Research article

Response of wheat to additional nitrogen fertilizer application after pig slurry on over-fertilized soils

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Abstract – Pig slurry is a valuable nutrient resource but constitutes a waste disposal problem in areas of high animal density. In the semiarid area of Pla d’Urgell, in the Ebro Valley, North-East Spain, irrigated crops receive large amounts of nutrients in the form of manure and mineral fertilizers. We studied the effect of pig slurry and additional side-dress mineral fertilizers on irrigated wheat, *Triticum aestivum* L., on a coarse loam soil, with high soil P and K levels. Yields increased by 62.3% when using pig slurry. The application of ammonium sulfate nitrate sidedress did not significantly increase wheat production. The average apparent recoveries were higher for potassium (88.7%) than for nitrogen (51.3%) and phosphorus (36.3%). Greater amounts of soil NO3-N were measured over the four growing seasons, which was consistent with the amount of N applied. Macronutrient and micronutrient uptake was significant higher for pig slurry treatments, but only small differences were found between the pig slurry and pig slurry plus ammonium sulfate nitrate treatments. The unfertilized treatment showed significantly lower soil P, K, Cu and Zn content than pig slurry treatments; 34%, 21%, 34%, and 26% respectively. These findings could be used to develop a nutrient management plan based on knowledge of soil test results and crop nutrient removal. This could help to improve the use of pig slurry and mineral fertilizers on limited available land areas and prevent the accumulation of potentially toxic elements in soils and the export of nutrients through agricultural drainage.

over-fertilized soils / irrigated wheat / nutrient uptake / nutrient recovery / pig slurry

1. INTRODUCTION

Intensive swine production is the most important livestock activity in Catalonia (Spain). There are around 6 million heads of pig and 7 900 pig farms in Catalonia, which produce more than 8 000 000 m³ of pig slurry per year. About 265 000 ha of agricultural land are irrigated in Catalonia, with the majority of this being surface irrigation. A significant percentage of this land receives pig slurry, which has a clear effect on non-point source water pollution and water quality. Large quantities of pig slurry are applied in the irrigated area of the Pla d’Urgell and subsequently drain off into the Segre River (Ebro Valley, North-East Spain). The area suffers problems due to over-fertilization and many soils do not respond to N applied as was reported by Villar-Mir et al. (2002). Wheat and corn are the primary crops in the area that receives these slurries. As in other areas (Fleming et al., 1998) pig slurry applications are largely subject to the proximity of available land, due to transport costs. Due to the limited land availability, applications are often not based on crop nutrient requirements. Pig slurry contains high concentrations of N and P and due to the feed additives involved, it may also contain relatively high concentrations of copper (Cu), manganese (Mn), and zinc (Zn) (Hsu and Lo, 2000). As a consequence, over-application of N, P, Zn, and Cu results in their accumulation in soil. Even so, some farmers apply pig slurry based on the N needs of crops such as corn and wheat.

Wheat production in irrigated areas of the Ebro Valley involves the addition of N fertilizers and/or manures. In the case of wheat, pig slurry N and P applications are in general higher than N and P uptake while K applications are lower than K uptake. The tendency is therefore, for the N and P content of the soil to increase while the K soil content decreases. Changes over time in average soil test P and soil test K will reflect the P and K balance. Long-term pig slurry applications, without any strategy or plan, will have a negative effect upon environmental quality and crop production. A soil testing survey carried out in the area (Pla d’Urgell, Lleida, Spain) reported that 68% of 72 soils resulted in soil test P (Olsen Method) (0–30 cm) > 25 mg P kg⁻¹, with an average of 53 mg P kg⁻¹; interpreted as a very high or even excessive concentration. At a sampling depth of 30–60 cm, average soil test P was 37 mg P kg⁻¹; interpreted as very high. This enrichment at a depth of 30–60 cm suggested P movement in calcareous soils in an area with already elevated pH values. Spain has not assigned an environmental soil test P threshold to improve pig slurry management and little field research has so far been done in this area. For example, in Colorado State the threshold soil test P (Olsen method) level has been established at 100 mg P kg⁻¹. Sharpley

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and Tunney (2000) reported soil test P values and P management recommendations for several USA states. Idaho State, for example, established an agronomic soil test P (Olsen method) threshold of 12 mg P kg\(^{-1}\) and an environmental soil test P value of 50 mg P kg\(^{-1}\) for sandy soils and 100 mg P kg\(^{-1}\) for silt loam soils. In Ireland it is not permitted to apply pig manure when the soil test P (Olsen method) is above 60 mg P kg\(^{-1}\).

Pig slurry is treated as a waste disposal problem, although it is also a valuable nutrient resource in our area. In addition to pig slurry, local farmers also use excessive quantities of mineral fertilizers (Villar-Mir et al., 2002). There is no nutrient management program in the area of the type defined by VanDyke et al. (1999) that specifically focuses on pig slurry and other types of manure. Maximum total quantities of N recommended for wheat in the area are 250 kg N ha\(^{-1}\). Maximum quantities of N from organic fertilizers must be less than 210 kg N ha\(^{-1}\) per year.

Nutrient management planning is an accepted strategy for optimizing economic returns from nutrients while minimizing their negative impact on the environment, especially from diffuse sources (Beegle et al., 2000). At present there is insufficient information on nutrient uptake to develop a viable strategy. Nitrogen fertilizer needs to be adjusted for already N applied as animal manure. To establish such a nutrient management plan, several field research experiments need to be conducted and action must be taken to persuade farmers that it is possible to manage the application of nutrients on a yearly basis in order to achieve the expected yield goals and to minimize adverse environmental side-effects. Hansen et al. (2004) showed the importance of nitrate soils testing for ability to predict corn yield responses to fertilizer N applied after animal manure. The effects of excess quantities of N and P and heavy metals in agricultural systems have been well documented (Fern, 1998; Rochette et al., 2000; Krebs et al., 1998). Nutrient (pig slurry and commercial fertilizers) applications should be managed to maintain the goal of attaining high yields and improving environmental quality while reducing nutrient losses from soils. The main objective of the paper was to determine whether additional mineral N fertilizer is necessary when using pig slurry on over-fertilized soils. We evaluated the effects of applying pig slurry and additional mineral nitrogen fertilizer to irrigated wheat on calcareous soils with particular reference to yield, recovery and residual nutrients. A second objective was to contribute to the development of a nutrient management plan for the area.

### 2. MATERIALS AND METHODS

This study was conducted from 1999 through 2003 at a commercial farm (41° 39' N, 00° 57' E; elev. 264 m), in an area with a mean annual rainfall of 377 mm. The farm was located in the irrigated area served by Urgell Channel. The main criteria for selecting this commercial farm as an experimental site were that it had received no organic manure applications in the previous three years (to avoid any possible residual effects) and had not grown alfalfa either (to avoid potential N credits). Other criteria were that the farm did not reuse irrigation water (which contained salts and nitrates) and did not use water mixed with well water (which was high in nitrates in this area). The soil type was a Seana loam series (loamy, calcareous, mixed, mesic, shallow Xerolic Paleorthid) (USDA-NRCS, 1998; Herrero et al., 1993), Calciisol petric (FAO, 1998) with a petrocalcic horizon within 60 cm of the surface (effective soil depth). There were no salinity problems. The soil texture was loam (USDA) (clay 240 g kg\(^{-1}\) and sand 418 g kg\(^{-1}\)). The main hydraulic characteristics were low water holding capacity (80 mm), high infiltration and rapid drainage. Soil water characteristics for texture were defined using the functions developed by Saxton et al. (1986). This soil was representative of coarse medium textured soils in the Ebro Valley with moderate potential yields. Wheat was continuously produced over a period of four years for the experiment.

The experimental design was a randomized complete block with three replications. Individual plots were 10 m wide and 30 m long. The rates of fertilizer application varied from year to year. Treatments were: (1) unfertilized control, (2) pig slurry (32, 21, 15, 20 m\(^3\) ha\(^{-1}\), for 1999–2000, 2000–2001, 2001–2002, and 2002–2003, respectively), and (3) pig slurry plus ammonium sulfate-nitrate (26%N, 15%S) (50 kg N ha\(^{-1}\) in the first year, and 75 kg N ha\(^{-1}\) in the second, third and fourth years). The pig slurry contained 12.8%, 7.2%, 2.6%, and 6.9% of dry matter respectively. Pig slurry was broadcast over the soil surface before planting using a spreading machine (Nov. 10th, Nov. 22nd, Nov. 23rd and Oct. 24th, in the respective years) and immediately incorporated (15–20 cm) using a field cultivator. Uniform broadcast applications of ammonium sulfate nitrate as a side-dress fertilizer was carried out by hand (Feb. 2nd, Feb. 21st, Feb. 18th, and Mar. 3rd). The respective quantities of nutrients applied (pig slurry and pig slurry plus side-dress ASN) are shown in Table I. Total N in pig slurry was the Kjeldahl N. NH\(_4\)-N content represented as 65%, 70.6%, 67.8%, and 70% of total N.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>1999–2000 kg ha(^{-1})</th>
<th>2000–2001 kg ha(^{-1})</th>
<th>2001–2002 kg ha(^{-1})</th>
<th>2002–2003 kg ha(^{-1})</th>
<th>Cumulative NPK applied kg ha(^{-1})</th>
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<tr>
<td></td>
<td>N</td>
<td>P</td>
<td>K</td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Pig slurry</td>
<td>298</td>
<td>63</td>
<td>153</td>
<td>194</td>
<td>32</td>
</tr>
<tr>
<td>Pig slurry + ASN</td>
<td>348</td>
<td>63</td>
<td>153</td>
<td>269</td>
<td>32</td>
</tr>
</tbody>
</table>

Soils on which plots were established were sampled (10 cores) to determine initial soil fertility (0–30 cm) prior to planting; in autumn 1999 (Nov. 10th). The Soil Testing Laboratory (LAF) at Sidamon (Lleida, Spain) performed all soil and plant analyses. Soil samples were collected from all plots twenty times in total during the four-yr period. All samples were extracted with water (1:5 soil/water ratio per solution) and colorimetrically analyzed for NO\(_3\)-N using a Technicon
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Table II. Wheat grain yield response to three fertilizer treatments.

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<td></td>
<td>Grain yield Mg ha⁻¹</td>
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<td>Grain yield Mg ha⁻¹</td>
<td>Grain yield Mg ha⁻¹</td>
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<tr>
<td>Unfertilized control</td>
<td>4.88 (0.39)b</td>
<td>3.91 (0.67)b</td>
<td>3.37 (0.31)b</td>
<td>2.15 (0.39)b</td>
<td>3.58b</td>
</tr>
<tr>
<td>Pig slurry</td>
<td>7.63 (0.52)a</td>
<td>7.70 (0.26)a</td>
<td>4.89 (0.55)a</td>
<td>3.02 (0.40)ab</td>
<td>5.81a</td>
</tr>
<tr>
<td>Pig slurry + ASN</td>
<td>8.28 (0.68)a</td>
<td>7.61 (0.11)a</td>
<td>5.82 (0.24)a</td>
<td>3.37 (0.09)a</td>
<td>6.27a</td>
</tr>
</tbody>
</table>

Within columns, means followed by the same letter do not significantly differ from each other at a 0.05 probability Duncan’s multiple range test. Values in parenthesis are standard deviations of replicate analyses (n = 3).

Autoanalyzer (Anasol 4P2S1BM2P, ICA Instruments, Tonbridge, Kent, UK). Organic matter was determined by the Walkley-Black procedure. Soil pH was measured at a soil/water ratio of 1:2.5. Soil P was extracted with NaHCO₃ according to Olsen et al. (1954). Soil K was extracted with 1 M ammonium acetate (NH₄C₂H₃O₂). Soil bulk density was measured as 1.4 Mg m⁻³. The soil gravel contents > 2 mm in volume were 39.8%, 33.5%, and 37.5% at depths of 0–20, 20–40, and 40–60 cm respectively. The NO₃-N concentration data (mg kg⁻¹) were multiplied by bulk densities of 0.84, 0.93, and 0.87 Mg m⁻³ for 0–20, 20–40, and 40–60 cm respectively, in order to calculate the quantity of NO₃-N (in kg ha⁻¹) present within the profile. NH₃ volatilization was measured (data not shown), but the values obtained were very low because pig slurry was immediately buried.

Winter wheat (cv. Anza for the first and second years and cv. Bancal for the third and fourth years) was planted on Nov. 24th, Dec. 14th, Nov. 30th, and Nov. 16th, in the four successive campaigns. Harvest occurred on June 23rd, June 26th, July 3rd, and June 26th, in successive campaigns. Anza and Bancal have similar yield responses in irrigated fields in the area. Anza is used as a check variety in official wheat field trials (IRTA-UdL, http://www.irta.es/cat/que/xarxes/varietats/xarxa.html). All plots were irrigated to field capacity by flooding three times per season. Irrigation doses were between 700 and 800 m³ ha⁻¹. The plots were mechanically harvested. Grain weights were adjusted for moisture of 120 g kg⁻¹. All plant samples were dried at 65 °C for 2 d in a forced-air dryer and then weighed. Harvested plant samples were separated into leaves, stems and grain for subsequent nutrient total analysis. Nitrogen concentration was determined by kjeldhal digestion. P, K, Ca, Mg, S, Mn, Cu, Zn and Na were analyzed by ICP. Dry matter accumulation and harvest index, were determined but data are not shown. Some of this information will be used for modeling purposes. Annual nutrient removal was calculated by multiplying dry mass by nutrient concentration. Apparent nutrient recovery was calculated on the basis of the following relationship:

\[
\text{Nutrient Recovery} = \frac{(\text{Nutrient Uptake from treated plot}) - (\text{Nutrient Uptake from unfertilized control plot}) \times 100}{\text{Nutrient Applied}}
\]

Some authors also refer to this index as apparent nutrient use efficiency (Eghball and Power, 1999). This index was evaluated for nitrogen, phosphorus and potassium. During the survey, weather conditions were recorded by an automated station (Campbell Sci., Logan, UT) located at El Poal (41° 40’ N, 00° 51’ E; elev. 227 m) (Weather stations network, DARP, Generalitat of Catalunya) and within 5 km of the experimental site. Analysis of variance was performed using the Statistical Analysis System (SAS Institute, 1999). Means were separated using Duncan’s multiple range test.

3. RESULTS AND DISCUSSION

3.1. Soil fertility and meteorological conditions

Rainfall from November through to June 15th (wheat growing season) was respectively 245, 235, 302 and 270 mm for the four years of the study. Accumulated reference evapotranspiration (ETo) from March to June 15th was 332, 373, 321 and 376 mm, respectively for the 1st, 2nd, 3rd, and 4th growing seasons. The irrigation schedule in this area is not flexible, and so fortnightly turns are generally established. Rainfall and available water capacity are also important variables in irrigated areas where traditional methods are applied. In autumn 1999, the upper 30 cm of the soil profile contained 26 g of organic matter kg⁻¹, which is a relatively high value for irrigated semiarid land: there was also 17 mg of NO₃-N kg⁻¹, which constitutes a high nitrate content. The soil pH was 8.2 and the CO₃Ca equivalent was 240 g kg⁻¹. The soil test P value was very high (44 mg P kg⁻¹), while the soil test K value was interpreted as normal-high (253 mg K kg⁻¹) according to Cottenie (1980). The nutrient application rate criterion for P drawdown and K maintenance can be established for soil fertility levels above sufficiency criteria, especially for P.

3.2. Wheat grain yield

In all four years, pig slurry significantly increased wheat grain yields with respect to the unfertilized control (Tab. II). Continuous wheat cropping resulted in lower yields for all treatments. The unfertilized treatment resulted in a 56% decline in yield over the years in question. Average wheat grain yield for the unfertilized control was 3 580 kg ha⁻¹. The pig slurry treatment resulted in similar wheat grain yields (5 810 kg ha⁻¹) to those obtained with the pig slurry plus side-dress ASN (6 270 kg ha⁻¹). The side-dress fertilizer effect was apparent but not significant in the third year when low N content pig slurry was used. The lowest yields were obtained during the fourth growing season. In this season, lower yields were observed across the whole area due to the meteorological conditions during the grain filling period (the highest ETo and lowest
precipitation were registered during the second half of May). In the fourth year irrigation was applied on March 20th, April 22nd, and May 6th (12 days earlier than in other years) and the lowest rainfall was registered in March, April, and June. Seasonal precipitation makes a significant contribution to water requirements in semiarid irrigated areas, while water deficits after anthesis limit yields. Air dryness was most pronounced in the last growing period and resulted in grain filling problems. High temperatures, large vapor pressure deficits and high values for solar radiation resulted in the highest ETo values being recorded in the fourth growing season. Our results indicated that pig slurry applications prior to planting provided a similar quantity of the nutrients required by the wheat crop to that provided by the treatment with additional side-dress N. Similarly, after research with corn, Van de Woestyne and Blackmer (2002) concluded that it is not profitable to apply nitrogen fertilizer when liquid swine manure was injected into soil. Declining yields are expected when wheat is continuously grown on the same soil due to pathological problems. Even so, no such problems were clearly apparent in the fields in the study area. Declining soil nitrate levels in subsequent years can produce a positive response to side-dress application, but no such tendency was observed in the course of our four-yr experiment. Only the mineral nitrogen soil test can help in taking appropriate decisions. The dose of pig slurry to be used should be calculated before application and should take into account the results of N soil tests as suggested by Diez et al. (2001).

3.3. Soil NO3-N and NH4-N levels

Pig slurry treatments resulted in higher soil NO3-N at the end of the growing season, but values were always below 20 mg kg−1 (0–20 cm). Measurements of soil NO3-N showed significant differences at a depth of 0–20 cm (Fig. 1). A similar pattern resulted from the natural N soil cycle and initially high soil organic matter content (2.6%). Mineral soil N (NO3-N and NH4-N) came from soil organic matter mineralization and from crop stubble and root decomposition. Maximum N uptake in spring resulted in the sharply declining slopes in Figure 1. During the period between harvest and the beginning of the next crop season, N rose, as shown in Figure 1. The critical preplant nitrate test (PPNT) and pre-sidedress nitrate test (PSNT) established for irrigated wheat in our semiarid environment are 30 and 20 mg N kg−1, respectively, for the 0–30 cm soil sampling depth. NH4-N contribution to total mineral N was significantly lower than that of NO3-N. The unfertilized treatments resulted in nitrate tests values below the critical limits in all four growing seasons for depths of 0–20 and 0–60 cm. NO3-N kg−1 (preplant nitrate test) values for the pig slurry treatment ranged between 20.7 and 51.9 mg for the 0–20 cm soil sampling depth. Values for the pig slurry plus ASN treatment ranged between 27.7 and 47.5 mg NO3-N kg−1 (preplant nitrate test) for the 0–20 cm soil sampling depth. The significant differences in soil NO3-N between harvest and pig slurry application is one of the most important issues and is difficult to explain without applying the isotope N technique. Soil organic matter mineralization, NH4 soil fixation, soil microbial immobilization, soil watering, and crop and organic residue mineralization are some of the main processes taking place in these soils. All of this nitrate plus the N applied in autumn can be leached down to a fluctuating water table before significant crop N uptake takes place. The lowest values corresponded to the third growing season in which the pig slurry used had very low dry matter content and a low N content. Soil nitrate levels before side-dress were always higher than critical pre-sidedress nitrate test values. The amount of residual NO3-N in the soil profile (0–60 cm) at the end of the 4 year study was directly related to the quantity of N applied. The unfertilized treatment had a lower N content than the pig slurry treatments. The treatment consisting of pig slurry plus ASN produced a significantly higher quantity of NO3-N than the pig slurry treatment alone.

3.4. Nutrient above ground biomass and recovery

Total NPK above ground biomass was significantly lower for the unfertilized treatment in all of the growing seasons (Tab. III). No significant differences were found between the pig slurry treatment and pig slurry plus ASN treatment, other than differences in N in the first year. Commercial fertilizer increased the quantity of N applied by 41.3%. Accumulated total N above ground biomass for the pig slurry treatment was 653 kg N ha−1, while that for pig slurry plus ASN was 743 kg N ha−1. This represented an increase of 14.4%. These results clearly show the low crop N removal in response to the extra amount of N provided: 1 kg of N was removed out of each 3 kg N applied. This constitutes an inefficient use of mineral N fertilizer. Total P above ground biomass on wheat included uptake from residual soil P and applied P. The total quantity of P removed from wheat grain and straw over the 4 year period for the unfertilized treatment was 75 kg P ha−1. The total amount of P removed during the 4 year study was 120 kg P ha−1 for the pig slurry treatments, with and without mineral fertilizer, and similar to the quantity of P applied (122 kg P ha−1). The total amount of K removed from wheat grain and straw during the 4 year period was 297.7 kg K ha−1 for the unfertilized treatment. The total quantity of K removed from wheat grain and straw during the 4 year study was 639 kg K ha−1 for the pig slurry treatment, which was greater than the total quantity of K applied (385 kg K ha−1). The total quantity of K removed was 719 kg K ha−1 for the pig slurry plus ASN treatment.
Table III. Total N, P and K above ground biomass.

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<tr>
<td></td>
<td>N P K</td>
<td>N P K</td>
<td>N P K</td>
<td>N P K</td>
<td>kg ha⁻¹</td>
</tr>
<tr>
<td>Control</td>
<td>85.4 (3.8)c</td>
<td>22.8 (1.5)b</td>
<td>95.6 (10.6)b</td>
<td>68.2 (9.6)b</td>
<td>17.8 (7.1)b</td>
</tr>
<tr>
<td>Pig slurry</td>
<td>172.8 (14.7)b</td>
<td>37.6 (2.8)a</td>
<td>215.1 (22.3)a</td>
<td>201.5 (26.2)a</td>
<td>32.4 (9.5)a</td>
</tr>
<tr>
<td>Pig slurry + ASN</td>
<td>207.0 (5.8)a</td>
<td>39.9 (1.5)a</td>
<td>250.7 (16.8)a</td>
<td>211.0 (10.9)a</td>
<td>29.7 (7.1)a</td>
</tr>
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Within columns, means followed by the same letter do not significantly differ from each other at 0.05 probability applying Duncan’s multiple range test. Values in parenthesis are standard deviations for three replicate plots.

Table IV. Apparent recovery of total N, P, and K.

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<tr>
<td></td>
<td>N P K</td>
<td>N P K</td>
<td>N P K</td>
<td>N P K</td>
<td>%</td>
</tr>
<tr>
<td>Pig slurry</td>
<td>29.3 23.4 78.1</td>
<td>68.7 42.8</td>
<td>101.0 157.5</td>
<td>64.3 48.1</td>
<td>48.6 124.7</td>
</tr>
<tr>
<td>Pig slurry + ASN</td>
<td>34.9 27.1 101.4</td>
<td>53.1 34.3</td>
<td>117.4 71.8</td>
<td>74.6 42.1</td>
<td>54.1 160.5</td>
</tr>
</tbody>
</table>

Recovery varied widely over the growing seasons mainly due to the different quantities of slurry applied each year (Tab. IV). The greater nutrient quantities applied in the first year resulted in lower recovery. Under the conditions of the experiment, N recovery was greater in the second and third years than in the first. This was due to the smaller quantities of N applied, and the availability of nutrients from the application of pig slurry in the previous year. Average apparent N recoveries for the four year period were 51.3% and 45.9% for pig slurry and pig slurry plus ASN, respectively. Average apparent P recoveries for the same period were 36.3% and 36.8% for pig slurry and pig slurry plus ASN, respectively. Greater P recovery was registered in the third year (over 100%) due to the very small quantity of P applied with the slurry and probably also to the residual effect of the previous year’s application. Average apparent four year K recovery was 88.7% and 109%, for pig slurry and pig slurry plus ASN, respectively.

The aboveground removal ratio for N:P:K was 5:1:5. The ratio for N:P in the pig slurry (cumulative applied values) used in the experiment was 5.5:1.3. There was therefore no over-application of P and K during the experiment. In our area, the normal ratio for N:P in pig slurry is 4:1:2.9. If farmers applied pig slurry based on N levels and used the same aboveground removal that we obtained, this would result in a slight over-application of P and a shortage of K, but not to the degree registered in our experiment.

3.5. Residual nutrients in the soil

The addition of nutrients that were not recovered by the wheat crop resulted in their evident accumulation in the soil. Residual levels of phosphorus, potassium, copper and zinc found in the surface layer (depth of 0–20 cm) at the end of the experiment are presented in Table V. The unfertilized treatment depleted soil test K by 27.2%, with a reduction from 253 to 184 mg K kg⁻¹ (69 mg K kg⁻¹). 1 mg kg⁻¹ soil test K is equivalent to 2.8 kg K ha⁻¹. Over the four year period, the total accumulated K uptake was 298 kg K ha⁻¹ for the unfertilized treatment. Soil K depletion (69 × 2.8 = 193 kg K ha⁻¹) was smaller than K removal, which indicated that we need to consider other sources of K (crop residues, soil mineral weathering, and fixed K). The unfertilized treatment depleted soil test P by 37%, from 44 to 27.7 mg P kg⁻¹ (16.3 mg P kg⁻¹). 1 mg kg⁻¹ soil test P is equivalent to 2.8 kg P ha⁻¹. Soil P depletion (16.3 × 2.8 = 45.6 kg P ha⁻¹) was smaller than P removal (75.4 kg P ha⁻¹). Other sources of P included soil organic matter mineralization, crop residues and sorption-desorption P balance over the four growing seasons. P and K soil content at the
end of the experiment in the unfertilized treatment had diminished by 34% and 21%, respectively, compared with pig slurry and pig slurry + ASN treatments (average values). The fast drawdown of P and K in the unfertilized treatment reflected the negative nutrient balance. Total applied P was 122 kg P ha⁻¹, which was similar to crop P removal after the 4-year experiment, and resulted in a similar soil test P at the end of the experiment. Total accumulated K uptake for the pig slurry and pig slurry plus ASN treatments was 639.3 and 719.4 kg K ha⁻¹ respectively. That difference of 80 kg K ha⁻¹ in K uptake corresponded to a soil test K difference of 20.7 mg K kg⁻¹. Cu and Zn soil content increased by 33.3% and 26.5% respectively for the pig slurry and pig slurry plus ASN treatments when compared with the unfertilized control. No significant differences were found between the pig slurry and pig slurry plus side-dress ASN application. Some soils in the area receive higher annual quantities of pig slurry than those referred to in this research (20–40 m³ ha⁻¹). Farmers need to consider soil testing as a means of controlling and assessing the risks associated with continuous pig slurry applications. Long-term applications of pig slurry would produce significant increases in Cu and Zn soil content. Pig slurry applied without commercial PK fertilizers would maintain appropriate P and K soil levels. Using similar management criteria to those used in this experiment, it would take several years for soil test P to reach the sufficiency level (around 20 mg P kg⁻¹). The application of greater doses of pig slurry (and larger dry matter contents) would increase soil test P. Soils with high soil test P as a result of long-term over fertilization and/or excessive use of organic wastes constitutes just one of the situations in which a significant export of P is associated with agricultural drainage (Sims et al., 1998). The Cu and Zn soil content thresholds for soils with pH > 7.0 are 210 and 450 mg kg⁻¹ respectively. It would take several years to reach these levels applying these quantities of pig slurry.

4. CONCLUSION

The quantities of pig slurry used in this experiment should be considered low or moderately low in comparison with the quantities used by farmers in this intensive livestock production area and the limited land available. This research shows that the benefits of side-dress mineral fertilizer application are not apparent when pig slurry is applied before planting. Furthermore, the use of mineral fertilizer when they are not required only increases costs. Better management of pig slurry on this semiarid irrigated land could help to avoid over-fertilization. To improve nutrient management, thereby maintaining yields and reducing nutrient impact, it is necessary to adopt measures that takes into consideration all sources of nutrients and nutrient removal by crops in the area. An important question when using pig slurry is to measure the nutrient content (especially total N, P and K) and dry matter content. Soil testing is needed to control P accumulation and K depletion and also the accumulation of heavy metals associated with the use of pig slurry. Soil nitrate tests should be used on semiarid irrigated lands to adjust the supplemental need for N in the pre-sidedress period. In the case of the pig slurry treatments, equivalent quantities of P applied and removed after 4 growing seasons resulted in similar soil tests P at the end of the experiment as at the beginning. In all treatments, the quantity of K removed was greater than that applied. Thus, P and K levels were not excessive for our application rates. An important depletion of P and K resulted from the unfertilized treatment. A significant soil accumulation of Cu and Zn was measured in the pig slurry treatment both with and without side-dress N fertilizer. When soil nitrate levels are very low at planting or at pre-side-dress it is possible to obtain an economical positive response to side-dress N application. Using a crop system model can help to provide an appropriate answer. Quantities of between 20 and 30 m³ ha⁻¹ of pig slurry tend to be equilibrated with respect to P balance. Thus, when soils cannot supply sufficient N and K to equilibrate their N and K balances without causing further increases in soil test P, it is necessary to replace organic manure top dressings with mineral fertilizers. This is particularly true for over-fertilized soils.

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