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Abbreviations: DM, dry matter; M mineral fertilizer; NAE, nitrogen agronomic efficiency; NHI, nitrogen harvest index; NRF, nitrogen apparent recovery fraction; Nupt, 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.

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}), 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 or not 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-year) N rate close to 173 kg N ha^{-1} (±40kg 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.

Keywords: Best environmental practices, Mineral fertilizer, Nitrogen, N-balance, N-efficiency indexes, N-uptake.

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 favours 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 (SGPG, 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 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 Atkinson, 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 and 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 Hérnandez 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). 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 (41º 52″ 34′ N, 0º 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 years 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 content was very low in these soils and was not determined in the soil analysis.

The region has a semiarid Mediterranean climate with high summer temperatures and low annual precipitation (Fig. 1). The average temperature and total rainfall for each growing season from October to September were 13.7ºC and 404 mm (first season), 11.9ºC and 419 mm (second season), 13.4ºC and 488 mm (third season), and 12.1ºC and 546 mm (fourth season), respectively. These values are in general agreement with a historical period of 10 years (starting in 2000) with annual averages of

12.6ºC and 436 mm for temperatures and rainfall, respectively. Data were obtained from an automatic meteorological station installed at the experimental site.

2.2. Treatments and design

The treatments were arranged in a split-block design with three blocks. The fertilization treatments at sowing, 25 Mg ha^{-1} of PSf (PN) or without N fertilization (UN), were randomized against each block. Under field conditions, the initial UN or the PN treatments were both justified as the amount of nitrate N from 0 to 0.30 m at the start of the experiment (41 kg NO_3^--N ha^{-1}) was almost at the threshold of 40 kg NO_3^--N ha^{-1} established later in the area for N applications at sowing in winter cereals (Sió et al., 2002). Two main plot positions were maintained during the two first growing seasons, while in the next two consecutive (third and fourth) seasons, the fertilization treatments alternated at sowing. Thus, treatments at sowing for the four-year rotation can be described as PN-PN-UN-UN or UN-UN-PN-PN according to the treatment plot received in the first-second-third-fourth year, respectively.

Furthermore, nine fertilization treatments as side-dressing were also randomized against the block and were maintained in the same positions during the whole period of four years.

Thus, each fertilization treatment at sowing was combined each year with the nine (from 0 to 8) side-dressing treatments applied in mid-February to early March. This period coincided with the cereal tillering stage (21-24 of the Zadoks-Chang-Konzak decimal scale; Zadoks et al., 1974) for wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.). The following treatments were used: mineral fertilization (M) at rates of 60 and 120 kg N ha^{-1} applied as ammonium nitrate (named 1 and 2, respectively); PSf at rates of 17, 30, 54 Mg ha^{-1} (named 3, 4 and 5, respectively); PSs at rates of 25, 45, 81 Mg ha^{-1} (named 6, 7 and 8, respectively); and a treatment in which no nitrogen was applied as a side-dressing (named 0).

Another plot was maintained as a control in each block without N fertilization during the whole period of four years.

Slurry rates followed the theoretical proportional rate factor of 1.8 established by an adjustment of tractor speed. Rates were also checked by the tank weight differences after each application. Minimum application rates were determined because of the technology available to the farmers, which makes it difficult for them to uniformly apply rates lower than 20-25 Mg ha^{-1}. At sowing the control and mineral N treatments received phosphorus (96 kg P_2O_5 ha^{-1} yr^{-1}) and potassium (107 kg K_2O ha^{-1} yr^{-1}).

Slurry was always surface applied by splash-plate, as this is the most popular practice in the area because it is a cheap and easy application method. PS was incorporated at sowing on the day of application by disc harrowing. The fertilizer was not buried in the soil at side-dressing. Direct PS incorporation was not used because of the practical difficulties that it presents under conditions of low soil moisture content (Yagüe and Bosch-Serra, 2013). Injection is very expensive in dryland areas because of the costs associated with the energy needed, machinery maintenance and labour. In some cases, the presence of stones is another practical limit to injection and further increases the cost of slurry incorporation.

The total number of plots for each block was 18 plus a control. The size was 274 m^2 (11 m wide and 25 m long) for plots receiving slurry at side-dressing and 174 m^2 (7 m wide and 25 m long) for the other plots. This accounted for a total of 57 plots.

2.3. Slurry, soil, and plant analysis

A composite slurry sample was taken in the field from each tank before each application, and the samples were analysed in the laboratory. In total, 40 samples were analysed for a four-year period: 23 samples from PSf and 17 samples from PSs. The following analytical methods were used: pH by potentiometry (1:5; slurry: distilled water), electrical conductimetry at 25ºC, gravimetric dry matter content at 105ºC, organic matter by calcination at 550ºC, organic nitrogen by the Kjeldahl method, and ammonium nitrogen by distillation and titration according to methods 4500-NH_3 B-C from APHA (2012). Total phosphorus and potassium were analysed by acid digestion (wet) and further determined using inductively coupled plasma atomic emission spectrometry (USEPA, 1992). The average slurry density of 1006±11 (±SD) kg m^{-3} was adopted according to Moral et al. (2005).

Soil NO_3^--N content was determined in each growing season just before PS fertilization at sowing and also four months after the last harvest (fourth growing season). Soil was not sampled at harvest because from harvest until September, the soil water content (0-0.60 m) is usually close to the permanent wilting point (data not shown). This fact is in accord with reports from other authors in the area (Villar, 1989). For each plot, a mixture of three soil cores at 0.30-m intervals to a depth of 0.90 m were mixed to obtain a composite soil sample. Three composite samples were thus analysed per plot for each sampling time. Soil nitrate was extracted with distilled water (1:1, w/w), and Merckoquant® nitrate test strips and a commercially available Nitracheck® reflectometer by spectrophotometry were used for determination of the soil nitrate content (Norman et al., 1985).

Four different rows in each plot were harvested at physiological maturity. The four rows were selected along a diagonal line inside the plot. Each row was hand-harvested along 1 m. Thus, 0.48 m^2 per plot were hand-harvested in order to establish the harvest index: aboveground biomass divided by total biomass (grain and straw). The edge rows were not sampled. The remaining harvesting of the plot was performed mechanically on two 1.5-m-wide areas along the length of the experimental plot – an area of 150 m^2. The grain moisture level was calculated in a 300 g sample from each plot. Grain yield was adjusted to dry content. Nitrogen concentrations in grain obtained at harvest time and in straw obtained from harvest-index samples were analysed by the Kjeldahl method (Umbreit and Bond, 1936).

2.4. Nitrogen balance and N efficiency parameters

The calculation of the simplified N balance was performed according to the general conservation of mass equation for any soil-crop system (Meisinger and Randall, 1991). The unaccounted-for nitrogen (Nunc) was calculated for the whole period of 4 years. It was estimated (Eq. [1]) by considering as inputs the total N applied in PS (N_{PS}) or in mineral N fertilizer (N_{fert}) and the initial mineral N (N_{is}) in the soil profile (0 to 0.90 m) and as outputs the final soil mineral N (N_{fs}) content in the soil profile and the N uptake by the crop (N_{upt}):

$$\mathrm{Nunc} = N_{input} - N_{output} = N_{is} + N_{PS} + N_{fert} - N_{fs} - N_{upt} \qquad [1]$$

Nitrogen efficiency indexes were defined as follows: i) nitrogen agronomic efficiency (NAE, kg kg^{-1}) as the increment of grain yield (with respect to the control treatment) to applied N, ii) nitrogen apparent recovery fraction (NRF, %) as the increment of crop above-ground N uptake (compared to the control treatment) to applied N, iii) nitrogen utilization efficiency (NUtE, kg kg^{-1}) as the ratio of grain yield to total above-ground plant N uptake, iv) nitrogen harvest index (NHI, %) as the ratio of N in grain to total above-ground plant N uptake, and v) nitrogen use efficiency (NUE, kg kg^{-1}) as the ratio of grain yield to N supply. Nitrogen supply includes the total N applied as fertilizer, the mineralized N (N_{min}) and the initial N (NO_3^--N) soil content. Net mineralization (N_{min}) was estimated from the unfertilized N treatment (Bhogal et al., 1999), and it was considered to be equal in all treatments. Nitrogen efficiency terminology follows that of Huggins and Pan (1993) and López-Bellido and López-Bellido (2001).

2.5. Statistical analysis

The statistical analyses were performed with the statistical package SAS (SAS Institute 1999-2001). In the first and second cropping seasons, multiple comparisons (least-squares means) were performed according to the Tukey-Kramer test. To evaluate all possible pairs of treatment means, separation of overall strategies' means (four cropping seasons) was performed according to Duncan's multiple-range test (DMRT, α=0.05).

3. Results

As was expected, slurries from sows contained lower average DM contents and nutrient concentrations than slurries from fattening pigs (Table 1). In each growing season, we found some variability in the N application rates from the theoretical ones because of variations in the DM content of the slurries (Table 1), but the rate proportion of 1.8 was maintained at side-dressing. During the four growing seasons, climatic conditions were representative of this semiarid Mediterranean area, which receives precipitation below evapotranspirational demand (Fig. 1). Rainfall totals for each of the four cropping seasons and during the crop cycle (from November to June) were 265, 257, 273 and 355 mm, respectively.

3.1. Yield and N balance

The unfertilized N plots (UN0-UN0 treatment; no-N during 4 yr) attained an average dry matter yield of 2423 kg ha^{-1} (Table S1, supplementary material). This means dry matter yields for the first, second, third, and fourth seasons of 2454, 3101, 1826 and 2314 kg ha^{-1}, respectively (Tables S2, S3, S4, S5, supplementary material). Additionally, the total N uptake (grain plus straw) was 58, 76, 33 and 57 kg N ha^{-1}, respectively.

During the two first consecutive growing seasons, yields responded to N fertilization (Fig. 2A and B). Some rates of PS always produced maximum yields. No significant difference ($p>0.05$) between the two mineral treatments (UN1 and UN2) was found in either of the growing seasons, nor between the highest mineral treatment (UN2) and PS treatments in the first growing season (Fig. 2A and B). Nevertheless, in the second cropping season, some slurry treatments from 138 up to 250 kg N ha^{-1} (PN6, UN8, PN7, and PN3) achieved higher yields than the mineral fertilizers. Additionally, the associated maximum average yields of these treatments (from 4888 up to 5003 kg ha^{-1}) were higher than the maximum obtained in the first season (4052 kg ha^{-1}).

During the whole rotation of four cropping seasons, which included the biennial alternation of PS applied at sowing, the highest average yields (14.4-16.0 Mg ha^{-1} as accumulated yield, 3.6-4.0 Mg ha^{-1} as annual average yields) were achieved using, at cereal tillering, a wide range of PS rates (Figs. 3A, B, and C; Table S1) or the low mineral fertilizer rate (60 kg N ha^{-1} yr^{-1}).

Data from the plot maintained as a control during the four-year period indicate that soil organic matter mineralization contributed a total amount of 221 kg N ha^{-1} to crop production, which equals an annual average of 56 kg N ha^{-1}. At the end of the rotation, the soil mineral NO_3^--N content was highest for the treatments UN2-PN2 and UN5-PN5, with averages of 236 kg N ha^{-1} and 212 kg N ha^{-1}, respectively (Figs. 3A,B and C). For the rest of the treatments it fluctuated from 97 (PN1-N1) to 160 kg N ha^{-1} (PN2-N2). The unaccounted-for N at the end of the rotation (4 years) and for each type of fertilizer tended to increase with the total N rate applied (Figs. 3A, B and C).

3.2. Nitrogen efficiency indexes for the whole rotation of four cropping seasons

Nitrogen agronomic efficiency decreased with increasing rates of PS applied at side-dressing independently of the slurry type. The highest average values (Table 2) were between 7.4 and 9.4 kg kg^{-1}. Some slurry side-dressings (6 and 7) were not different from treatments associated with the lowest mineral side-dressing (60 kg N ha^{-1}

yr^{-1}), corresponding to UN1-PN1 or PN1-UN1 strategies with NAE values of 8.4 and 8.6 kg kg^{-1}, respectively.

The nitrogen apparent recovery fraction was in the range of -2.3 to 24.1% (Table 2). The highest values were for some of the treatments which also achieved the highest NAE records: treatment 1 at side-dressing (whatever the fertilization at sowing; NFR= 21.3-22.7%) and PN6-UN6 or PN7-UN7 strategies with NFR of 17.8% and 20.5%, respectively.

In addition, low rates of PSs (strategies UN6-PN6 or UN7-PN7) or even PSf (treatment UN3-PN3) also accounted for maximum NUtE and are thus included in the range of 47 to 51 kg grain per kg N uptake.

The nitrogen use efficiency (from 5.8 to 14 kg kg^{-1}) and the NHI (from 66.5 to 81.7%) were affected by side-dressing treatments (Table 2), but the lowest N rates of PSs at cereal tillering (treatments 6 and 7) were located in the upper part of the value range.

4. Discussion

4.1. Yield and N balance

The higher yields in the second season compared with the first can be explained by the higher spring rainfall and especially by the 75.8 mm recorded in April (Fig. 1). Soil water availability is a key factor in these areas, especially during the grain-filling period (Bosch-Serra, 2010). In addition, in the second cropping season (Fig. 1), the reduced winter rainfall (46.7 mm in three months, from November to January) resulted in limited nitrate leaching before the side-dressing was applied (mid-February to early March).

At the end of the two first growing seasons (Figs. 2A and B), the soil profile’s nitrate accumulation (0-0.90 m), which in some cases showed Nfs values higher than

100 kg NO_3^--N ha^{-1} (UN2, PN2, or PN5; Fig. 2B), indicated that some treatments will not be environmentally sustainable in the long run. According to the yields obtained and the N balance, the treatments with slurry at sowing and combined at side-dressing with the highest rates of each type of fertilizer (Fig. 2B) should be rejected, a result that is even more striking when one considers that the treatments do not increase yields and, in some cases, actually reduce them.

The results for the whole rotation of four cropping seasons have further strengthened our conclusions from previous experiments that for each type of fertilizer; it is unwise to apply the highest rates with the fertilization side-dressing. The soil mineral NO_3^--N content at the end of the rotation was unacceptably high for the highest mineral and slurry side-dressing rates (treatments 2 and 5) (Figs. 3A and B).

The introduction of biennial alternation and the maintenance of PS application at sowing during two cropping seasons suggested the idea that the side-dressing is an advisable technique because it increases yields and can also extend the period of use of slurries throughout the year. Our results indicate that as the highest accumulated yields can be achieved with an annual average (4-year) N rate of approximately 173 kg N ha^{-1} (±40 kg N ha^{-1} as standard deviation), PS treatments PN7-UN7 (3.9 Mg grain ha^{-1} yr^{-1}), PN6-UN6 (3.7 Mg grain ha^{-1} yr^{-1}) and PN3-UN3 (3.7 Mg grain ha^{-1} yr^{-1}) should be recommended (Figs. 3B and C). If side-dressing is applied using N mineral fertilizers, a rate of up to 60 kg N ha^{-1} yr^{-1} (treatment 1; Fig. 3A) should be recommended.

However, the increased slurry rates did not result in significant yield reductions; this was also the case with treatment PN5-UN5, which had the highest N dose (466 kg N ha^{-1} yr^{-1}). This is why farmers do not easily understand the limitations imposed on the amount of slurry that can be used (Figs. 3B and C).

The unaccounted-for N includes the N content in roots, as 10-20% of the total N in wheat is in the roots (Andersson and Johnasson, 2006), part of soil organic N (from N reorganization) and a proportion of immobilized NH_4^+-N (Morvan et al., 1997; Sorensen and Amato, 2002), despite the fact that these forms of N can be mineralized. It also includes some N losses by leaching, denitrification or volatilization (Sorensen and Thomsen, 2005). Although leaching can occur, depending on the year, in general, leaching and denitrification in this semiarid environment are limited (Zhou et al., 2013). Furthermore, according to the figures of slurry dry matter (Table 1), volatilization is controlled to some extent by crust formation in PSf or by the enhancement of infiltration in PSs (Sommer and Hutchings, 2001; Bosch-Serra et al., 2014).

Our results on the N rates for maximum yields in this dryland agricultural system concur with the European regulations (European Union, 1991), which established 170 kg N ha^{-1} as the maximum amount of N from organic sources that can be applied in nitrate-vulnerable areas. They are also in accord with Spanish legislation in areas with high pig density (NW of Spain) such as Catalonia (Generalitat de Catalunya, 2009), where it is established that 210 kg N ha^{-1} is the maximum allowed for winter cereals in non-vulnerable areas such as ours. However, our case presents an important point to consider: our average N rate was obtained within a rotation and included the concept of an alternation of slurry application at sowing, which allows for integrated slurry management throughout the year.

The biennial alternation that we propose could be a useful alternative to avoid mineral N accumulation by reiterative applications while taking advantage of the residual effect described by some authors in winter cereals (Cela et al., 2011; Yagüe and Quílez, 2013). Furthermore, the addition of PSf or PSs at low N rates at side-dressing may be a sufficient source of P and K to cover cereal needs (Table 1).

4.2. Nitrogen efficiency indexes

The rotation maintained in the experiment (three years of barley and one year of wheat) is typical for Mediterranean semiarid areas in order to control weeds. As a preliminary premise, we assumed that barley and wheat respond in a similar way to N fertilization in terms of yield, as was observed in a similar Mediterranean environment by Cossani et al. (2012).

In our study, increases in yield response to N supply (NAE values, Table 2) were in the upper range of results for these agricultural systems (Angás et al., 2006). When side-dressing fertilization is included in the strategies, our highest NAE values can be associated with the lowest rates of N applied at side-dressing as mineral fertilizer (treatment 1) or as PSs (treatments 6 and 7). In addition, NUE values in the just-mentioned treatments were not above the limit of 14 kg kg^{-1} achieved by treatment PN0-UN0 (Table 2). This last point indicates that a constraint still remains, which is probably linked to water availability (Cossani et al., 2012).

Regarding the unfertilized N plots (UN0-UN0 treatment; no-N during 4 yr), it is interesting to observe that the amount of mineralized N from organic matter allowed the plots to maintain average yields close to 2.4 Mg ha^{-1} yr^{-1}. Thus, it allowed yields close to 60% of the annual (or for the whole period of 4 years) maximum yields recorded (Table S1). Total N uptake by the control accounted for 53% of the total N uptake obtained for the PN2-UN2 strategy, which achieved the maximum NRF value of 24.1% (Tables 2 and S1). For the rest of the treatments, the uptake of the mineralized N by the control treatment resulted in a reduction of the ratio between the increment of crop above-ground N uptake and the N applied (NRF; Table 2). As a consequence, the NRF values that we found were lower than those recorded by other authors, such as Angás et al. (2006). They found a maximum of 46% in NRF value in a barley crop. Nevertheless, in a wheat-wheat rotation, López-Bellido et al. (2006) obtained NRF values from 7.8% to 30%. This variability between cropping seasons is associated with changeable climatic conditions. Under their conditions, this variability was attributed to heavy rainfall, and in our case, it was due to limited water availability during the crop cycle, which constrained N uptake and yields in fertilized plots.

Nevertheless, the ability of the crop to translate the N absorbed into economic grain yield (NUtE index) evaluated in the slurry side-dressing of treatments 3 (PSf), 6 and 7 (PSs) were in agreement with Giambalvo et al. (2010), who found NUtE values in durum wheat fertilized with mineral N, ranking from 31 to 50 kg grain per kg N uptake. These three treatments (3, 6, and 7) also had the highest ratios of N in grain to N uptake (NHI from 75 to 82%). However, these results were not reflected in an increased grain quality, in disagreement with various authors (Tran and Tremblay, 2000; Fuertes-Mendizábal et al., 2012). We also found that the NHI values of treatments 3, 6, and 7 were similar to those from plots only fertilized at sowing (from 77 to 80%), indicating that the excess N was used by the plant to increase the straw biomass (data not shown). However, our data coincide with those of other authors, such as López-Bellido et al. (2006) or Giuliani et al. (2011), in similar environments with mineral fertilizer.

Overall, the PS-based fertilizer strategies studied showed similar N efficiencies compared with those observed in other experiments with mineral N fertilizers (López-Bellido and López-Bellido, 2001; Giambalvo et al., 2010; Giuliani et al., 2011) under semiarid Mediterranean conditions. Slurry dressings at the lowest rates tended to improve (or significantly improved in the UN6-PN6 strategy) the NUtE and NHI indexes compared with recommended M dressings (treatment 1), with no significant differences in other indexes such as NAE, NRF or NUE (Table 2). Thus, the use of PS at cereal tillering is supported not only by its high efficiency but also by the ability to achieve the highest recorded yields.

On the basis of the yields and values of the different N indexes derived from our study lasting 4 years, it is possible to recommend the strategy with PS side-dressing applied annually because the results are similar to those of the treatment with a mineral side-dressing of 60 kg N ha^{-1} (treatment 1) without leading to increases in NO_3^--N content in the soil. The best results were obtained with treatments 6 (PSs, 20 Mg ha^{-1}), and 7 (PSs, 45 Mg ha^{-1}). Treatment 3 (PSf, 17 Mg ha^{-1}) could be accepted if rates at tillering and at sowing could be adjusted to an average below 210 kg N ha^{-1}yr^{-1}.

The combination of N balance and N efficiency indexes inside a rotation offers a sound basis on which to adjust N fertilizer rates and to optimize N management for productivity and sustainability in management fertilization plans when using pig slurries.

5. Conclusions

This study demonstrates that in dryland Mediterranean agricultural systems, fertilizer side-dressings of winter cereals with PS is a viable agronomic alternative to N mineral fertilizers while also being environmentally friendly.

The biennial alternation of PSf applied at sowing at minimum technical rates close to 20-25 Mg ha^{-1} (~ 6 kg total N Mg^{-1}) is justified, as it controls mineral N soil build-up and allows an annual distribution of slurry produced in farms, which is better balanced during the year over a four-year rotation.

The annual complementary fertilization at cereal tillering with slurries from sows (~2 kg total N Mg^{-1}) at rates from 25 to 45 Mg ha^{-1} yr^{-1} (treatments 6 and 7) is recommended. Depending on the strategy adopted, it allows the crop to achieve the highest N index values for NAE (~8 kg grain kg^{-1}N applied), NRF (18-21%), NUtE (47-51 kg grain kg^{-1}N uptake), NUE (13-14 kg grain kg^{-1} N supply), and NHI (76-79%). Side-dressing with PSf should not be accepted according to N efficiency results. However, in this case, taking into account the range of its N content, the technical restriction should be to apply PSf doses just below 17 Mg ha^{-1} either at sowing (biennial alternation) or at cereal tillering (annual application). This limiting condition can be overcome if more precise machinery for slurry application becomes readily available to farmers.

In view of these results, future work will focus on further adjusting the slurry rates, taking into account the potential N residual effects in the context of a long-term experiment, and also with a view to achieving higher efficiencies of the N applied in slurry.

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Figure legends:

Fig. 1. Mean air temperature, monthly rainfall and reference crop evapotranspiration (ET_0, FAO Penman-Monteith equation) for each annual growing season (period: October 2000-September 2004).

Fig. 2. Average grain yield biomass (0% moisture), plant N uptake (Nupt), initial (Nis) and final (Nfs) mineral nitrogen (NO_3^--N) soil profile (0-0.90 m) content for each treatment and total N applied yearly: A) First crop season; B) Second crop season. Treatments' letters indicate if slurry was applied at sowing (PN, 25 Mg ha^{-1} yr^{-1}) or not (UN) and they are separated by a vertical dotted line. Numbers are associated to fertilizer side-dressing treatment: Mineral (M) as ammonium nitrate; 0: 0 kg N ha^{-1} yr^{-1}; 1:60 kg N ha^{-1} yr^{-1}; 2:120 kg N ha^{-1} yr^{-1}; Slurry from fattening pigs (PSf), 3: 17 Mg ha^{-1} yr^{-1}, 4: 30 Mg ha^{-1} yr^{-1}, 5: 54 Mg ha^{-1} yr^{-1}; Slurry from sows (PSs), 6: 25 Mg ha^{-1} yr^{-1}, 7: 45 Mg ha^{-1} yr^{-1}, 8: 81 Mg ha^{-1} yr^{-1} .Vertical bars indicate ± one standard deviation of the mean (n=3). For yields, multiple comparisons (least-squares means) were done according to the Tukey-Kramer test; means followed by the same letter are not significantly different (p>0.05).

Fig.3. Accumulated yield (0% humidity) and components of the N balance for the whole four period (4 years): plant N uptake (Nupt); initial mineral nitrogen (NO_3^--N) content (Nis, October first season) and final mineral N content (Nfs, October fourth season) in soil profile (0-0.90 m) and unaccounted N (Nunc) for each fertilizing strategy. All strategies present a biennial alternation of slurry applied at sowing: two years where pig slurry was applied at sowing (PN, 25 Mg ha^{-1} yr^{-1}) plus two sequent years with no application (UN) and viceversa. Numbers are associated to fertilizer side-dressing treatment: A) Mineral as ammonium nitrate; 0: 0 kg N ha^{-1} yr^{-1}; 1:60 kg N ha^{-1} yr^{-1}; 2:120 kg N ha^{-1} yr^{-1}; B) Slurry from fattening pigs, 3: 17 Mg ha^{-1} yr^{-1}, 4: 30 Mg ha^{-1} yr-1, 5: 54 Mg ha^{-1} yr^{-1}; C) Slurry from sows, 6: 25 Mg

ha^{-1} yr^{-1}, 7: 45 Mg ha^{-1} yr^{-1}, 8: 81 Mg ha^{-1} yr^{-1}. Vertical bars indicate ± one standard deviation of the mean (n=3). For yields, means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (p=0.05).

Table 1. Physicochemical average values of pig slurry applied in the four year rotation: at sowing (PN) from fattening pigs (n=11) and at cereal tillering, as side-dressing, from fattening pigs (n=12) or sows (n=17). Values in brackets are standard deviation.

Parameters	Sowing	Side-dressing	
	Fattening pigs	Fattening pigs	Sows
pH	8.2 (±0.6)	8.1 (±0.4)	7.9 (±0.3)
Electrical conductivity (dS m^{-1})	33.7 (±4.2)	37.6 (±4.5)	13.9 (±8.1)
Dry matter (kg DM m^{-3})	73.8 (±25.8)	86.8 (±22.7)	25.5 (±16.9)
Organic matter (kg OM m^{-3})	50.6 (±20.0)	60.1 (±17.7)	17.3 (±12.6)
Ammonium N (kg N m^{-3})	4.6 (±0.9)	4.9 (±0.6)	1.3 (±0.4)
Organic N (kg N m^{-3})	2.0 (±0.5)	2.3 (±0.3)	0.6 (±0.4)
Total N (kg N m^{-3})	6.6 (±1.2)	7.0 (±0.9)	2.0 (±0.8)
Phosphorus (kg P_2O_5 m^{-3})	3.3 (±1.0)	4.1 (±1.6)	1.2 (±1.1)
Potassium (kg K_2O m^{-3})	5.9 (±0.8)	5.4 (± 1.0)	1.2 (±0.2)

Table 2. Total N applied, N indexes[a] for the fertilizing strategies[b] considering four growing seasons[c] as a whole.

Strategies (2 yr - 2 yr)	**Total N applied** ($kg\ ha^{-1}$)	**NAE ($kg\ kg^{-1}$)** $\frac{\text{Yield Ti} - \text{Yield Tc}}{\text{N applied}}$		**NRF (%)** $\frac{\text{Nupt Ti} - \text{Nupt Tc}}{\text{N applied}} * 100$		**NUtE ($kg\ kg^{-1}$)** $\frac{\text{Yield Ti}}{\text{N plant uptake}}$		**NUE ($kg\ kg^{-1}$)** $\frac{\text{Yield Ti}}{\text{N supply}}$		**NHI (%)** $\frac{\text{N grain uptake}}{\text{N plant uptake}} * 100$	
UN0-PN0/	301	4.2	fgh	-2.3	f	50.5	a	13.7	a	77.5	abcde
PN0-UN0	350	9.2	a	11.5	de	48.8	ab	14.0	a	79.6	ab
UN1-PN1/	541	8.4	abc	21.3	abc	42.0	de	13.6	a	73.1	cdefg
PN1-UN1[c]	***590***	***8.6***	***abc***	***22.7***	***ab***	***41.2***	***e***	***12.5***	***abc***	***72.9***	***defg***
UN2-PN2/	781	5.5	defgh	21.5	abc	35.7	fg	9.7	de	71.3	fgh
PN2-UN2	830	5.2	defgh	24.1	a	32.9	g	9.0	de	69.9	gh
UN3-PN3/	791	6.0	bcdef	9.2	e	48.6	ab	11.7	bc	81.7	a
PN3-UN3	***840***	***6.1***	***bcdef***	***14.0***	***cde***	***43.5***	***cde***	***10.7***	***cd***	***77.5***	***abcde***
UN4-PN4/	1117	4.7	efgh	12.0	de	42.1	de	9.1	de	74.7	bcdefg
PN4-UN4	1167	5.3	efgh	15.2	bcde	39.5	ef	9.0	de	71.9	fghe
UN5-PN5/	1814	2.6	h	12.5	de	32.1	g	6.0	f	66.5	h
PN5-UN5	1864	2.9	gh	11.8	de	34.4	g	5.8	f	70.6	fgh
UN6-PN6/	473	7.4	abcde	7.8	e	50.6	a	14.0	a	79.1	abc
PN6-UN6	***523***	***9.4***	***a***	***17.8***	***abcd***	***46.1***	***bcd***	***13.7***	***a***	***76.0***	***abcdef***
UN7-PN7/	***642***	***8.0***	***abcd***	***14.1***	***cde***	***47.3***	***abc***	***13.9***	***a***	***78.6***	***abcd***
PN7-UN7	***692***	***8.7***	***ab***	***20.5***	***abc***	***43.0***	***de***	***12.8***	***ab***	***74.6***	***bcdefg***
UN8-PN8/	1036	5.8	cdefg	15.3	bcde	41.1	e	9.9	de	74.0	bcdefg
PN8-UN8	1117	4.9	efgh	14.2	cde	39.8	e	8.8	e	74.7	bcdefg
Significance	-	***		***		***		***		***	

NS: not significant (p>0.05); S: significant (** p<0.01, *** p<0.001). Within columns, means having a common letter are not significantly different according to DMRT (α=0.05).

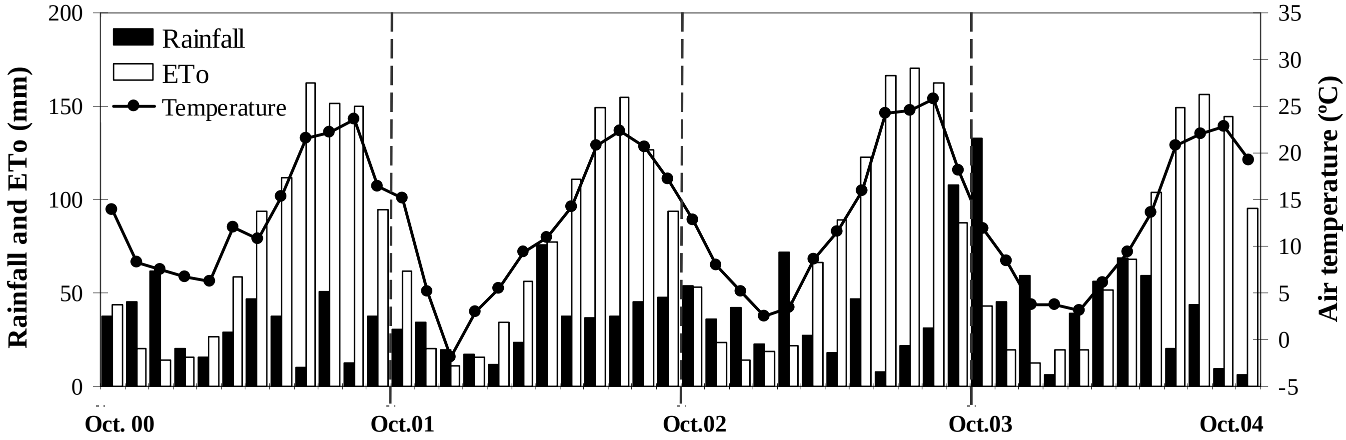
[a] NAE: nitrogen agronomic efficiency ; NRF: nitrogen apparent recovery efficiency; NUtE: nitrogen utilization efficiency; NUE: nitrogen use efficiency; NHI: nitrogen harvest index; Ti: values for the treatment; Tc: values for the control; Nupt: N plant uptake.

[b] UN: No nitrogen was applied at sowing; PN: slurry from fattening pigs applied at sowing at a rate of 25 t ha^{-1} yr^{-1}. Numbers indicate fertilization as side-dressing: Mineral as ammonium nitrate; 0: 0 kg N ha^{-1} yr^{-1}; 1:60 kg N ha^{-1} yr^{-1}; 2:120 kg N ha^{-1} yr^{-1} ; Slurry from fattening pigs, 3: 17 t ha^{-1} yr^{-1}, 4: 30 t ha^{-1} yr^{-1}, 5: 54 t ha^{-1} yr^{-1} ;Slurry from sows, 6: 25 t ha^{-1} yr^{-1}, 7: 45 t ha^{-1} yr^{-1}, 8: 81 t ha^{-1} yr^{-1}

[c] Strategies and values of indexes in bold and italic type indicate the values of high yielding recommended strategies.

713 **Fig. 1**

714



Rainfall
ETo
Temperature
Rainfall and ETo (mm)
Air temperature (ºC)
200
150
100
50
0
35
30
25
20
15
10
5
0
-5
Oct. 00
Oct.01
Oct.02
Oct.03
Oct.04

Fig. 2

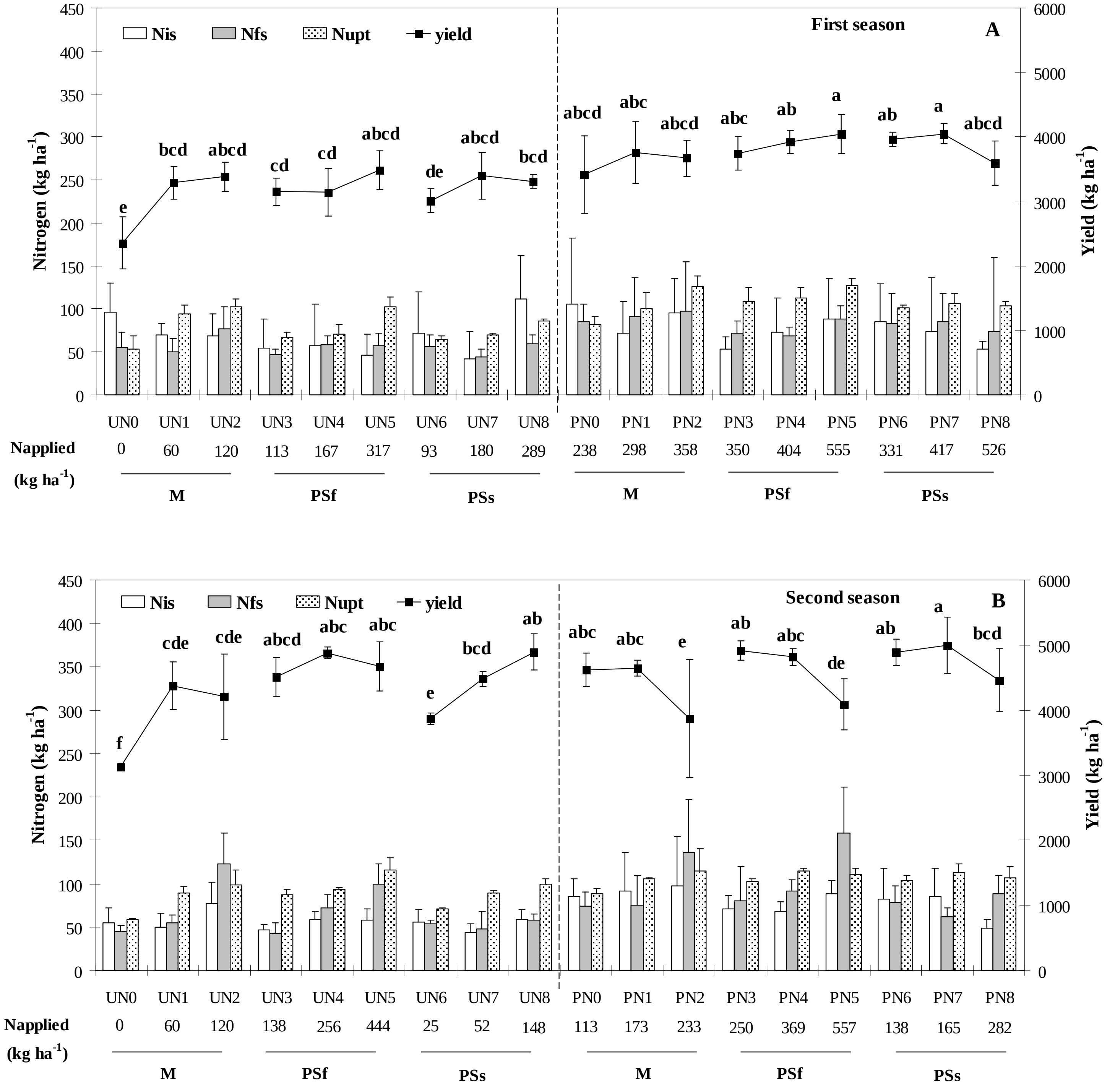
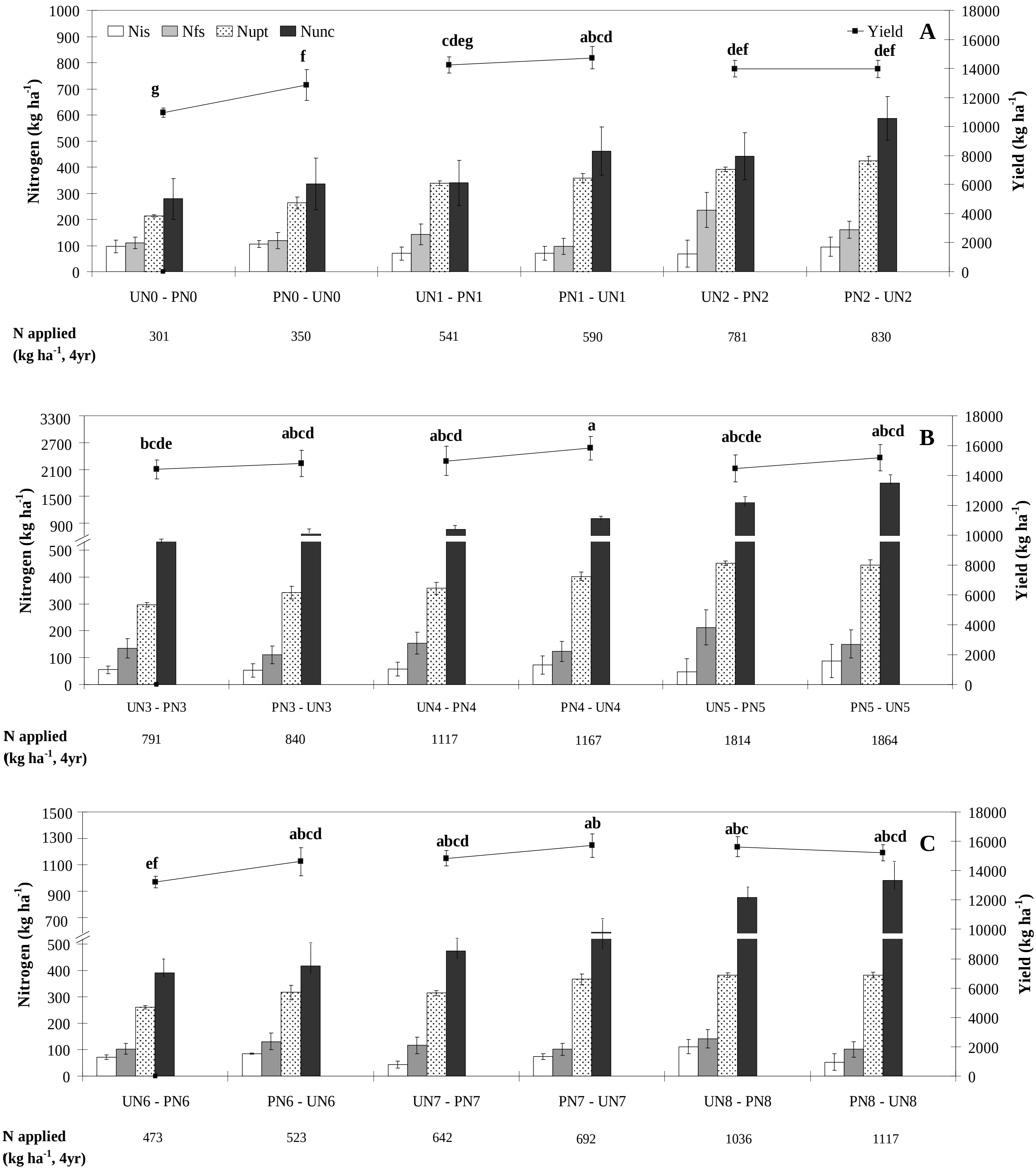

Nis
Nfs
Nupt
yield
First season
A
Nitrogen (kg ha-1)
Yield (kg ha-1)
450
400
350
300
250
200
150
100
50
0
6000
5000
4000
3000
2000
1000
0
e
bcd
abcd
cd
cd
abcd
de
abcd
bcd
abcd
abc
abcd
abc
ab
a
ab
a
abcd
UN0 UN1 UN2 UN3 UN4 UN5 UN6 UN7 UN8 PN0 PN1 PN2 PN3 PN4 PN5 PN6 PN7 PN8
Napplied (kg ha-1)
0 60 120 113 167 317 93 180 289 238 298 358 350 404 555 331 417 526
M
PSf
PSs
M
PSf
PSs
Nis
Nfs
Nupt
yield
Second season
B
Nitrogen (kg ha-1)
Yield (kg ha-1)
f
cde
cde
abcd
abc
abc
e
bcd
ab
abc
abc
e
ab
abc
de
ab
a
bcd
UN0 UN1 UN2 UN3 UN4 UN5 UN6 UN7 UN8 PN0 PN1 PN2 PN3 PN4 PN5 PN6 PN7 PN8
Napplied (kg ha-1)
0 60 120 138 256 444 25 52 148 113 173 233 250 369 557 138 165 282
M
PSf
PSs
M
PSf
PSs

Fig. 3


Nis
Nfs
Nupt
Nunc
Yield
A
Nitrogen (kg ha-1)
Yield (kg ha-1)
g
f
cdeg
abcd
def
def
UN0 - PN0
PN0 - UN0
UN1 - PN1
PN1 - UN1
UN2 - PN2
PN2 - UN2
N applied (kg ha-1, 4yr)
301
350
541
590
781
830
B
bcde
abcd
abcd
a
abcde
abcd
UN3 - PN3
PN3 - UN3
UN4 - PN4
PN4 - UN4
UN5 - PN5
PN5 - UN5
N applied (kg ha-1, 4yr)
791
840
1117
1167
1814
1864
C
ef
abcd
abcd
ab
abc
abcd
UN6 - PN6
PN6 - UN6
UN7 - PN7
PN7 - UN7
UN8 - PN8
PN8 - UN8
N applied (kg ha-1, 4yr)
473
523
642
692
1036
1117