Residual effects of pig slurry applied to a Mediterranean soil on yield and N uptake of a subsequent wheat crop

A. Daudén*, D. Quílez & C. Martínez

Abstract. In areas of intensive pig farming, fresh pig slurry is often applied annually to the same fields. Thus, to avoid nitrogen (N) losses correct fertilizer practice should take account of residual effects of slurry on the following crops. The residual effects of different rates of slurry applied during three years were evaluated in subsequent wheat crops. The experiment was conducted on an irrigated Mediterranean Typic Xerofluvent soil, where plots were left unfertilized or fertilized with 150 kg N ha⁻¹ as ammonium nitrate. Grain yield and grain N uptake increased with slurry rates in both fertilized and unfertilized treatments. The increases in the unfertilized treatments were interpreted as a nitrogen effect of the previous 1996–98 slurry applications. The equivalent mineral N released from the pig slurry was underestimated by two existing decay-series approaches. Although decay-series are useful tools for estimating manure residual effects they should be adjusted for local conditions. A significant positive relationship was detected between apparent N use efficiency of the slurry and the total amount of applied organic N, which was interpreted as a specific residual effect rather than due to the N dose of previously applied pig slurry.

Keywords: Pig slurry, N uptake, residual N, organic manure, fertilizer value, decay-series, N loss

INTRODUCTION

Pig farming has steadily increased in many regions of Spain over the last 20 years. This intensification has made a positive contribution to the social and economic development in rural areas, but it has led to pig slurry (PS) disposal problems. This has commonly resulted in the need for repeated application of PS to the same fields as a crop fertilizer. As a consequence, it is important to ascertain the cumulative effects of these multiple applications on the availability of nitrogen (N) and other nutrients to the succeeding crops and on the risk of adverse environmental effects such as gaseous losses to the atmosphere and nitrate leaching to water bodies (Nicholson et al. 1999).

The majority of studies dealing with N fertilization have been conducted on the plant-available N, mainly ammonium (NH₄⁺) and uric acid, as these fractions are associated with immediate N uptake by plants, ammonia volatilization and nitrate leaching (Smith & Chambers 1993; Paul & Beauchamp 1995). However, studies dealing with PS fertilization are more complex, as it has been shown that most of the organic N in PS (which amounts to around 30% of total N) is not available to crops during the same growing season but may be mineralized in the following years (Bernal et al. 1993). Also, a significant proportion of the PS ammonium N may be biologically immobilized or fixed on clays shortly after its application to the soil (Scherer & Weimar 1994; Griffin & Honeycutt 2000; Chantigny et al. 2001). Moreover, the repeated application of animal wastes to agricultural fields may lead to indirect beneficial effects derived from the addition of organic matter, macro- and micronutrients, and improvements in soil structure, water infiltration rate, and water holding capacity (Brechin & McDonald 1994).

Usually, the residual nitrogen effects of PS manure applications have been estimated using a decay-series approach (Pratt et al. 1976; Klausner et al. 1994), whereby the proportion of the total N applied becoming available decreases with successive years. However, most results on N availability have been obtained in the laboratory and they need to be expanded and validated under field conditions. Thus, a better understanding is needed on the dynamics of N release from the soil and on the processes affecting the fixation–immobilization–remineralization of the organic and inorganic N forms in PS. This knowledge would allow improved recommendations on best management alternatives for animal slurries in irrigated Mediterranean environments. The achievement of more efficient use of PS nitrogen should lead to significant economical savings and environmental benefits.
This study, conducted in an irrigated Mediterranean environment, had two objectives. The first was to evaluate the residual effects of different rates of PS applied over three consecutive years on the yield and N uptake of a subsequent winter wheat crop. The second was to ascertain the adequacy of existing decay-series for estimating the equivalent mineral N released from previous applications of PS.

**MATERIALS AND METHODS**

**Field experiment**

The experiment was performed at the experimental farm of the Agronomic Research Service of the Government of Aragon in Zaragoza (Spain) on a Typic Xerofluvent, a silty clay loam (Table 1). Typic Xerofluvent soils are located on the river terraces, where a sustainable agriculture has been developed during thousands of years on the most productive of the Mediterranean soils. The climate of the area is semiarid Mediterranean, with high temperatures in summer and low annual precipitation (Figure 1).

The experiment was conducted during the period November 1998 to July 1999 in a 8 km² field. Between 1996 and 1998, the response of corn to inorganic N fertilizer (PS0) and to three rates of fresh PS had been studied in this field using a randomized block design with three replicates (Daudén & Quílez 2003). The PS was applied once a year, 1 month before sowing, at target rates of 50 t ha⁻¹ (PS1), 100 t ha⁻¹ (PS2) and 150 t ha⁻¹ (PS3). The PS1 rate was set to evaluate applications of PS in spring, before sowing, complemented with mineral N topdressing. The PS2 rate was chosen to evaluate the effect of a single PS application that could cover the whole fertilization need for corn. With the PS3 rate, we intended to evaluate the environmental effects of high rates. The totals of PS applied were 183 t ha⁻¹ (PS1), 290 t ha⁻¹ (PS2), and 430 t ha⁻¹ (PS3) and the amounts of organic N applied were 320 kg ha⁻¹ (PS1), 526 kg ha⁻¹ (PS2) and 787 kg ha⁻¹ (PS3). The composition of the PS applied is typical of the fatting pig farms in the region (Table 2).

![Figure 1. Monthly precipitation (P) and mean air temperature (T) for the period 1982–2002 (historical) and for the November 1998 to July 1999 experimental period.](image)

![Table 1. Physicochemical properties of the soil.](image)

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth (cm)</th>
<th>pH</th>
<th>ECe (dS m⁻¹)</th>
<th>CaCO₃ (mg kg⁻¹)</th>
<th>OM (g kg⁻¹ dry soil)</th>
<th>Sand (g kg⁻¹)</th>
<th>Silt (g kg⁻¹)</th>
<th>Clay (g kg⁻¹)</th>
<th>Olsen P (mg kg⁻¹)</th>
<th>K (NH₄Ac) (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0–35</td>
<td>8.6</td>
<td>1.1</td>
<td>332</td>
<td>15</td>
<td>186</td>
<td>476</td>
<td>338</td>
<td>29</td>
<td>246</td>
</tr>
<tr>
<td>Bw1</td>
<td>35–85</td>
<td>8.3</td>
<td>0.6</td>
<td>322</td>
<td>10</td>
<td>196</td>
<td>526</td>
<td>278</td>
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<tr>
<td>Bw2</td>
<td>85–130</td>
<td>8.2</td>
<td>0.5</td>
<td>311</td>
<td>8</td>
<td>180</td>
<td>517</td>
<td>302</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>130–185</td>
<td>8.4</td>
<td>0.4</td>
<td>367</td>
<td>5</td>
<td>437</td>
<td>371</td>
<td>192</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ECe = electrical conductivity of the soil saturation extract.

![Table 2. Characteristics of the pig slurry (PS) applied in 1996, 1997 and 1998.](image)

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total N (kg N m⁻³)</td>
<td>5.1</td>
<td>6.0</td>
<td>8.1</td>
</tr>
<tr>
<td>Ammonium-N (kg N m⁻³)</td>
<td>3.8</td>
<td>3.7</td>
<td>6.1</td>
</tr>
<tr>
<td>Density (kg L⁻¹)</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>pH</td>
<td>7.4</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>Dry matter (kg m⁻³)</td>
<td>51.6</td>
<td>54.8</td>
<td>76.2</td>
</tr>
<tr>
<td>Organic matter (kg m⁻³)</td>
<td>12.4</td>
<td>12.5</td>
<td>14.3</td>
</tr>
<tr>
<td>Total P (kg m⁻³)</td>
<td>0.8</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>K (kg m⁻³)</td>
<td>2.7</td>
<td>3.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Mg (kg m⁻³)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Ca (kg m⁻³)</td>
<td>1.3</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>
The experimental field consisting of 24 plots and the surrounding area were sown with winter wheat (*Triticum aestivum* cv. Anza) on 11 December 1998. Essential plant nutrients, except N, were applied at adequate levels for optimal growth. The ammonium nitrate applications in the 12 fertilized subplots consisted of 27 kg N ha\(^{-1}\) at sowing, 61.5 kg N ha\(^{-1}\) at tillering (10 March 99) and 61.5 kg N ha\(^{-1}\) at ear emergence (3 May 1999). Thus, the total N applied to the winter wheat was 150 kg N ha\(^{-1}\), which is the recommended level in the region for an expected grain yield of 5000 kg ha\(^{-1}\) (Pérez-Berges 1999).

The wheat was irrigated five times, at sowing and at 15-day intervals between 13 April and 31 May 1999. The volume of water applied at each irrigation was measured with a Cipolleti flowmeter (a standard trapezoidal weir) and amounted to a total of 578 mm.

Sampling

Soil samples at 0–0.3, 0.3–0.6, 0.6–0.9 and 0.9–1.2 m depths were taken in the main plots on 30 October 1998 (before sowing) and in all plots after harvest on 14 July 1999. Samples were air-dried, ground and sieved to 2 mm. Nitrate concentrations were determined in 1:3 soil:saturated calcium sulphate solution extracts (Sempere *et al.* 1993) by ion chromatography (Dionex 2001 SP).

The dates of ear emergence, the physiological maturity and the height of the plants at maturity were determined. At harvest (1 July 1999) 0.5 m\(^2\) of each plot was hand-harvested to obtain the harvest index, length of the ears, number of ears per ha, number of grains per ear, 1000-grain weight, grain moisture content and specific weight. The grain yield in each plot was obtained by mechanical harvesting of a 22 m\(^2\) area and adjusted to 88% dry matter content. Above-ground dry matter was estimated from grain yield and harvest index. The grain N uptake was obtained by multiplying the grain yield by the percentage total N content in the grain.

Crop response to different sources of N

The crop response to soil in the absence of applied N, or apparent soil effect (ASE), was estimated from the average response of wheat in the unfertilized control plots which had not received slurry from 1996–98 (PS0 UFP).

The apparent mineral fertilizer effect (AME) in each PS\(i\) treatment (\(i = 0, 1, 2, 3\) in Table 3) was estimated from the difference in the average response of wheat in the fertilized (FP) and unfertilized (UFP) plots of each PS\(i\) treatment.

The apparent pig slurry residual effect (PSRE) was estimated from the difference in the average response of wheat in the fertilized (FP) and unfertilized (UFP) plots of each PS\(i\) treatment.

These three apparent effects were calculated using as measured response the grain yield, the above-ground dry matter (AGDM) and the grain N uptake.

Although these estimates are relevant since they allow for the separation of the soil, mineral fertilizer and pig slurry residual effects, they have some limitations. Thus, the apparent soil effect was assumed to be the same in all treatments. This is a plausible hypothesis in the unfertilized plots (UFP), where the available N was less than the crop needs, but in the fertilized plots (FP) it will represent maximum soil contributions due to the typically lower N use efficiencies (NUE) of the fertilized crops. Also, the AME and PSRE estimates will represent the lower limits of the real values – in the case of AME because the NUE should be lower in FP than in UFP, and in the case of PSRE because

| Table 3. The responses of wheat to residual effects (PSRE) of previously applied pig slurry (PS) in 1996–98 to soil (ASE) and to fertilizer N (AME) applied to the soil. |
|-------|-------|-------|
| Treatment | Measured\(^a\) | ASE\(^b\) | PSRE\(^c\) |
|          | Measured\(^a\) | AME\(^d\) | PSRE\(^e\) |
|          | ASE\(^b\)+AME\(^d\)+PSRE\(^e\) |
| Grain yield (kg ha\(^{-1}\)) |
| PS0 | 2376 (135) | 2376 – | 4445 (106) | 2069 – | – |
| PS1 | 3044 (299) | 2376 669 | 4819 (107) | 1775 374 | 4525 |
| PS2 | 3221 (104) | 2376 845 | 4899 (336) | 1678 454 | 4907 |
| PS3 | 3688 (434) | 2376 1313 | 5192 (139) | 1504 747 | 4627 |
| Above-ground dry matter (kg ha\(^{-1}\)) |
| PS0 | 5060 (258) | 5060 – | 10705 (465) | 5645 – | – |
| PS1 | 6836 (248) | 5060 1776 | 12207 (728) | 5371 1502 | 11933 |
| PS2 | 7497 (477) | 5060 2437 | 12666 (1252) | 5169 1961 | 12191 |
| PS3 | 9110 (943) | 5060 4050 | 14339 (1270) | 5228 3634 | 13922 |
| Grain N uptake (kg N ha\(^{-1}\)) |
| PS0 | 49 (5) | 49 – | 94 (4) | 45 – | – |
| PS1 | 58 (6) | 49 9 | 103 (2) | 45 10 | 102 |
| PS2 | 65 (3) | 49 16 | 110 (9) | 45 17 | 111 |
| PS3 | 76 (7) | 49 27 | 123 (9) | 47 29 | 125 |

\(^{a}\)Standard errors are given in parentheses.

\(^{b}\)Apparent soil effect (ASE) = measured in PS0 of UFP treatments (PS0\(_{UFP}\)).

\(^{c}\)Apparent pig slurry residual effect (PSRE) = measured PS\(_i\) – measured PS0; \(i = 1, 2, 3\).

\(^{d}\)Apparent mineral fertilizer effect (AME) = measured PS\(_i\) in FP – measured PS\(_i\) in UFP; \(i = 0, 1, 2, 3\).

\(^{e}\)Apparent pig slurry residual effect (PSRE) = measured PS\(_i\) in FP – measured PS\(_0\); \(i = 1, 2, 3\).
NUE should be higher in the PS0 than in the PS1 treatments. For these reasons, in the PS1 plots the values of (ASE+AME+PSRE) were different from the measured crop response (Table 3). However, the differences were small (less than 11% for grain yield, 4% for above-ground dry weight and 2% for grain N uptake), giving confidence in the ASE, AME and PSRE estimates.

**Prediction of N release from the pig slurry**

A decay-series approach was applied to estimate the equivalent mineral N (EMN) or amount of mineral N released during 1998–99 that originated from the PS applied in 1996–98. Two decay-series were used, obtained in different climatic conditions and with different approaches. Pratt et al. (1973) obtained the decay-series ‘0.75, 0.15, 0.10, 0.05’ for irrigated lands in California, where the climate is similar to our semiarid Mediterranean. This series was obtained for fresh bovine slurry, similar to PS, and indicates that 75% of the total N applied will be mineralized in the first year, 15% of the residual N from the first year (i.e. 3.8% of the total N applied) will be mineralized in the second year, and so on. Klausner et al. (1994) obtained the decay-series ‘0.21, 0.09, 0.03, 0.03, 0.02’ for manure organic N applied in a cooler region in Germany, indicating that 21%, 9%, 3%, 3%, and 2% of the organic N applied in year 1 will be available to the crop in the following years 2 to 5, respectively.

The apparent fertilizer nitrogen use efficiency (FNUE) in the PS treatments of the fertilized plots (FP) was estimated as the ratio of the mineral fertilizer (AME) recovered in grain N uptake to the mineral fertilizer applied (150 kg N ha⁻¹). Although the efficiencies would be greater for the total wheat N uptake, this approach allows comparison of the efficiencies between the different treatments.

Finally, the equivalent mineral nitrogen (EMN) (Table 4) was estimated, using the pig slurry nitrogen (PSRE) recovered in grain N uptake of the fertilized plots, assuming that the nitrogen use efficiencies for the mineral N fertilizer and for the N released from the slurry were equal. Thus, the equivalent mineral nitrogen of the PS was estimated from the FNUE values obtained in each PS treatment as:

\[ EMN = \frac{EMN_{(experiment)}}{FNUE} \]

Thus, the fertilizer N use efficiency for treatment PS1 (32 kg N ha⁻¹, Table 4) was estimated as the ratio between the PSRE for PS1 in the FP plots (10 kg N ha⁻¹, Table 3) and the fertilizer nitrogen use efficiency (FNUE) for treatment PS1 (0.30, Table 4).

**Apparent slurry nitrogen use efficiency (NUE)**

The efficiency of wheat grain in using the nitrogen applied in the PS, or apparent pig slurry nitrogen use efficiency (PSNUE, Table 4), was calculated for the PS1 to PS3 treatments of the unfertilized (UPF) and fertilized (FP) plots as the ratio of pig slurry residual effect on grain N uptake to the total amount of organic N applied in PS from 1996–98. Only the organic N was included in the calculations because most of the mineral-N forms would be exhausted through plant uptake, volatilization and leaching, and the fraction of the mineral N applied with the PS that is immobilized and re-mineralized could not be quantified.

**Soil nitrate**

At the beginning of the experiment (October 1998), no significant differences were observed in the effects of treatment or depth on nitrate content of the soil. The average nitrate concentration in the soil profile was 4.5 mg NO₃⁻N kg⁻¹, representing 57 kg NO₃⁻N ha⁻¹ in the 0–0.9 m depth (ρₙ = 1.4 g cm⁻³).

At the end of the experiment (July 1999) there were no significant differences in nitrate concentration between treatments for any of the depths except for the UPF at the 30–60 cm depth where nitrate concentration was greater in PS2 than in PS0, even though variation was high. The average nitrate concentration in the 0–0.9 m profile (Figure 2) was 3.2 mg NO₃⁻N kg⁻¹ (40 kg NO₃⁻N ha⁻¹ in the 0–0.9 m depth).

**Crop development and yield**

Emergence of wheat ears in UPF (3 May 1999) was 11 days later than in FP (22 April 1999), probably due to the deficiency of nitrogen. The physiological maturity was attained on the same date (29 June 1999) in all treatments. The plants at physiological maturity were taller in FP than in UFP (average of 0.71 m) than in UFP (average of 0.60 m), and plant height and PS rates were significantly correlated in
both FP and UFP. The ears were longer in FP (average 6.7 cm) than in UFP (average 5.5 cm).

Grain yield, above-ground dry matter and grain N uptake were greater in FP than in UFP (Table 3). The greater yield in FP was due only to the larger number of ears per m² (723 in FP vs 518 in UFP). Due to the larger number of ears per m² in FP, the harvest index in FP (0.39) was smaller than in UFP (0.43) (Sieling et al. 1998).

Wheat grown in UFP and FP responded positively to the amount of organic N applied with PS in the previous 1996–98 years, as indicated by the significant linear regressions of grain yield (Figure 3), above-ground dry matter (not shown), and grain N uptake (Figure 3) against organic N. Thus, grain yield increased by 162 kg ha⁻¹, above-ground dry matter by 502 kg ha⁻¹ and grain N uptake by 3.94 kg N ha⁻¹ for each 100 kg organic N previously applied to UFP (0.43) (Sieling et al. 1998).

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The apparent ‘wheat response versus organic-N’ linear regression in the unfertilized plots (UFP) was expected since N was a growth-limiting factor. This confirmed that the mineralization of the organic N in slurry contributed significantly to the nutrition and growth of the wheat crop. In contrast, the positive response of wheat to the applied organic N in the 150 kg N ha⁻¹ fertilized plots (FP) was not expected because it was considered that N was not a growth-limiting factor according to the results of Pérez-Berges (1999), who obtained maximum grain yields (6.10 t ha⁻¹) with 132 kg N ha⁻¹ in experiments performed on the same farm and soil, in the same year, with the same wheat variety given similar management practices.
rates (AME = 45–47 kg N ha⁻¹), indicating a luxury consumption of N by wheat at high rates of N.

**Prediction of N release from pig slurry**

The equivalent mineral nitrogen (EMN) of the PS applied between 1996 and 1998 estimated from the experimental data was higher than that estimated from the decay-series of both Pratt et al. (1976) and Klausner et al. (1994). On average, the EMN estimates of the Pratt method amounted to 74% of the experimental EMN, as compared to an average 46% for the Klausner method (Table 4).

The Klausner series was developed in a cooler environment and considers only the organic N fraction in PS. However, the release of the previously immobilized (Sorensen & Amato 2002) or fixed (Scherer & Weimar 1994) ammonium N can be important factors in the residual effect of slurry. The immobilization of NH₄⁺ contributes significantly to the soil storage of slurry N. The subsequent NH₄⁺ remobilization is small in the year following PS application and most of it remains in the soil after 2–3 years, adding to the long-term pool of soil organic N (Morvan et al. 1997). The release of this NH₄⁺ is a part of the residual N effect in the years following animal slurry applications (Paul & Beauchamp 1995; Jensen et al. 2000; Chantigny et al. 2001; Sorensen & Amato 2002). By contrast, the release of the previously fixed NH₄⁺ is considered, in general, to be small in the years following application, owing to its fast release (Scherer & Weimar 1994).

The Pratt series was developed in a warmer environment and considers the total N present in PS. The differences between estimates using this series and the experimental values obtained may be attributed to specific weather and soil conditions that affect mineralization rates and the immobilization/fixation and release of NH₄⁺-N in slurry (Follet et al. 1989).

The usefulness of decay-series in making N recommendations following applications of animal slurries could be enhanced by developing them for local soils, management and weather. The type of soil has a large influence on the cycling and turnover of nitrogen through the process of immobilization–mineralization, which is strongly affected by soil properties (Follet et al. 1989).

**Apparent slurry nitrogen use efficiency (NUE)**

The PSNUE (Table 4) ranged between 2.9% (PS1 in UFP) and 3.7% (PS3 in FP). A significant linear relationship was obtained between PSNUE and the total amount of organic N applied between 1996 and 1998, so that PSNUE increased by 0.13% for each 100 kg increase in organic N (Figure 4). The significant increase of PSNUE with the organic N applied could be interpreted as due to an additional specific effect of the PS applied in 1996–98.

The applied pig slurry in the fertilized plots improved wheat growth, inducing more N uptake irrespective of its source. Others have also observed the specific effects of manure applications on the growth of crops. Sorensen & Amato (2002) found unexpected N uptake in optimally fertilized barley cropped in the first year after PS application. Nyamangara et al. (2003) found that uptake efficiency of mineral N by crops was enhanced when manure and mineral N fertilizer were jointly applied. Lorenz & Steffens (1992) and Panse et al. (1995) observed that the combined use of mineral N and slurry N led to higher cereal yields than mineral N alone. Sieling et al. (1998) found that autumn slurry applications increased grain N uptake in wheat, even in plots receiving the largest mineral N rates. According to Sieling et al. (1998), this positive effect of slurry application could not be explained only by the additional N, but possibly the continuous mineralization of the formerly immobilized slurry may have improved the timing of N supply.

The reasons for these positive side-effects of pig slurry applications in our experiment cannot be fully substantiated or understood without further investigation. However, it is suggested that some of the positive effects could be related to increases in organic matter (the PS used in this work contained 12–14 kg OM m⁻³) and other nutrients (Table 2) or, according to Sieling et al. (1998), to the different timing of nitrogen availability which can improve water and nutrient adsorption by wheat.

**CONCLUSIONS**

The experimental data in the unfertilized plots indicates that the mineralization of the nitrogen in pig slurry contributed significantly to the nutrition and growth of the wheat crop, and therefore its residual effect should be considered in recommending optimum fertilizer application beyond the year of application. The equivalent mineral fertilizer (EMN) values obtained in the experiment were underestimated by two decay-series to the extent of ~26% (Pratt series) and ~54% (Klausner series). The decay-series approach should take account of the specific local environment. This emphasizes the need for the establishment of experiments to measure slurry residual effects in different climatic conditions, soil types, and with different crops that could help to develop and test a general model to predict the residual effects of the slurry.

The significant positive relationship between apparent nitrogen use efficiency of the pig slurry and the total amount of organic N applied was interpreted as a specific residual effect of the previously applied pig slurry.
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