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Long-term effects of pig slurry combined with mineral nitrogen on maize in a Mediterranean irrigated environment

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ABSTRACT

Intensive pig farming generates large amounts of manure which is applied to agricultural fields as slurry. It is therefore important to know the nitrogen (N) fertilizer values and long-term environmental effects of different pig slurry application rates. We investigated the performance of sprinkler-irrigated maize crops in a Mediterranean environment with different fertilizer treatments as part of a 12-year experiment (2002–2007, 2010–2015). We compared pig slurry applied using the surface splash plate method at rates of 0, 30 and 50 m^3 ha^{-1} yr^{-1} combined with mineral N fertilizer application rates of 0, 100 and 200 kg N ha^{-1} yr^{-1} as a side-dressing. The fertilizer treatments affected maize grain and biomass yields, N uptake, chlorophyll levels, soil N levels, N use efficiency (NUE) and basal stalk nitrate levels. Satisfactory average grain yields (~13.5 Mg ha^{-1}) were achieved at application rates of ~200–300 kg N ha^{-1} with average residual soil N levels below 180 kg N ha^{-1} (0–90 cm depth) and a NUE greater than 50%. However, the maximum average grain yields (~14.5 Mg ha^{-1}) required treatments providing more than 400 kg N ha^{-1} yr^{-1} but resulted in residual soil N levels greater than 300 kg N ha^{-1} and the NUE fell below 50%. The 12-year average relative N fertilizer value of pig slurry applied at 30 and 50 m^3 ha^{-1} yr^{-1} was 51% of the mineral N value applied at side-dress, suggesting that more efficient application methods for pig slurry are required. The end of season basal stalk nitrate test was useful for the quantification of excess nitrogen, and 2.5 g NO_3^- kg^{-1} was considered the maximum optimal concentration for our cropping conditions and grain yields.

1. Introduction

Intensive pig farming is an economically important industry in several European countries. Spain is the leading European producer with 29 million head in 2016 (Eurostat, 2017), 49% of which were farmed in the Ebro River Valley (MAPAMA, 2016a). This provides social and economic benefits in rural areas, but the disposal of manure is a problem. In 90% of the intensive production facilities in Spain, the liquid manure is applied to agricultural land using the rapid and inexpensive splash plate method (Sisquella et al., 2004). The benefits of agricultural application include the fertilizer value of pig slurry, the provision of organic matter and the improvement of soil quality (Brechin and McDonald, 1994; Zebarth et al., 1999; Biau et al., 2012). However, there are also negative environmental consequences if management is not adequate. Such as nitrate leaching to groundwater and the release of ammonia and greenhouse gases into the atmosphere (Nicholson et al., 1999).

Nitrate is one of the most common chemical contaminants found in water. Many areas in Europe have been designated as vulnerable to nitrate leaching, and 22% of springs in the USA have nitrate levels exceeding federal limits (USEPA, 1990; World Resources Institute, 1998). Most of these polluted zones are irrigated areas that are used to grow crops such as maize with a high nitrogen (N) demand, but others are areas used for livestock production (Strebel et al., 1989). In Spain, 36% of all cultivated land (~6.4 million ha) is considered vulnerable to nitrate leaching (Fernandez, 2007). In these areas, the European Nitrates Directive 91/676 and corresponding local regulations establish maximum amounts of N from organic materials and/or mineral fertilizer that can be applied to agricultural land annually depending on the crop. In Mediterranean areas, the N limits for manures and slurries are often determined using information which is inappropriate for these conditions (Yagüe and Quílez, 2010a).

The fate and dynamic behaviour of N applied with pig slurry is complex. Pig slurry contains ~70% inorganic N (in the form of NH_4^+) which rapidly transforms into nitrate and is predominantly available to the crop during the year of application (Chantigny et al., 2004). This source of N is susceptible to volatilization, but the amount lost is influenced by the application method which determines how the slurry-N

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is incorporated into the soil (Huijsmans and De Mol, 1999; Schils and Kok, 2003; Scröder, 2005). Splash plate application results in the loss of 20% of the NH_4^+ in the first 3–4 h after application before the remainder is incorporated into the soil (Yagüe and Bosch-Serra, 2013). Pig slurry also contains organic N, although a lower proportion than other manures (Schröder, 2005). This must be mineralized before it is available to crops (Bernal and Roig, 1993; Sørensen and Amato, 2002). Some of the organic N is immobilized by microbes, and NH_4^+ may be fixed by minerals in clay soils (Chantigny et al., 2004). This generates a residual effect that can last for several years after application.

Long-term pig slurry applications have a cumulative effect on the availability of N and other nutrients (Yagüe and Quílez, 2010b; Cela et al., 2011). The nitrogen fertilizer value (NFV) and residual effect have been tested in the laboratory, and medium-term field studies have also been reported in some areas of Europe (Giola et al., 2012; Sieling et al., 2014). Maize is important in this regard because it is the second most widely cultivated crop in the EU (Eurostat, 2016) and the principal crop in the irrigated areas of the Ebro River Valley (MAPAMA, 2016b), and because N uptake is higher in maize than in other common crops (Chen et al., 2014). Maize monoculture is often fertilized with pig slurry complemented with a side-dressing of inorganic N fertilizer (Sisquella et al., 2004; Schröder et al., 2005). The slurry can partially or completely replace inorganic N fertilizer but repeated or large applications run the risk of nitrate pollution (Berenguer et al., 2008; Yagüe and Quílez, 2010a). The NFV of pig slurry has been determined in the absence of mineral N fertilizer to evaluate the residual effects of repeated applications (Yagüe and Quílez, 2013) but the NFV of pig slurry in the year of application has not been reported. Excess N accumulates in the lower portion of maize stalks and this effect can be used as a guide for N management strategies in subsequent years. The end-of-season basal stalk nitrate (BSN) test measures nitrate concentrations in the lower portion of the stalks at physiological maturity, and can highlight when "luxury consumption" of N has occurred (Binford et al., 1992b; Fox et al., 2001).

Nitrogen use efficiency (NUE) is a very useful indicator in agriculture, and it is one of the most common and effective indicators of increasing crop productivity and profitability with limited environmental degradation as reported by the EU Nitrogen Expert Panel (EUNEP, 2015). There are many definitions of the NUE (Moll et al., 1982; Ladha et al., 2005). The EUNEUP has recently proposed and approved a definition that is the ratio of the N output (removed by harvesting) to the N input to the system (EUNEUP, 2015). NUE has influenced many of the Sustainable Development Goals for the post-2015 era, recently accepted by 193 countries of the United Nations General Assembly (SDSN, 2015). The NUE of pig slurry is difficult to determine due to variations in slurry composition, time of application, application method, application rate, soil quality, climatic conditions, and N mineralization rates (Schröder et al., 2005; Lalor et al., 2011). Some studies have assessed the short and medium term effects, as NUE, crop yield and soil N, of PS on irrigated maize (Daudén and Quílez, 2004; Berenguer et al., 2008; Yagüe and Quílez, 2010a), but effects spanning more than 4 years have not been reported.

Here we compared the effects of three pig slurry application rates before sowing (0, 30 and 50 $m^3 ha^{-1}$) combined with three rates of mineral N side-dressing (0, 100 and 200 kg N ha^{-1}). These application rates approximate the maximum N rate allowed by the European Directive 91/676 for organic N sources (170 kg N ha^{-1}) and about twice this rate. We hypothesized that satisfactory but not maximum grain yields could be achieved at these rates and therefore sought to determine the environmental effects of higher rates. The studies should address the medium-term and long-term effects of fertilization, being only in the available bibliography studies of PS applications of 4-year length in irrigated environments (Berenguer et al., 2008; Yagüe and Quílez, 2010a). With the purpose of providing information about the long-term effects of pig slurry application we carried out a 12-year experiment, to determine the NFV of PS compared to mineral N fertilizer. Also to assess the long-term effects of different fertilization rates on maize grain and biomass yields, soil N concentrations at the beginning and end of the growing season, plant and grain N uptake, NUE, chlorophyll levels and BSN levels.

Table 1
Major soil properties at the beginning of the experiment (2002).

		Horizon depth (cm)	
	Ap 0–23	Bw 23–69	Bk 69–117
Sand, g kg^{-1}	390	380	450
Silt, g kg^{-1}	400	420	380
Clay, g kg^{-1}	210	200	170
pH*	8.3	8.3	83
Ec, dS m^{-1}	0.2	0.34	0.59
CEC, $cmol_c$ kg^{-1}	24	–	–
Organic carbon, g kg^{-1}**	13	8	4
Bulk density, g cm^{-3}	1.40	1.56	1.63
Available water holding capacity, mm	29	67	54
P, mg kg^{-1}***	31	–	–
K, mg kg^{-1}****	217	–	–

*Water (1:2.5).
**Walkey-Black method.
***Olsen method.
****Ammonium acetate method.

2. Materials and methods

2.1. Field experiment

The maize field experiment was conducted at the IRTA research station in Gimenells, north-east Spain (41°65′N, 0°39′E) over 12 years (2002–2007 and 2010–2015). The soil was well-drained petrocalcic calcixerept soil (Soil Survey Staff, 2014) with a petrocalcic horizon at 90–100 cm depth and no salinity (Table 1). The climate in the area is semi-arid Mediterranean, with high temperatures (historical mean 19.4 °C) and low precipitation (historical mean 184 mm) during the growing season (historical 1989–2015) (Fig. 1). The trial was conducted with sprinkler irrigation, providing approximately 650 mm water depending on the climatic conditions during the growing period in each year. The irrigation water was good quality and did not contain significant amounts of nitrates.

The experimental design was a split-plot, with three pig slurry rates

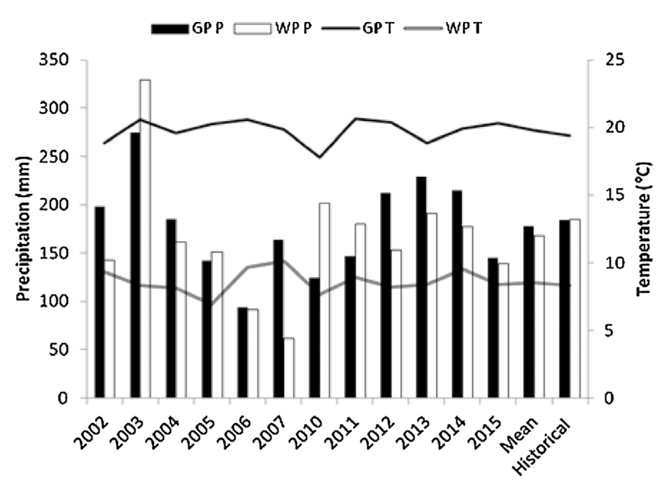

Fig. 1. Annual precipitation and mean temperature for the experimental period (2002–2015) and the historical period (1989–2015). Maize Growing Period Precipitation (GP P), Winter Period Precipitation (WP P), Maize Growing Period Temperature (GPT) and Winter Period Temperature (WPT). Growing Period and Winter Period, from April to September and October to March, respectively.