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EFFECTS OF UREASE AND NITRIFICATION INHIBITORS ON YIELDS AND EMISSIONS IN GRASSLAND AND SPRING BARLEY

by

Patrick J. Forrestal[1], David Wall[1], Rachael Carolan[2], Mary Harty[1], Leanne Roche[1], Dominika Krol[1], Catherine Watson[2], Gary Lanigan[1] and Karl Richards[1]

[1] Teagasc, Soils and Land-Use Department, Crops, Environment and Land Use Programme, Johnstown Castle, Co. Wexford, Ireland.
[2] Agri-Food and Biosciences Institute (AFBI), Newforge Lane, BT9 5PX, Belfast,United Kingdom.

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SUMMARY.

In trials conducted in the temperate maritime climate of Ireland on a range of acidic soils, calcium ammonium nitrate (CAN) and urea gave comparable yield performance. There was little evidence of reduced yields by using urea for grassland or spring barley. Our finding that urea produced annual yields that 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. However, there are also published results from trials conducted in temperate Irish grassland showing equal yield performance of CAN and urea in the 1970s. Based on yield performance and the cost of fertiliser there is scope to dramatically increase the level of urea usage in straight and blended fertilisers in the temperate maritime climate of Ireland in both grassland and spring barley. Such an increase will bring substantial benefits in terms of reducing direct nitrous oxide (N_2O) emissions from fertiliser applied to soil, particularly in poorly draining soils subject to high levels of precipitation. Nitrogen recovery by plants tends to be more sensitive to differences in fertiliser efficiency than is yield. Although yields did not differ between urea and CAN; urea had a lower nitrogen recovery indicating that urea usage will also result in a reduced level of fertiliser use efficiency. Reduced efficiency is less tangible to farmers who tend to be primarily concerned with dependable yield results. Reduced efficiency is a problem nonetheless, particularly as it is closely linked to NH_3 emissions in urea usage. European countries including Ireland have committed to reduce national NH_3 emissions to comply with the revised National Emission Ceilings Directive (2001/81/EC) in Europe. Increased urea usage, which looks attractive from a yield, cost and direct N_2O perspective in Ireland, runs counter to meeting these commitments. Additionally, NH_3 is a source of indirect N_2O emissions that will negate some of the N_2O savings from urea. Due to the issues of yield dependability, fertiliser efficiency, N_2O and NH_3 emissions the urease inhibitor N-(n-butyl) thiophosphoric triamide (NBPT) is a particularly attractive option for making urea use more efficient by addressing its key weakness in the area of variable NH_3 loss and efficiency. The urease inhibitor NBPT along with the nitrification inhibitor dicyandiamide (DCD) were tested with urea in comparison with calcium ammonium nitrate (CAN). The nitrification inhibitor DCD was very effective in reducing fertiliser N associated N_2O emissions. Indeed, its usage allowed N_2O levels to be reduced to levels comparable to where no application of N fertiliser was made at some site-years. However, at the DCD incorporation rate tested, DCD contributed to variability in NH_3 loss from urea and suppressed both yield response and fertiliser efficiency. Use of the urease inhibitor NBPT in addition to DCD went a substantial way to resolving these shortcomings. Continuing work is needed to tailor the rate of existing and new urease and nitrification inhibitors to optimise the balance between suppression of gaseous N emissions, agronomic performance and economic considerations.

CONTENTS

Agrotain® is a registered trade mark of Koch Agronomic Services, Wichita, KS, USA.

Keywords: Fertiliser nitrogen, urease inhibitor, nitrification inhibitor, nitrous oxide, ammonia, grassland, spring barley, yield, efficiency.

1. INTRODUCTION.

Application of nitrogen (N) fertiliser is a cornerstone of many intensive agricultural systems, including those in Ireland, and is a key input moving crops closer to fulfilment of their genetic yield potential. It is estimated that N and other mineral fertilisers feed around half of the global population (Sutton *et al.*, 2013). A key challenge is how to continue to apply fertiliser N to underpin crop yields while curtailing reactive N losses, including gaseous N emissions from fertiliser applied to diverse soils under varying weather conditions. Varying soils and precipitation patterns (Figure. 1) increase this challenge in environments such as Ireland. The challenge of gaseous N loss has come into particular focus recently due to national commitments across Europe to reduce losses of NH_3 and greenhouse gases (GHGs), including N_2O. Nitrous oxide comprises approximately 32% of agricultural GHG emissions (U.S. EPA, 2012) and is a potent GHG, with a global warming potential 265 times greater than CO_2 over a 100 year time frame and N_2O has an atmospheric lifetime of 121 years (IPCC, 2014).

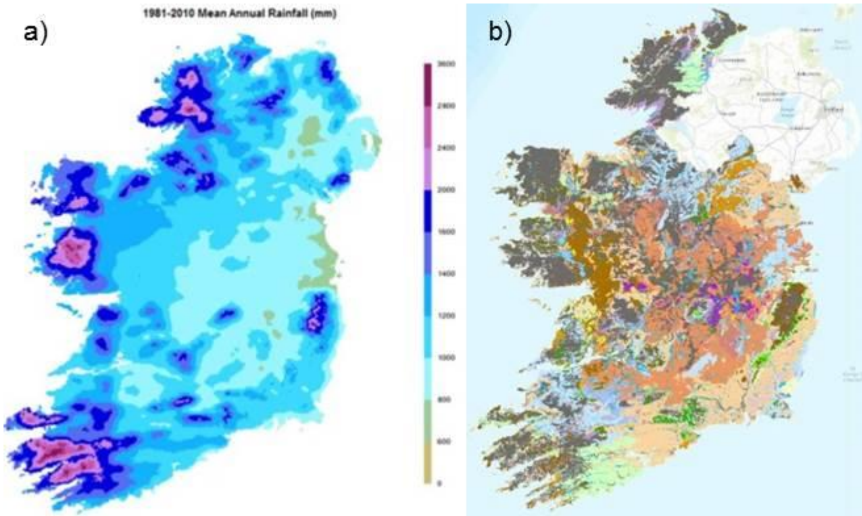

Figure 1: *a) Mean annual precipitation (mm) (source Met Eireann) b) the soils of Republic of Ireland (source: the Irish Soil Information System).*

The use of urea in place of ammonium nitrate-based fertiliser in intensive grassland has been linked to reduced direct N_2O emissions in cool wet soils (Dobbie and Smith, 2003). However, urea is vulnerable to NH_3 volatilisation (Chambers and Dampney 2009; Forrestal *et al.* 2016). Ammonia volatilisation is problematic from the perspective of reducing national NH_3 losses and also represents a source of indirect N_2O emissions as NH_3 is re-deposited and nitrified. A urease inhibitor can reduce NH_3 volatilisation from urea by inhibiting the enzyme urease which catalyses urea hydrolysis. The urease inhibitor NBPT has been shown to reduce NH_3 loss from urea (Watson *et al.*, 1990, 1994; Goos *et al.*, 2013). Working on a different pathway, nitrification inhibitors, such as DCD, inhibit ammonia mono-oxygenase, which catalyses oxidation of ammonium

(NH_4^+) to nitrite (Kim *et al.* 2012). Although effective for reducing N_2O emissions and leaching, nitrification inhibitors may increase NH_3 emissions. In a meta-analysis, Kim *et al.* (2012) reported that the effect of nitrification inhibitors on NH_3 emissions was inconsistent, with increased NH_3 emissions in 26 studies, no change in 14 studies and decreased emissions in six studies. Lam *et al.* (2016) suggest that the beneficial effects of nitrification inhibitors in decreasing direct N_2O emissions may be undermined or outweighed by increased NH_3 emission and the associated indirect N_2O emission.

This paper will examine the results of recent trials assessing the effects of fertiliser type, urease and nitrification inhibitors on yields, fertiliser efficiency and gaseous emissions in the temperate maritime climate of Ireland. In the context of sustainable intensification of Irish agriculture, where environmental protection and economic competitiveness are equal and complementary (FoodWise 2025 in the Republic of Ireland and Going for Growth 2020 in Northern Ireland), solutions for the challenge of using fertiliser N with reduced reactive N losses including gaseous losses are particularly in focus. In Ireland, agriculture must take action for national NH_3 and GHG reduction commitments to be realised. In the Republic of Ireland agriculture accounts for c.98% of national NH_3 emission and c.32% of GHG emissions. Northern Ireland has a similar agricultural emissions profile with agriculture accounting for c.93% of NH_3 emissions and c.29% of GHG emissions. Fertiliser N application is associated with emissions of NH_3 and N_2O, making the use of N sources and/or inhibitors capable of reducing these reactive N losses particularly relevant.

Currently, the main straight fertiliser N used in Ireland is CAN with urea and urea amended with a urease inhibitor taking up a smaller portion of the market.

2. MATERIALS AND METHODS.

2.1. Grassland sites.

To measure the effect of fertiliser N type on grass yield, N_2O, NH_3 and soil mineral N, replicated field experiments were conducted at three grassland sites in Ireland (Figure 2) in 2013 and 2014 (six site-years). The locations were Johnstown Castle, Co. Wexford, Moorepark, Co. Cork and Hillsborough, Co. Down. The site details are provided in Table 1. The sites were chosen to represent a range of soil and geo-climatic conditions across intensively managed agricultural areas in Ireland.

The experimental design was a randomised complete block with five replicates at each site-year. The CAN, urea and urea+NBPT fertiliser treatments were applied at annual N rates of 100, 200, 300, 400 and 500 kg/ha in five equal split applications between March and September. Plots received a basal application of P, K, and S in line with soil test recommendations to ensure that these nutrients were not limiting. Soil pH levels at the experimental sites were below the recommended level of 6.3. However, no lime was applied to the experimental sites to avoid the confounding effects of liming on the performance of the urea fertiliser (Watson *et al.*, 1987). Of the 28,137 grassland soil samples received for testing by Teagasc in 2015 64% were below pH 6.3. Indeed, 46% of grassland soils received by Teagasc were below pH 5.9.

Table 1: *Climate and soil physical and chemical properties for the six site-years tested (adapted from Harty et al., 2016).*

Site-year	HB, 2013	HB, 2014	MP, 2013	MP, 2014	JC, 2013	JC, 2014
GPS 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
Drainage[a]	Imperfect	Imperfect	Good	Good	Good	Moderate
Soil pH	5.7	5.6	5.6	5.4	5.5	5.7
Soil texture	Clay loam	Clay loam	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Sand (%)	41.0	42.9	58.8	57.8	52.9	51.7
Silt (%)	33.9	34.6	27.8	28.2	33.2	33.9
Clay (%)	25.1	22.4	13.5	14.1	13.9	14.4
BD	0.86[1]	0.79	1.02	1.18	1.11	1.27
Soil TC (%)	5.99	5.16	3.00	3.02	3.16	2.83
TN (%)	0.557	0.451	0.318	0.321	0.304	0.284
Soil LOI (%)	14.3	12.5	7.40	7.90	7.30	7.02
CEC (meq/100g)	28.5	25.4	16.7	18.4	15.6	15.5
Rainfall (mm)						
Annual	1,113	1,047	1,130	1,002	1,021	939
30-year average	885	885	1,018	1026	1,060	1,060
Main growing season[b]	560	478	407	459	336	441
30-year average growing season	478	478	509	512	534	534

[a] Drainage Classification was based on the soil associations from the Soil Map of Ireland (Gardiner and Radford, 1980).
[b] Main growing season (1 March to 30 Sept).

Urea+DCD and urea+NBPT+DCD were applied at the 200 kg N/ha rate only. In addition there was a zero N control treatment. The source of the urease inhibitor NBPT was Agrotain®, which was coated onto urea granules at 660 ppm NBPT (on a urea weight basis). Watson *et al.* (2008) reported little additional benefit from exceeding 250 ppm. However, based on their work, the 660 ppm NBPT level was expected to achieve near maximum NH_3 loss abatement. For the urea+DCD treatment the DCD had been added to urea at the molten stage at the rate of 3.5% on a urea-N basis. Urea+DCD granules were coated with Agrotain® on site to a rate of 660 ppm NBPT to make urea+NBPT+DCD.

Nitrous oxide emissions were measured from each plot using the static chamber technique (Chadwick *et al.*, 2014). Yield and N uptake was measured by harvesting dedicated agronomic plots (2 m x 10-12 m at the end of each grass growth cycle (Figure 2). Soil mineral N was measured by sampling the dedicated soil sampling area of the plots. Ammonia emissions were measured from each of the fertiliser treatments at the Johnstown Castle and Hillsborough sites during 2014 using a system of wind tunnels (Lockyer, 1984; Meisinger *et al.*, 2001). Each wind tunnel covered an area of 0.5 x 2 m. There were three replications per treatment. Ammonia measurements were conducted adjacent to those used for N_2O and yield measurements with fertiliser applications applied at the same timing as for the other plots (Figure 2). For the detailed experimental setup see Forrestal *et al.* (2016) and Harty *et al.* (2016).

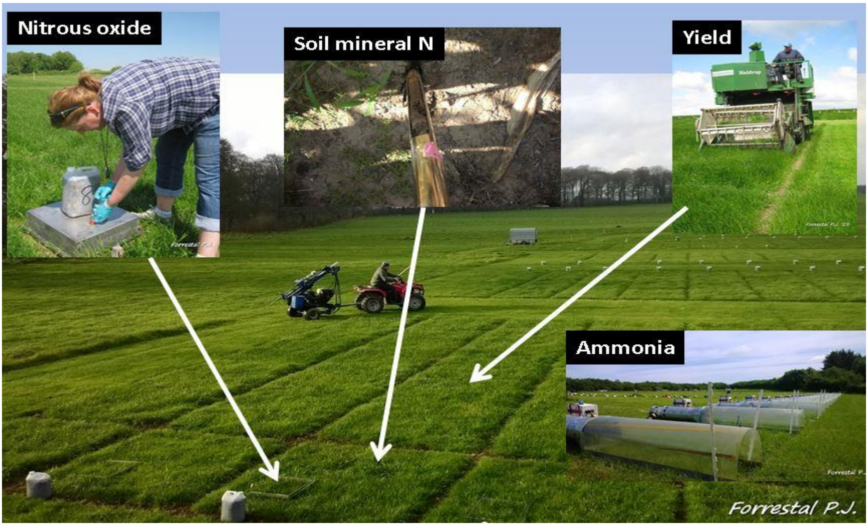

Figure 2: *The arrangement of each experimental unit in the grassland site.*

2.2. Spring barley site.

The spring barley trial was conducted on one free-draining loam site located in Marshalstown, Co. Wexford (52° 33' 37.3" N 6° 36' 09.0" W) over three years. The experimental design was a randomised complete block with five replicates. The layout of each experimental unit was similar to the grassland sites (Figure 2) with a dedicated N_2O, soil mineral N and yield measurement area. The same suite of fertilisers used in the grassland experiment were applied in two split applications. The first split application of 30 kg N/ha was surface applied shortly following planting. The second and final split application to balance to the target N rate was applied at early to mid-tillering. Nitrous oxide emissions were measured using the static chamber technique (Chadwick *et al.*, 2014). The soil pH was 6.8, total C 2.9% and the CEC 100 meq/100g (Roche *et al.*, 2016). Forty five percent of tillage soils received for testing by Teagasc in 2015 had a pH >6.5. The field site where experiments were conducted was located within a major malting barley growing region in Ireland and was representative of the typical soil type used for spring barley production in Ireland. The site had been in long-term arable production for the previous 20 years.

3. RESULTS AND DISCUSSION.

3.1. Grassland.

3.1.1. Grassland yields.

Figure 3 summarises the response to N fertiliser rate for the six site-years tested under a cutting regime and demonstrates that grassland responds strongly to N addition (Figure 3). For the three fertiliser types tested over a range of N rates (CAN, urea and urea+NBPT) there was no significant interaction between N rate and fertiliser type nor was there a main effect of fertiliser type on yield (Forrestal *et al.*, in review). Across this range of rates the three fertilisers produced yield which did not differ significantly. Our finding that urea produced annual yields that 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 (Rodgers *et al.*, 1984; Chaney and Paulson, 1988). However, our results are not unprecedented in Irish temperate grassland. Keane *et al.* (1974) also found that urea yielded as well as CAN in Irish temperate grassland in the 1970s.

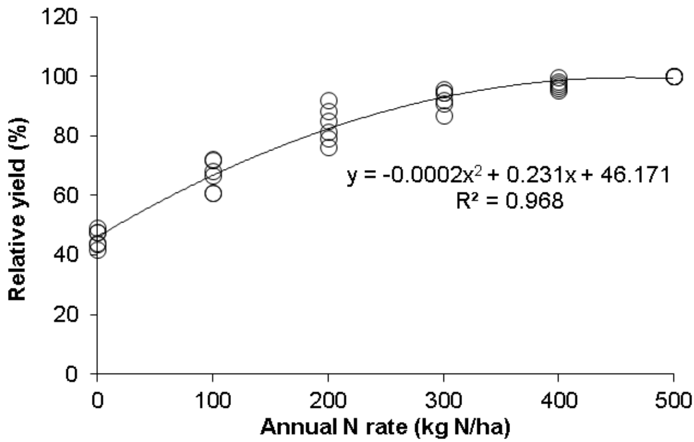

Figure 3: *Grassland yield relative to the 500 kg N/ha rate for six site-years under a cutting regime. No significant N fertiliser type effect was detected at P<0.05. Adapted from Forrestal et al. (in review).*

A larger suite of fertilisers was examined at the 200 kg N/ha/yr rate. The 200 kg N/ha rate is at a point in the response curve where these grassland sites were still responding strongly to N fertiliser addition under a cutting regime (Figure 3). Grass yield was similar for all fertiliser treatments except for urea with the nitrification inhibitor DCD alone (Figure 4). The meta-analysis of Kim *et al.* (2012) indicates that nitrification inhibitors such as DCD may increase NH_3 loss from urea. In this study, when NBPT was added to DCD treated urea, grass yields were similar to the highest yielding treatments. This result lends weight to the hypothesis that the NH_3 loss pathway is an important reason why urea+DCD alone had poorer yield performance than the other fertiliser treatments.

3.1.2. Nitrogen uptake and apparent fertiliser recovery in grassland.

Urea is vulnerable to NH_3 loss in temperate grassland (Watson *et al.*, 1990) and the proportion of NH_3 loss tends to increase with increasing urea rate (Chambers and Dampney, 2009; Forrestal *et al.*, 2016). Despite this, in these trials, no significant yield difference was detected between urea and CAN or

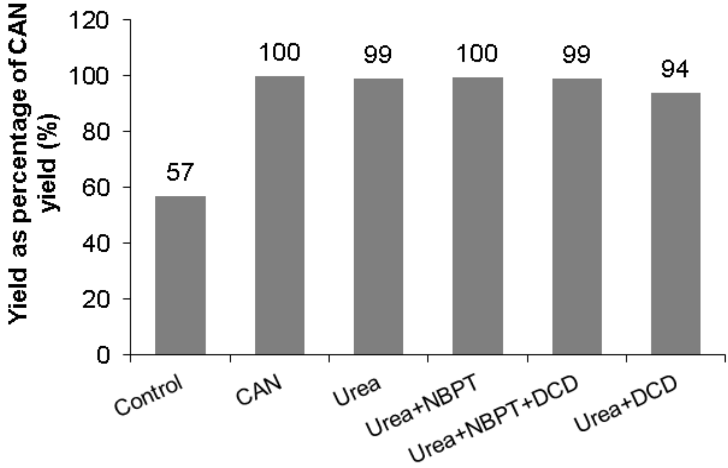

Figure 4: *Average grassland yield expressed as a percentage of CAN yield. Data from six site-years fertilised at 200 kg/N/ha adapted from Harty et al. (in press).*

urea+NBPT even at high N rates (Figure 3). Nitrogen uptake and recovery by plants is more sensitive to detection of differences in N availability between treatments than is yield. Figure 5 demonstrates this point. Significantly lower N uptake was measured for urea compared with both CAN and urea+NBPT at higher N rates whereas no significant yield difference was detected at these N rates (Figure 3). It is worth noting that all N rates were applied in five split applications ranging from 20 to 100 kg N/ha/spilt. In a silage setting the higher N rates are likely to be applied by a farmer at least once in a growing season.

Comparison of the full suite of fertiliser products at the 200 kg N/ha/yr rate also provides insight into the efficiency of the various fertiliser products. Across the six site-years urea+NBPT and CAN had the highest apparent fertiliser N recovery (AFR). Urea treated with the nitrification inhibitor DCD had the poorest AFR (Figure 6). Soil type effects on DCD degradation have been identified (Cahalan *et al.*, 2015 and McGeough *et al.*, 2015). McGeough *et al.* (2015) reported that DCD is less effective in soils with high clay and high organic matter contents. The lowest yields noted for urea+DCD in the present study were associated with weather conditions conducive to volatilisation (Harty *et al.*, in press). Tailoring the nitrification inhibitor rate may address the issue of reduced AFR and yield when urea is treated with DCD. The DCD rate used in the present study may have been too high for best agronomic outcomes in these particular systems and climate. The DCD application method used in these experiments is highly targeted, being incorporated in to the fertiliser granule. Di and Cameron (2005) applied 10 kg/ha DCD in a fine suspended particulate spray across the pasture in a single application. In comparison the rate of DCD applied with the fertiliser at 200 kg N/ha/year was 7 kg/ha/year or

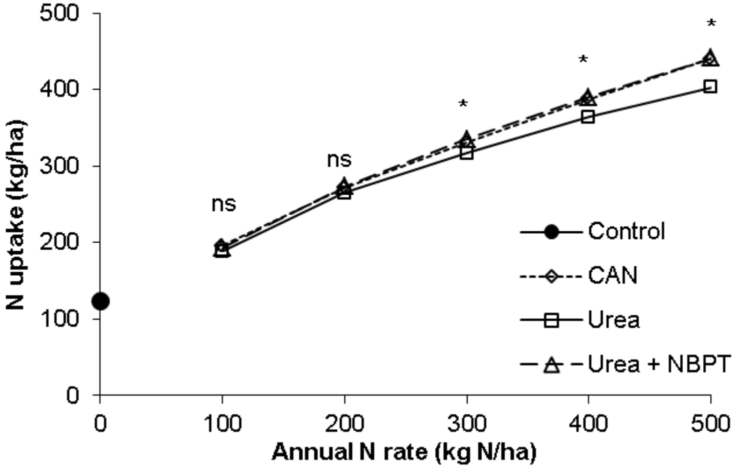

Figure 5: *Average grassland N uptake for CAN, urea, urea+NBPT across N rates. Fertiliser applied in five equal split applications. Data from six site-years, adapted from Forrestal et al. (in review). ns: not significant*
** indicates a treatment effect at P<0.05.*

1.4 kg DCD/40 kg N/ha application. Despite the relatively low DCD loading rate the overall results of these trials suggest a potential for even lower inclusion rates when DCD is applied in a targeted manner with the fertiliser granule because, as shown later, even at the rate tested DCD was highly effective in reducing N_2O emissions.

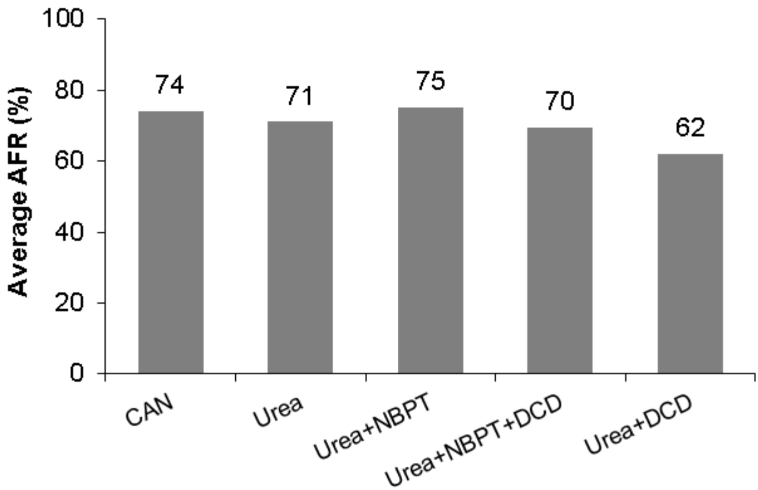

Figure 6: *Average grassland apparent fertiliser N recovery (AFR). Data from six site-years fertilised at 200 kg N/ha adapted from Harty et al. (in press).*

Urea+NBPT could be expected to behave similarly to urea for N loss pathways except for volatilisation. Consequently, the difference in AFR between urea+NBPT and urea gives a crude estimate of apparent NH_3 loss from urea based on 30 individual applications of fertiliser over six site-years in the temperate maritime climate of Ireland. This loss difference is 4% (Figure 6) and across N rates tested ranges from 4% to 7.6% (Forrestal *et al.*, in review).

3.1.3. Ammonia emissions from grassland.

Figure 7 summarises the results of the NH_3 emissions measurement conducted using wind tunnels. This methodology permits inter-comparison of a large suite of fertilisers in a replicated setting and is useful for determining relative performance and abatement potential of treatments (Forrestal *et al.*, 2016). Ryden and Lockyer (1985) found that wind tunnels can overestimate NH_3 losses by a factor of 2.4 to 6 during periods of rainfall, hence their usefulness for relative rather than absolute comparison. Our results showed no significant difference in NH_3 loss from CAN and urea+NBPT in any of ten applications. Both fertilisers had relatively low levels of loss. Ammonia emissions from urea+DCD+NBPT did not differ significantly from CAN in nine out of ten applications, but were significantly higher on one occasion (Forrestal *et al.*, 2016). Compared to untreated urea, the urease inhibitor NBPT reduced NH_3 loss by 78.5% on average across both sites (Figure 7).

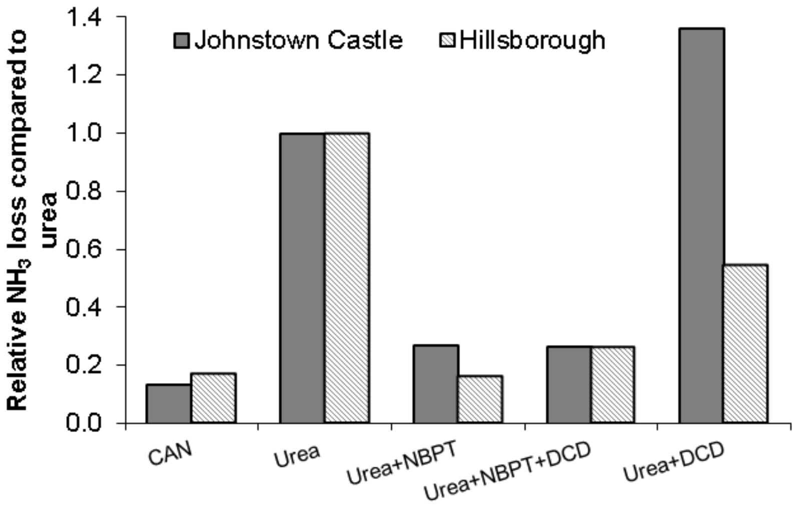

Figure 7: *Ammonia (NH_3) loss from fertiliser treatments expressed relative to loss from untreated urea. Each histogram indicates the average of five N applications at 40 kg N/ha. Adapted from Forrestal et al. (2016).*

Contrasting effects of DCD on NH_3 emissions were measured at Johnstown Castle and Hillsborough with greater emissions from urea+DCD compared with urea at Johnstown Castle and lower emissions for urea+DCD at Hillsborough. A meta-analysis by Kim *et al.* (2012) also reported a limited number of cases where DCD decreased NH_3 emissions but the reduction was much lower than that observed at

Hillsborough. More frequently Kim *et al.* (2012) reported increased or not significantly different NH_3 emissions due to use of a nitrification inhibitor, as was observed at Johnstown Castle.

Measurements of NH_3 loss were conducted in spring and summer. It was found that NH_3 loss from urea can be a significant issue in both spring and summer, indeed the highest loss measured for an individual application occurred in spring (Forrestal *et al.* 2016). This in agreement with Black *et al.* (1985) who noted no marked seasonal pattern of NH_3 loss from urea in New Zealand grassland. What is clear from our NH_3 measurements is that the urease inhibitor NBPT is highly effective in reducing NH_3 emissions from urea to levels comparable to those from CAN. This technology represents a pathway toward reducing NH_3 losses in agriculture, a key priority of EU national governments committed to reducing national NH_3 losses.

3.1.4. Nitrous oxide emissions from grassland

The Intergovernmental Panel on Climate Change (IPCC) uses the same 1% default N_2O emission factor (EF) irrespective of N fertiliser or soil type. In the present study large differences between fertilisers where observed (Figure 8). Across the six site-years CAN had the highest average direct N_2O EF of 1.49% (Figure 8). Similarly Hyde *et al*. (2016) reported an EF exceeding the IPCC value in Irish grassland. They reported an EF of 2.15% for a single application of CAN. In addition to having the highest EF in the present study; importantly CAN was the most variable treatment, with an across site-year coefficient of variation (c.v.) of 61%. Urea+NBPT and urea had lower direct N_2O emissions and were less variable, with c.v.s of 29% and 14%, respectively (Figure 8).

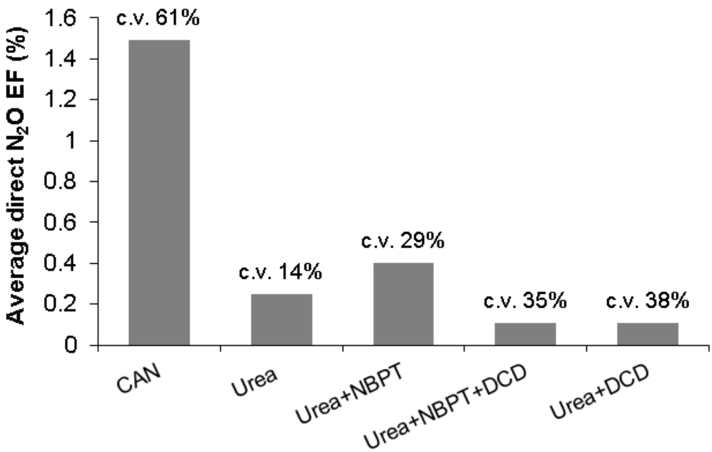

Figure 8: *Average N_2O emission factor (EF) and coefficient of variation (c.v.) from six grassland site-years at an annual N fertilisation rate of 200 kg/ha. Adapted from Harty et al. (2016).*

Thus the urea products reduced the N_2O emission factor and in addition reduced the uncertainty associated with direct EF levels across site-years. The reduction in the uncertainty is an important point as the precipitation levels and soils of Ireland vary dramatically across the landscape (Figure 1). As a consequence the EF for CAN is likely to be highly variable across sites and seasons. Use of a urea based fertiliser is an option which meets not only the challenge of reducing absolute emissions of N_2O but also stabilising N_2O loss outcomes across the landscape in temperate maritime climates such as Ireland.

When the indirect N_2O emissions associated with urea NH_3 loss were estimated in this study the N_2O emissions for urea and urea+NBPT were similar (Harty *et al.*, 2016). The results of the present study demonstrate that, compared with CAN, urea amended with the urease inhibitor NBPT is an effective strategy for reducing the N_2O emissions associated with fertiliser application in temperate maritime Irish grassland. Using urea treated with NBPT the N_2O reduction can be achieved without causing a large increase in NH_3 emissions, as would be the case if unamended urea usage were increased. Further reductions in N_2O emissions beyond those possible by substituting urea+NBPT for CAN are technically possible by using a nitrification inhibitor such as DCD. In these experiments the lowest overall N_2O emissions were for urea treated with both the nitrification inhibitor DCD and the urease inhibitor NBPT, which resolves the NH_3 and associated indirect N_2O emission difficulty of applying nitrification inhibitors alone.

3.2. Spring barley.

3.2.1. Spring barley yields.

Figure 9 summarises the relative yields compared to CAN for three years at a free-draining spring barley site. The data presented is for the 100 kg N/ha rate. This N rate is significantly below the optimum rate for the site and as a consequence crops grown at this N rate are expected to be highly sensitive to differences in crop available N between treatments. Nevertheless, the yields of CAN, urea and urea+NBPT were similar (Figure 9).

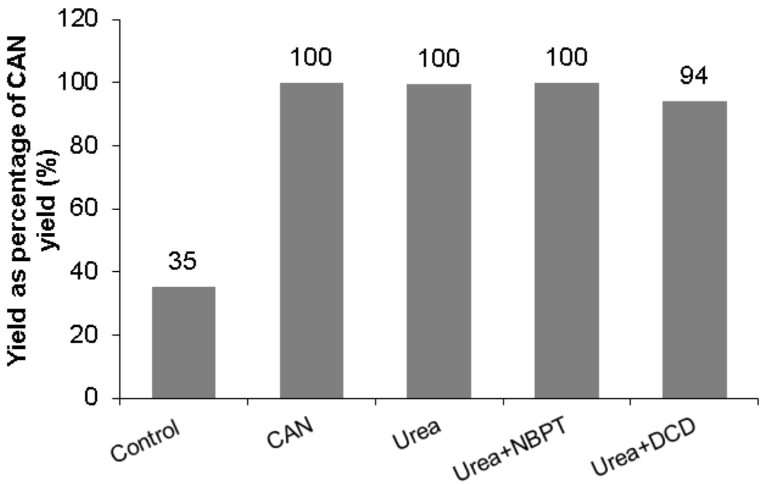

Figure 9: *Average spring barley yield expressed as a percentage of CAN yield. Data from three site-years fertilised at 100 kg/N/ha. Adapted from Roche et al. (in preparation).*

The finding that urea yielded as well as CAN differs from that of Devine and Holmes (1963) who reported a relative yield of 86% for urea relative to ammonium nitrate for trials conducted on 14 'light' soils. However, they also reported a relative yield of 99% for urea for eight experiments conducted on soils with pH of 7 and below. The soils in the current experiment were also below pH 7. Gately (1994) compared CAN and urea at nine winter wheat sites and showed significant yield reductions with urea at all sites ranging from 0.24 – 0.64 t/ha. Urea with DCD alone had a lower relative yield of 94%, which is consistent with the grassland trials (Figure 4) and evidence in the literature of increased NH_3 loss due to use of nitrification inhibitors (Lam *et al.*, 2016).

3.2.2. Spring barley apparent fertiliser N recovery.

The difference in the sensitivity of total N recovery versus yield for detecting differences in the efficiency of different fertilisers can be seen by comparing Figure 9 and Figure 10. In terms of yield CAN, urea and urea+NBPT were similar. However, apparent fertiliser recovery was lowest for urea, which is likely to be a reflection of its potential for NH_3 loss. Urea+NBPT had the highest AFR, although at the 150 kg N/ha rate Roche (in preparation) found no significant difference in N uptake between CAN and urea+NBPT. Urea had lower N uptake than both CAN and urea+NBPT. Based on the 100 kg N/ha rate data presented here, a crude estimate of NH_3 loss can be made by the difference in N recovery of urea compared with CAN and urea+NBPT. This difference was 4-10% on average for these three site-years; very similar to that in the grassland trials.

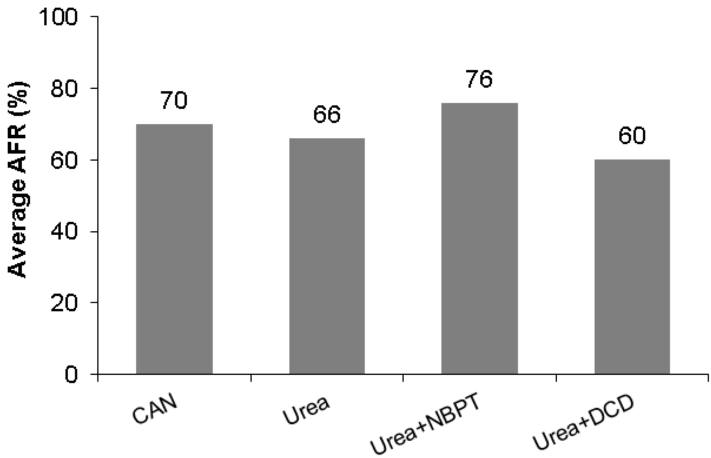

Figure 10: *Average spring barley apparent fertiliser N recovery (AFR). Data from three site-years at Marshalstown fertilised at 100 kg N/ha.*

As was observed in the grassland sites the level of AFR was lowest for urea+DCD. This is counter to findings of increased average yield and nitrogen use efficiency by use of nitrification inhibitors in the meta-analysis of Abalos *et al.* (2014). However, Abalos *et al.* (2014) do state that effectiveness of inhibitors was dependent on the environmental and management factors of the studies. In the current study, and perhaps surprisingly in the temperate maritime climate of Ireland, the use of DCD alone with urea appears to confer an efficiency disadvantage. As discussed earlier in the grassland section there may be scope to address this efficiency disadvantage by reducing the DCD rate in the granule and by inclusion of NBPT to address the NH_3 uncertainty associated with adding DCD to urea (Forrestal *et al.* 2016).

3.2.3. Nitrous oxide emissions from spring barley

Overall N_2O emissions for all fertilisers tested were relatively low at the Marshalstown spring barley site (Figure 11) in comparison to the grassland sites (Figure 8). The fertiliser N_2O emission factor was less than 0.5% for all fertiliser treatments at this spring barley site. In addition the c.v. for CAN of 28% was lower than the c.v. of 61% observed for the grassland sites. Similar to the grassland sites the use of urea reduced the N_2O c.v. compared to CAN (Figure 11).

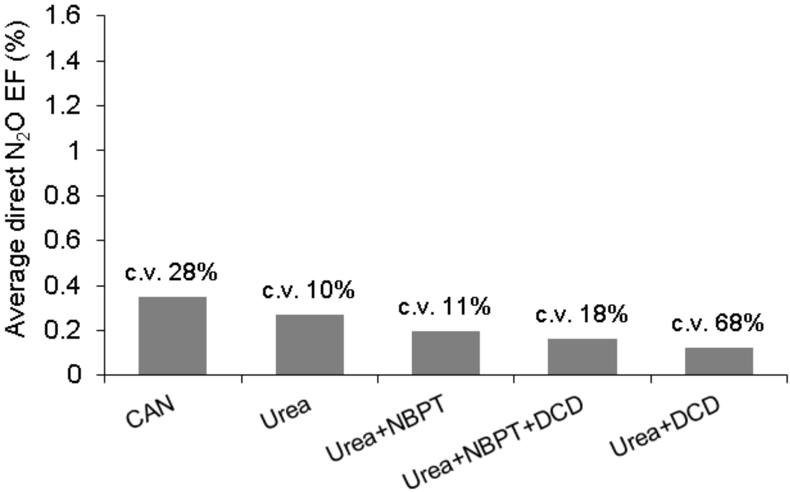

Figure 11: *Average N_2O emission factor (EF) and coefficient of variation (c.v.) over two years at a freely drained spring barley site at an annual N fertilisation rate of 150 kg/ha. Adapted from Roche et al. (2016).*

The CAN EFs of the present study showing relatively low N_2O emissions from fertiliser N applied to spring barley are consistent with a previous Irish study which reported an EF of 0.5% for CAN during the growing season (Abdalla *et al.*, 2010). There were few differences in N_2O emissions between CAN and urea and urea+NBPT. A comparison between urea and ammonium nitrate (AN) at three UK sites cropped to cereals also found no difference in N_2O emissions between fertiliser CAN and urea (Bell *et al.*, 2015). Similarly, Louro *et al.* (2015) reported no significant effect of N source on N_2O emissions in maize production in the humid Atlantic climate of Galicia, Spain.

The low and less variable EF, compared to the grassland sites, in the present spring barley studies could be explained, at least in part, by the soil characteristics. The soil was a free-draining cambisol with a carbon content of 2.88%, which is typical of Irish soils cropped to spring barley. In a meta-analysis of over 1,000 studies, Stehfest and Bouwman (2006) concluded that N_2O emissions were significantly lower on soils with soil organic carbon <3% and Gilsanz *et al.* (2016) observed the lowest EFs in soil textures with low clay content (less than 50%) and with sand content greater than 50%.

The inclusion of a nitrification inhibitor has potential to further reduce N_2O emissions from fertilisers and some reduction was observed in the present study. However, the N_2O loss reduction potential of nitrification inhibitors is likely to be greatest under high N_2O loss conditions. The free-draining soils typically cropped to spring barley in Ireland tend to have relatively low levels of N_2O loss. However, to date little work has been done to examine N_2O emissions in winter wheat production in the temperate maritime climate of Ireland. The soils cropped to winter wheat generally tend to have poorer drainage characteristics than those soils cropped to spring barley in Ireland. Nevertheless, in the present study the lowest direct N_2O EF measured was for urea+DCD in 2014 (0%). This outcome indicates potential to grow a spring barley crop fertilised to produce optimal yield but to have the N_2O emission of an unfertilised crop through the use of fertiliser technologies such as nitrification inhibitors and urease inhibitors to control the NH_3 emission uncertainty of urea.

4. CONCLUSIONS.

4.1. Yield.

- The yield of CAN and urea was not significantly different in these trials.
- Urea treated with the urease inhibitor NBPT consistently yielded as well as CAN.
- The use of the nitrification inhibitor DCD alone decreased grassland and spring barley yields relative to CAN.
- Addition of NBPT to urea treated with DCD recovered the yield lag caused by the nitrification inhibitor.

4.2. Efficiency: apparent fertiliser nitrogen recovery (AFR).

- Urea has the potential for lower (AFR) compared to CAN particularly at higher nitrogen rates.
- Use of the urease inhibitor NBPT ensured that the AFR of urea was consistently at least equal to CAN.
- The nitrification inhibitor DCD used alone had a pronounced negative effect on AFR at the inclusion rate tested in these trials. However, inclusion of NBPT in addition to DCD significantly mitigated this negative effect.

4.3. Ammonia.

- Inclusion of the urease inhibitor NBPT reduced NH_3 losses from urea by 78.5% on average. As a result NH_3 loss from urea+NBPT was not significantly different to CAN.
- Variable ammonia loss is a feature of urea usage, however based on comparing the N recovery in plants fertilised with urea, compared to urea+NBPT or CAN, NH_3 losses are apparently generally low to moderate in temperate Irish grassland and spring barley production.
- Addition of the nitrification inhibitor DCD to urea fertiliser at the rate tested introduces additional uncertainty to the behaviour of urea fertiliser in terms of NH_3 loss.

4.4. Nitrous oxide.

- Nitrous oxide emissions were highly variable between sites. The free-draining spring barley site had lower emission levels than the grassland sites.
- CAN had the highest direct N_2O emissions in the temperate maritime climate of Ireland, on average exceeding the IPCC default loss. In addition, emissions from CAN were more variable than from urea and urea+NBPT at both the spring barley and grassland sites.
- Urea and urea treated with the urease inhibitor NBPT had lower nitrous oxide emissions than CAN. The magnitude of the loss saving was greatest when emissions were high, with little difference in N forms at the free draining spring barley site but important differences at the grassland sites.
- Addition of the nitrification inhibitor DCD to urea was an effective tool for further suppressing N_2O emissions. At some sites the use of DCD suppressed emissions to levels comparable to the control receiving no N.

The present study found that the fertiliser N form applied along with enhanced efficiency technologies such as urease and nitrification inhibitors are tools which can help to address the key challenge of how to continue to apply fertiliser N to underpin crop yields while curtailing reactive N losses. These trials demonstrate that it is possible to achieve important reductions in nitrous oxide emission, particularly in grassland, without cutting N rates or sacrificing yield or fertiliser efficiency. Options to achieve the N_2O reductions seen in this study by substituting urea+NBPT or urea+NBPT+DCD for CAN in temperate maritime grassland without compromising yield are rare. CAN is generally more expensive than urea as a N source. The resultant price differential provides scope to add urease and/or nitrification inhibitor technologies to urea and remain cost competitive with CAN. As more urease and nitrification inhibitors and formulations enter the market field testing will remain important to evaluate efficacy and to optimise inhibitor rates to meet economic, agronomic and environmental loss mitigation objectives.

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