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Crop diversification and digestate application effect on the productivity and efficiency of irrigated winter crop systems

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ABSTRACT

Irrigated winter crops can reduce input demands when compared with irrigated summer cropping systems in the Mediterranean area. The sustainability of these systems can be further improved resorting to diverse rotations, but also to fertilisation with digestate, a by-product from anaerobic digestion of organic waste. Post-treatments such as drying and acidifying can improve the fertiliser value of this product. In this study, we compare wheat performance in a three-year full cereal rotation or in a diverse rotation, with pea and canola. Besides, untreated and dried acidified digestates are tested as fertilisers for all crops, comparing to mineral fertilisation at a rate of 140 kg N ha^{-1} and a control with no fertilisation. To assess productivity and efficiency of the different systems, grain yield and N concentration, N uptake efficiency (NUpE) and water use efficiency (WUE) were determined, along with soil nitrate dynamics and total N at the end of the experiment. Results showed an average wheat yield increase of 1.79 t ha^{-1} by the last year of the diverse crop rotation rather than the cereal rotation ($p < 0.001$). Although there was no yield increase in the previous year, wheat after pea showed higher grain N concentration ($p < 0.001$). However, the NUpE of wheat remained steady due to a higher soil N availability after pea, which suggests that fertilisation can be adjusted. Although wheat WUE increased due to canola and pea precedents ($p < 0.001$), the cereal rotations should be more adapted to systems with low water availability. Nonetheless, both rotations required about 30% of irrigated water than the typical irrigated summer crops of the Ebro valley region. Fertiliser effect on yields was variable according to the tested crop mainly due to differences in N demand along each growing cycle. Overall, dried acidified digestate application resulted in similar soil nitrate levels than the mineral fertiliser. The diverse rotation raised soil nitrates content compared to the cereal rotation at sowing and harvesting times ($p = 0.002$ and $p < 0.001$, respectively). Higher soil nitrate levels were found when associating these two practices, while nitrate levels after mineral fertilisation showed to be less dependent on the implemented rotation. The diverse rotation also raised soil total N at the end of the experiment ($p = 0.023$). Similarly, the dried acidified digestate application resulted in higher soil total N than mineral fertilisation ($p = 0.011$). These findings show how these management practices should allow for a chemical fertilisation reduction in irrigated winter crop systems.

1. Introduction

Agro-ecosystems in the Mediterranean basin are threatened with increased water scarcity and land degradation due to climate change and the intensification of certain agricultural practices. Thus, there is an urgent need of alternative crop production systems that mitigate these issues while adapting to these threats (Lee et al., 2019).

Although irrigated summer crops are high yielding, it is projected water shortage and the rise of water prices, which will reduce the profit margin to farmers who employ these systems. Winter crops generally have lower irrigation requirements than summer crops making them a promising alternative for farmers situated in regions with sparse water availability, such as the Ebro Valley, where annual precipitation ranges from 250 to 500 mm (Cantero-Martínez et al., 2003; Lagacherie et al., 2018; Zeleke and McCormick, 2022; Zhao et al., 2015). Input reduction also allows for a lower environmental impact for some winter crops. For example, maize production has higher fertiliser demands when compared to wheat, contributing more to greenhouse gases (GHG) emissions and freshwater eutrophication (González-García et al., 2021).

Increasing crop diversity, specifically at a temporal level, also allows

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for a reduction in external inputs. Efficient crop sequences can improve soil fertility, and disrupt weed and disease cycles, ultimately increasing yields. Moreover, diversified cropping systems are more resilient, providing a more stable, but also a more diversified income for the farmer, which is becoming ever more important in a changing climate (Harkness et al., 2023; Shah et al., 2021). The production of alternative crops such as pea and canola on its own is of growing importance, as the demand for alternative protein, oil and biofuel sources increases (Jha et al., 2022; Schillinger and Paulitz, 2018). Several studies have shown the potential for leguminous and cruciferous crops to increase N provision to following cereal crops (Assefa et al., 2018; Dresbøll et al., 2016; Oliveira et al., 2019; Rezgui et al., 2020; Zhao et al., 2022). In Angus et al. (2015) review, preceding wheat with legumes or canola, was shown to increase wheat grain yield on average by 0.9 and 0.8 t ha^{-1} respectively, while barley only induces an average yield increment of 0.2 t ha^{-1} compared to monocropping systems.

Fertilisation practices are another subject of great focus in the search for increased sustainability in agricultural systems. There is a growing trend for the use of waste products as organic fertilisers over the use of chemical fertilisers to improve soil quality while recycling plant nutrients and carbon from the food production chain back into the soil (Seleiman et al., 2020). Digestate is a by-product derived from anaerobic digestion, a process which its main goal is biogas production by breakdown of organic matter. The raw material used is usually made up of animal and crop waste, but also household and industrial waste, making it a process with high economic advantages and GHG mitigation potential (Daniel-Gromke et al., 2018). Fertiliser value of digestates is relatively high when compared to other organic fertilisers, but its quality will mainly depend on the feedstock. Although high levels of plant nutrients are kept when compared to the original material, there is a reduction in carbon content and an ammonia content increase, which should lead to a faster N release for the crops, but still increasing the soil organic N pool compared to mineral fertilisers (Gutser et al., 2005; Walsh et al., 2012).

An untreated digestate (UD) has a high-water content which poses difficulties to storing, transport and application on the field. Liquid-solid separation by centrifugation is a common technique to obtain a more concentrated product. However, the solid fraction only reaches dry matter concentrations below 30% and most of the total N will remain in the liquid fraction, reducing its fertiliser potential (Grillo et al., 2021). Drying instead of mechanical separation can further concentrate the raw digestate, while maintaining greater levels of N in the product. Solar drying becomes a cost-effective method in regions with high clear sky irradiance and low air moisture (Salamat et al., 2022). Still, since the UD has a high pH, ammonia volatilization may be exacerbated by the drying process, so a pre-acidification of the product by sulfuric acid addition is an efficient method to prevent N losses at pre- and post-application (Pantelopoulos et al., 2016). There is still scarce research on crop performance under dried acidified digestate (DAD) fertilisation. While for UD, yield results are variable compared to mineral fertilisers, also depending on the studied crops and application rates (Barłóg et al., 2020; Siebielec et al., 2018; Šimon et al., 2015).

Differences in fertilisation practices and crop precedent should also affect the grain quality of crops. Since protein intake is crucial in human and animal diet, grain N concentration (GNC) is also an important indicator of productivity (Jha et al., 2022). Besides, the efficiency of the production systems must be considered, as the ultimate goal is input optimisation. N uptake efficiency (NUpE) and water use efficiency (WUE), along with soil nitrate dynamics are useful to determine which management practices increases the sustainability of the cropping system (Grillo et al., 2021; Jacobsen et al., 2012; st. Luce et al., 2020). Given the aforementioned past literature, it was hypothesised that:

1. A diverse crop rotation will result in higher soil nitrates availability, higher wheat grain yield, GNC and WUE than in a cereal crop rotation.
2. Dried acidified digestate is a suitable substitute to the mineral fertiliser in terms of soil nitrates availability, crop productivity, GNC and NUpE.

2. Material and methods

2.1. Experimental design

To accomplish the objective, an experimental field was set up located in the province of Lleida, Catalonia, Spain (41°42'36"N 0°26'21"E). The soil of the site classifies as mesic calcixerolic-xerochrept (Soil Survey Staff, 2022) of clay loam texture with a depth of 60 cm limited by a petrocalcic horizon. Soil pH is of 8.3, with 44% of calcium carbonate equivalent and 38 g kg^{-1} of soil organic matter (SOM) content.

The experiment had a duration of three cropping seasons (2019–2020, 2020–2021 and 2021–2022). Before the setup, there was an alfalfa (*Medicago sativa* L.) cropping system in place, followed by cereal cropping for one year. A randomized block design was adopted where 5 crops were grown under two different rotations: a cereal rotation composed by barley (*Hordeum vulgare* L.) – triticale (*X triticosecale* Wittmack) – wheat (*Triticum aestivum* L.) and a diverse rotation including canola (*Brassica napus* L.) – pea (*Pisum aestivum* L.) – wheat. The three phases of the rotations where present in each year. Plot arrangement was fixed for each fertilisation treatment and crop sequence and replicated over three blocks for a total of 72 plots with 75 m^2 per plot (Supplementary Fig. A.1). Fixed references were placed in the field to be sure that the location of the plots would not change across years. 'Artur Nick' wheat, 'Scrable' barley, 'Senatrit' triticale and 'Mythic' pea were sown in November at a sowing rate of 450, 400, 450 and 180 seeds m^{-2}, respectively. 'ES Imperio' canola was sown between September and October at 80 seeds m^{-2}.

Sprinkle irrigation was applied at sowing to facilitate canola germination and resumed at the end of winter until crop maturity. Irrigation rates and periods were the same for all crops, which were calculated following the guidelines of the Agriculture Department of the Regional Government of Catalonia based on Allen et al. (1998) method, considering the typical irrigation needs and growing cycle of wheat, the meteorological data of the area and the type of irrigation system. Information on phytosanitary applications can be consulted in Supplementary Table A.1. Harvesting was done using a combine harvester (WINTERSTEIGER Classic). The straw was chopped and spread evenly in each plot for the summer fallow. Specific dates for sowing, flowering or heading, maturity and harvest are available in Supplementary Table A.2.

Soil preparation was done by chisel ploughing at 40 cm, followed by disc harrowing at 20 cm and rotary harrowing. For each crop, there were four different fertilisation treatments: Untreated Digestate (UD), Dried Acidified Digestate (DAD), Mineral Fertiliser (MF), and a Control (C) without fertilisation. On average, digestate feedstock was composed by 50% pig manure, 30% slaughterhouse sewage sludge, 9% municipal sewage sludge, 6% dairy sewage sludge and 5% brewery sewage sludge. Further details on anaerobic digestion and digestate treatment procedures (i.e., acidification and solar drying) are described in Morey et al. (2023). The main chemical properties of digestate products are shown in Table 1. Application of digestates was done as basal-dressing at a rate of 140 kg Total N ha^{-1}. UD was applied using a slurry applicator, while the DAD and MF were applied manually. For the MF treatment we applied 50 kg N ha^{-1} as basal-dressing using di-ammonium phosphate in 2019 and ammonium sulphate in 2020 and 2021. At this stage, 60 kg K ha^{-1} was also applied as potassium chloride. Calcic ammonium nitrate was later applied as top-dressing at a rate of 90 kg N ha^{-1}, except for pea. No fertiliser was applied in the C treatment throughout the experiment.

2.2. Soil and crop sampling and processing

Soil samples were taken for nitrate and water content determination from 0 to 60 cm of depth in all plots, as the major rooting zone was

Table 1
Mean values of the main chemical properties of the untreated digestate (UD) and the dried acidified digestate (DAD).

	pH	DM[a]	Carbon	Nitrogen	NH_4-N	Phosphorus	Potassium
		g kg^{-1} FM[b]			g kg^{-1} DM		
UD	8.2	60.1	334.0	104.4	68.8	29.0	15.8
DAD	5.4	916.8	269.1	64.8	33.3	21.6	13.9

[a] DM: Dry Matter
[b] FM: Fresh Mass

limited by the petrocalcic layer below this depth. Samples were done at the initial stage of the season (i.e., before basal-dressing), at tillering stage of cereals (BBCH: 22–29) and at the final stage of the season (i.e., shortly after harvest). Soil nitrate nitrogen content (SNNC; kg ha^{-1}) was determined by water extraction followed by segmented flow analysis (Seal Analytical). Soil water content (SWC; mm) was obtained by weight difference after drying soil samples at 100 °C for 48 h. Total N content of the soil at the end of the experiment was determined by the Dumas combustion method after taking samples from 0 to 30 cm with an auger.

Grain yield in dry weight was calculated with data from the combine harvester and grain moisture tester (GAC 2100). Straw biomass production was calculated via harvest index by collecting one linear metre samples of aboveground plant material prior to harvesting, while for pea 1 m^2 of aboveground biomass was collected. Both GNC and straw N concentration values were obtained by grinding dried samples from harvest to 1 mm dimension followed by the Dumas combustion method.

2.3. Calculations

The NUpE is the ratio between N uptake and N supply and was calculated as in López-Bellido and López-Bellido (2001). The N uptake was calculated as the sum of the products of the GNC and straw N concentration by the grain yield and straw biomass, respectively. The N supply was obtained by adding the N mineralisation and fertiliser N to the soil nitrate concentration at sowing. N mineralisation was estimated as the N uptake plus the soil nitrate difference between harvest and sowing in the control plots averaged by each block and year. Total N content was considered for the fertiliser N of the digestates, as the most conservative approach.

The grain WUE was calculated as the ratio between grain yield and water use (WU), which is given by Eq. (1):

$$WU = SWC_i - SWC_f + P + I - L \tag{1}$$

where SWC_i and SWC_f are, respectively, the initial and final SWC in each season, P is the accumulated precipitation values obtained from the closest meteorological data, and I is the applied irrigation between sowing and harvest of each crop. L accounts for the water losses by percolation, assuming losses by runoff were null due to the topography of the field. Capillary rise was considered to be negligible, as the hydrogeologic unit of the site classifies as an aquitard with low permeability with local aquifers, evidenced by the observed petrocalcic horizon below 60 cm of depth. To estimate percolation, a soil water balance was simulated using the dual crop coefficient method (Allen et al., 1998) along the cycle of the crops. Daily precipitation, minimum relative humidity, wind velocity and reference evapotranspiration (ET_0) data were retrieved from the closest meteorological stations, where the latter was computed according to the Penman-Monteith method (Allen et al., 1998). Climate data and daily irrigation data were merged to compute the soil evaporation coefficient (K_e). Total and readily evaporable water of the soil (39 and 11 mm, respectively) were also considered, where the former was calculated using measured values for volumetric soil water content at field capacity and wilting point (0.36 and 0.19 m^3 m^{-3} respectively) using the gravimetric method. Lengths of development stages, basal crop coefficient curves (K_{cb}), crop height and exposed soil fraction (f_{ew}) for pea, canola and cereals were based in Allen et al. (1998) to calculate the crop evapotranspiration (ETc) and were adapted to field observations (e.g., flowering and maturity dates) and to the measured SWC points (Supplementary Table A.3). When the simulated SWC surpassed the threshold of the maximum water holding capacity of the soil from 0 to 60 cm of depth (i.e., 213 mm), the excess was accounted as water loss by percolation.

2.4. Statistical Analysis

Statistical tests were performed using JMP 16. Except for soil nitrate dynamics and crop WU, all ANOVA were performed separately by crop. Year, fertilisation and rotation (i.e., cereals and diverse) were considered as main effects of the wheat ANOVA, where the latter was nested in each year, since only the first cycle of the rotation was tested. For the remaining crops, only year and fertilisation were considered as main effects. NUpE ANOVA was done excluding the control treatment of every crop. Canola suffered crop failure due to heavy rains just before harvest of the last season. Thus, for yield, WUE and NUpE responses of canola, only the data from the first two seasons was considered. Canola GNC data for the last year was retrieved from the samples taken for harvest index calculation. Soil nitrate data was log-transformed for the ANOVA and the means comparison tests, using the same effects as in wheat ANOVA. Slice tests were added for each sampling moment. Mean comparisons were performed using the Tukey HSD test and the Student's T test when comparing factors with only two levels. Plots were built using RStudio. For simplification, year effect levels refer to the years of harvest of each season.

3. Results

3.1. Weather conditions and irrigation

Monthly average temperature and accumulated precipitation are show in Fig. 1. Annual accumulated precipitation was 518, 379 and 302 mm for the first, second and third seasons, respectively. Overall, the last season was also the hottest, with higher average temperatures in spring and summer. Crops received 127, 231 and 206 mm of water in the three consecutive growing seasons by sprinkle irrigation. Canola additionally received 20 mm of water in the first two seasons and 35 mm in the last season for germination purposes. Although irrigation rates were increased, total water inputs of the last two seasons were not as high as in the initial season. According to the soil water balance simulation (Supplementary Fig. B.1), 76.6, 24.5 and 27.2 mm of water were lost by percolation in the first, second and third season, respectively. All percolation events occurred between sowing and cereal tillering (i.e., from November to February). Estimated percolation for the different crops is available in Supplementary Table B.1.

3.2. Crop precedent effect on wheat performance

Wheat yields changed according to the cropping season ($p = 0.011$) and the rotation where it was inserted ($p < 0.001$). Averages ranged from 4.45 t ha^{-1} in 2022 when preceded by barley and triticale to 7.46 t ha^{-1} in 2021 when preceded by pea (Fig. 2a). In 2021, yields were similar whether wheat followed pea or triticale. In 2022 we observed a strong yield reduction. However, while wheat in the diverse rotation only suffered an average reduction of 1.30 t ha^{-1} in yield compared to

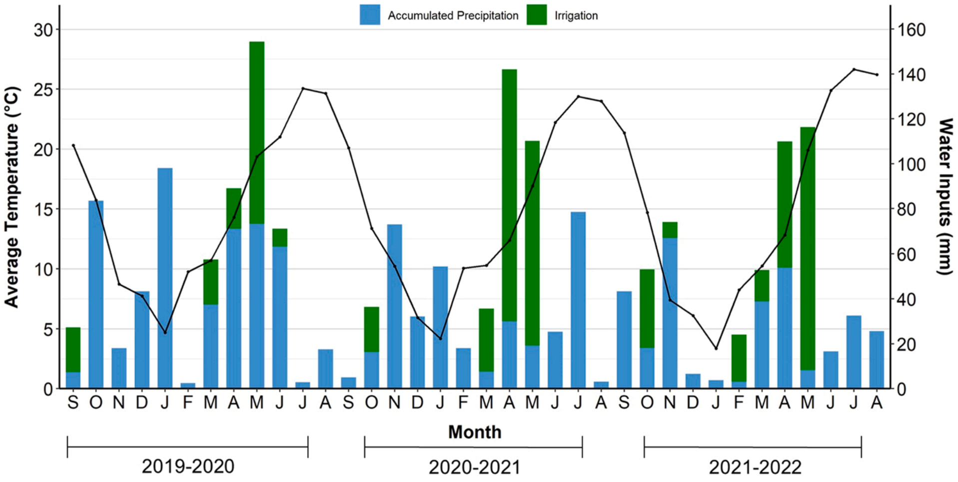

Fig. 1. Monthly average air temperatures (continuous line; °C) and water inputs comprised of accumulated precipitation (blue bars; mm) and irrigation (green bars; mm). Data shown for the three seasons from September 2019 to August 2022.

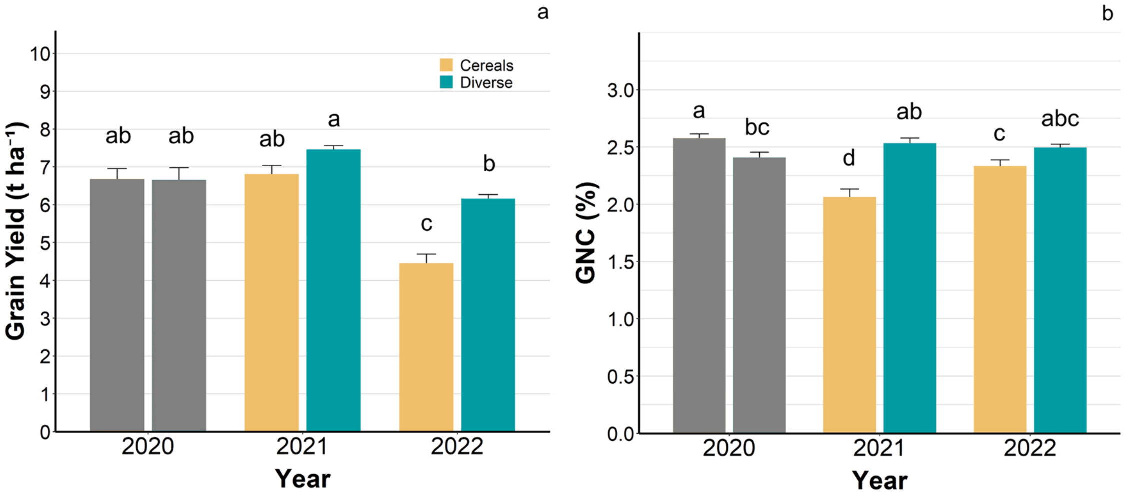

Fig. 2. Grain yield (a; t ha^{-1}) and grain N concentration (GNC; b; %) means of wheat according to year of harvest and crop precedent in each year of the rotation: pea (diverse; blue) or triticale (cereals; yellow) in 2021 and canola-pea (diverse; blue) and barley-triticale (cereals; yellow) in 2022. Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$).

the previous year, the wheat yield in the cereal rotation was 2.36 t ha^{-1} lower, resulting in a significant average yield difference of 1.79 t ha^{-1} in the last year. It is worth noting that the variability in yields tended to be lower in the two years of the diverse rotation.

Wheat GNC followed a different pattern from yield, where there were differences due to the preceding crops only in 2021 (Fig. 2b). In this year, GNC was overall lower than other years. Still, while wheat after pea reached similar values as in the other years, when preceded by triticale, wheat GNC had the lowest observed mean at 2.06%.

Although wheat yields were relatively high in the first year, the yearly mean of the WUE was low due to a higher WU in this season (Table 2). Contrastingly, the WUE of wheat peaked in 2021($p = 0.001$) as the WU was lower, reaching an average of 19.9 kg ha^{-1} mm^{-1} with no differences between rotations. In 2022, wheat in the diverse rotation yielded 4.6 kg ha^{-1} mm^{-1} more than in the cereal rotation ($p < 0.001$). Although there were no significant differences in WU, there was 15 mm less available water when sowing the wheat after canola than the wheat following triticale ($p = 0.001$). This result is in accordance with the crops WU means comparison along the study, where canola used around 35–108 mm more water than other crops ($p < 0.001$; Fig. 3). Overall, crops used more water in 2020 than in the following years ($p < 0.001$) despite higher losses by percolation.

Although there was a trend for higher NUpE in wheat in the diverse rather than the cereal rotation, there were no significant differences between rotations nor between seasons (Fig. 4).

3.3. *Fertilisation effect on field crops performance*

Fertilisation practices affected the yield of wheat regardless of crop precedent ($p = 0.035$). When fertilised with DAD, wheat yielded on average 0.72 t ha^{-1} more than the control treatment while other products were not able to significantly raise wheat yields (Fig. 5). The yields of all the remaining crops differed along the years (Supplementary Table B.2), usually reaching lower levels in 2022. Pea had the steepest yield decrease, with an average yield of 1.46 t ha^{-1} in 2022. When it comes to fertilisation, only canola and barley had a response in yield ($p = 0.006$ and $p = 0.014$). There was not an obvious pattern between the responses of these crops and wheat. Canola performed the best when fertilised with MF, with an average yield of 5.91 t ha^{-1}, while canola fertilised with DAD provided the lowest yields, averaging 4.89 t ha^{-1}. Intermediate yields of 5.04 t ha^{-1} were reached by fertilising canola with UD. As for barley yield, UD was the best performing fertiliser and MF the worst,

Table 2

Means and standard errors (SE) of initial soil water content (SWC_i; mm), water use (WU; mm) and water use efficiency (WUE; kg ha^{-1} mm^{-1}) of wheat according to season and rotation. Means followed by different letters are significantly different at $p < 0.05$ by Tukey HSD or Student's T test when comparing two factor levels. SWC_i values for 2020 were excluded from statistical analysis.

	SWC_i (mm)		WU (mm)		WUE (kg ha^{-1} mm^{-1})	
	n	mean ± SE	n	mean ± SE	n	mean ± SE
Year						
2020	24	137.6 ± 3.1	24	463.4 ± 3.5^{a}	24	14.4 ± 0.5^{b}
2021	24	116.6 ± 2.7^{b}	24	360.1 ± 4.9^{c}	24	19.9 ± 0.5^{a}
2022	24	137.6 ± 3.1^{a}	24	398.0 ± 2.4^{b}	23	13.5 ± 0.6^{b}
Rotation						
Cereal (2020)	12	134.7 ± 5.0	12	459.6 ± 6.1^{a}	12	14.6 ± 0.7^{c}
Diverse (2020)	12	140.6 ± 3.8	12	467.2 ± 3.3^{a}	12	14.2 ± 0.7^{c}
Cereal (2021)	12	123.1 ± 4.0^{bc}	12	355.9 ± 8.9^{a}	12	19.3 ± 0.8^{a}
Diverse (2021)	12	110.17 ± 2.8^{c}	12	364.4 ± 4.1^{a}	12	20.5 ± 0.4^{a}
Cereal (2022)	12	145.4 ± 4.2^{a}	12	402.9 ± 3.2^{a}	11	11.0 ± 0.6^{c}
Diverse (2022)	12	129.9 ± 3.6^{b}	12	393.1 ± 3.2^{a}	12	15.7 ± 0.3^{b}

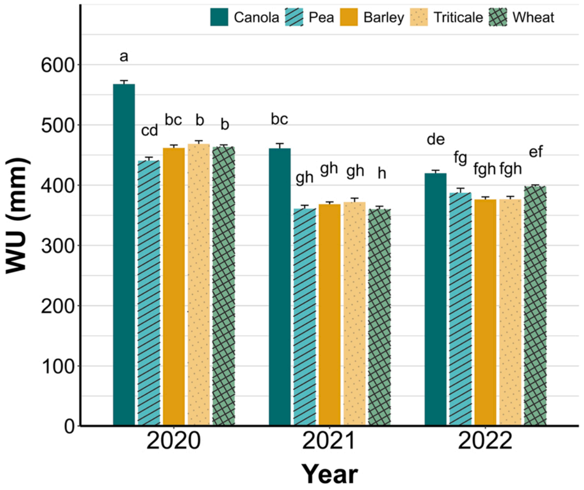

Fig. 3. Mean water use (WU; mm) of canola, pea, barley, triticale and wheat in each year of the experiment. Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$).

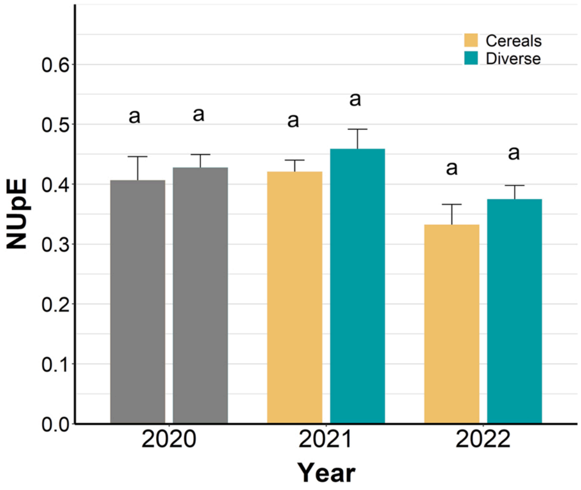

Fig. 4. N uptake efficiency (NUpE) means of wheat according to crop precedent in each year of the rotation: pea (diverse; blue) or triticale (cereals; yellow) in 2021 and canola-pea (diverse; blue) and barley-triticale (cereals; yellow) in 2022. Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$).

with yields averaging to 8.20 and 7.44 t ha^{-1}, respectively.

The GNC of all crops were affected by fertilisation, except pea (Fig. 6). For the fertilised wheat, all values were similar and higher than the control. However, there was a significant interaction between fertiliser treatments and years ($p = 0.013$). This is mainly due to a general decrease in GNC in 2021, except for wheat fertilised with DAD. Barley and triticale had similar responses, with higher GNC when the crops were fertilised with MF, rather than with UD or DAD. Canola GNC values were similar across the tested fertiliser products. However, the MF was the only one which provided higher GNC than the control treatment.

The WUE means of both canola and pea tended to be lower than of cereals, ranging close to 10.1 kg ha^{-1} mm^{-1}, while barley, triticale and wheat had WUE averages of 19.7, 16.5 and 16.0 kg ha^{-1} mm^{-1} respectively (Fig. 7). Except for canola, the WUE of each crop changed significantly across seasons (Supplementary Table B.2), peaking in 2021. However, while the WUE of barley and triticale were lowest in 2020, the WUE of pea was lowest in 2022, averaging to only 3.8 kg ha^{-1} mm^{-1}. There were no significant differences in the initial SWC, WU and WUE of wheat due to fertilisation nor interactions with rotations and years. The WU of the remaining crops were also similar between fertilisation treatments. Still, the WUE of canola and barley were different according to fertilisation treatment ($p = 0.004$ and $p = 0.017$), following a similar pattern to the grain yield differences.

Pea and barley were the only crops that had significantly different NUpE across the years ($p = 0.008$ and $p = 0.004$). The average NUpE of pea went from 0.75 in 2021 to only 0.27 in 2022, while barley NUpE went from 0.28 to 0.52 in the first two seasons. Averaged by years, NUpE levels ranged from 0.38 to 0.61 with both extremes being found in mineral fertilised crops (Fig. 8). While the NUpE of cereal crops were unaffected by fertilisation, we observed changes in canola and pea ($p = 0.044$ and $p = 0.024$). Canola had a significant NUpE increase of 49% when fertilised with MF compared to the average of both digestates, while for pea this increase was of 23%.

3.4. Rotation and fertilisation effect on soil nitrate dynamics and total N content

Except for the middle season, initial nitrate availability was high, averaging at 450.6 kg N ha^{-1} (Table 3). However, in both theses seasons there was a strong decline in nitrate levels until tillering followed by a net increase after harvesting regardless of treatment (Fig. 9).

There was a significant effect of rotation on SNNC at the start and end of the seasons ($p = 0.002$ and $p < 0.001$, respectively). However, there was also a significant interaction effect between fertilisation and rotation ($p = 0.036$ and 0.049 respectively), resulting in only two sampling moments with noticeable differences between rotations (Fig. 9a). Before sowing there was a general reduction in the rotation effect when

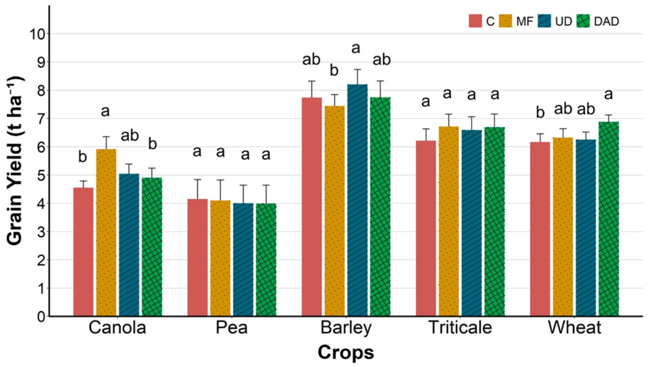

Fig. 5. Mean grain yield (t ha^{-1}) of canola, pea, barley, triticale and wheat according to fertilisation treatment: Control (C; red); Mineral Fertiliser (MF; yellow); Untreated Digestate (UD; blue); Dried Acidified Digestate (DAD; green). Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$) for each crop.

fertilising with MF. While after harvesting, rotation effect was consistent only for DAD fertilised plots. When evaluating each sampling moment, significant differences in SNNC due to the rotations and fertilisation treatments were only noticeable after the 2021 harvest. At this point, the soil of diverse rotation plots had on average 54.6 kg N ha^{-1} more than the cereal rotation plots. This difference almost doubled during the summer fallow but remained insignificant until the end of the experiment. It is worth noting that SNNC in canola plots were on average 100 kg N ha^{-1} lower than in pea plots at cereal tillering and after harvest (data not shown).

Throughout the experiment, DAD fertilised plots had on average 68.8 kg N ha^{-1} more than the control plots at tillering ($p = 0.002$). Although other fertiliser treatments were not able to significantly raise nitrate levels at this stage, top-dressing of the MF was to be applied. After harvesting there was a higher SNNC in the soil of DAD and MF fertilised plots rather than the control and UD fertilised plots ($p < 0.001$). However, there was an interaction effect between fertilisation and years ($p = 0.014$), as differences were only significant in the last two seasons (Fig. 9b). There was no significant fertilisation effect for the soil nitrates content at the beginning of the two last seasons (i.e., before basal dressing).

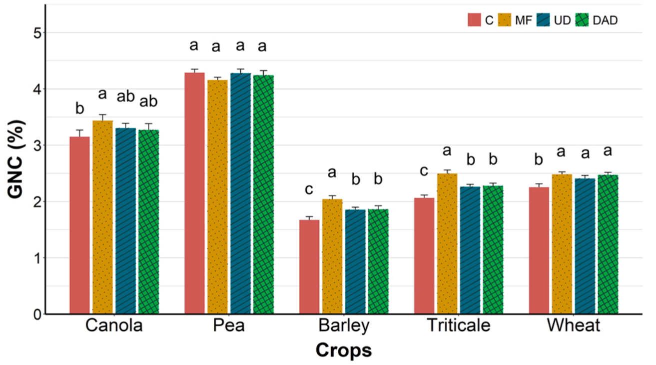

Fig. 6. Mean grain N concentration (GNC, %) of canola, pea, barley, triticale and wheat according to fertilisation treatment: Control (C; red); Mineral Fertiliser (MF; yellow); Untreated Digestate (UD; blue); Dried Acidified Digestate (DAD; green). Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$) for each crop.

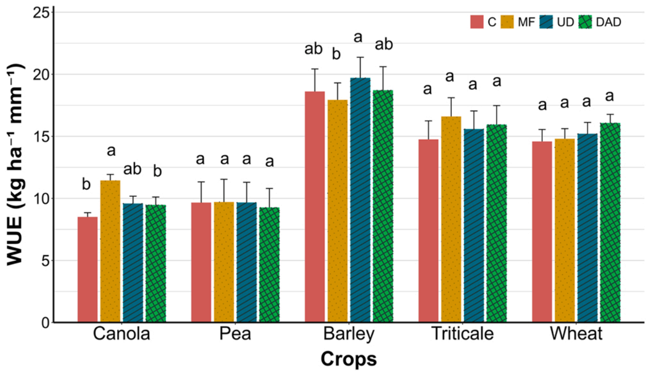

Fig. 7. Mean WUE (kg ha^{-1} mm^{-1}) of canola, pea, barley, triticale and wheat according to fertilisation treatment: Control (C; red); Mineral Fertiliser (MF; yellow); Untreated Digestate (UD; blue); Dried Acidified Digestate (DAD; green). Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$) for each crop.

At the end of the experiment, there were differences in the soil total N content due to crop rotation and fertilisation ($p = 0.023$ and $p = 0.011$, respectively). There was 0.6 t N ha^{-1} more in the soil were there was the diverse rotation instead of the cereal rotation (Table 3). Similarly, plots fertilised with the DAD had on average 1.3 t N ha^{-1} more than plots that received MF.

4. Discussion

4.1. Irrigated winter cropping with diverse versus cereal rotations

A more diversified crop rotation has shown to be effective in increasing wheat yields compared to a full cereal rotation, in accordance with Preissel et al. (2015) and Angus et al. (2015) findings. Although water use was similar between the two last seasons, there was a sharp decrease in yields in the final season, mainly due higher temperatures in spring and summer which shortened the grain filling stage by 10 days compared to the previous year (Supplementary Table A.2). Nonetheless, there was a stronger yield loss mitigation when wheat was preceded by pea and canola rather than by other cereals (Fig. 2a). Besides, there was less variability in yields due to fertilisation treatments in the diverse rotation. Yield stabilization has been reported as one of the main benefits in a diversified cropping system in hot and dry climates (Gaudin et al., 2015). This is confirmed by the differences found in the WUE of wheat due to crop precedent in the last year (Table 2). Although there were no changes in the WU of wheat due to the preceding crop, the SWC before sowing wheat was lower after growing canola. Canola used more water than other crops, in which most of this increment was mainly due

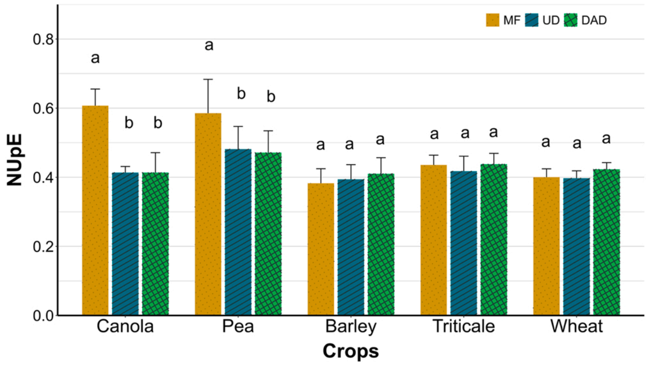

Fig. 8. Mean NUpE of canola, pea, barley, triticale and wheat according to fertilisation treatment: Mineral Fertiliser (MF; yellow); Untreated Digestate (UD; blue); Dried Acidified Digestate (DAD; green). Standard errors are represented by whisker bars. Different letters indicate significant differences according to the Tukey HSD test ($p < 0.05$) for each crop.

Table 3

Means ± standard errors (SE) of soil nitrate nitrogen content (SNNC; kg N ha^{-1}) at the start (initial), cereal tillering stage (tillering) and end of the season (final), and soil total N content (t N ha^{-1}) at the end of the experiment according to year, rotation and fertilisation treatment. Means followed by different letters are significantly different at $p < 0.05$ by Tukey HSD or Student's T test when comparing two factor levels. Initial soil nitrate content in 2020 was excluded from statistical analysis.

	SNNC (kg N ha^{-1})						Total N Content (t N ha^{-1})	
	Initial		Tillering		Final		Final	
	n	mean ± SE	n	mean ± SE	n	mean ± SE	n	mean ± SE
Year								
2020	69	456.9 ± 14.5	72	70.2 ± 4.7^{b}	71	192.7 ± 12.0^{a}	-	-
2021	72	254.7 ± 9.9^{b}	72	199.5 ± 11.0^{a}	72	143.2 ± 8.3^{b}	-	-
2022	72	438.0 ± 14.1^{a}	72	202.9 ± 12.3^{a}	72	251.1 ± 18.0^{a}	72	9.2 ± 0.1
Rotation								
Cereal (2020)	35	496.5 ± 22.7	36	67.2 ± 6.3^{b}	35	177.1 ± 10.3^{b}	-	-
Diverse (2020)	34	416.2 ± 15.3	36	73.2 ± 6.9^{b}	36	207.9 ± 21.3^{ab}	-	-
Cereal (2021)	36	247.3 ± 12.4^{c}	36	193.5 ± 10.8^{a}	36	115.9 ± 9.1^{c}	-	-
Diverse (2021)	36	262.1 ± 15.5^{c}	36	205.5 ± 19.4^{a}	36	170.5 ± 12.5^{b}	-	-
Cereal (2022)	36	384.6 ± 19.1^{b}	36	181.5 ± 9.8^{a}	36	220.3 ± 14.0^{ab}	36	8.9 ± 0.2^{b}
Diverse (2022)	36	491.3 ± 21.5^{a}	36	224.2 ± 22.3^{a}	36	282.0 ± 32.6^{a}	36	9.5 ± 0.1^{a}
Fertilisation*								
C	36	320.8 ± 25.2^{a}	54	122.8 ± 10.2^{b}	53	161.2 ± 14.5^{b}	18	9.2 ± 0.3^{ab}
MF	36	379.7 ± 26.6^{a}	54	165.7 ± 14.3^{ab}	54	229.5 ± 13.8^{a}	18	8.6 ± 0.3^{b}
UD	36	345.8 ± 26.6^{a}	54	150.0 ± 13.4^{ab}	54	169.1 ± 11.2^{b}	18	9.1 ± 0.3^{ab}
DAD	36	339.0 ± 20.9^{a}	54	191.6 ± 16.8^{a}	54	222.4 ± 14.5^{a}	18	9.9 ± 0.3^{a}

*Control (C), Mineral Fertiliser (MF), Untreated Digestate (UD) and Dried Acidified Digestate (DAD).

to the additional precipitation by sowing in October, earlier than other crops. Still, canola was also dependent on additional irrigation for a successful germination, as at least 20 mm of water inputs are needed (Koszel et al., 2020). In our Mediterranean conditions, this amount is usually not available at optimal canola sowing time (Álvaro-Fuentes et al., 2009). Besides, the WUE of cereals was not as affected as the WUE of pea in 2022, when there was a reduction of WU compared to the first season. Thus, a full cereal rotation should be more appropriate in systems with low water availability. When irrigated systems are available though, choosing either rotation will allow a much lower irrigated water use than the typical irrigated summer cropping systems of the Ebro Valley. On average, less than a third of the net irrigation requirements of corn (*Zea mays* L.) or alfalfa was applied. A change to irrigated winter cropping systems can potentially safeguard farmers income in a future scenario with lower water availability and higher irrigation restrictions (Cavero et al., 2017; Pareja-Sánchez et al., 2019; Zhao et al., 2015). Canola and pea yields tended to be lower and more sensitive to climate conditions, as they were more affected by rainfall at maturity in the last year. Still, lower yields from these crops may be financially compensated by fertiliser and pesticide savings for the cereal crops (Preissel et al., 2015), but also by the producer prices, which have been 50% higher compared to triticale and barley in the last 10 years in Spain (FAO).

Differences in N provision due to contrasting crop precedents seemed to have played a role in wheat development. Pea has lower soil N needs due to its capacity to fixate atmospheric N, ultimately acting as a N input for the system (Zhao et al., 2022). N uptake of canola is high during the growing cycle, but it also leaves high amounts of N after harvest via residues (Dresbøll et al., 2016). We were also able to observe that even when there is no yield increase, we can still obtain a higher GNC when preceding wheat with pea. A slower and more continuous N release from legume residues can mean a late N supply, increasing GNC and potentially grain protein content, which can increase revenue via unitary price (Flower et al., 2017; López-Bellido and López-Bellido, 2001). It is worth noting that other unaccounted factors might have also affected wheat development depending on the crop precedent, such as pest and weed control, or differences in other nutrients levels (Preissel et al., 2015). Still, wheat yield and WUE increments due to canola and pea precedent was not accompanied by an increase in NUpE (Fig. 4), as the increase in wheat N uptake was proportional to the increase in N provision. Therefore, our hypothesis that a diverse crop rotation would result in higher soil nitrate availability, and higher wheat grain yield, grain quality and WUE than in a cereal crop rotation was confirmed.

Concerning nitrate dynamics of the whole experiment, we observed that there was an already high N availability and N mineralisation rates, as there was a nitrate level increase in unfertilised plots even when crop N uptake was high (Fig. 9). It is common to find N surplus in agricultural fields of many regions in Spain and Europe where there is high livestock density (Cruz et al., 2019). Besides mineral fertilisation, high amounts of pig slurry have been applied in these fields over the last years (Sanz-Cobena et al., 2014), evidenced by the observed SOM content and SNNC. The observed soil nitrate level decrease coupled with the exceptional percolation events suggest that there were some nitrate losses by leaching in the system due to excessive precipitation. Employing a rotation with grain legumes rather than non-leguminous crops resulted in wheat yield increments but also lead to moments with higher SNNC, which can potentially increase N losses in the system (Hansen et al., 2019). Still, canola high N uptake capability (Dresbøll et al., 2016) can counteract this effect. Besides, a reduction in fertiliser inputs or the adoption of mitigation strategies (e.g., incorporation, injection) can further prevent N losses, allowing for resource use reduction especially in systems characterized by high N surpluses (Preissel et al., 2015; Sanz-Cobena et al., 2014).

Total N content in the soil at the end of the experiment was also higher following the diverse rotation (Table 3). As most of this N is in the organic form, it should be more easily retained in the soil than mineral nitrogen and be steadily released to satisfy the crops N demands, potentially reducing further fertiliser N needs (Hansen et al., 2019).

4.2. Fertilisation with digestates

The DAD was the only fertiliser able to increment wheat yields with also high GNC. Indeed, the DAD generated similar nitrate levels than in MF fertilised plots on the average season, contrary to the UD. In Pantelopoulos et al. (2016), it was shown that acidifying and drying digestates increased the net N mineralisation potential, in part due to an increase in carbon stability. Besides, in Wei et al. (2021) meta-analysis, the authors have shown that the physico-chemical properties of each organic fertiliser are major determinants for the potential reduction of N losses comparing to mineral fertilisers. Thus, the acidification and drying treatments of the digestate might have been crucial to prevent N losses in the soil (Wagner et al., 2021). Soil nitrate levels in mineral N fertilised plots were generally independent of the implemented rotation, contrasting to plots fertilised with the DAD. It is possible that the MF application suppressed the microbial processing of the extra organic N from the pea and canola residues, reducing the potential benefits provided by the diverse rotation (Breza et al., 2023).

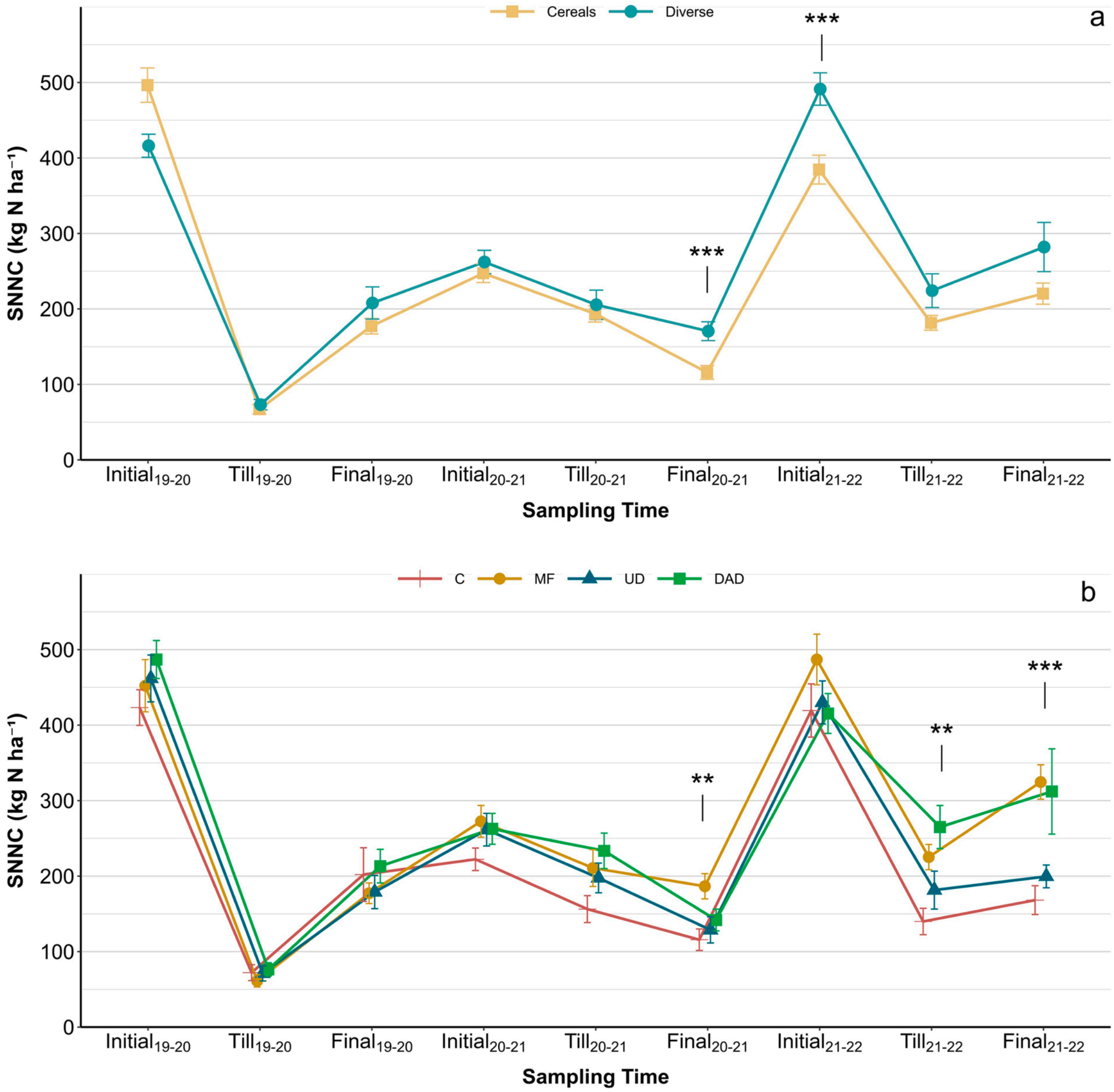

Fig. 9. Soil nitrate nitrogen content (SNNC; kg N ha^{-1}) from 0 to 60 cm of depth at the start, cereal tillering stage and end of each season (2019–2020, 2020–2021, 2021–2022) as affected by crop rotation (a) and by fertiliser treatment (b). Standard errors are represented by whisker bars. Least significant differences (*:$p< 0.05$; **:$p < 0.01$; ***:$p < 0.001$) are represented in each sampling moment using slice tests.

Still, at the end of the experiment there were higher levels of total N in DAD fertilised soils compared to the MF, regardless of the implemented rotation (Table 3). Application of DAD as organic fertiliser should then hinder organic and mineral nitrogen deficiency, preventing reduced yields or increased fertiliser needs in the long-term (Ghimire et al., 2018; Sanz-Cobena et al., 2014). Further years of experiment would be needed to determine the evolution of soil N fertility and crop yields under this type of products.

High nitrate availability in the soil was a limitation to this study as fertilisation effect on the yields of some of the crops was masked and the DAD did not show a clear advantage. Other crop responses might be explained by differences in the N demands along the growing cycle of each crop. For example, split-application should explain why canola yielded higher with MF (Fig. 5), ultimately resulting in higher WUE and NUpE. As canola growth is limited during winter, fall N application has a low effect on canola yield (Sieling and Kage, 2010). When temperatures increase in spring there is a spike in N uptake which can be satisfied by the top-dressing of MF (Porter et al., 2020), but not by the steadier N release of the digestates applied in fall (Gutser et al., 2005). Thus, for better canola yields, application of digestates should be done before main shoot elongation (Koszel et al., 2020). As for barley, N demands are lower than wheat, in part due to a higher N translocation efficiency (Delogu et al., 1998), which resulted in intermediate yields when no fertiliser was applied. Although mineral fertilised barley had lower yields than barley fertilised with UD, the GNC was higher (Figs. 5 and 6). Grain quality of has been shown to be more easily affected by spring N applications than yield (Siller et al., 2021), also evidenced by the triticale GNC. Thus, split-application ultimately resulted in a similar NUpE than barley fertilised with digestates. The lack of response of pea to different fertiliser products is somewhat expected due to the high N availability and its biological N fixation capacity. It is worth noting that NUpE of pea was higher with chemical fertilisation, since only 50 kg N ha^{-1} was applied. These results reinforce how crop rotations that include legumes allow for fertiliser savings (Preissel et al., 2015).

In the case of wheat, the DAD performed similar to the MF in terms of nitrate provision, crop productivity, GNC and NUpE, confirming our second hypothesis. However, exceptions were found for other crops, as previously discussed. Although digestate suitability for fertilisation of field crops has been document before (Barłóg et al., 2020; Šimon et al., 2015; Walsh et al., 2012), there is also some discrepancies in the literature due to differences in the post-treatments of digestates, in the application dates and techniques, and ultimately in the tested crops (de

França et al., 2021). Besides, it is difficult to reach a consensus about digestate fertiliser potential due to a high variability in the livestock used (e.g., animal waste, energy crops). These factors partially obstruct the widespread use of these products and the environmental benefits that they might provide (Daniel-Gromke et al., 2018; Kovačić et al., 2022). Future research focusing on digestate use as fertilisers should allow for a more thorough characterisation of these products, so that farmers can adjust application techniques and timings according to the expected nutrient release to the demands of each crop along the growing season.

5. Conclusions

This study has shown that diversifying winter crop rotations by integrating non-cereal crops can bring yield stability, grain N content and higher water use efficiency for irrigated wheat via increased nitrate and total N levels in the soil. Although a full cereal rotation should be overall more appropriate for water scarce cropping systems, a diverse rotation with irrigated winter crops instead of summer crops is still a viable solution for a possible scenario with increased scarcity of irrigated water. Moreover, fertilisation can be adjusted in rotations with N rich crops to reduce inputs and prevent N losses. Anaerobic digestates are by-products that have shown to be appropriate for fertilisation of field crops, allowing for a further reduction in chemical fertilisation. Still, different application strategies should be employed to better synchronise their N release according to the specific crop N demands. Although both digestate products have shown overall similar fertiliser performances with the mineral fertiliser, the dried acidified digestate has shown better capacity to retain N in the cropping system, which may result in increased yield stability in the long-term. Digestate application combined with efficient crop sequencing, can thus reduce chemical fertiliser dependency for farmers. There is although a need for a standardization of the different available digestate products according to their chemical composition and expected fertiliser performance for a broader use of these by-products as fertilisers.

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CRediT authorship contribution statement

Gonçalo Nascimento: Investigation, data curation, formal analysis, writing (original draft, review and editing), visualisation. **Dolors Villegas**: Conceptualisation, methodology, investigation, formal analysis, data curation, writing (review and editing), supervision, project administration, funding acquisition. **Carlos Cantero-Martínez**: Conceptualization, methodology, resources, writing (review and editing), supervision, project administration, funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dolors Villegas reports financial support was provided by European Union. Carlos Cantero-Martinez reports financial support was provided by the Spanish State Agency of Research.

Data availability

Data supporting the findings of this study are openly available in CORA at: https://doi.org/10.34810/data726.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126873.

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