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Direct and residual response of wheat to swine slurry application method.

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Abstract

Swine production represents more than 25% of net agricultural incomes in some Spanish regions. Most of the 25 million t of swine slurry produced yearly in Spain is applied to agricultural fields by surface broadcasting (splash-plate) with important atmospheric N losses that reduce the fertilizer value of the slurry. Surface banding, incorporation, and injection into the soil are recommended methods to reduce N losses. We examined during two consecutive years the response of a wheat crop to swine slurry (SS) applied in the first year at two rates (30 and 60 Mg ha^{-1}) using two application methods: splash-plate (SP) and soil incorporation (SI). After SS application, the soil was sampled intensively to establish the actual amount of SS in the soil (N recovery) and its spatial variability (distribution uniformity) in the two methods. Wheat yield, above ground dry matter and N uptake were measured along the two years. Swine slurry distribution uniformity and soil N-recovery were higher in SI than in SP, but grain yield and N uptake were independent of the application method in the two years. Reliable management practices compatible with the protection of the environment require further studies on the pathways and the availability of N to crops subject to SS incorporation in the soil at the moment of application.

Introduction

Swine production in Spain amounts to about 26 million heads per year, the second European country producer with 17% of total production in the European Union. The 25 million t of swine slurry (SS) yearly produced in Spain are mainly used as fertilizers, but inadequate rates and methods of application may have a major negative environmental impact on soils, waters and the atmosphere. These negative impacts are of great social concern in Europe and constrain the expansion of this important industry in many European countries. However, adequate SS applications in terms of rates and timing have proved to be an efficient way for its disposal and a good example of nutrients recycling and saving in mineral fertilizers and energy (Petersen, 1996; Zebarth *et al.*, 1996; Jensen *et al.*, 2000).

Most of the SS applied in northern Spain is surface broadcasted and buried in the soil in the next 24 hours. Since 75% of the nitrogen (N) is in the ammonium form, N losses to the atmosphere as ammonia volatilization are substantial (Smith et al., 2000), reducing the fertilizer value of the slurry (Jarvis and Pain, 1990; Morvan et al., 1997; Sørensen and Amato, 2002) and impacting negatively on air quality. These volatilization losses take place in the first hours after application (Gordon et al., 2001; Sommer and Hutchings, 2001, Huijsman, 2003; Chantigny et al., 2004), and depend on several factors and, in particular, in the application method (Pahl et al., 2001; Sommer and Hutchings, 2001; Misselbrook et al., 2002; Rodhe and Rammer, 2002). The direct application of SS on the soil surface reduces its time of contact with the air, so that ammonia volatilization is significantly reduced in comparison to splash-plate broadcasting. Hence, surface banding, incorporation and injection into the soil are recommended methods to reduce N losses (Sommer and Hutchings, 2001).

Several studies have evaluated atmospheric N losses under different SS application methods, but only a few have focused on its effects on crop response and the components of the N budget, either the year of application (Rochette et al., 2001; Mooleki et al., 2002; Rodhe and Rammer, 2002; Rodhe, 2004), or the year after application (i.e., residual effects) (Sørensen and Amato, 2002, Berntsen et al., 2007). None of these studies have been conducted under irrigated Mediterranean, temperate conditions. This information is essential to establish reliable SS fertilization plans and to determine the most efficient application methods.

Swine slurry application methods have an important role in the immobilization of N. Sørensen and Jensen (1995), Sørensen and Amato (2002), and Sørensen (2004) found that N immobilization increased when cattle or swine slurries were mixed with the soil as compared to injection or surface-band applications. The immobilised N was initially associated with the easily decomposable soil organic matter fraction, and as the microorganisms died and their residues decomposed, part of the immobilised N was remineralised again. These N-turnover processes may have an impact on the release of manure derived-N in the years after application (Sørensen and Amato, 2002). This “residual effect” (Pratt, et al., 1973; Sørensen and Amato, 2002; Wen et al., 2003; Daudén et al., 2004; Cusick et al., 2006) is associated to the organic N fraction, clay-fixed NH_4^+ and immobilized N, and it may depend on the SS application method (Sørensen and Amato, 2002).

The objective of this work was to determine under Mediterranean irrigated conditions the performance of two SS application methods: splash-plate broadcasting and soil incorporation. This comparison was determined by analysing with each method the efficiency of application (or slurry N recovery), distribution uniformity, dynamics of soil mineral N, and response of a wheat crop in terms of yield, above ground dry matter, N uptake, and the efficiency in the use of N along two consecutive years (i.e., direct and residual effects), as well as the N replacement value in the second experimental year.

Materials and methods

Experimental design

The study was conducted at the experimental farm of the Centro de Investigación y Tecnología Agroalimentaria de Aragón (Zaragoza, NE Spain, 41º 43’ 09’’ N - 0º 49’ 11’’ W) on a Typic Xerofluvent (Soil Survey Staff, 1999) silt loam soil during the period November 2001 to June 2003. Some of the top soil (0-0.30 m) characteristics at the beginning of the experiment are: organic matter = 13.0 g kg^{-1}, sand = 280 g kg^{-1}, silt = 503 g kg^{-1}, clay = 217 g kg^{-1}, nitric-N = 9.0 kg Mg^{-1}, P = 18.0 kg Mg^{-1} and K = 144.0 kg Mg^{-1}. The climate is semiarid (Figure 1) with high summer temperatures (14.8ºC annual average 1982-2003), low precipitations (409 mm annual average 1982-2003), and high potential evapotranspiration (1100 mm annual average 1982-2003).

Five treatments were established in November 2001 in a randomized block design with three replications. The treatments were the combinations of two SS application rates, 30 Mg ha^{-1} (S30) and 60 Mg ha^{-1} (S60), and two distribution methods, splash-plate (SP) and soil incorporation (SI), plus a control treatment without SS application (S0). The low SS rate (S30), deficient in terms of crop N requirements, was established to evaluate the effects of the application method in the year of application. The high SS rate (S60), excessive in terms of crop N requirements, was established to evaluate the effects one year after application (i.e., SS residual effect).

The experimental plots had a length of 30 m and a width of 6 m for the SI method and the control treatments and 8 m for the SP method. A plain scoop was used in the SP method with the equipment adjusted to get an application width of 7 m. The incorporation machine used in the SI method consisted of a tube divided into three hoses, two laterals and one central, with a total application width of 4.8 m. Each outlet was located between two shares, the share located before the tube opened a slot in the soil and the back share buried the applied SS at a depth of about 0.15-0.20 m.

Previous to the application, the machinery was calibrated to apply the target rates by the two distribution methods. The day of application, 29 Nov. 2001, the slurry was stirred several minutes in the storage pit before being pumped to the tank, to ensure homogeneity in each tank and between tanks. The average amount of SS applied was 33.6 Mg ha^{-1} for the S30-SP treatment, 58.8 Mg ha^{-1} for the S60-SP, 33.0 Mg ha^{-1} for the S30-SI treatment, and 56.4 Mg ha^{-1} for the S60-SI treatment. The slurry applied in the SP plots was buried in the soil 20 hours after application, according to the enforced regulations (Gobierno de Aragón, 1997). The following meteorological variables were measured in the day of SS application: average air temperature = 11.3 ºC, average relative humidity = 61%, average wind speed = 2.2 m s^{-1}, soil temperature at 0.20 m depth = 7.7 ºC and class A pan evaporation = 2.0 mm day^{-1}.

Several slurry samples were taken from each tank, mixed to make a composite sample, frozen and sent to the laboratory for analysis. Some of the physico-chemical characteristics of the SS applied are given in Table 1. The average amounts of NH_4-N applied with the slurry were 126 kg N ha^{-1} in the S30 treatments (127 in S30-SP and 125 in S30-SI), and 218 kg N ha^{-1} in the S60 treatments (223 in S60-SP and 214 in S60-SI).

On 11 December 2001, wheat (*Triticum aestivum, cv* Anza) was sown at a density of 300 kg ha^{-1}, and 40 kg P ha^{-1} (200 kg superphosphate ha^{-1}) and 90 kg K ha^{-1} (170 kg potassium chloride ha^{-1}) were applied. These rates supply enough P and K for a 6000 kg ha^{-1} grain yield. The plot was flood-irrigated four times in 2002: 110 mm in 21 January and 16 March, and 90 mm in 23 April and 16 May.

In the second year, each of the 30-m long splash-plate (SP), soil incorporation (SI) and control plots were subdivided in five 6-m long individual plots. Five mineral N rates (0 (N0), 40 (N40), 80 (N80), 120 (N120), and 160 (N160) kg N ha^{-1}), were randomly applied configuring a split-plot design with the S0, S30-SP, S30-SI, S60-SP, and S60-SI treatments as main plots and the mineral N treatments as subplots.

On 28 Nov. 2002, wheat (*Triticum aestivum,* cv Anza) was sown at a density of 300 kg ha^{-1}, and 40 kg P ha^{-1} (200 kg superphosphate ha^{-1}) and 90 kg K ha^{-1} (170 kg potassium chloride ha^{-1}) were applied. Nitrogen was applied in the form of urea (N1= 87 kg urea ha^{-1}; N2= 174 kg urea ha^{-1}; N3= 261 kg urea ha^{-1}; N4= 348 kg urea ha^{-1}), 1/4 before sowing, (19 Nov. 2002), and 3/4 at side-dressing (11 Feb. 2003), following the usual practices in the area. Only two irrigations were applied in 2003 (40 mm each in 4 May and 27 May) as rain amount and distribution (Figure 1) were adequate to cover the remaining crop water needs.

Sampling and analysis

The amount and distribution of applied SS was measured four days after application (when it was possible to access the field) in 0-0.30 m depth soil samples taken in two of the S60 plots, one in the SP (plot # 12) and one in the SI (plot #3) application method. These soil samples were taken every 0.20 m in three transects evenly distributed along each plot (at 5-, 15- and 25- m from the border of the plot) and perpendicular to the SS application direction.

Changes in soil mineral N after SS application were studied in 0-0.30 m depth soil samples taken from each plot at ten different dates during the first growing season (3, 10 and 17 December 2001 and 17 January, 12 February, 16 March, 2 April, 20 May, 16 June, and 2 July 2002). Additional soil samples were taken at 0-0.30 m and 0.30-0.60 m depths on 28 Nov. 2001 (before SS application), 17 July 2002 (after first year wheat harvest), 14 Nov. 2002 (before second year wheat sowing), and 28 July 2003 (after second year wheat harvest). The locations of the sampling points were labelled in the first sampling date and the subsequent samplings along the study period were consecutively displaced 0.40 m in the direction of the SS application. The samples were taken in four locations per experimental plot and mixed for each soil depth. All soil samples were taken with a 0.10 m diameter Edelman auger (Eijkelkamp®).

Nitrate concentrations (cadmium column technique, Maynard and Kalra, 1993) in all samples, and ammonium concentration (colorimetry at 660 nm, Houba, et al., 1988) in the 0-0.30 m depth samples were determined in 1:3 soil extracts (10 g fresh soil sieved at 2 mm extracted with 30 mL of 1M KCl solution). Soil water content was measured by oven drying at 105ºC ± 2ºC for 48 h.

Nitrate concentration and EC were measured in water samples taken after each irrigation and precipitation events. Average nitrate concentrations were 3.2 mg NO_3-N L^{-1} in 2002 and 1.4 mg NO_3-N L^{-1} in 2003 (irrigation water), and 0.11 mg NO_3-N L^{-1} (rain water). Average electrical conductivity of irrigation water was 1.98 dS m^{-1} in year 2002 and 1.13 dS m^{-1} in year 2003. These values are below the salinity threshold of wheat for a 100% potential yield (Ayers and Westcot, 1994).

Wheat was mechanically harvested in two strips, 1.5 m wide x 30 m long in 3 July 2002, and 1.5 m wide x 6 m long in 26 June 2003 in each experimental plot. Before harvesting, two 0.5 m^2 circular areas per plot were hand-harvested to measure the harvest index. Grain humidity and specific weight were measured using a PM-600 Keller grain moisture. Total N concentrations in grain and straw were determined in a FP-528 LECO (Dumas, 1831).

Efficiency of N Application (N recovery) and N Distribution Uniformity (DU)

The efficiency of N application or N recovery was calculated using equation 1, where $(NH_4\text{-}N)_{4DASS}$ and $(NH_4\text{-}N)_{initial}$ denote, respectively, ammonium-N in the 0-0.30

m soil depth four days after SS application (4DASS) and before SS application (initial), and $(NH_4\text{-}N)_{SS}$ ammonium-N in the applied slurry. Using this equation we assume that nitrification of slurry ammonium was small in the four days between PS application and soil sampling.

$$\text{N recovery (\%)} = \frac{(\text{NH}_4 - \text{N})_{\text{4DASS}} - (\text{NH}_4 - \text{N})_{\text{initial}}}{(\text{NH}_4 - \text{N})_{\text{SS}}} \text{ x } 100 \qquad \textbf{[1]}$$

The difference between the amount quantities of ammonium measured in the soil and the ammonium applied can be attributed to losses by volatilization, denitrification or percolation below 0.30 m depth and N transformations as nitrification or immobilisation that occurs during SS application and in the subsequent four days.

The N distribution uniformity (DU) was defined following the *irrigation distribution uniformity* of Merriam and Keller (1978), as the ratio between the average low quarter (25% percentile) soil ammonium concentration $[(NH_4\text{-}N)_{25\%}]$ and the average soil ammonium concentration $[(NH_4\text{-}N)_{average}]$ (Eq. [2]). DU was calculated using ammonium concentration 4DASS $[(NH_4\text{-}N)_{4DASS}]$. Prior to the DU calculations, soil NH_4-N concentrations were averaged over 0.40 m to avoid the effects of band localization in the incorporation method.

$$\text{DU} = \frac{\left[\text{NH}_4^+ - \text{N}\right]_{25\%}}{\left[\text{NH}_4^+ - \text{N}\right]_{\text{average}}} \text{ x100} \qquad \textbf{[2]}$$

Efficiency in the use of Nitrogen: N Agronomic Efficiency (AE) and apparent N Use Efficiency (ANUE)

Nitrogen Agronomic Efficiency (AE, kg grain per kg applied N) for each treatment was calculated using Eq. [3], and Apparent Nitrogen Use Efficiency (ANUE, %) for each treatment was calculated using Eq. [4] (Craswell and Godwin, 1984).

$$\text{AE (Treatment)} = \frac{\text{Grain Yield (Treatment)} - \text{Grain Yield (Control)}}{\text{N applied (Treatment)}} \qquad \textbf{[3]}$$

$$\text{ANUE (Treatment)} = \frac{\text{Crop N uptake (Treatment)} - \text{Crop N uptake (Control)}}{\text{N applied (Treatment)}} \text{x100} \qquad \textbf{[4]}$$

AE and ANUE, of the slurry derived NH_4-N, in the 2001-2002 growing period (i.e., year 2002) were calculated for the S30-SP, S30-SI, S60-SP, and S60-SI treatments. The S0 treatment was the “control” and the $N_{applied}$ was the amount of NH_4-N applied with the slurry. In the 2002-2003 growing period (i.e., year 2003) AE and ANUE were calculated for the four mineral rates (N40, N80, N120, and N160) in each of the 2002 treatments (S30-SP, S30-SI, S60-SP, and S60-SI). The N0 treatment in each of the above 2002 treatments was used as “control” and the $N_{applied}$ was the amount of mineral N applied in each treatment.

Swine slurry N fertilizer replacement value (NRV)

The fertilizer equivalent method compares crop yield or N uptake in plots receiving solid or liquid manures with those receiving mineral N. The N replacement value (NRV) is the amount of mineral N needed to obtain the same yield or N uptake than in the manured plots. The swine slurry NRV gives the apparent availability of the N in the slurry in terms of mineral fertilizer.

The NRV was established by the difference method proposed by Lory et al. (1995) to evaluate the effects of precedent legume crops that considers the non-N effects of the slurry or change in maximum yield due to management (legume crop, manure, etc.) in the antecedent year. First, linear-plateau equations (Cerrato and

Blackmer, 1990) were adjusted to model the response of wheat yield to the five mineral N rates applied in 2003 for each of the five 2002 SS treatments (S0, S30-SP, S30-SI, S60-SP, and S60-SI). The NRV of the four SS applied treatments were calculated as the difference between the critical rate of N fertilization estimated for each treatment and the critical rate of N fertilization estimated for the control treatment (S0). The critical rate of N fertilization is defined as the minimum dose of mineral N required to obtain the maximum yield (Cerrato and Blackmer, 1990) and it is one of the 3 fitted parameters of the linear-plateau response model.

Nitrogen budget

The nitrogen budget was established for the 0-0.60 m soil depth using Eq. [5]. It was assumed that water and N extraction by the wheat crop below 0.60 m was not significant (Hoad et al., 2004). The generalized root length density (RLD) model defined by Zuo et al. (2004) using 610 data sets of RLD winter wheat, estimates that RLD for the 0-0.60 m depth was higher than 93% of total RLD.

The outputs (N_{out}) in the N budget were crop N uptake (N_{upt}) and soil mineral N at the end of the studied period (N_{fs}). The inputs (N_{in}) were soil mineral N at the beginning of the period (N_{is}), N applied with SS or mineral fertilizers (N_f), nitrogen in irrigation and rain water ($N_{irr+rain}$), and mineral N provided by the soil (N_m).

$$\text{Unaccounted N} = N_{inputs} - N_{outputs} = \left(N_{is} + N_f + N_{irr+rain} + N_m\right) - \left(N_{upt} + N_{fs}\right) \qquad \textbf{[5]}$$

The N_m was estimated as the difference between N inputs and outputs in the control treatment (Bhogal et al., 1999). This method of estimation assumes that nitrate leaching and atmospheric losses are negligible in the control treatment and, if they occur, they are included in the N_m value. In addition, the method does not consider the possibility of a fertilizer priming effect (Myrold and Bottomley, 2008).

Statistical analysis

Statistical analysis were performed with the statistical package SAS (SAS Institute, 1999-2001). The effects of the treatments were evaluated by analysis of variance using the GLM procedure. The application rates were compared by Tukey mean separation procedure, and the application methods (incorporation vs. splash-plate) by orthogonal contrast when the analysis of variance F-test was significant ($p<0.05$). The yield response to mineral N was fitted to linear-plateau models (Cerrato and Blackmer, 1990) using the PROC NLIN of SAS (Eq. [6]):

$$\begin{aligned} Y &= a + b \cdot N \quad N \le C \\ Y &= a + b \cdot C \quad N > C \end{aligned} \qquad \textbf{[6]}$$

where Y is grain yield , N is the nitrogen rate and C is the critical rate of nitrogen fertilization. Linear-plateau response models fitted to different treatments were compared using an F-test (Dixon, 1985 p. 245).

Results

Effect of SS application method on the efficiency of N application (N recovery) and N distribution uniformity (DU)

The average NH_4-N content in the 0-0.30 m soil depth measured four days after swine slurry application (4 DASS) was 208 kg ha^{-1} in the S60-SI plot and 104 kg ha^{-1} in the S60-SP plot (Figure 2). The N recovery (Table 2) in the SI method (96%) was significantly higher ($p < 0.05$) than in the SP method (47%).

In the SP method 25% of the plot surface received only 21% of the average SS rate (DU=21%, Table 2) as compared to 52% in the SI method. The coefficients of variation (CV) of soil NH_4-N concentrations were 61% in the SP and 36% in the SI method. Chambers et al. (2001) suggests that slurry and manure spreaders should be chosen and operated to give a CV lower than 25%.

The N distribution uniformity has two components: a longitudinal uniformity related to the variability in SS spreading with time, and a lateral or transversal uniformity related to the variability associated with the distribution of the application at a given time. The transversal DU (DU_T) was evaluated using the soil NH_4-N concentration of the average line of the three sampling transects in each plot (Figure 2). The longitudinal DU was not evaluated because only three measuring transects were available in the longitudinal direction. The transversal DU was 73% in the soil incorporation method and 45% in the splash plate method (Table 2). These transversal DU are higher than the global DU because the distribution variability with time is not considered. The CV of the NH_4-N concentrations in the average line (CV_T) was also higher for the splash plate (CV_T=22%) than for the soil incorporation method (CV_T=13%).

Effect of SS rate and application method on the dynamics of soil N

The maximum NH_4-N content at the 0-0.30 m soil depth was measured in the first sampling date after SS application (4 days after SS application, 4DASS) in all treatments except in the S30-SI treatment, where NH_4-N content increased until 20 DASS (Figure 3A). Ammonium content sharply decreased after 4DASS whereas NO_3-N content increased up to 50 DASS (Figure 3B). These NO_3-N increases in the SS treatments indicates the fast nitrification of SS under fall conditions, as NO_3-N content in the control treatment (S0) did not increase significantly. Soil NH_4-N, NO_3-N and mineral N were not significantly affected by the application method at any sampling date (Figure 3C). Soil mineral N tended to be higher in the S60 than in the S30 application rate until about 50 DASS (NH_4-N), 80 DASS (NO_3-N), and 97 DASS (mineral N), and were similar along the rest of the study period (Figure 3C). Soil mineral N sharply decreased in the period between 49 and 97 DASS, in coincidence with wheat stalking, the phase with maximum N nutritional needs.

Effect of SS rate and application method on the response of wheat in the same year of SS application (i.e., SS direct effect)

Grain yield, aboveground dry matter (AGDM) and N uptake were higher in the SS treatments than in the control treatment (Table 3), indicating the positive effects of SS applications on wheat. Grain yield was significantly higher in the S60 than in the S30 treatment (Table 3) indicating that N was a limiting factor for crop yield in the S30 treatment. In contrast, no significant differences where found for AGDM and N uptake for the two SS rates (Table 3).

Wheat yield, AGDM and N uptake for each S30 and S60 treatment and for the combined treatments where independent of the application method (Table 3). This result is in agreement with the previous finding in that soil NH_4-N, NO_3-N and mineral N contents were independent of the application method (Figure 3C).

Effect of SS rate and application method on the response of wheat the year after SS application (i.e., SS residual effect)

The grain yield response curves of wheat to the five mineral N rates applied in 2003 did not differ significantly between the SP and SI application methods in both the S30 and S60 SS rates applied in 2002. Thus the SS residual effect on wheat grown the year after SS application was independent of the application method.

The critical rate of N fertilization, estimated for the joint data of the two application methods, decreased ($p<0.05$) with increases in the amount of the SS applied in the previous year: 100 kg N ha^{-1} for the control treatment (S0), 65 kg N ha^{-1} for the S30 rate and 54 kg N ha^{-1} for the S60 rate (Figure 4). The estimated maximum yield was significantly higher ($p < 0.05$) for the S30 and S60 application rates (5.4 Mg ha^{-1}) than for the control (5.0 Mg ha^{-1}), suggesting a so-called residual non-N, specific effect (Scröder, 2005) of applied SS on yield.

The N replacement value (or apparent availability of N in the slurry in terms of mineral fertilizer), that quantifies the SS residual N-effect was 46 kg N ha^{-1} for the S60 treatment (14% of the total applied N) and 35 kg N ha^{-1} (17% of the total applied N) for the S30 treatment.

Nitrogen use efficiency

Nitrogen use efficiencies (N agronomic efficiency, AE, and apparent N use efficiency, ANUE) were unaffected by the application method in year 2002 (Table 3). Swine slurry rates affected AE (15.1 kg kg^{-1} N for S30 and 11.1 kg kg^{-1} N for S60) although they did not affect ANUE (Table 3). Nitrogen use efficiencies (AE and ANUE) were not affected by the application method in year 2003 (data not presented). However, AE was affected significantly by the SS rates applied in year 2002 (Figure 5). Pooling together the data of both application methods the AE in year 2003 for the S0, S30 and S60 treatments were maxima below the corresponding mineral N critical rates and decreased thereafter (Figure 5). The maximum AE's were 14.6 kg kg^{-1} in the S0 treatment for N = 80 kg N ha^{-1} (critical rate = 100 kg N ha^{-1}), 28.9 kg kg^{-1} in the S30 treatment, for N= 40 kg N ha^{-1} (critical rate = 65 kg N ha^{-1}) and 19.2 kg kg^{-1} in the S60 treatment for N= 40 kg N ha^{-1} (critical rate = 54 kg N ha^{-1}).

Effect of SS rate and application method on the N budget

The mineral N provided by the soil (N_m) during the 2001-2002 wheat growing season was estimated as 22 kg N ha^{-1} from the difference between the N inputs and outputs in the control treatment (Table 4). This low N_m value includes unmeasured potential losses to the atmosphere and nitrate leaching.

Applied N in the irrigation and rain waters was low, 16 kg N ha^{-1}, and its contribution to the total N inputs in the S30 and S60 treatments was less than 6%. The initial soil mineral N (N_{is}) was 61 kg N ha^{-1}, and the final soil mineral N (N_{fs}) ranged between 35 and 47 kg N ha^{-1} and was not affected by the SS rate and application method (Table 4).

Unaccounted N or differences between N inputs and outputs, were positive and significant ($p < 0.05$) in all treatments, but they were not significantly affected by the application method (Table 4).

The mineral N (N_m) provided by the soil during the 2002-2003 wheat growing season was estimated as 91 kg N ha^{-1}. Since only two light irrigations were given in this period, potential nitrate leaching losses were believed to be lower than in the precedent crop cycle, where four irrigations were given. Soil mineral N at pre-seeding was higher in the slurry (73 kg N ha^{-1}) than in the non-slurry plots (50 kg N ha^{-1}), indicating that it was affected by the SS applied in the precedent year. Soil mineral N content at harvest were similar in 2002 and 2003, without significant differences between treatments. The unaccounted N or differences between inputs and outputs were not significantly different from zero in any of the treatments.

Measured N inputs and outputs along the period 17 July 2002 to 28 July 2003 were similar in all the SS treatments, as shown by the linear regression equation in

Figure 6, with a coefficient of regression not significantly different from one. This result suggests that any amount of N mineralized-remineralized have remained in the 0-0.60 m soil depth in this period. Hence, the second year of this experiment is considered an appropriate period to quantify the residual effect of SS applied in the previous year.

Discussion

Effect of SS rate and application method on the response of wheat in the same year of SS application (SS direct effect)

The efficiency of N application (N recovery) in the soil incorporation method (SI) doubled that in the splash-plate method (SP) (N recovery = 96% in SI and 47% in SP). It is known that ammonia losses by volatilization should be greatly reduced in the SI method because of the lower contact of the SS with the air as compared to that in the SP method. Thus, decreases in ammonia losses of 26% (Misselbrook et al., 2002) and 39% (Smith et al., 2000) were found for band spreading in comparison to surface broadcasting. Moreover, in our study the ammonia losses should be further reduced because of the incorporation of the SS to a soil depth of 0.15-0.20 m at the same time than its application. Rochette et al. (2001) found decreases in ammonia volatilization losses of 80% when the slurry was buried with residues 5 cm deep in the soil, and Sommer and Hutchings (2001) found decreases of more than 90% when the slurry was buried more than 15 cm deep in the soil. Hence, the difference in N recovery found between the two application methods is congruent with high ammonia volatilization losses in the SP method versus negligible losses in the SI method, the rest of the terms of the N budget being small during the four days after SS application.

However, despite the higher N recovery in the SI method, wheat yield, AGDM, N uptake, AE, and AUNE were similar to those in the SP method (Table 3). The amount of N applied with the S60 rate in the two application methods was adequate to satisfy the theoretical wheat N requirements, as shown by the high yields obtained (5 Mg ha^{-1}). Although the amount of NH_4-N applied in the SI method (206 kg N ha^{-1}) doubled that in the SP method (102 kg N ha^{-1}), wheat yields were similar because the critical N requirements were reached in both treatments.

In contrast, the lower yields obtained in the S30 rate (Table 3) indicate that N was a limiting factor for crop development in the S30 rate. Although N recovery was not measured in the S30 treatment, Sommer and Hutchings (2001) concluded that ammonia emissions in surface-applied slurry, expressed as a proportion of the total ammonium applied, decreased with increasing SS application rates because of the greater proportion of the slurry infiltrating the soil. Hence, N recovery in the S30-SI method should at least double that in the S30-SP method. However, wheat yields were independent of the application method (Table 3), suggesting that part of the NH_4-N applied in the SI method was not available for wheat development.

The N budget shown in Table 4 indicates that, for a given SS rate, crop N uptake (N_{upt}), soil mineral N at harvest (N_{fs}) and unaccounted N were similar in the SP and SI methods. Nitrate leaching did not differ significantly in both methods, since their soil nitrate concentrations were similar along the study period (Figure 3B). Moreover, denitrification losses in both methods should be similar, since the amounts or fresh organic mater applied were analogous. So, the only explanation is that part of the N applied with the SS was fixed, adsorbed or immobilized in the soil in the incorporation application. This conclusion is supported by results found by other authors. Thus, Sørensen and Jensen (1995) and Sørensen and Amato (2002) found that ammonium immobilization was higher in SI than in SP, and concluded that when the slurry is mixed with the soil (SI method) a high proportion of microorganisms remain protected from their predators, whereas in the SP method the microorganisms remain unprotected as they live directly in the slurry. Rochette et al. (2001) found that, despite important reduction of ammonia volatilization when the slurry is incorporated into the soil, no differences in soil mineral N were found between incorporated and surface applied slurry, suggesting that other processes such as N immobilization-mineralization or denitrification, were more active when the slurry is incorporated in the soil. Jensen et al. (2000) also found a significant immobilization of cattle slurry NH_4^+-N into the microbial biomass. However, fast microbial turnover depleted the microbial biomass before spring and leaching of slurry-derived N was also fast.

Additionally, it has to be considered that the lack of a significant crop response to the application methods could be in part due to an uneven spread pattern of the slurry reflected in high coefficients of variation (CV (SP) = 61% and CV (SI) = 36%). In this sense Thomsen et al. (2003) indicates that a higher number of repetitions are needed when studying the behaviour of organic manures.

Effect of SS rate and application method on the response of wheat the year after SS application (SS residual effect)

During the second wheat growing season (year 2003), we did not found a significant effect of the application method on crop response. It was concluded that a fraction of the N applied with the SS in year 2002 was fixed, adsorbed or immobilized in the soil in the SI application method. Sørensen (2004) concluded from a study of the immobilization and remineralisation of slurry ammonium using labelled NH_4-N that a significant part of the organic N retained in the soil after SS application is derived from the immobilised ammonium-N and will be slowly released over many years contributing to the residual N effect of SS. In our study the release of the previously immobilized slurry NH_4 in the SI treatments was not observed in the response of the wheat crop. The N budget for the period 17 July 2002 to 28 July 2003 shows that the losses were negligible (Figure 6) so that any amount of N mineralized-remineralized should have remained in the soil in this second year. So the pathways of the N applied with the slurry in the SI method are unknown.

The N residual effect in year 2003 of the SS applied in year 2002 was quantified between 14% and 17% of the total N applied with the slurry depending on SS rates. This residual effect is mainly associated in this experiment to the organic N applied with the slurry, as the effects of immobilized slurry NH_4 in the SP method were not detected. Similarly, first year residual effects (as percentage of total N applied with the organic manure) have been obtained by other authors in places with similar Mediterranean climatic characteristics. Irañeta et al. (2002) found an 8% residual effect in Navarra (Spain) and Ziegler and Heduit (1991) a 13% residual effect in Southern France. In both studies the SS was applied in fall by the SP method.

The increase of the crop potential yield (Figure 4) related to SS application in the previous year was not associated to N quantity because in that case the maximum yield should be reached at the highest rates of mineral N (120-160 kg N ha^{-1}) in the S0 treatment. Although the reasons for the increase of the potential yield can not be substantiated with our data, it is suggested that it can be related, besides other factors, to the continuous mineralization of the SS organic-N that may improve the timing of N supply (Sieling et al., 1998). Another reason could be increases of other nutrients applied with the slurry (Daudén et al., 2004; Shröder, 2005), as microelements scarcely present in the crop under monoculture conditions that could be supplied sufficiently with the SS, even at low rates (30 t ha^{-1}), to cover crop needs. It seems clear that, independently from doses, the application of SS produced an increase of the productive potential the following year.

Conclusions

The amount of nitrogen applied to the soil with swine slurry (SS) and its distribution uniformity were higher in the soil incorporation (SI) than in the splash-plate (SP) application method. However, no effects on wheat yield were detected between the two methods in the year of the SS application (SS direct effects) and in the year after application (SS residual effects). Our results suggest that part of the N applied with the SI method was immobilized in the soil and was not available for the crop the year of application. Some experiments have pointed out that the immobilized N is released in the following years contributing to the residual effect of the slurries.

Noticeable N and non-N SS residual effects were observed. The N residual effect was demonstrated by the critical rates of N fertilization that were lower in the slurry than in the non-slurry treatments. The non-N residual effect was reflected by the higher yield potential of wheat in the slurry than in the non-slurry treatments. However, the residual effect was not related to the SS application method. The pathways and dynamics of N in the soil-plant system when SS is applied in Mediterranean conditions are not well understood and further studies should be undertaken to make reliable recommendations in the use of SS as a fertilizer using different application methods.

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References

Ayers RA, Westcot DW (1994) Water quality for Agriculture. FAO irrigation and drainage paper 29 rev. 1. ISBN 92-5-102263-1

Berntsen J, Petersen N, Sørensen P, Olensen J (2007) Simulating residual effect of animal manures using 15N isotopes. Plant Soil 290 (1-2):173-187

Bhogal A, Hactch DJ, Shepherd MA, Jarvis SC (1999) Comparison of methodologies for field measurements of net nitrogen mineralisation in arable soils. Plant Soil 207:15-28

Cerrato ME, Blackmer AM (1990) Comparison of models for describing corn yield response to nitrogen fertilizer. Agron J 82:138-143

Chambers B, Nicholson N, Smith K, Pain B, Cumby T, Scotford I (2001) Spreading systems for slurries and solid manures. Booklet 3. Managing Livestock manures. ADAS Gleadthorpe Research Centre Ministry of Agriculture, Fisheries and Food, 7pp.

Chantigny MH, Rochette P, Angers DA, Masse D, Cote D (2004) Ammonia volatilization and selected soil characteristics following application of anaerobically digested pig slurry. Soil Sci Soc Am J 68:306–312

Craswell ET, Godwin DG (1984) The efficiency of nitrogen fertilizers applied to cereals grown in different climates. (Ed). Praeger Publishers USA. Tinker PB, Lauchil A (Eds) In: Adv Plant Nutr 1:1-56

Cusick PR, Kelling KK, Powell KA, Muñoz GR (2006) Estimates of residual dairy manure nitrogen availability using various techniques. J Environ Qual 35:2170-2177

Daudén A, Quílez D, Martínez C (2004) Residual effects of pig slurry applied to a Mediterranean soil on yield and N uptake of a subsequent wheat crop. Soil Use Manage 20 (2): 156-162

Dixon W J (1985) BMDP statistical software. University of California Press. Berkeley, California.

Dumas J.B.A (1831) Procédés de l´analyse organique. Annales de Chimie et de Physique 247: 198-213

Gobierno de Aragón (1997) DECRETO 200/1997, de 9 de diciembre por el que se aprueban las Directrices Parciales Sectoriales sobre Actividades e Instalaciones Ganaderas. BOA 147 22/12/1997.

Gordon R, Jaieson R, Rodd V, Patterson G, Harz T (2001) Effects of surface manure application timing on ammonia volatilization. Can J Soil Sci 81:525-533

Hoad SP, Russell GG, Kettlewell PS, Belshaw M (2004) Root system management in winter wheat: practices to increase water and nitrogen use. Project Report nº 351. Home-Grown Cereals Authority (HGCA). http://www.jxb.oxfordjournals.org/cgi/reprint/46/5/557.pdf . Cited Nov 2004

Houba VJG, Lee JJ van der, Novozamsky J, Walinga I (1988) Soil and plant analysis. Part 5: Soil analysis procedures. Wageningen Agricultural University. The Netherlands

Huijsman JFM (2003) Manure application and ammonia volatilization. PhD. Dissertation. Wageningen University

Irañeta I, Armesto AP, Segura A, Lafarga A, Arregui L, Merina M, Baroya E, Quemada M (2002) Herramientas de ayuda a la decisión para el manejo correcto de los fertilizantes nitrogenados en cereales de invierno. Navarra Agraria 133:7-16

Jarvis SC, Pain BF (1990) Ammonia volatilization from agricultural land. Fertiliser Society. Proceeding nº 28. (Ed) Greenhill house Thorpe wood. Peterborough PE3 6GF

Jensen LS, Pedersen IS, Hansen TB, Nielsen NE (2000) Turnover and fate of 15N-labelled cattle slurry ammonium-N applied in the autumn to winter wheat. Eur J Agron 12: 23-35

Lory JA, Ruselle MP, Peterson TA (1995) A comparison of two nitrogen credit methods: traditional versus difference. Agron J 87:648-651

Maynard DG, Kalka YP (1993) Nitrate and exchange ammonium nitrogen. *In* Sampling and method of analysis. Carter MR (Ed), Canadian Society of Soil Science. Lewis Publishers. CCR Press Inc., Boca Raton, FL. 25-38 pp

Merriam JL, Keller J (1978) Farm irrigation system evaluation: a guide for management. Third edition. Utah State University. Logan, Utah USA

Misselbrook TH, Smith KA, Johnson RA, Pain BF (2002) Slurry application techniques to reduce ammonia emissions: results of some UK field-scale experiments. Biosyst Eng 81 (3): 313-321

Mooleki SP, Schoenau JJ, Hultgreen G, Wen G, Charles JL (2002) Effect of rate, frecuence and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in East-Central-Saskatchewan. Can J Soil Sci 82, (4): 457-467

Morvan T, Leterme P, Arsene GG, Mary B (1997) Nitrogen transformations after the spreading of pig slurry on bare soil and ryegrass using 15N-labelled ammonium. Eur J Agron 7:181–188

Myrold, DD, Bottomley PJ (2008) Mineralization and immobilization of nitrogen in soils. Chapter 5, pp 153-167. Scheepers JS and Raun WR (Eds), In: Nitrogen in Agricultural Soils, Monograph no 49. American Society of Agronomy, Madison, WI

Pahl O, Godwin RJ, Hann MJ, Waine TW (2001) Cost-effective pollution control by shallow injection of pig slurry into growing crops. J Agr Eng Res 80(4): 381-390

Petersen J (1996) Fertilization of spring barley by combination of pig slurry and mineral nitrogen fertilizer. Journal of Agricultural Science. Cambridge, 127:151-159

Pratt PF, Broadbent FE, Martin JP (1973) Using organic wastes as nitrogen fertilizers. California Agriculture 27 (6):10-13

Rochette P, Chantigny MH, Angers DA, Bertrand N, Côte D (2001) Ammonia volatilization and soil nitrogen dynamics following fall application of pig slurry on canola crop residues. Can J Soil Sci 81:515-523

Rodhe L (2004) Development and evaluation of shallow injection of slurry into Ley. Ph D. diss. Departament of Biometry and Engineering. Swedish Univ of Agricultural Sciences. Agraria vol 483. Uppsala

Rodhe L, Rammer C (2002) Application of slurry to ley by spreading and injection methods. Biosyst Eng 83 (1):107-118

SAS Institute (1999-2001) Version 8.2 SAS, Cary, NC, USA

Shröder JJ (2005) Manure as a suitable component of precise nitrogen. Proceedings of the International Fertiliser Society no 574:1-32

Sieling K, Schöder H, Finck M, Hanus H (1998) Yield, N uptake and apparent N use efficiency of winter wheat and winter barley grown in different cropping system. J Agric Sci 131(4):375-387

Smith KM, Jackson DR, Misselbrook TH, Pain BF, Johnson RA (2000) Reduction of ammonia emission by slurry techniques. J Agric Eng Res 77 (3):277-287

Soil Survey Staff (1999) Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. USDA-SCS Agric. Handb. 436, U.S. Gov. Print. Office, Washington, DC

Sommer SG, Hutchings NJ (2001) Ammonia emission from field applied manure and its reduction. Eur J Agron 15(1):1-15

Sørensen SG, Amato M (2002) Remineralization and residual effects of N application of pig slurry to soil. Eur J Agron 16:81-95

Sørensen P (2004) Immobilization, reminaralization and residual effects in subsequent crops of dairy cattle slurry nitrogen compared to mineral fertilizer nitrogen. Plant Soil 267(1-2):285-296

Sørensen SG, Jensen ES (1995) Mineralization-immobilization and plant uptake of nitrogen as influenced by the spatial distribution of cattle slurry in soils of different texture. Plant Soil 173:283-291

Thomsen IK, Djurhuus J, Christensen BT (2003) Long continued applications of N fertilizer to cereals on sandy loam: grain and straw response to residual N. Soil Use Manage 19(1):57-64

Wen G, Schoenau JJ, Charles JL, Inanaga S (2003) Efficiency parameters of nitrogen hog and cattle manure in the second year following application. J Plant Nutr Soil Sci. 166(4):490-498

Zebarth BJ, Paul JW, Schmidt O, McDougall R (1996) Influence of the time and rate of liquid manure application on yield and nitrogen utilization of silage corn in South Coastal British Columbia. Can J Soil Sci 76:53-164

Ziegler D, Heduit M (1991) Engrais de ferme. Valuer fertilisante, gestion environnement. Ziegler, D et Heduit, M, (Eds).35p. Institut Technique du Porc (ITP) et Institut Techniques de Céréales et des Fourrages (ITCF)

Zuo Q, Jie J, Zhang R, Meng L (2004) A Generalized Function of Wheat’s Root Length Density Distributions. Vadose Zone Journal 3:271–277

FIGURE LEGENDS

Figure 1. Monthly precipitation (P), and mean air temperature (T) for the experimental period (2001-2003) and the historical period (1982-2004) in the experimental field

Figure 2. Ammonium content in the 0-0.30 m soil depth measured four days after swine slurry application in the transversal direction to the soil incorporation (SI) and splash-plate (SP) application methods. Each line is the average of three transversal locations. The horizontal line is the average amount of NH_4-N applied with the swine slurry in both application methods. Vertical bars denote 1 standard deviation

Figure 3. Amounts of (a) ammonium N, (b) nitrate N, and (c) mineral N in the 0-0.30 m soil depth measured along the first experimental year 2001-2002 after swine slurry application on 29 Nov. 2001. S0: control treatment; S30 and S60: swine slurry application rates of 30 Mg ha^{-1} and 60 Mg ha^{-1} respectively; SP: splash-plate method; SI: soil incorporation method

Figure 4. Grain yield response curves of wheat to mineral application rates of 0, 40, 80, 120, and 160 kg N ha^{-1} given in 2003. S0: control treatment; S30 and S60: swine slurry application rates of 30 and 60 Mg ha^{-1} respectively; SP: splash-plate method; SI: soil incorporation method

Figure 5. Nitrogen agronomic efficiency (kg grain yield per kg N applied) for wheat grown in 2003 under the mineral application rates of 40, 80, 120, and 160 kg N ha^{-1} for the three swine slurry application rates of 0 (control), 30 and 60 Mg ha^{-1} given in 2002 Vertical bars denote 1 standard error

Figure 6. Nitrogen Budget for the 0-0.60 m soil depth established for the three swine slurry application rates of 0 (control), 30 and 60 Mg ha^{-1} along the period 17 July 2002 to 28 July 2003. Relationships between measured outputs and inputs and linear regression equation

Table 1. Swine slurry physico-chemical characteristics

Characteristic	**Value**
Specific weight, g L^{-1}	1031
pH	7.10
Dry matter, kg DM Mg^{-1}	82.84
Organic matter, kg OM Mg^{-1}	17.36
Ammonium N, kg N Mg^{-1}	3.79
Organic N, kg N Mg^{-1}	2.04
Total N, kg N Mg^{-1}	5.81
P, kg Mg^{-1}	1.20
K, kg Mg^{-1}	3.93

Table 2. Efficiency of N application (N-Recovery, %), and ammonium-N distribution uniformity (DU) and Coefficient of Variation (CV) in the splash-plate broadcasting (SP) and the soil incorporation application (SI).

Method	**N-recovery** [a]	**DU**[b]	**CV**[b]	**DU_T**[b]	**CV_T**[b]
SP	47%±35%	21%	61%	45%	22%
SI	96%±24%	52%	36%	73%	13%

[a] ± 1 Standard deviation

[b] Ammonium- N distribution uniformity (DU, %) and Coefficient of Variation (CV, %) using all data of the three transects and ammonium-N distribution uniformity (DU_T, %) and Coefficient of Variation (CV_T, %) using the average line of the three transects (transversal variation).

Table 3. Grain yield (12% moisture content), above-ground dry matter (AGDM), N uptake (N uptake), N agronomic efficiency (AE, kg grain kg^{-1} N), and apparent N use efficiency (ANUE, %) for the different treatments and application rates in wheat grown in 2002

		Yield[a b]		**AGDM**		**N uptake**		**AE**	**AUNE**
Treatment		**Mg ha^{-1}**		**Mg ha^{-1}**		**kg ha^{-1}**		**kg gr kg^{-1} N**	**%**
S0		2.6	±0.5	7.6	±2.3	60	±17	-	-
	S0	2.6 a	±0.5	7.6 a	±2.3	60 a	±17	-	-
S30-SP		4.1	±0.1	11.6	±1.2	97	±3.3	13.8	32
S30-SI		4.4	±0.4	13.1	±1.8	108	±19	16.4	42
	S30	4.3 b	±0.3	12.4 b	±1.6	102 b	±14	15.1a	37
S60-SP		5.1	±0.5	14.9	±2.9	131	±33	11.3	31
S60-SI		5.0	±0.6	14.4	±2.4	119	±29	10.8	26
	S60	5.1 c	±0.5	14.6 b	±2.4	125 b	±29	11.1 b	29
Treatment[c]		S		S		S		S	NS
Application method		NS		NS		NS		NS	NS
Application rate		S		S		S		S	NS

[a] Values followed by the same letter in the same column do not differ significantly at the 0.05 probability level.

[b] ± 1 standard deviation

[c] S: Significant and NS: No Significant, at the 0.05 probability level

Table 4. Nitrogen budget for the 0-0.60 m soil depth in the period 28 Nov. 2001-17 Jul. 2002.

	N inputs[a] **(kg N ha^{-1})**				**N outputs (kg N ha^{-1})**		**Unaccounted N** [bc] **(kg N ha^{-1})**
Treatment	**N_{is}**	**N_f**	**N_{irr+r}**	**N_m**	**N_{fs}**	**N_{upt}**	
S0	61	0	16	22	39	60a	0
S30-SP	61	195	16	22	35	97b	162a ±25
S30-SI	61	192	16	22	39	108b	143a ±7
S60-SP	61	342	16	22	47	131b	262b ±34
S60-SI	61	328	16	22	43	119b	265b ±35
Treatment[d]					NS	S	S
Application method					NS	NS	NS
Application rate					NS	S	S

[a] Nitrogen inputs: initial soil mineral nitrogen (N_{is}), total N added with organic or mineral fertilizers (N_f), nitrate in irrigation and rain water (N_{irr+r}), and N supplied by the soil (N_m) estimated as the difference between inputs and outputs in the control treatment (S0); N outputs: final soil mineral nitrogen (N_{fs}) and crop N uptake (N_{upt}) and Unaccounted N obtained as the difference between N inputs and N outputs

[b] Values followed by the same letter do not differ significantly at the 0.05 probability level.

[c] ± 1 standard deviation

[d] S: Significant and NS: No significant, at the 0.05 probability level