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Fertiliser and Management Innovations Can Improve Nitrogen Use Efficiency and Reduce Nitrate Leaching in an Arable Cropping System

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Abstract

Increases in N fertiliser prices and awareness about the negative environmental impacts of reactive N highlight the need for innovations and practices that reduce loss of nitrogen from agricultural systems and improve nitrogen use efficiency. The use of nitrification inhibitors, controlled release fertilisers, and reduced intensity tillage practices, have been proposed to reduce N leaching and improve crop nitrogen use efficiency (NUE); however, more evidence is needed to verify the impact of these strategies in temperate arable cropping systems. We conducted three single season field trials to investigate the effects of: conventional tillage compared with no tillage on winter N leaching following destruction of a two-year grass/clover ley; a DMPP based nitrification inhibitor on an autumn ploughed ley and subsequent winter N leaching; and controlled-release urea (CRU) fertiliser during the cropping season on nitrogen use efficiency in potatoes. Winter NO_3^--N leaching was ~7 times higher in no tillage compared to conventional tillage. DMPP usage reduced soil NO_3^--N concentrations by 24% and NO_3^--N leaching by 72%. The use CRU at 85% of the recommended N rate improved the nitrogen use efficiency of the potato crop when compared to the recommended rate of nitrogen. The results demonstrated the potential to use inhibitors and controlled release fertilisers to reduce N losses during the drainage season and improve N use efficiency during crop growth. No tillage, while potentially improving soil health, may negatively affect water quality. Investigations of the impacts of these practices on rotational-scale N use efficiency is required.

Keywords: Nitrate leaching; Nitrification inhibitor (DMPP); Tillage; Controlled release urea; Nitrogen use efficiency

Abbreviations: CRU: Controlled release urea; DMPP: 3, 4 dimethyl pyrazole phosphate; NUE: Nitrogen use efficiency

Introduction

Farmers in humid temperate regions, face significant challenges to efficiently manage N supply to crops over the cropping year. During the growing season the risk of N losses from leaching is generally low as soil water tends to move upwards into the atmosphere through evaporation and transpiration; however, losses of N from ammonia volatilisation and denitrification can still reduce efficiency of N use during crop growth. In the late autumn and winter the soil water balance shifts so that net drainage dominates with a high risk of leaching if any surplus nitrates are present in the soil column. With increasing pressure from regulatory bodies to reduce N losses and the recent spike in N fertiliser prices, farmers are searching for ways to optimize the use of N during the growing season and mitigate N losses over the winter [1]. Innovations in tillage practice, use of nitrification inhibitors, and controlled release fertilisers, are all relatively accessible and easy to implement strategies which could significantly reduce N losses and improve crop N use efficiency.

The method of tillage used can affect soil processes that influence N leaching in different ways. Reduced disturbance of the soil in no till systems can increase soil moisture contents and decrease temperatures resulting in lower rates of N mineralisation. This decreases the pool of nitrate available for leaching during the winter drainage season (Zibilske & Bradford, 2007). In contrast, conventional tillage can promote rapid mineralization of organic nitrogen to nitrate through destruction of soil aggregates and exposure of previously protected pools of organic nitrogen , thus stimulating a flush of mineral N and increasing the risk of N leaching in the autumn [2]. But differences in soil physical properties can alter soil physical properties which affect downward water movement in the soil. Saturated hydraulic conductivity can be higher in no till systems due to the maintenance of root or earthworm preferential-flow channels which may increase water flow through the profile and enhance losses of N by leaching [3,4]. In conventional systems drainage may be inhibited by destruction of natural channels in the soil and development of a less permeable plough pan. The balance between N mineralisation and downward water movement in each system is still not fully understood. With the rapid increase in the uptake of no till crop production among regenerative farmers in the UK [5] is important that impacts on N losses to groundwater due to this practice are better understood.

Nitrification inhibitors are a broad group of substances which prevent *Nitrosomonas sp*. from converting NH_4^+ to nitrite NO_2^-. They have been studied for many years as technologies which can improve fertiliser N use efficiency and decrease denitrification and leaching losses of N [6]. Although several compounds have been tested as nitrification inhibitors only a few are commercially available, with the dicyandiamide (DCD) and 3, 4 dimethyl pyrazole phosphate (DMPP) [7].

A DMPP-based nitrification inhibitor, Vizura® (BASF), has been specially formulated for use with liquid manure (slurry) in the UK; however, recent lysimeter studies in Germany showed that Vizura® can significantly reduce N2O emissions from ploughed grass/clover leys [8], suggesting that it may also it may also reduce nitrate leaching from ploughed leys. DMPP may also be appropriate for use in regenerative systems as it does not negatively affect soil microorganisms [9], earthworm feeding behaviour [10], or residue mineralization [11]. Based on these findings, we hypothesized that the application of DMPP (Vizura®) to a grass/clover ley prior to incorporation could effectively reduce NO_3^--N leaching during the winter months in our humid temperate climate. During the growing season fertiliser N is commonly supplied as urea-N or ammonium nitrate-N. Products which can slow down the hydrolysis of urea to ammonium (urease inhibitors) and the conversion of ammonium to nitrate (nitrification inhibitors) can help retain more N on soil colloids and reduce losses of nitrogen to groundwater or the atmosphere during the growing season [12]. This improves crop nitrogen use efficiency (NUE), reducing potential for losses of N as ammonia, nitrous oxide or nitrate, during the growing season and minimizing the risk of high levels of residual N post-harvest, thus reducing the risk of N leaching during the winter drainage season.

Nutrisphere-N® (Verdesian) is urea coated with a branched polymer with a 30-40 mer long chain and a strong negative charge (1800 meq 100 g^{-1}) designed to attract multivalent nickel cations, copper and iron directly, making these cations unavailable to form the urease enzyme. The hydrolysis of urea into ammonia ceases in the absence of urease, thus slowing the production of nitrate from urea fertilisers. According to the manufacturer, NutriSphere-N® does not harm soil bacteria, earthworms, and other soil life and eventually breaks down into carbon, oxygen, hydrogen, and calcium, making it an environmentally safe product. Since the molecule is too large to be taken up by the plant, there are no residues in the harvested crop [13].

We hypothesized that the use of a polymer coated urea fertiliser (NutriSphere-N®) on a growing potato crop and a DMPP-based nitrification inhibitor (Vizura®) sprayed on a ley prior to incorporation will improve crop nitrogen use efficiency (NUE) during the growing season and significantly reduce nitrogen losses as leaching over the winter drainage period. We also hypothesized that no tillage practices will result in less nitrate leaching compared to conventional tillage in winter wheat. The documentation of effects of these accessible, simple management practices will provide valuable evidence for farmers and policy makers to make decisions about environmentally and economically sound nutrient management practices in northern temperate climates.

Materials and Methods

a. Site description

Field sampling and experiments were conducted between November 2018 and September 2019 at Newcastle University's Nafferton Farm (54°59′09″N; 1°43′56″W, 60 m), Northumberland, UK using the Nafferton Factorial Systems Comparison trial as a platform. The average annual temperature and total precipitation from 1981 to 2018 at the site are 8.6°C and 638.6 mm, respectively [14]. The Nafferton farm soil is mapped as a Dystric Stagnosol, which is dominated by stagnogley characteristics. The underlying geology is greyish till derived from Carboniferous shale and sandstone, which is a seasonally moist, slowly permeable, acidic loamy to clayey soil with low fertility [15].

The Nafferton Factorial Systems Comparison Trial (NFSC), was established in 2003 to study low-input, sustainable and organic approaches to crop management. A detailed description of this trial is included in Cooper, Sanderson [16]. This study used a subset of plots from two of the four experiments as described below. Before the experiment topsoil samples from each experiment (A, B and C) were collected for initial characterisation of chemical properties. All the soil samples were oven-dried (105°C) and stored until analysis. Total carbon (C) and nitrogen (N) were measured using a Leco CN-2000 dry (Dumas) combustion analyser. Soil pH was determined in water (1:2.5 soil:solution ratio) (Mclean [17]). Available P (Olsen's method, 0.5M NaHCO3 solution at pH 8.5) and ammonium nitrate-extractable K were measured as described in [18].

b. Experiment A: Assessment of a nitrification inhibitor to reduce N leaching from autumn ploughed leys

Nitrate leaching was monitored during the 2018/2019 drainage season following mouldboard ploughing of a three-year grass/clover ley in the southern half of Experiment 1 of the NFSC trial, shown as experiment A in Figure 1. Previously, the experiment was used to compare two fertilisation strategies (FM): synthetic fertilisers (NPK) or compost (COMP), although no

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fertiliser treatments were applied during the experimental period. In autumn 2018, all fertility management (FM) sub-sub plots (COMP and NPK) in the organic crop protection (ORGCP) subplots were divided in half, creating four sub-sub-sub plots (12 m x 12 m) in each replicated block.

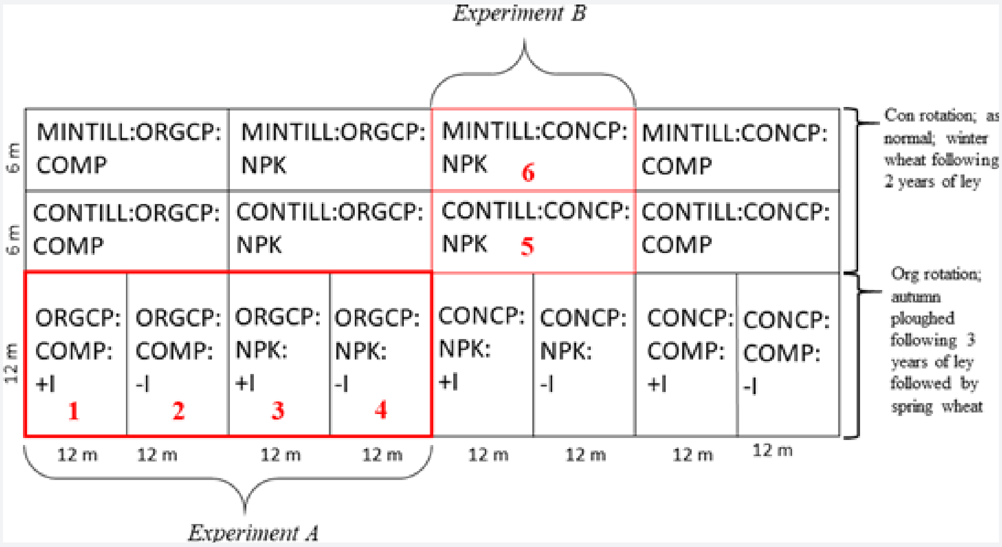

Figure 1: Detailed illustration of treatments in Block 1 of Experiment 1 of the trial. Plots monitored for nitrate leaching and soil mineral nitrogen (SMN) in the 2018/2019 drainage season for DMPP assessment (+I/-I ; numbered 1, 2, 3 and 4) and tillage effect (numbered 5 and 6) Note: plots are not drawn to scale MINTILL=minimum tillage, CONTILL=conventional mouldboard ploughing, ORGCP=organic crop protection, CONCP=conventional crop protection, COMP=compost and NPK=chemical fertilisers.

DMPP was sprayed (1 kg ha-^{1}) on the grass/clover ley before ploughing in autumn (22/10/2018) on half of these plots (indicated as +I). N leaching was monitored in plots 1, 2, 3 and 4: comparing the mean leaching from plots 1 and 3 versus plots 2 and 4 allowed us to assess the efficacy of the nitrification inhibitor in reducing N leaching post ploughing of a ley. This approach was replicated in all four field blocks.

c. Experiment B: Effect of no tillage and conventional tillage on nitrate leaching

In the conventional (CON) crop rotation plots in Experiment 1 (Figure 1), the trial was slightly modified to test the effects of autumn ploughing a two-year grass/clover ley on N leaching compared to no tillage. In 2012 minimum tillage was introduced as an additional factor into Experiment 1. The conventional crop rotation main plot was split into two longitudinal subplots (each 6 m x 96 m) with minimum tillage practices implemented in the northern half of the plot and conventional mouldboard ploughing used in the southern half of the plot. All the activities reported in this section took place in Experiment B in Figure 1.

The plots labelled MINTILL:CONCP were sprayed with glyphosate in autumn 2018 and direct drilled to winter wheat on 25/10/2018 using a combination seed drill. Those labelled CONTILL:CONCP were sprayed with glyphosate and then mouldboard ploughed (~25 cm depth) and planted with winter wheat using the same seed drill. Monitoring of N leaching in plots labelled 5 and 6 in Figure 2 in all four replicates (a total of 8 plots) was conducted in the 2018/19 winter drainage season. No other chemicals for crop protection or nutrients were applied during the drainage period. Initial soil samples from two depths (0-30 and 30-50 cm) were collected from each plot prior to the experiment and stored in a freezer at -20 °C for later nitrate and ammonium-N analysis. Porous ceramic cups (Curley and McDonnell 2010) were installed in experiments A and B on 6th November 2018 for monitoring NO_3^--N in the soil solution during the drainage season using porous ceramic cup samplers. Soil solution samples were collected from the porous cups every week over the winter and stored at -20 °C until later analysis. At the same time, soil samples were collected from the 0-30 cm layer (three cores collected from random locations around the plot) and mixed to form one sample from each plot; these were also stored at -20 °C until later extraction for soil mineral nitrogen (SMN).

d. Experiment C: Impact of controlled release urea (CRU) on soil N dynamics and nitrogen use efficiency of potatoes

NFSC Experiment 4 was used to study the impact of a commercially available controlled release urea fertiliser (NutriSphere-N®, Verdesian) on soil nitrogen dynamics and crop yield. Treatments were focused on the fully conventional subset of plots within the conventional rotation (Cooper et al. 2011). Each CONCP:NPK plot was divided into three subplots 12 m x 8 m in size. This was replicated four times across the trial. Each subplot received a different N treatment: 180 kg N ha^{-1} plain urea, 180 kg N ha-CRU, and kg N ha^{-1} CRU. The full N rate is based on the AHDB Nutrient Management Guide (RB209) [19] for a deep clayey soil following winter barley in a low rainfall area (considering the Northeast UK's very dry conditions during the 2018/19 winter). The lower N rate was 85% of total N recommended in RB209 based on the product manufacturer's recommendation. The fertilisers were broadcast on the soil surface and immediately incorporated before planting potato planting. Details of potato crop management during the experiment are shown in Table 1.

Table 1: Detailed management practices and application dates for testing of controlled release urea (CRU) in a potato crop grown in northern England, 2019.

Management	Description
Fertilizer input	180 kg of N ha^{-1} as Urea and CRU and, 153kg N ha^{-1} as CRU (24/04/2019); broadcast and incorporated into the soil
Planting date	2/5/2019
Herbicides	Praxim 3l ha^{-1} (21/05/2019), Wicket 3l ha^{-1} (21/05/2019) Laser 2.25 l ha^{-1} (27/06/2019), Reglone 3l ha-1 (10/09/2019)
Fungicides	Shirlan 300 ml ha^{-1} (18/06/2019 and 18/07/2019) Mancozeb 1.7kg ha^{-1} (10/07/2019)
Harvesting	23/10/2019

Soil samples were collected using a manual soil augur biweekly from the topsoil (0-30 cm) soil layer to monitor SMN during the potato growing season from May to September 2019. To monitor the crop's response to the fertiliser, plant above and below-ground biomass at two growth stages (during tuber development and pre-senescence) and final potato yield were collected. Subsamples of the aboveground biomass, root and tubers fresh weight were used to determine dry weights. The final yield was assessed using the harvested potatoes from the two middle rows from 4m^2 of each plot.

e. Soil mineral nitrogen determination

Soil mineral nitrogen (SMN) was determined by extraction with 2 M KCl (Keeney [20] Nitrate and ammonium concentrations in both the soil extracts and the soil solution samples were were measured with a Brann+Luebbe Autoanalyzer 3 and the hydrazine reduction method forNO_3^--N and the salicylate method for NH_4^+-N [21].

f. Estimation of evapotranspiration and drainage

A step-by-step standard, the Penman-Monteith equation proposed by Allen, Pereira [22], is used to estimate crop evapotranspiration. The reference evapotranspiration (ETo) is first calculated using only climate factors for a standard crop (grass), and soil properties are kept constant over time. The crop coefficients (Kc) are then used to adjust ETo to evaluate the actual ET (ETc) in mm day^{-1} for winter wheat during the drainage season 2018/2019. The Nafferton Farm weather station provided all of the weather data. Daily maximum and minimum temperatures (°C), rainfall (mm day^{-1}), mean daily wind speed (m s^{-1}), solar radiation (sum for the day) in KW m^{-2} (converted to MJ m^{-2} day^{-1} following the equation, KW m-2 86.4 = MJ m^{-2} day^{-1}) and average daily humidity (%) were all used as input weather parameters to calculate ETo.

$$ET_O = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)}$$

Where ETo is the reference evapotranspiration (mm day^{-1}), Rn is net radiation at the crop surface (MJm^{-2} day^{-1}), G is soil heat flux density (MJm-2 day^{-1}) but the value was ignored for daily records therefore G=0, T is average daily air temperature at two meters height (°C), u_2 is wind speed at two meter height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure deficit (kPa), e_s- e_a is saturation vapour pressure deficit (kPa), Δ is slope of the vapour pressure curve (kPa/°C), γ is psychrometric constant (kPa/°C). These input parameters (slope and saturation vapour pressure) were calculated by using the equations,

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{\left(T+237.3\right)^2}$$

Where Δ slope of the vapour pressure curve and T is is air temperature.

$$e_s = \frac{e^0\left(T_{\max}\right) + e^0\left(T_{\min}\right)}{2}$$

Where es is saturation vapour pressure, e^0 is saturation vapour pressure at air temperature.

The value of the γ psychrometric constant used during the calculation was 0.067.

Evapotranspiration was calculated using the Penman-

Monteith equation, and available water contents at field capacity were reported by Almadni [23], obtained from the pressure plate (0.05 bar) from similar experimental fields. The average soil water content in the 0-90 cm profile was 279 mm at field capacity. Daily meteorological data and calculated evapotranspiration and average available water contents at soil field capacity (cm^3 cm^{-3}) and soil moisture deficit (SMD) were used to measure cumulative drainage. The trapezoidal rule was used to measure nitrate loss over the trial duration. The area under the plot of NO_3^--N concentrations (mg l^{-1}) against drainage (mm) is nitrate loss in kg NO_3^--N ha^{-1}. The trapezia from successive sampling concentrations (C1, C2 mg l^{-1}) and drainage volume (V1, V2 mm) was used in the following equation,

$$\text{Nitrate Leached (kg } NO_3^- \text{-N ha}^{-1}) = 0.5 \times (C1 + C2) \times (V1 - V2) \div 100$$

g. Statistical analysis

In all scenarios, the data were analysed using linear mixed-effects models [24] with the fixed effect of treatment factors, e.g. fertilizer management, tillage and nitrification inhibitor, and random effect of block and sampling date to generate ANOVA P-values for key effects including fertilizer management (FM) and nitrification inhibitor (I) for experiment A, effect of tillage practices (no tillage and conventional tillage) in experiment B and effect of fertilizer management (Urea and CRU) in experiment C and all interactions using the R software (nlme package) [25]. To follow the normal data distribution criterion, the normality of the residuals of all models was tested using qqnorm, and data were transformed using square root or log where necessary. Tukey contrasts in the multcomp package's general linear hypothesis testing (glht) function were used to test differences among interaction means [26].

Results

h. Weather Conditions

The 2018/2019 drainage season was dry with 140.20 mm of total rain from November 2018 to February 2019 compared to the previous year when 248.4 mm fell between November and February. Monthly rainfall during the study was the highest (75 mm) in November 2018 and lowest (13.60 mm) in February 2019. The highest monthly average temperature was 7.59°C in November and a minimum of 3.14°C in January, which was the coldest month recorded during this study.

i. Effect of Nitrification inhibitor

The pH of plots with a history of conventional fertiliser inputs (NPK) was slightly lower than those which had previously been amended with compost (COMP) (5.9 versus 6.4). Olsen's P was significantly higher in COMP plots than NPK plots (17.8 mg kg^{-1} versus 8.0 mg kg^{-1}). Other parameters were not different (P=0.05) although there were some clear trends: the soil organic carbon (SOC) and total nitrogen concentrations in COMP plots (15.1 g kg^{-1} and 1.25 g kg^{-1}) were numerically higher than the NPK plots (11.9 g kg^{-1} and 1.09 g kg^{-1}), and available potassium (K) concentration was slightly higher in NPK plots (91.1 mg kg^{-1}) compared to 87.6 mg kg^{-1} in COMP plots.

There were no significant effects of the past management (FM) and nitrification inhibitor (I) treatment on soil ammonium-N contents, but soil nitrate-N levels were affected. There were similar patterns of concentration change in nitrate-N over time for all four treatments (COMP -I, COMP +I, NPK -I and NPK+I). During the study period soil in the COMP-I plots had the highest mean NO_3-N levels (47.56 kg ha^{-1}; data not shown) compared to all other treatments. The lowest nitrate values were measured in the plots where NPK had historically been used to fulfil crop nutrient demand and the nitrification inhibitor was sprayed before ploughing in autumn 2018 (average over the measurement period: 32.49 kg ha^{-1}).

There was a statistically significant effect of I on soil NO_3^--N ($P < 0.05$), and significant interactions of inhibitor treatment with past fertility management (FM) and sample date (D) were found. On the first sample date the NO_3^--N concentration in soils was significantly higher (58%) in NPK plots compared to COMP plots regardless of treatment with DMPP. From the 3rd sampling date (35 days after nitrification inhibitor application), soil nitrate-N in NPK +I treatment were always lower and significantly lower after 45, 71 and 92 days of nitrification inhibitor application compared to NPK -I. At the end of the experiment, NO_3^--N in the soil of NPK +I was 30% lower than in NPK -I plots.

Nitrate-N concentration (mg l^{-1}) from soil solution samples collected using porous cups were plotted against cumulative drainage to estimate the actual NO_3^--N leaching (kg ha^{-1}) losses from all treatments. The cumulative drainage was calculated to be 22.7 mm at the start of the sampling period and 113.5 mm at the end, as shown in Figure 3. Maximum NO_3^--N was leached from the NPK -I plot over the 2018/19 drainage season. Up until the fifth sampling date both compost treatments and the NPK treatment had similarly low levels of nitrate in leachate; however, from the fifth to the eighth sampling date the COMP +I treatment had significantly lower concentrations of nitrate in the leachate compared to the other three treatments. Total N leached from this treatment at the end of the season was 20.4 kg N ha^{-1} which was not significantly higher than the amount leached from the COMP -I (Table 2).

The NPK -I treatment had consistently higher concentrations of nitrate in the leachate for the first three sampling dates and overall resulted in the highest nitrate leached (42.9 kg N ha^{-1}; Table 2).

j. Effect of Tillage Practices

Soil chemical properties did not vary between minimum tillage and conventional tillage plots. The available P in MINTILL plots was ~210% more than the available P in CONTILL plots. Similarly,

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the exchangeable K in MINTILL plots was ~45% higher than in CONTILL plots. The details of soil chemical properties are in S2. There were no significant differences in the mean nitrate-N or ammonium-N concentrations between the two tillage treatments across all sample dates (Figure 4).

Table 2: Total Nitrate-N leached (kg ha^{-1}) during the drainage season in an experiment evaluating the commercial nitrification inhibitor (I) as a nitrate leaching mitigation strategy in autumn ploughed leys. Interaction means for FMxI are presented; the FMxI interaction was significant.

Fertility management		NO_3^--N leaching (kg ha^{-1})
NPK	+I	24.8
	-I	42.94
	ANOVA P-value	0.001
Compost	-I	18.4
	+I	20.35
	ANOVA P-value	0.362

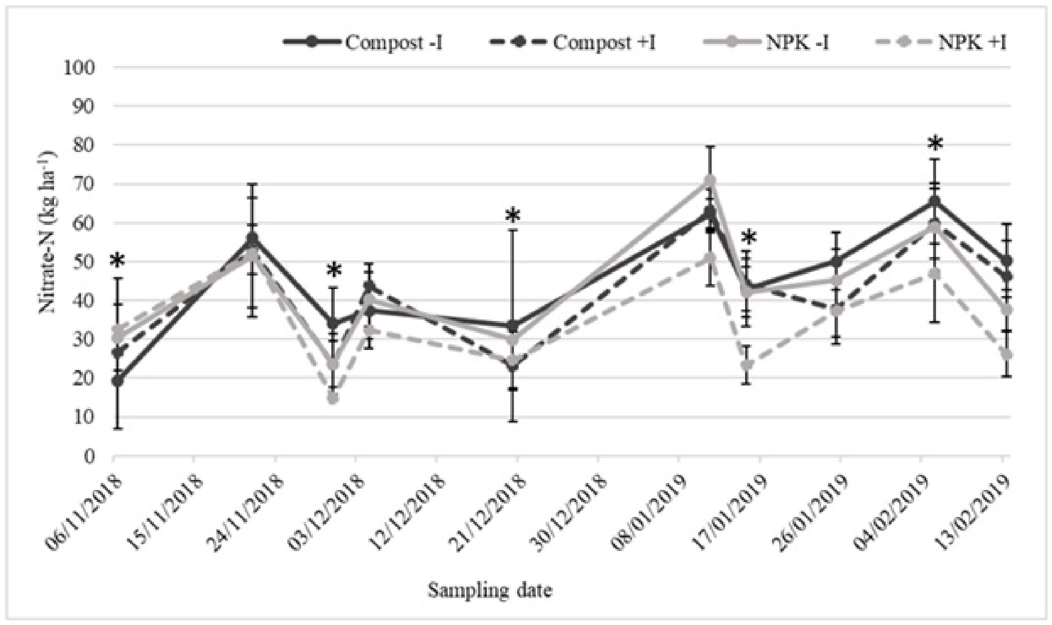

Figure 2: Topsoil nitrate-N (kg ha-1) changes over the study period in plots with a history of compost or NPK amendment treated with a nitrification inhibitor (COMP +I, NPK +I) and without a nitrification inhibitor (COMP -I, NPK -I) prior to incorporation of a grass/clover ley phase. (error bars represent standard error, and * represents the significant difference: in all the sampling dates, nitrate-N were significantly lower in NPK +I except on the first sampling date, when nitrate-N was significantly lower in COMP-I).

The temporal variations in concentrations of topsoil nitrate-N during the winter season are shown in Figure 5. The amount of NO_3^--N in the MINTILL plots was higher for most of the sampling dates i.e., 209% more NO_3^--N on 04.12.2018 and 90% more on the last sampling date. The NO_3^--N leaching losses from both tillage systems (CONTILL and MINTILL) were measured using nitrate-N concentrations in the soil solution (mg l^{-1}) and cumulative drainage, as shown in Figure 6. The total nitrate-N lost via leaching from the MINTILL treatments was 70.6 kg ha^{-1} in contrast to CONTILL plots which only lost 10.4 kg ha^{-1} nitrate-N (P-value = <0.05).

The mean NO_3^--N (mg l^{-1}) concentration from the beginning of the experiment was numerically higher in MINTILL plots. The concentration of NO_3^--N (mg l^{-1}) in the soil solution was lower throughout the experiment therefore leaching losses from CONTILL plots were lower than MINTILL. The concentration was only similar in both treatments on one occasion when cumulative drainage was 108 mm and mean NO_3^--N in MINTILL plots was 11 mg l^{-1} compared to 9.6 mg l^{-1} in CONTILL plots. The particularly high NO_3^--N concentrations in MINTILL treatments (62, 87 and 75 mg l^{-1} on the first three sample dates) were measured in November corresponding to several heavy rainfall events.

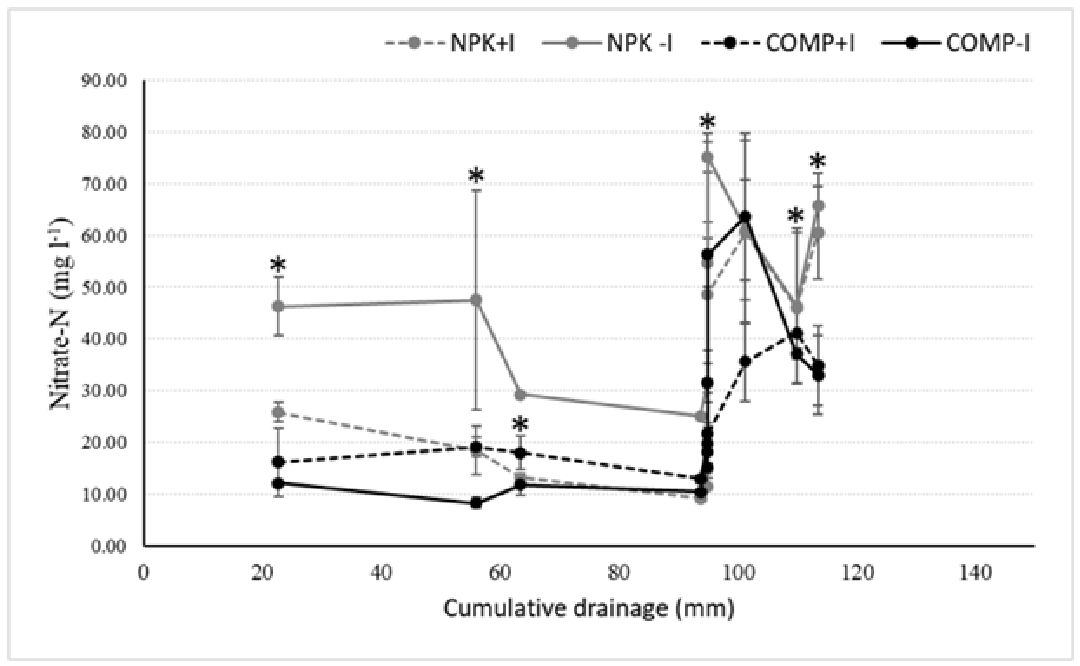

Figure 3: Nitrate-N concentration (mg l-1) in soil solution collected from porous cups plotted against calculated cumulative drainage (mm) over the 2018/2019 drainage season in plots with a history of compost or NPK amendment treated with a nitrification inhibitor (COMP +I, NPK +I) and without a nitrification inhibitor (COMP -I, NPK -I) prior to incorporation of a grass/clover ley phase. The area under each line is used to calculate total Nitrate-N loss due to leaching in kg N ha-1. Points labelled with * are significantly higher than the other three treatments on that sample date.

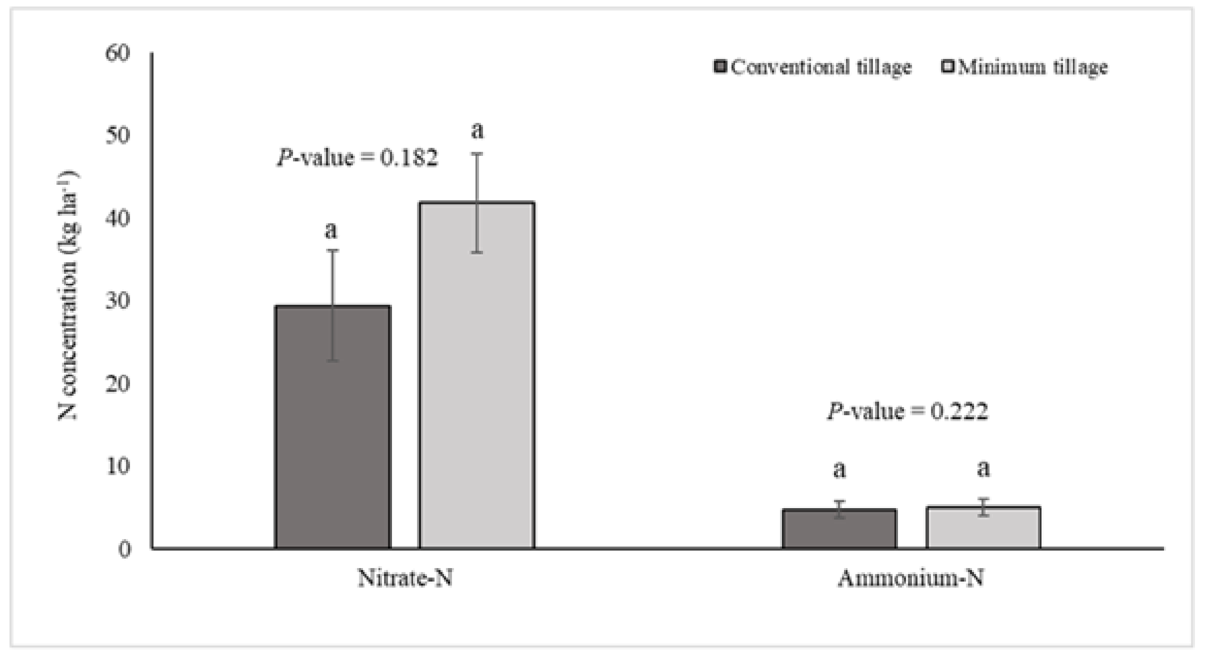

Figure 4: Soil mineral nitrogen in conventional and minimum tillage plots over the 2018/19 drainage season. Means of four replicated blocks (n=4) with error bars representing standard errors of means (SE).

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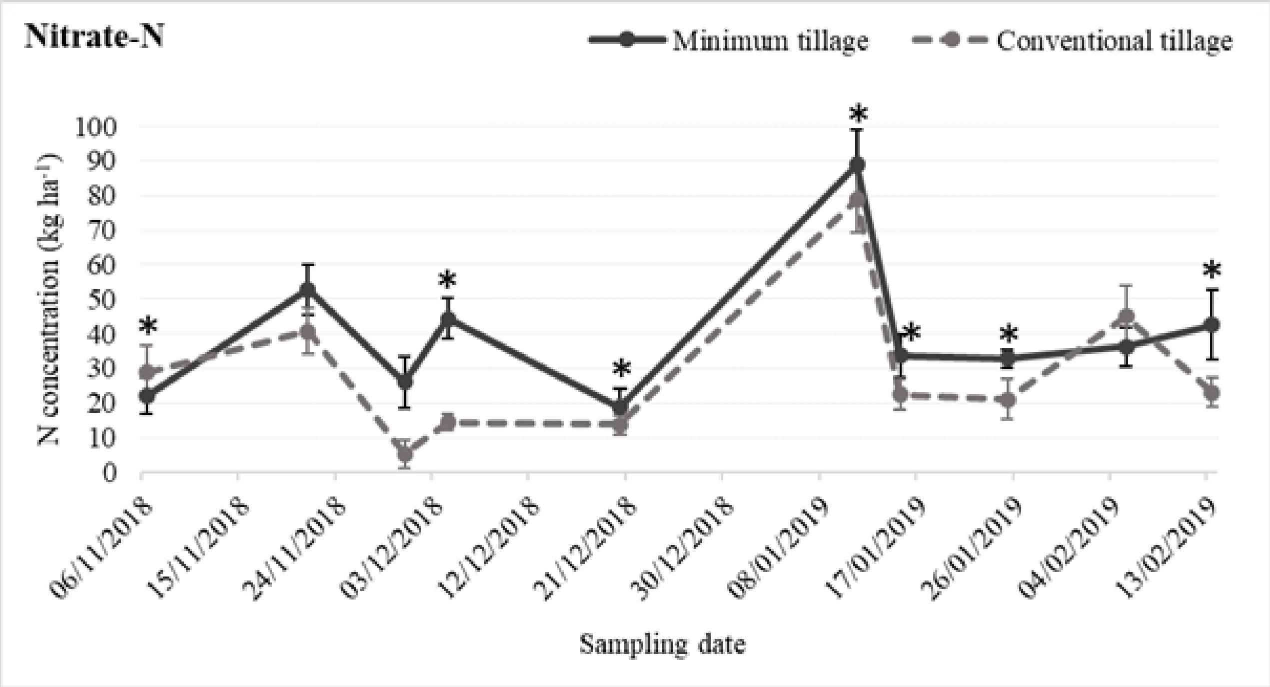

Figure 5: Nitrate-N in the topsoil (0-30 cm) in conventional tillage and minimum tillage treatments during winter 2018/19 following a grass/clover ley. Each value represents the mean of four replicated blocks (n=4) with error bars depicting standard error (SE). * is used to indicate significant differences (P<0.05) in Nitrate-N on that sample date.

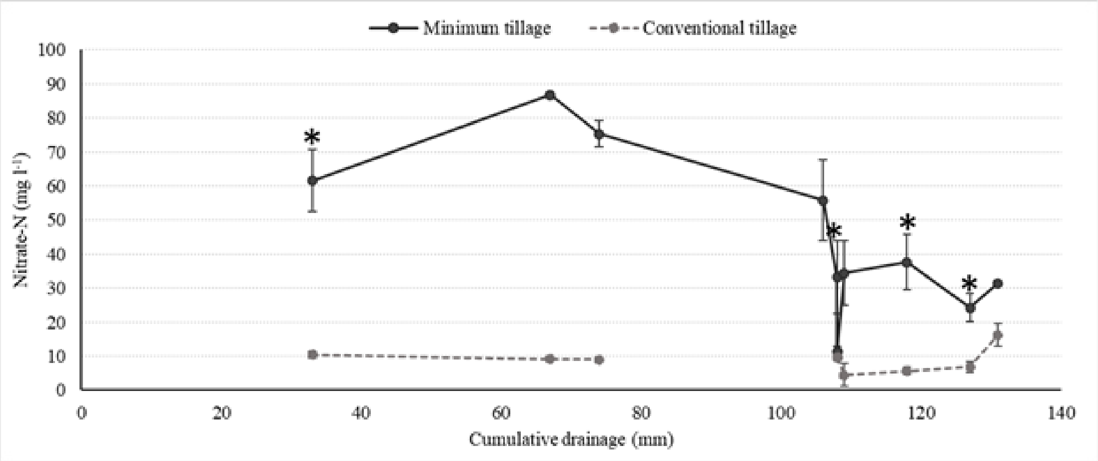

Figure 6: Nitrate-N concentration (mg l-1) in soil solution against cumulative drainage (mm) during winter 2018/19 in conventional tillage and minimum tillage treatments following a grass/clover ley. The area under the curve was used to calculate total Nitrate-N leached. Note: The gap in the CT line indicates one date when there was no sample in the porous cups; only one replicate sample was available on the dates with no SE.

k. Effect of controlled release urea

Initial soil properties before the application of experimental treatments were topsoil (0-30 cm) pH in H_2O was moderately acidic (5.6± 0.04). Soil organic C and N were 15.2± 0.33 and 1.30± 0.06 g kg^{-1}. Whereas available soil P and K were 6.55(0.97) and 136.9(9.18) mg kg^{-1} respectively.

N source had no significant effect on the on average soil NO_3^--N and NH_4^+-N contents in the 0-30 cm soil layer during the potato growing season (NO3 -- N P-value= 0.9204; NH_4^+-N contents P-value = 0.5443). However, there were significant interactions between soil mineral nitrogen (SMN) and sample date as shown in Figure 7. On the first sample date there were no significant

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differences in SMN among the three treatments, however, by 28 days post-fertiliser application, SMN levels were significantly higher for both the urea and CRU compared to the 85% CRU (247 and 253 compared to 194 kg of N ha^{-1}). A similar pattern emerged for the following two sample dates, although values SMN in general were much lower. The agronomic responses to different N sources are shown in Error! Reference source not found. The final yield of potatoes was 37.8, 41.2 and 38.1 t fresh weight ha^{-1} from U, CRU and 85% CRU treatments. Use of CRU had no significant effect on potato yield, but it did improve the nitrogen use efficiency of potatoes which was highest for 85%CRU (46 kg kg^{-1}) compared to 38 kg kg^{-1} when plain urea was used as an N source.

Table 3: Agronomic response of different N sources as tuber yield and fertiliser nitrogen use efficiency.

Source of N	Tuber dry weight (tuber development stage)	Final tuber yield	Fertiliser Nitrogen Use Efficiency
	(g m^{-2})	t ha^{-1}	kg DM kg N^{-1}
Urea	369.9 (49.00)	37.8	38
CRU	266.1 (29.45)	41.2	41
85% CRU	253.4 (39.69)	38.1	46
ANOVA P-values	0.159		

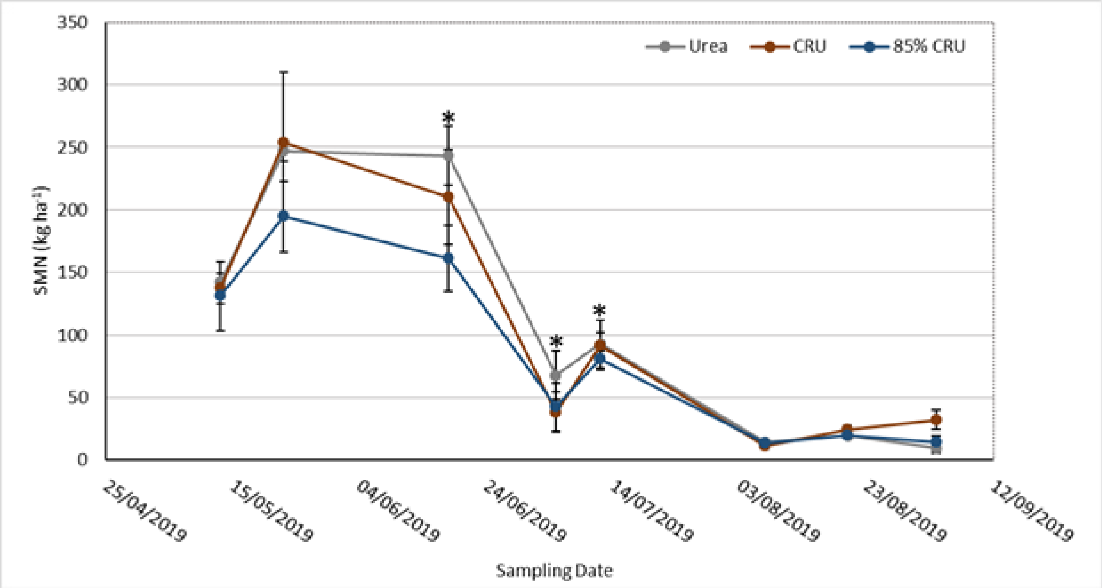

Figure 7: Topsoil mineral nitrogen (SMN) dynamics during the study period in a potato crop fertilised with plain urea, controlled release urea (CRU) and 85% controlled release urea (85% CRU). * Indicates sample dates when there were significant differences among the treatments.

Discussion

The use of DMPP (3,4-dimethylpyrazole phosphate) as a nitrification inhibitor has been well-documented in various studies, with its effectiveness in reducing greenhouse gas emissions and nitrate leaching in slurry treated arable soil and winter wheat [8,27,28]. However, less research has been conducted on the potential of DMPP to reduce nitrate leaching following incorporation of grass/clover leys in autumn in the UK. The results supported the hypothesis that treating grass/clover with a nitrification inhibitor before incorporation can alter soil N dynamics and reduce the risk of nitrate leaching over the winter period.

The DMPP clearly lowered NO_3^--N in the topsoil in the treatments with a history of NPK fertiliser throughout the study period. Vilas, Verburg [29] provided a framework for assessing the efficacy of nitrification inhibitors over time, describing persistence (how long the chemical lasts in the soil) and bioactivity (their effect on nitrification in soils) as both affecting the longevity of the inhibition. In our study, the longevity of inhibition was as long a ~120 days after application. This is longer than would be expected considering the persistence of DMPP reported in other studies; for example, Doran et al. (2018) reported that DMPP had a half-life of less than a month in an agricultural soil. The bioactivity of the DMPP may have been much longer (~four months post-application) and suggests that the microbial

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community responsible for nitrification (archaeal and bacterial ammonia oxidisers) did not fully recover their function even after the DMPP no longer persisted in the soil. In light of the increased awareness among the farming community about the importance of maintaining a healthy soil microbial community [30] there may be some reticence towards adopting a product which functions by suppressing microbial activity.

However, the evidence indicating that DMPP does not risk contamination of groundwater is positive. A lysimetric study performed at the Jülich Research Centre over three years [31] compared leaching of DMPP when applied to potatoes and winter wheat found no DMPP in the leachate collected during the study. The results of this study suggest that DMPP is particularly effective at reducing nitrate leaching from plots with a history of NPK treatment. However, the nitrification inhibitor did not perform well in reducing leaching losses from soil with a history of organic fertility management. This difference in performance may be attributed to the adsorption capacity of the soil, which can reduce the activity of DMPP [32,33]. Adsorption capacity may have been higher in the COMP plots which had higher soil organic C contents (15.1 g kg^{-1} versus 9.1 g kg^{-1}). Zhu, Ju [34] found that DMPP was less efficient in an agricultural soil collected from a temperate region of the UK with high C contents (27.4 g kg^{-1}) compared to soils with low C contents. In this long-term experiment plots with a history of compost additions have also been reported to have higher microbial activity [35] which may have resulted in more rapid degradation of DMPP [36] and also a more rapid recovery of the microbial community following DMPP addition. To improve the effectiveness of DMPP in COMP plots, a higher rate of application may be recommended. This highlights the importance of understanding the specific characteristics of the soil and fertility management practices in order to optimize the use of DMPP as a nitrification inhibitor.

This study also explored the impact of conventional and no-tillage practices on soil nitrogen dynamics in the topsoil (0-30 cm) and nitrate leaching in a winter wheat crop that was grown following two years of grass/clover ley. With the increased uptake of regenerative agriculture practices which include no-till as a core principle (Newton et al. 2020) it is likely that more ley phases will be destroyed using a herbicide with an arable crop established by direct drilling. The results of the study revealed that higher nitrate leaching was observed in the no-till plots. These findings are consistent with previous studies that have shown that no-tillage practices cause less disturbance to the soil structure, leading to the formation of macropores that are in direct contact with the soil surface. These macropores provide a pathway for water to flow to the maximum depth of the soil profile, resulting in greater nitrate leaching in no-tillage plots compared to deep tillage practices, which disrupt the soil structure and impedes water flow [37]. However, in our study, drainage was calculated without accounting for preferential flow through macropores, so the higher leaching calculated was a direct effect of higher concentrations of nitrate in the soil water samples considering equivalent drainage rates (Figure 6). If water movement through the profile was actually more rapid in the no-till plots, then we can expect that even higher rates of N leaching took place. Further studies on soil structure across the profile and its impacts on hydraulic conductivity are needed to improve estimates of N leaching under no-till systems.

The source of the higher levels of nitrate in soil water samples in no-till treatments may be due to greater N mineralisation rates. On several dates SMN was higher in the no-till plots (Figure 5). This finding is in contrast to other studies (e.g., [38]) who reported higher levels of soil mineral N in conventionally ploughed plots. It is possible that the non-inversion of no-till plots left a concentration of crop residues on the soil surface that were more exposed to biological activity and breakdown than the residues that were buried in the conventional till plots. These results demonstrate that the processes controlling mineralisation of N from crop residues are complex and determined by multiple factors including local climate, past crop management and current soil conditions; hypotheses about impacts need to be verified by local experimentation.

A key to improving yield without increasing the amount of N fertiliser used is to improve the nitrogen use efficiency (NUE) of fertilisers. This study provided some evidence that controlled release fertilisers (CRU) can improve NUE of potatoes. The use of CRU appeared to delay N supply to the growing potatoes, as evidenced by the lower values for SMN relative to both plain urea and ammonium nitrate early in the growing season (Figure 7). Below-ground biomass was also lower in the CRU treatments at the tuber development stage (data not shown). This was also evidenced However, by harvest, yields were similar for all N sources and NUE was higher for the CRU treatments, suggesting that N had been supplied later in the season by the CRU treatments. Numerous other studies have reported similar yields when comparing controlled release fertilisers with plain fertiliser sources. However, Heiniger, Smith [39] also reported an increase in NUE by using CRU and optimum yield was achieved by using less N, which corresponds with our findings.

Conclusion

The study aimed to investigate methods to decrease nitrate leaching and enhance nitrogen utilization in crop growth by testing three approaches, including a commercially available nitrification inhibitor (Vizura®) and controlled release urea fertilizer (NutriSphere-N®), and differences in tillage practice. The results demonstrate that there are already products on the market (e.g., nitrification inhibitors, controlled release fertilisers) that can improve efficiency of N cycling in the field. The use of CRU allowed a reduction of N fertiliser rates by at least 15%, with potentially larger reductions possible. Combining this technology with precision fertilisation methods and splitting applications may have further improved efficiency of N supply.

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Reductions in N leaching by using a nitrification inhibitor also showed promise but impacts on soil microbial communities need to be better understood if this approach is to gain traction in the regenerative farming community. A range of factors are driving a trend towards reduced tillage intensities in UK arable systems; these include reduced labour and fuel costs, purported gains in soil C, and growing interest in preserving soil structure and soil health. However, potential tradeoffs with impacts on water quality through increased N leaching need to be taken into consideration. The study suggests that a combination of commercially available technologies and appropriate tillage practices can improve crop nitrogen use efficiency and reduce the risk of N leaching. Further research should investigate the combined effects of various agronomic strategies to maximize system nitrogen use efficiency.

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