^- discharge at 1.4 m

depended mainly on the irrigation water applied and the fertilizer treatment used (Figure 1). As observed by Díez *et al.* (2000), total leaching depended mainly on drainage and less on variations in NO_3^- concentration at the percolation depth. Significant differences ($P < 0.05$) between treatments were recorded in the cumulative NO_3^- leaching over the whole experimental period, with losses of 329, 215, 173 and 78 kg N ha^{-1} for P3, P1, U and P0 treatments, respectively. The influence of pig slurry rate was large: the N loss induced at the triple rate (P3) was twice that at the single rate (P1). The proportional N losses due to leaching, expressed as a percentage of N applied in slurry fertilizer (discounting the N leached in the control), were 18, 27 and 21% for the P3, P1 and U treatments, respectively.

Changes in soil salinity

Before the first application of the slurry, the mean soil solution ECs were 3.07, 2.86 and 4.20 dS m^{-1} at 50, 90 and 140 cm depth, respectively. The amount of soluble salts expressed as total dissolved salts (TDS) was calculated using the equation proposed by Caballero *et al.* (2001) obtained from data of a previous experiment performed in the same soil.

$$\text{TDS (g L}^{-1}\text{)} = 8.887 \text{ EC (S m}^{-1}\text{)} + 0.135 \quad (2)$$

$$(r^2 = 0.885; n = 464)$$

Soil salinity in the pig slurry plots indicated by EC values increased significantly between 1998 and 2001 (2019 and $6058 \text{ kg TDS ha}^{-1}$ for the P1 and P3 treatments, respectively). Electrical conductivity in the soil solution also increased with soil depth (Figure 2), since salt is highly mobile under conditions of irrigation and high soil permeability. Owing to the root depth for maize in this soil (70–80 cm), the movement of water, and consequently salts, was always downward at depths of 80–140 cm. These results are consistent with those of Hao & Chang (2003), who studied the use of cattle manure.

Figure 3 shows the cumulative curves for the leached TDS. Significant differences between P1 and P3 ($P < 0.05$) were recorded in the cumulative TDS leached over the whole experimental period, with losses of 37.5, 28.1 and 25.8 t ha^{-1} for the P3, P1 and P0 treatments, respectively. The increases in TDS losses over the control

Table 5. Mean nitrate concentration^a of the soil solution at 0.5, 0.9 and 1.4 m depth given as cumulative values for different treatments for the duration of the experiment (1998, 1999 and 2001).

Soil depth (m)	Nitrate concentration ($\text{mg NO}_3^- \text{-N L}^{-1}$) ^a				
	ANOVA	P0 ^b	U	P1	P3
0.5	$F = 21.06$ $P = 0.001$	$41 \pm 53 \text{ a}$	$92 \pm 59 \text{ b}$	$102 \pm 62 \text{ b}$	$258 \pm 174 \text{ c}$
0.9	$F = 23.90$ $P = 0.001$	$57 \pm 47 \text{ a}$	$181 \pm 91 \text{ b}$	$87 \pm 47 \text{ a}$	$172 \pm 101 \text{ b}$
1.4	$F = 69.03$ $P = 0.001$	$64 \pm 31 \text{ a}$	$147 \pm 61 \text{ b}$	$180 \pm 98 \text{ b}$	$258 \pm 95 \text{ c}$

^aData based on six replicate ceramic cup extractions at 1.4 m depth ($2 \times \text{plot}$) per fertilizer treatment and three replicate at 0.5 and 0.9 m depth per fertilizer treatment (33 samplings over the three growing seasons). Mean followed by standard deviation; different small letters for each row indicate significant differences between treatments ($P < 0.05$, Duncan test).

^bFor treatment key, see Materials and Methods.

Figure 1. Cumulative nitrate losses by leaching at a soil depth of 1.4 m during the experiment. $\diamond$ = control treatment (no slurry) (P0); $\circ$ = urea treatment (U); Δ = optimal N rate of pig slurry treatment (P1); $\square$ = three times the optimal N rate of pig slurry (P3). Arrows indicate harvest date.

Figure 2. Electrical conductivity (EC) in soil solution at 50, 90 and 140 cm depth during the experiment. $\diamond$ = control treatment (no slurry) (P0); Δ = optimal N rate of pig slurry treatment (P1); $\square$ = three times the optimal N rate of pig slurry (P3).

caused by pig slurry were 2030 and 7437 kg ha⁻¹ for the P1 and P3 treatments, respectively (Table 6). These amounts are similar to the quantities of salt added. However, this coincidence was not clear in the annual balance, since some of the salts added during 1998 and 1999 were leached in 2001. Heavy rainfall during the summer after the barley harvest (August and September 2000) accelerated the leaching of salts accumulated in the soil during the cultivation of the preceding maize crop (Figure 3). These results confirm those of Bustos *et al.* (1996), who concluded that the salts accumulated in the soil during the maize growth season in a Mediterranean climate might leach into the groundwater after harvest, thereby intensifying the risk of groundwater pollution.

Increases in soil salinity were associated with changes in Na⁺ concentration (Figure 4), reflecting the amount of sodium added over the entire experimental period (52 and 157 kg Na ha⁻¹ with P1 and P3 treatments, respectively). The soil solution Na⁺ concentration correlated significantly with EC values in the P3 treatment at a depth of 140 cm ($r = 0.488$; $P < 0.001$).

Figure 3. Cumulative TDS (total dissolved salts) losses by leaching to groundwater during the experiment. $\diamond$ = control treatment (no slurry) (P0); Δ = optimal N rate of pig slurry treatment (P1); $\square$ = three times the optimal N rate of pig slurry (P3). Arrows indicate harvest date.

Table 6. Total dissolved salts balance as influenced by pig slurry applied.

	1988	1999	2001	Total
EC (S m ⁻¹) pig slurry	2.00	0.64	2.21	
Pig slurry rate P1 (m ³ ha ⁻¹)	54.3	60.0	35.2	
TDS added ^a (g L ⁻¹)	17.90	5.85	19.77	
Soluble salts added (kg ha ⁻¹)	P1 972	351	695	2019
	P3 2917	1053	2087	6058
Soluble salts leached (kg ha ⁻¹)	P1 ^b 401	1420	209	2030
	P3 ^c 1379	2830	3228	7437

^aTDS = total dissolved salts. These values were calculated from equation (2) (Caballero *et al.* 2001); ^bTDS.P1 – TDS.P0; ^cTDS.P3 – TDS.P0.

Large rates of slurry accentuate the problem of groundwater salinization and nitrate pollution, so much less than 200 m³ ha⁻¹ yr⁻¹, as was proposed by Bernal *et al.* (1992) for a similar soil, should be applied. In this work, the optimal P1 treatment rate was 35–55 m³ ha⁻¹ yr⁻¹, depending on soil N content, slurry N content and crop N requirements.

The analysis of variance for each treatment corresponding to Na⁺ concentration of the soil solution at 1.4 m depth during the experiment is shown in Table 7. The mean soil solution Na⁺ concentration for the experimental period was less in the U treatment (184, 265 and 342 mg Na L⁻¹ at 50, 90 and 140 cm depth, respectively) than in the corresponding control treatments (207, 339 and 412 mg Na L⁻¹) because more salts were taken up by the urea-treated crops.

N uptake and grain yield

Significant differences ($P < 0.05$) were detected between the different treatments with respect to dry matter, plant N uptake and grain yield in both the 1998 and 2001 maize crops (Table 8). However, in 1999 only the crop N uptake in the control differed from the other treatments. Grain yield differences between P1 and P3 treatments were only observed in 1998. The application of high slurry rates

Figure 4. Na⁺ concentration in soil solution at 50, 90 and 140 cm depth, during the experiment. $\diamond$ = control treatment (no slurry) (P0); Δ = optimal N rate of pig slurry treatment (P1); $\square$ = three times the optimal N rate of pig slurry (P3).

Table 7. Mean Na concentration of the soil solution at 1.4 m soil depth given as cumulative values for different treatments for the duration of the experiment (1998, 1999 and 2001).

Soil depth (m)	Sodium concentration (mg Na L ⁻¹) ^a				
	ANOVA	P0 ^b	U	P1	P3
1.4	$F = 170.59$	412 ± 120 b	342 ± 114 a	508 ± 143 c	658 ± 231 d
1.4	$P = 0.001$				

^aData based on six replicate ceramic cup extractions at 1.4 m depth (2 × plot) per fertilizer treatment (33 samplings over the three growing seasons). Mean followed by standard deviation; different small letters for each row indicate significant differences between treatments ($P < 0.05$, Duncan Test). ^bFor treatment key, see Materials and Methods.

Table 8. Effect of application of increasing rate of pig slurry and urea fertilizer on dry matter, N uptake and yield of maize in the three growing seasons.^a

Year	Treatments ^b	Dry matter (kg ha ⁻¹)	Plant N uptake (kg ha ⁻¹)	Grain yield (kg ha ⁻¹)
1998	P0	20930 ab	171 a	12824 a
	U	20321 a	171 a	12827 a
	P1	21566 b	230 ab	13523 a
	P3	23951 c	241 b	15460 b
	P	0.0001	0.0460	0.0014
1999	P0	17865 a	139 a	12445 a
	U	19327 a	196 b	13359 a
	P1	19580 a	198 b	13682 a
	P3	20152 a	199 b	13938 a
	P	0.098 NS	0.0020	0.2630 NS
2001	P0	17894 a	45 a	2820 a
	U	24386 b	127 b	6205 b
	P1	24313 b	118 b	5748 b
	P3	25161 b	147 c	6485 bc
	P	0.015	0.001	0.020

^aDifferent small letters in a column for each year indicate significant differences between treatments ($P < 0.05$, Duncan Test) ($P > 0.05$ denotes not significant NS).

therefore appears to increase plant N uptake without increasing grain production, which confirms the results of Díez *et al.* (2001).

CONCLUSIONS

The results of this study indicate that application rates of pig slurry that are larger than optimal have little or no effect on crop yield, but they do increase soil salinization and nitrate pollution of water. The increases in TDS losses over the control caused by pig slurry were 2030 and 7437 kg ha⁻¹ for the P1 and P3 treatments, respectively, during the experiment. The salt concentration of the soil solution generally increased with profile depth and increasing slurry application. Calculating optimal slurry rates, taking into account their N content, the available soil N and crop requirements, is an effective way to reduce these risks.

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