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AUTHORS Patrick J. Forrestal, Mary A. Harty, Rachael Carolan, Catherine J. Watson, Gary J. Lanigan, David P. Wall, Deirdre Hennessy, Karl G. Richards

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Title

Can the agronomic performance of urea equal calcium ammonium nitrate across nitrogen rates in temperate grassland?

Keywords: Fertiliser Nitrogen, Urea, Calcium ammonium nitrate, urease inhibitor, NBPT, Grassland, Pasture

Authors and order

Patrick J. Forrestal[1], Mary A. Harty[1,2], Rachael Carolan[3], Catherine J. Watson[2,3], Gary J. Lanigan[1], David P. Wall[1], Deirdre Hennessy[4], Karl G. Richards[1]

[1]Crops Environment and Land Use Program, Teagasc, Johnstown Castle, Wexford, Ireland.
[2]Queen's University Belfast, University Road, BT7 1NN Belfast, U.K.
[3]Agri-Food and Biosciences Institute (AFBI), Newforge Lane, BT9 5PX Belfast, U.K.
[4]Animal and Grassland Innovation Centre, Teagasc, Moorepark, Fermoy, Cork, Ireland.

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Abstract

In temperate grasslands urea has previously been shown to have lower nitrous oxide emissions compared to ammonium nitrate based fertiliser and is less expensive. However, nitrogen (N) loss via ammonia volatilisation from urea raises questions regarding its yield performance and efficiency. This study compares the yield and N off-take of grass fertilised with urea, calcium ammonium nitrate (CAN) and urea treated with the urease inhibitor *N*-(*n*-butyl**)** thiophosphoric triamide (NBPT) at six site-years. Five annual fertiliser N rates (100 to 500 kg N/ha) applied in five equal splits of 20 to 100 kg N/ha during the growing season were tested. There was tendency for urea to produce slightly better yields than CAN in spring (103.5% of CAN yield) and slightly poorer yield in summer (98.4% of CAN yield). However, there was no significant difference in annual grass yield between urea, CAN and urea + NBPT. Urea had the lowest cost per tonne of DM grass yield produced. However, the urea treatment had lower N off-take than CAN and this difference was more pronounced as N rate increased. There was no difference in N off-take between urea + NBPT and CAN. While this study shows that urea produced yields comparable to CAN, N use efficiency of urea tends to be lower. Urea selection in place of CAN will also increase national ammonia emissions which is problematic for countries with targets to reduce ammonia emissions. Promisingly, NBPT provides a technical solution which allows agronomic performance of urea to consistently equal that of CAN across N rate by addressing the ammonia loss limitations of urea.

Introduction

Fertiliser N input is a cornerstone of intensive farming systems globally, including those prevalent in temperate grasslands. While N is abundant in the atmosphere, the production of bio-available mineral fertiliser N is an energy intensive process, one estimated to consume circa 1% of global energy (Stark and Richards, 2008). Fertiliser N usage is projected to grow at an annual rate of 1.4% to 2018 (FAO, 2015). Fertiliser, including N, is a large direct cost on farms, for example in Ireland fertiliser represents 20% of direct costs on average (Hanrahan *et al*., 2013).

Globally urea is the predominant mineral N fertiliser used. However, although urea is less expensive than ammonium nitrate (AN) in Western and Central Europe ammonium nitrate (AN) and calcium ammonium nitrate (CAN) hold a larger portion of the market (IFADATA, 2013). Several studies have found that urea produced lower grass yields than AN or nitrate based fertilisers (Devine and Holmes, 1963; Chaney and Paulson, 1988). Other studies found no significant annual yield difference between urea and CAN fertiliser (Keane *et al*., 1974) or in early season grass growth (Murphy, 1983; Watson *et al*. 1990) in temperate maritime grassland. Nevertheless, in Ireland CAN accounts for the 84% of the straight N market (Duffy *et al*., 2014) in sharp contrast to New Zealand grasslands where urea makes up 80% of the fertiliser N used (Dawar *et al*., 2012).

The European Union has set a target to reduce greenhouse gas emissions by 40% by 2030 compared to 1990 levels (European Council, 2014). A number of studies have shown urea to be a useful tool for reducing emissions of the potent greenhouse gas nitrous oxide (N_2O) compared to AN fertiliser in temperate grassland (Dobbie and Smith, 2003; Harty *et al*., 2016). However, there may be yield, efficiency and ammonia emission trade-offs for substitution of urea for AN and European Union countries have also committed to reduction of national ammonia emissions. Urease inhibitors such as N-(n-butyl**)** thiophosphoric triamide (NBPT) may present an opportunity to overcome the uncertainty of ammonia losses from urea. Urea treated with NBPT effectively reduces ammonia loss from urea applied to grassland soils (Watson *et al*., 1990; Chambers and Dampney, 2009; Forrestal *et al*., 2016) because, in soil, NBPT rapidly converts to its oxygen analog, NBPTo (Engel *et al*., 2013) which inhibits the urease enzyme.

The current study investigates the potential for yield and N recovery efficiency trade-offs between fertiliser formulations over a range of N rates and geo-climatic environments. The hypotheses that a) the agronomic performance of untreated urea differs from CAN and NBPT treated urea and b) that the fertiliser N effect differs according to rate applied are evaluated.

Materials and Methods

Experimental sites

Field plot experiments were conducted at three permanent grassland sites at three locations in Ireland during the 2013 and 2014 growing seasons. The field site locations were Johnstown Castle, Co. Wexford (JC13 and JC14), Moorepark, Co. Cork (MP13 and MP14) and Hillsborough, Co. Down (HB13 and HB14). A new experimental site was used at each location in each year, herein after referred to as site-years (e.g. Forrestal *et al*., 2012). The field site-years captured a range of geo-climatic environments. A summary of site details and soil characteristics are provided in Table 1. The dominant grass species in the sward at each location was perennial ryegrass (*Lolium perenne* L.). Parallel studies also measured fertiliser N nitrous oxide (Harty *et al*., 2016) and ammonia emission performance (Forrestal *et al*., 2016) at these sites.

The experimental design was a randomised block with five replicates. Each experimental unit (the plot) measured 2 × 10 m at JC and MP and 2 × 8 m at HB. There were two factors in the experiment a) fertiliser treatment i.e. CAN, urea, urea + NBPT b) N rate with 5 levels applied in five equal split applications of 20, 40, 60, 80 and 100 kg N/ha between March and September which corresponded to annual applications of 100, 200, 300, 400 and 500 kg N/ha. Additionally, a zero N control treatment was included at all site-years. All fertilisers were granular products. The source of the urease inhibitor NBPT was Agrotain® (Koch Fertiliser LLC, Wichita, KS, U.S.A.) which was coated onto urea granules at a rate of 660 mg/kg (w/w). Plots received a basal application of P, K, and S in line with soil test recommendations to ensure that these nutrients were not limiting. Although soil pH levels were lower than optimum no lime was applied to avoid confounding effects of liming on the performance of the urea fertiliser (Watson *et al*., 1987). At each harvest, the grass was cut to a height of 5 cm and removed from the plot. The period between fertiliser application and harvest varied over the course of the growing season (Table 1) to reflect the changing N assimilation and grass growth rates. The total grass fresh weight per plot was recorded and a 100g subsample was collected to determine dry matter (DM) and N content. Nitrogen content was determined using a LECO combustion analyser (St. Joseph, MI, USA).

Fertiliser N response efficiency (NRE) was calculated as:

$\text{NRE (kg DM /kg N)} = (\text{Yield}_{\text{treatment}} - \text{Yield}_{\text{control}})/\text{N rate}$

Apparent fertiliser N recovery (AFNR) was calculated as:

$\text{AFNR (\%)} = ((\text{N off-take}_{\text{treatment}} - \text{N off-take}_{\text{control}})/\text{N rate})) \times 100$

$\text{Urea relative N off-take (URNO)} = (\text{N off-take}_{\text{Urea}} / \text{N off-take}_{\text{CAN}}) \times 100$

Statistical analysis

The effect of fertiliser N treatment on the dependent variables of grass yield and N off-take was tested using the PROC GLIMMIX procedure of SAS (© 2002-2010, SAS Institute Inc., Cary, NC, USA). The factors in the model were site-year, fertiliser N, fertiliser N rate and their interactions as fixed effects with block as a random effect. To compare yield and N off-take between fertiliser N treatments during the growing season a repeated measures analysis was conducted for each individual site-year using the GLIMMIX procedure of SAS. The factors in the model were fertiliser N and N rate as fixed effects, harvest as the repeated measure and block as a random effect. The least square mean output of SAS are presented.

Results

Environmental variables

The main growing season (1 March to 30 September) precipitation was above the 30 year average at HB13 and equal to the long-term average at HB14 (Table 1). However, for the JC and MP site-years the main growing season precipitation was below the long-term average by between 53 and 198 mm. The level of precipitation within the first 24 hours of fertiliser application was variable ranging from 0 – 13 mm (Table 1). On 12 out of 30 applications there was no precipitation within one day of fertiliser application. Cumulative precipitation for three days after N fertiliser application ranged from 0 – 30 mm. On 4 out of 30 applications there was no precipitation in the first three days after fertiliser application.

Total grass dry matter yield

A significant site-year x N rate interaction was detected for yield (Table 2) evidence that the N response differed significantly between some site-years. However, all sites responded positively to increasing N rate with significant yield responses up to 500 kg N/ha/yr at HB13, up to 300 kg N/ha/yr at JC14 and up to 400 kg N/ha/yr at the other four site-years (Table 3). Averaged across site-years NRE declined from 29.6 kg DM/kg N at 100 kg N/ha to 15.7 kg DM/kg N at 500 kg N/ha/yr. There was no significant interaction between N rate and fertiliser type (Table 2, Figure 1a) and the main effect of fertiliser type on yield did not meet the conventional 0.05 probability level (Table 2). Even with relatively high replication, five in the case of the present study, detection of small differences in yield between treatments in agronomic experiments can be challenging given inherent background variability in agricultural systems (Edmeades and McBride, 2012). The *P*-value for the main effect of fertiliser type was 0.087 in the present study, higher than the conventional 0.05 which denotes that the result has a 5% risk of Type I error. As the fertiliser N effect *P*-value approaches the 0.05 level the lsmeans for the individual fertilisers are yield presented. They are as follows; 6414, 12378, 12245 and 12424 kg dry matter per ha for the control, CAN, urea and urea + NBPT treatments, respectively. The urea relative yield (URY) (Watson *et al*., 1990), which expresses yield of urea treatments relative CAN, was 98.9% for urea and 100.4% for urea + NBPT on average.

Total N off-take

A significant fertiliser type x N rate interaction was detected for total N off-take (Table 2). The N off-take for urea treatments was significantly lower than for the CAN and urea + NBPT treatments at the annual rates of 300, 400 and 500 kg N/ha (Figure 1b). The N off-take of the urea + NBPT treatment was consistently equal the CAN treatment across N rates (Table 4). Apparent fertiliser N recovery was highest at 200 kg N/ha for all treatments and declined steadily as N rate increased (Figure 1c). Comparing the difference in AFNR between the urea and urea + NBPT treatments gives insight into the difference in N losses between urea and urea treated with NBPT averaged over the 30 applications in the present study. This difference increased from 4 to 7.6 percentage points as the N rate increased from 100 to 500 kg N/ha/yr. On average the difference between urea + NBPT and urea was 5.6% (standard error of the mean = 0.71%).

A significant site-year x N rate interaction for N off-take was detected (Table 2). Nitrogen off-take increased significantly with each 100 kg/ha increase in the annual N rate at all site-years (Table 4). However, the N off-take response to increasing N rate differed between site-years. For example at HB13 and HB14 the N off-take from the control plots was not significantly different but the N off-take at each incremental N rate from 100 to 500 kg/ha/yr was significantly higher at HB14 (Table 4). A similar divergence occurred between the JC13 and JC14 site-years at and above 300 kg N/ha/yr. In contrast, N off-take at the MP13 and MP14 was similar between site-years at each incremental N rate. Nitrogen off-take at each incremental N rate was higher at MP13 and MP14 compared with the other site-years including in the control treatment (Table 4).

Seasonal/harvest effect

Yield

Grass growth rates and N assimilation rate vary through the year and it follows that a significant harvest × N rate interaction was detected for yield at all site-years (Table 5). At five site-years no effect of fertiliser type was observed nor was there a significant fertiliser type x harvest interaction (Table 5). At one site-year, HB13, a significant harvest × N rate × fertiliser type interaction was detected (Table 5). At HB13 there was no effect of fertiliser type at the 100, 400 or 500 kg N /ha/yr rates. At the other N rates there was an inconsistent effect of fertiliser type with urea at 200 kg/N/ha producing higher yields than CAN on two occasions (second and fourth harvests, data not shown). Urea produced lower yields than CAN on three occasions at HB13 (at 200 kg N/ha at the third harvest and at 300 kg N/ha in third and fourth harvests). Fertiliser applied prior to the third harvest received 0.6 mm precipitation in the three days following application and 1.6 mm in the case of the fertiliser applied for the August harvest. The relationship between URY and three day post fertiliser application precipitation was examined using data from the 100 and 200 kg N/ha/yr treatments. For these treatments the soil mineral N had returned to background levels by the time of each sequential fertiliser split (Harty *et al*., 2016). However, the URY was variable and poorly correlated with three day post fertiliser application precipitation. In Ireland the months of spring are March to May (Met Eireann, 2016), however on farm use of urea declines as the season progresses. For the purposes of comparison, fertiliser applications 1 and 2 (Table 1) are set as “spring” and applications 3-5 are set as “summer”. For the 100 and 200 kg N/ha/yr applications, where lack of carry over mineral N was confirmed by soil sampling, the “spring” URY was > 100 in 12 of 20 cases (60% of cases) (mean URY = 103.5%). For “summer” applications the URY was > 100 in 14 out of 36 cases (39% of cases) (mean URY=98.4%).

N off-take

Similar to the yield results, for N off-take the harvest × N rate interaction was significant at five site-years and there was a significant harvest x N rate x fertiliser interaction at HB13 (Table 5). In contrast to the yield results the main effect of fertiliser type was significant in the absence of a higher level interaction at JC13, JC14 and MP13 (Table 5). At these three site-years, urea had lower N off-take than the CAN and urea + NBPT treatments (Table 6). Although no significant differences were detected N off-take lsmeans for MP14 and HB14 are also presented (Table 6). Nitrogen off-take for the urea + NBPT treatment was not significantly different to the CAN treatment. At HB13 there were inconsistent effects of fertiliser type (Table 5), with N off-take for urea being significantly lower than CAN and urea + NBPT at 500 kg N/ha at the fourth and fifth harvests. Nitrogen off-take from urea, urea + NBPT and CAN were 74, 86 and 89 kg N/ha, respectively, at the fourth harvest and 81, 95 and 92 kg N/ha, respectively, at the fifth harvest.

Similarly to the URY, the URNO (data not shown) was highly variable and weakly correlated (R^2 = 0.05) with three day post fertiliser application precipitation. The “spring” applications resulted in a URNO > 100 in 12 of 20 cases or in 60% of cases (mean URNO = 104%). The "summer" applications resulted in a URNO > 100 in 10 out of 36 cases or in 28% of cases (mean URNO = 96%).

Discussion

Yield

Effect of fertiliser N on annual yield

Grass yield responded positively to increasing N rate at all site-years up to levels of 300 to 500 kg N/ha under cutting, demonstrating how N input responsive grassland in a temperate maritime climate can be. Ammonia losses from urea might be expected to reduce yields from the urea treatment in the absence of rainfall following application. Sanz-Cobena *et al*. (2011) demonstrated that 7 and 14 mm of simulated rainfall immediately after urea application reduced NH_3 losses by 77 and 89%, respectively. However, in the present study rainfall exceeded 7 mm on the day of urea application in only two out of 30 applications (Table 1). Three day rainfall exceeded 7 mm on six occasions out of 30 applications. Consequently, precipitation was unlikely to have played a major ammonia loss mitigation role in these experiments. Our finding that urea produced annual yields which were not significantly different from CAN differs from previous studies which found that yields from urea were lower than those from ammonium nitrate or nitrate based fertiliser in the UK (Devine and Holmes, 1963; Chaney and Paulson, 1988). However, our findings are not unprecedented in Irish temperate grassland as Keane *et al*. (1974) also reported no significant difference between CAN and urea for grass yield. From a yield and cost perspective our results point towards the opportunity for much greater use of urea in temperate grasslands (Figure 1a,b).

4.1.2. Effect of season on fertiliser N yield performance

Previous studies have pointed to urea being more reliable in the spring than in the summer (Murphy, 1983) and urea being as good as CAN in terms of yield in spring but less effective in summer (Watson *et al*., 1990). However, statistical analysis of the current data showed no significant harvest × fertiliser type interaction at five of six site-years (Table 5) implying that the time of the year did not make a statistically significant difference at these five site-years. However, at one site-year, HB13, inconsistent effects of fertiliser type were detected (Table 5). At HB13 yield from the urea treatment was significantly lower than for CAN following three out of fifteen summer applications. Evaluating the entire data set using the URY approach of Watson *et al*. (1990) the URY exceeded 100 in 60% of cases in “spring” (mean 103.5%). This result contrasts with Antille *et al*. (2015) who reported that urea was less effective than CAN in spring. In “summer” the URY exceeded 100 in only 39% of cases in (mean 98.4%) suggesting a trend for urea to perform a little better than CAN in spring and a little poorer in summer. Antille *et al*. (2015) also reported that CAN was more effective than urea in summer. Nevertheless, the differences in the present study were minor and generally non-significant.

Based on the current dataset a significant yield difference between urea and CAN appears to be an irregular occurrence in temperate maritime grassland, at least when both are used over the entire growing season. The overall URY was 98.9% for urea compared to 100% for CAN, in general agreement with Eveillard *et al*. (2014) who noted a margin of 2.1% favouring AN in arable cropping over one growing season.

N off-take

Effect of fertiliser N on N off-take

Overall the apparent soil N supply from these grassland sites as estimated by N off-take from the control was substantial (mean 124 kg N/ha/yr, n=6). However, there were differences in apparent soil supply between site-years (Table 4), in particular between MP13 and MP14 and the other sites-years. The higher N off-take in the control plots at MP indicates relatively high N mineralisation potential of this site. Although they did not test these specific sites, McDonald *et al.* (2014) have previously highlighted differences in net mineralisation potential between grassland soils. The present study points towards a need for more site specific N management in future.

The AFNR was lowest for urea (Figure 1c) and the annual N off-take was significantly lower for urea compared with both CAN and urea + NBPT at annual applications of > 300 kg N/ha (individual applications > 60 kg N/ha) (Figure 1a). Similarly, when examining N off-take in arable cropping Eveillard *et al.* (2014) detected an N off-take advantage for AN over urea. The use of NBPT has been shown to reduce NH_3 losses from urea in temperate grassland (Watson *et al.*, 1990; Watson *et al.*, 1994; Forrestal *et al.*, 2016). Treatment of urea with NBPT resulted in N off-take and AFNR which consistently equalled CAN across N rates (Figure 1b,c) indicating that urea can give consistent agronomic performance at least equal to CAN when it is treated with NBPT.

Comparing N off-take data differences to ammonia loss measurement studies

Windtunnel experiments to measure ammonia loss from urea in UK grasslands have reported mean emissions of 30% for urea (Chamber and Dampney, 2009). Similar mean annual values of 25.1 and 30.6% were reported for JC14 and HB14, respectively in windtunnel experiments (Forrestal *et al.*, 2016) run in parallel to the current study. Nitrogen off-take data from the current study can be used to provide a coarse comparison with the losses measured by the windtunnels. Forrestal *et al.* (2016) reported that NBPT reduced urea ammonia losses by 78.5% to levels not significantly different to CAN. As both urea and urea + NBPT are the same form of N it is reasonable to suggest that they will be subject to similar loss pathways except for volatilization. Consequently, the difference the in AFNR between urea and urea + NBPT gives a coarse approximation of the ammonia loss difference between these two fertiliser types in temperate maritime grassland averaged over these six site-years and a range of application conditions. The difference in AFNR between urea and urea + NBPT increased from 4 to 7.6 percentage points with increasing N rate, consistent with the findings of Black *et al*. (1985) who showed that the proportion of urea lost as NH_3 increased with increasing N rate. On average the difference in AFNR for the rates tested was 5.6% (standard error of the mean = 0.71%). This single digit difference contrasts sharply with windtunnel values of 25 – 30% and suggests that ammonia losses from urea usage in a temperate maritime climate are much lower than the values obtained from windtunnel experiments. This is perhaps not so surprising when one considers that Ryden and Lockyer (1985) reported that windtunnels can overestimate NH_3-N losses by a factor of 2.4 to 6 during rainfall. Indeed average ammonia losses from urea usage in Irish temperate maritime grassland may be lower than the 13.7% loss for urea estimated by Misselbrook *et al*. (2004) in the U.K.

4.3 Potential long-term implications of greater urea usage

There was no statistical evidence of annual yield differences between the fertiliser types tested indicating the potential for significant cost savings to a farmer by using urea as a substitute for CAN. For example in 2015 the average urea cost was €0.89 /kg N compared to €1.16 /kg N for CAN (CSO, 2016), the impact on cost of production per tonne of DM can be seen in Figure 1d. However, urea did have lower N off-take and AFNR which may have implications for overall farm system N efficiency. Eveillard *et al*. (2014) compared urea and AN applied to the same plots over multiple years and for individual years. They detected a statistically significant fertiliser type effect on total yield more frequently when urea and AN were applied over multiple years compared to where they were applied for a single year.

Substitution of CAN with urea will increase national ammonia emissions which is problematic for national governments who have committed to reductions. However, at this time these commitments do not play a role in farmer fertiliser selection decisions in the absence of a yield penalty. In a parallel study urea reduced losses of the greenhouse gas nitrous oxide compared with CAN (Harty *et al*., 2016) and for this reason there is interest in urea usage as a tool to sustain N input which drives production (Figure 1a) while reducing greenhouse gas emissions from fertilised grassland soils. However, the increased ammonia losses relative to CAN (Forrestal *et al*., 2016) presents some efficiency and national emission reduction challenges. The use of NBPT is a tool for addressing this issue by ensuring that urea is consistently as efficient as urea while providing a tool for reduced greenhouse gas emissions without the negative effect on ammonia emissions. These type of solutions are particularly needed by European countries signed up to reduce ammonia and greenhouse gas emissions.

Conclusion

There was tendency for urea to produce slightly better yields than CAN in spring (103.5% of CAN yield) and slightly poorer yield in summer (98.4% of CAN yield). However, when CAN, urea and urea + NBPT are used throughout the growing season annual grassland yields were not significantly different. As a result urea holds a significant cost advantage per kg DM produced because urea is considerably less expensive than either CAN or urea + NBPT. Although less tangible to farmers there was an efficiency penalty, particularly at higher rates, when using urea compared with using CAN or Urea + NBPT. The efficiency disadvantage for urea compared to CAN or urea + NBPT ranged from 4 to 7.6%, a difference likely to be primarily associated with ammonia loss from urea. However, as yield and cost rather than ammonia emissions are currently more pertinent to on farm decisions the yield results of the current study and associated implications for cost per tonne DM production will promote additional urea usage amongst farmers. Such additional usage without a urease inhibitor such as NBPT will present a challenge for national governments committed to reducing national ammonia emissions. Urea + NBPT substitution for CAN is likely to create a small cost saving however there will be a net cost when urea + NBPT is substituted for urea.

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Table 1. Experimental site locations, soil characteristics, rainfall, fertiliser application (App) and harvest details

	HB 2013	**HB 2014**	**MP 2013**	**MP 2014**	**JC 2013**	**JC 2014**
Coordinates	54°27'827N, 6°04'57873W	54°45'127N, 6°04'5785W	52°9'27"N, 8°14'42"W	52°9'33"N, 8°14'43"W	52°18'27N, 6°30'14W	52°17'32"N, 6°30'7"W
Soil pH	5.7	5.6	5.6	5.4	5.5	5.7
Soil texture	Clay Loam[a]	Clay Loam	Sandy loam	Sandy loam	Sandy loam	Sandy Loam tending toward sandy silt loam
TN (%)	0.56	0.45	0.32	0.32	0.30	0.28
Soil LOI (%)	14.3	12.5	7.4	7.9	7.3	7.0
CEC (cmol $^{(+)}$ /kg)	28.5	25.4	16.7	18.4	15.6	15.5
MGSR[b] (mm)	560	478	407	459	336	441
30 avg. MGSR (mm)	478	478	509	512	534	534
App 1	11-Mar	24-Mar	19-Mar	10-Mar	19-Mar	10-Mar
Harvest 1	No cut	29-Apr	22-Apr	22-Apr	25-Apr	22-Apr
App 2	15-Apr	6-May	29-Apr	28-Apr	29-Apr	28-Apr
Harvest 2	13-May	2-Jun	22-May	26-May	22-May	28-May
App 3	20-May	9-Jun	27-May	3-Jun	27-May	3-Jun
Harvest 3	19-Jun	21-Jul	26-June	30-Jul	26-Jun	2-Jul
App 4	24-Jun	28-Jul	1-Jul	7-Jul	1-Jul	7-Jul
Harvest 4	14-Aug	1-Sep	20-Aug	12-Aug	21-Aug	13-Aug
App 5	19-Aug	8-Sep	26-Aug	18-Aug	26-Aug	18-Aug
Harvest 5	9-Oct	13-Oct	15-Oct	13-Oct	16-Oct	16-Oct
Precipitation (mm)						
App 1 P1D[c]	0	3	0	0.1	1.6	0.1
App 2 P1D	3.2	5.8	0.1	0.2	0.1	0
App 3 P1D	0.2	0	5.1	8.6	13	0
App 4 P1D	1.4	0.2	0.5	5.7	0	5.4
App 5 P1D	0	0	0	0	0	0
App 1 P3D[d]	0.2	4.6	25.8	0.1	30	0.4
App 2 P3D	18.2	11.6	0.1	4.1	0.1	2.1
App 3 P3D	0.6	1.0	5.7	8.8	16.9	2.2
App 4 P3D	1.6	2.4	3.6	6.7	0.5	6.0
App 5 P3D	2.6	0	0	0.7	0	0

[a] Soil texture classification determined using LandIS portal © Cranfield University, UK.

[b] MGSR: main growing season rainfall (the period 1 March to 30 September)

[c] P1D: precipitation one day from fertiliser application

[d] P3D: precipitation three days from fertiliser application

Table 2. Effect of site-year, fertiliser type, N rate and their interactions on dry matter yield and N off-take

	Dry matter yield	N off-take
Effect		
Site-year	***	***
Fertiliser	ns (0.087)	***
N rate	***	***
Site-year x fertiliser	ns	ns
Site-year x N rate	***	***
Fertiliser x N rate	ns	**
Site-year x fertiliser x N rate	ns	ns

ns: not significant ($P > 0.05$)
* $P \leq 0.05$
** $P \leq 0.01$
*** $P \leq 0.001$

Table 3. Grass dry matter yield at each site-year for N rates of 0 to 500 kg/ha. N rates were applied in five equal split applications during the growing season

Site year	Annual N rate (kg N/ha)					
	0	100	200	300	400	500
	Yield (kg DM/ha)					
HB13	6103 BC f	8497 D e	10624 D d	12120 C c	13292 B b	13952 CD a
HB14	6497 AB e	9432 C d	12234 BC c	14245 A b	14850 A a	15467 A a
JC13	5252 C e	7975 E d	9694 E c	10856 D b	11532 C a	11914 E a
JC14	7161 A d	10292 AB c	12783 AB b	14404 A a	14789 A a	15049 AB a
MP13	6596 AB e	9692 BC d	11820 C c	12665 C b	13067 B ab	13378 D a
MP14	6874 AB e	10333 AB d	13224 A c	13588 B bc	14325 A a	14381 BC a
Pooled standard error of the mean = 259.3 kg/ha (371.7 kg/ha for the control group)						

Mean comparison by *F*-protected LSD test ($P \leq 0.05$).

Within columns yields with different upper case letters are significantly different.

Within rows yields with different lower case letters are significantly different.

Table 4. The effect of site-year and N rate on total N off take in temperate grassland

Site year	Annual N rate (kg N/ha)					
	0	100	200	300	400	500
	N off take (kg N/ha)					
HB13	102 B f	148 C e	202 C d	249 D c	291 D b	349 D a
HB14	115 B f	182 B e	254 B d	325 B c	381 B b	431 B a
JC13	111 B f	169 B e	233 B d	288 C c	337 C b	377 C a
JC14	113 B f	172 B e	247 B d	314 B c	371 B b	409 B a
MP13	149 A f	239 A e	331 A d	391 A c	442 A b	502 A a
MP14	153 A f	243 A e	353 A d	400 A c	462 A b	500 A a

Pooled standard error of the mean = 8.4 kg N/ha (12.4 kg N/ha for the control group)

Mean comparison by *F*-protected LSD test (*P*≤0.05).
Within columns N off take values with different upper case letters are significantly different.
Within rows N off take values with different lower case letters are significantly different.

Table 5. Effect of harvest, fertiliser type, N rate and their interactions on dry matter yield and N off-take at six individual site-years

Site-year	JC 13	MP 13	HB 13	JC 14	MP 14	HB 14
Dry matter yield						
Harvest	***	***	***	***	***	***
N rate	***	***	***	***	***	***
Fertiliser	ns	ns	ns	ns	ns	ns
Harvest x N rate	**	***	***	**	***	***
Harvest x Fertiliser	ns	ns	*	ns	ns	ns
N rate x Fertiliser	ns	ns	ns	ns	ns	ns
Harvest x N rate x Fertiliser	ns	ns	**	ns	ns	ns
N up-take						
Harvest	***	***	***	***	***	***
N rate	***	***	***	***	***	***
Fertiliser	*	*	**	**	0.06	ns
Harvest x N rate	***	***	*	**	***	***
Harvest x Fertiliser	ns	ns	ns	ns	ns	ns
N rate x Fertiliser	ns	ns	*	ns	ns	ns
Harvest x N rate x Fertiliser	ns	ns	*	ns	ns	ns

ns: not significant ($P > 0.05$)
* $P \leq 0.05$
** $P \leq 0.01$
*** $P \leq 0.001$

Table 6. The main effects of fertiliser type on N off-take averaged across N rates and harvests

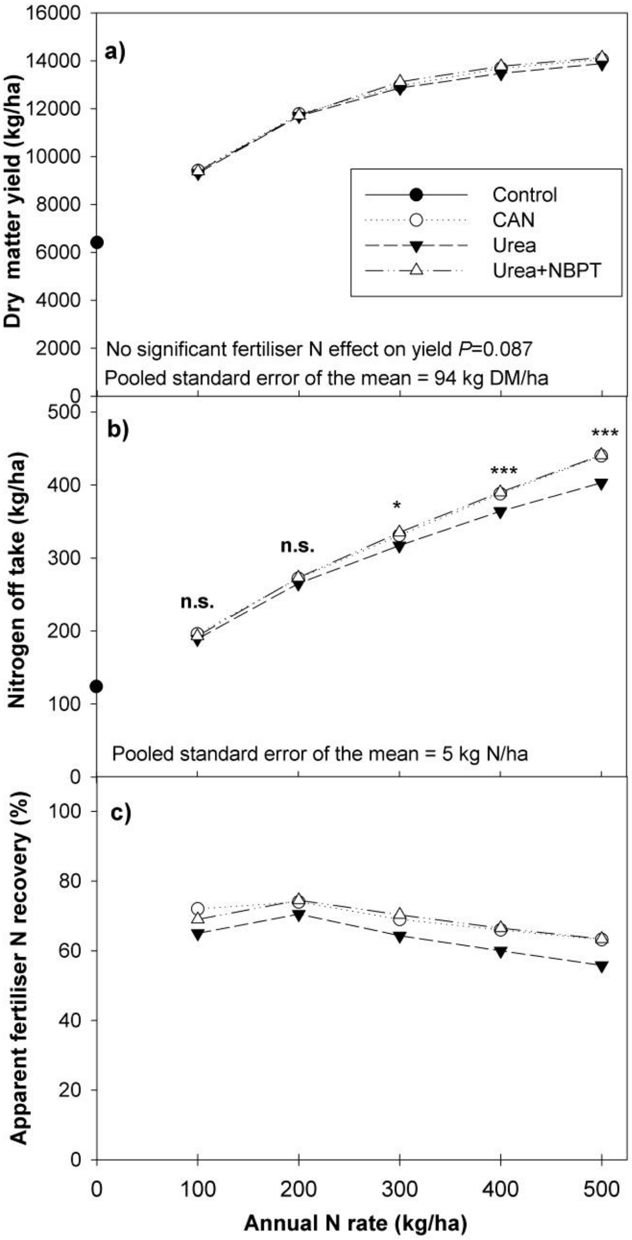
Siteyear	JC13	MP13	JC14	MP14	HB14
Fertiliser type	N off-take (kg N/ha/yr)				
CAN	58.9 a[a]	76.9 a	62.7 a	78.9	54.9
Urea	53.5 b	74.2 b	56.7 b	76.4	53.0
Urea + NBPT	57.0 a	77.3 a	62.2 a	79.6	55.6
S.E.M.	1.93	1.16	1.67	1.82	1.07

[a] N off take values with different letters within columns are significantly different according to *F*-protected L.S.D. test ($P \leq 0.05$).

Figure Captions

Figure 1a) effect of fertiliser nitrogen (N) type and N rate on annual dry matter yield, b) effect of fertiliser N type and N rate on annual N off-take, c) effect of fertiliser N type and N rate on apparent fertiliser N recovery, d) effect of fertiliser N type and N rate on the cost of grass DM production, fertiliser N cost used the average of 2015 €1.16/kg N and €0.89/kg N (CSO, 2016), urea + NBPT N cost set at 95% of the CAN N cost.

498


a)
Dry matter yield (kg/ha)
16000
14000
12000
10000
8000
6000
4000
2000
0
Control
CAN
Urea
Urea+NBPT
No significant fertiliser N effect on yield P=0.087
Pooled standard error of the mean = 94 kg DM/ha
b)
Nitrogen off take (kg/ha)
500
400
300
200
100
0
n.s.
n.s.
*
***
***
Pooled standard error of the mean = 5 kg N/ha
c)
Apparent fertiliser N recovery (%)
100
80
60
40
20
0
0
100
200
300
400
500
Annual N rate (kg/ha)