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Strategies to optimize nitrogen efficiency when fertilizing with pig slurries in dryland agricultural systems

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ABSTRACT

In dryland agricultural systems, pig slurry (PS) is usually applied to cereal crops only at sowing, and slurries accumulate for the rest of the year in pits. In this context, a four-year experiment was established in order to evaluate the feasibility of PS applications at the barley or wheat tillering stage. The main treatments were PS either applied at sowing (25 Mg ha^{-1}) or not, but they alternated after a two-year period. Both were annually combined with eight side-dressing treatments at cereal tillering: mineral N as NH_4NO_3 (M; 60 or 120 kg N ha^{-1} yr^{-1}), PS from fattening pigs (PSf; 17, 30, 54 Mg ha^{-1} yr^{-1}), PS from sows (PSs; 25, 45, 81 Mg ha^{-1} yr^{-1}) and a treatment without N. The combined fertilization treatments were 18 plus a control (no N applied). In the context of crop rotation, the biennial alternation of PS applied at sowing allowed the control of soil nitrate increments, while PS side-dressing improved N recovery compared with a unique application at sowing. The highest yields (>3.6 Mg ha^{-1} yr^{-1}) were obtained with an annual average (4-yr) N rate close to 173 kg N ha^{-1} (±40 kg N ha^{-1}). The best overall strategies corresponded to PSs side-dressings of 50–90 kg N ha^{-1}. These PSs rates also recorded the highest values on the five calculated N-efficiency indexes, which were higher than or similar to results from M side-dressings or those recorded in the literature. These similarities (M vs. PSs) were also shown by the reduction of unaccounted-for N inside the overall N balance. Thus, split PS application during the crop cycle is a sound fertilization option in dryland systems.

1. Introduction

In areas where high volumes of pig (*Sus scrofa domesticus*) slurries (PS) are produced, the cheapest solution for their disposal is to use them as fertilizers to apply to agricultural land. This solution favors nutrient recycling, although this recycling must be performed within the framework of preventing underground nitrate water contamination, which is one of the main issues affecting N fertilization in Europe (European Union, 2013).

In Spain, approximately 92% of the total cultivated area devoted to barley and wheat (4.6 million of hectares) is under rain-fed semiarid conditions. It accounts for 75% of the country's total cereal grain area (MARM, 2013). Annual Spanish pig production is close to 26 million pigs, while the ratio of sows:fattening pigs is approximately 1:7 (SGPC, 2012). This is important because the slurry produced by fattening pigs (PSf) is different in composition from the slurry from sows (PSs), with PSf having a dry matter (DM) content that is on average 31% more than that of PSs. In both slurries, ammoniacal N is the predominant form, which accounts for 65–70% of the total N (Yagüe et al., 2012).

In semiarid areas, the agronomic efficiency of N fertilizer in winter cereals (barley and wheat) is lower than that usually observed in temperate areas (Bosch-Serra, 2010), as soil water shortages limit the responses of crops to N fertilizer additions (Ryan et al., 2009). Split N application, which involves N side-dressing in spring, usually increases yield, grain wheat protein and N efficiency (Jackson and Smith, 1997; López-Bellido et al., 2012). In practice, slurry is mainly applied in autumn to the stubble of the preceding crop (at sowing) and/or more sparsely as a side-dressing at the cereal

Abbreviations: DM, dry matter; M, mineral fertilizer; NAE, nitrogen agronomic efficiency; NHI, nitrogen harvest index; NRF, nitrogen apparent recovery fraction; N_{upt}, nitrogen uptake; NUE, nitrogen use efficiency; NUtE, nitrogen utilization efficiency; PN, nitrogen applied at sowing as pig slurry; PS, pig slurry; PSf, pig slurry from fattening pigs; PSs, pig slurry from sows; UN, no nitrogen applied at sowing.

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tillering stage. However, a low efficiency in N use by crops can be expected when N is applied as slurries in autumn (Moal et al., 1995; Sieling et al., 1997), and very variable N efficiencies can be expected, with frequent low values, depending on the application date and the prevailing weather conditions; moreover, the efficiency in N use decreases with increasing application rates (Schröder, 2005; Webb et al., 2010).

As slurries accumulate in storage pits throughout the year, better synchronization of slurry production and spreading time is indispensable for the sustainable management of farms and for the long-term protection of environmental quality. Furthermore, manures still supply N to crops beyond the year of application (residual effects). Therefore, considering the whole rotation, or a wider period than just one growing season, will give a more reliable value for N efficiency associated with the mineralization of organic N. However, it should be noted that under semiarid Mediterranean conditions, Hernández et al. (2013) found that N residual effects from pig slurries do not extend longer than two years.

Under specified management practices, nitrogen budgets and N efficiency indexes may be used to identify the dominant processes of the N cycle and major soil–plant components of N efficiency (Moll et al., 1982; Raun and Johnson, 1999; Watson and Atkison, 1999; Huggins and Pan, 2003). In semiarid environments, N efficiencies in winter cereals have been mainly calculated when using mineral fertilizers (Kirda et al., 2001; López-Bellido et al., 2005, 2006; Arregui and Quemada, 2008; Giuliani et al., 2011; Cossani et al., 2012). The exceptions are the works of Webb et al. (2010), who, for Spanish conditions, roughly estimated that first-year N use efficiency from PS was between 40 and 70% of the total N, and of Hernández et al. (2013), who calculated different N efficiency indexes on an acid soil when slurry was applied at sowing in a winter barley crop. Nitrogen efficiency values for PS applied in winter and spring are scarce, and they have mainly been developed for spring sowings (Petersen, 1996; Jackson and Smith, 1997). The use of a liquid slurry fraction combined with inorganic N fertilizer in a single spring application was effective in improving N nutrition in Eastern Ireland (Meade et al., 2011).

Conversely, in the central area of the Ebro valley under a semiarid Mediterranean climate and with soils of moderately fine texture, N that is not fully used by the crop accumulates in soil (Cantero-Martínez et al., 1995a,b,b). Cantero-Martínez et al. (1995a) and Villar (1989) corroborated negligible drainage below 1.2 m with field measurements. In their studies, rainfall was between 202 and 407 mm, and according to the authors, most of the water used by the crops came from current rainfall and not from stored soil water from previous seasons. With high rainfall in the most humid years (>450 mm), some winter drainage can theoretically exist (data not shown); consequently, leaching of currently applied N and leaching of the N previously accumulated in soil could co-exist.

In dryland areas devoted to winter cereals some constraints must be considered in fertilization plans when using slurries. The minimum N slurry rate is limited by slurry composition and by the most widespread type of machinery available for application (without injection). Avoiding or alternating slurry applications before sowing could be useful to avoid excessive N build-up in soils.

We also hypothesized that if side-dressing in the spring increases N efficiency, it could be an option to increase N efficiency from slurries.

In addition, ammoniacal N is the main N source from PS, and the residual effect from the remainder (the organic N) does not last more than two years. If we consider a full rotation of four years, N efficiencies from slurry fertilizer plots could be quite similar to those from plots fertilized with mineral N. To simplify the number of parameters one needs to evaluate, mainly to avoid differences associated with different types of crops, a cereal–cereal rotation was considered the best case for the study. This rotation is often used in Mediterranean dryland conditions. In terms of cereal crops, farmers prefer to grow barley rather than wheat because of its shorter vegetative period, which helps to avoid water stress and high temperatures during grain filling (Cantero-Martínez et al., 1995a). Wheat is mainly introduced because it facilitates the control of weeds and pests. Other crops are less frequently grown because they require more complex management without increased economic benefits.

The aim of the present work was to evaluate yields and N efficiencies under different fertilizing strategies in Mediterranean dryland conditions. The schedule included the use of PS at two different periods during the cereal growing season: at sowing and at the cereal tillering stage. In a four-year experiment, strategies combined the biennial alternation of PSf applied at sowing with annual side-dressing fertilization at the cereal tillering stage. The biennial alternation of PSf applied at sowing means that it was applied in half of the plots during two consecutive years; afterwards, these plots were maintained for two more years without PS fertilization at sowing. In the opposite situation, during the first two years, the other half of the plots did not receive slurry at sowing. Combinations of the treatments were established to use slurry during the cereal growing period (N split) while avoiding potentially excessive soil nitrate increments.

This information will be useful in optimizing slurry use and maintaining the sustainability of Mediterranean dryland agricultural systems, which are currently under high economic and environmental pressure.

2. Material and methods

2.1. Experimental location

This study was conducted in an experimental field located in Oliola, Spain (41° 52″ 34′ N, 0° 19″ 17′ E; altitude 440 m a.s.l.) during four winter cereal growing seasons: 2000/01-2001/02-2002/03-2003/04. The rotation was the common one used in the area with barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.) as the main crops. The order of cropping was barley–barley–wheat–barley, and all plots hosted the rotation once.

In 2000 and 2001, cereal crops were sown on the 5th and 8th of November, respectively, and in 2002 and 2003, they were sown on the 30th and 31st of October, respectively. The sowing rate was 190 kg ha^{-1}, and the distance between rows was 0.12 m. They were harvested from the end of June to early July. Cereal straw was removed from the field, and stubble was buried by disc harrowing in autumn before sowing, (~0.15 m depth). The field did not receive any organic fertilizer for a period of at least 20 yrs prior to the experiment. If needed, plant protection was performed according to the treatments advised by agricultural extension specialists in the area.

The soil is deep (>1 m) and calcareous, with a calcium carbonate content from 30% at the surface layer (0–0.30 m) to 44% at the deepest layer (>0.75 m), and it is non-saline, as the electrical conductivity (1:5; soil:distilled water) is lower than 0.2 dS m^{-1}. The soil was classified as Typic Xerofluvent (Soil Survey Staff, 2014). Some relevant characteristics of the superficial layer include a silty loam texture (131 g kg^{-1} sand; 609 g kg^{-1} silt, and 260 g kg^{-1} clay), a water holding capacity of 173 mm (0–0.90 m depth), a pH (1:2.5; soil:distilled water) of 8.2, an organic matter content of 15 g kg^{-1}, an available P (Olsen) content of 17 mg kg^{-1} and an available K (NH_4OAc) content of 76 mg kg^{-1}. At the start of the experiment, the average nitrate N from 0 to 0.30 m was 41 kg NO_3^--N ha^{-1}, and that from 0 to 0.90 m was 72 kg NO_3^--N ha^{-1}. The ammonium