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TITLE Temperate Grassland Yields and Nitrogen Uptake Are Influenced by Fertilizer Nitrogen Source

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NOTICE: This is the author’s version of a work that was accepted for publication in *Agronomy Journal*. This is the accepted version of the article, which has been published in final form at Agron. J. 109:71-79. doi:10.2134/agronj2016.06.0362

Title: Temperate grassland yields and N uptake are influenced by N source.

Abstract

In temperate grassland N source influences greenhouse gas emissions (GHG). Nitrification and urea hydrolysis inhibitors can reduce these losses. The objective of this study was to evaluate the impact of N source, urease inhibitors and nitrification inhibitors on temperate grassland yields and N uptake. Experiments were conducted at three locations over two years (6 site-years) on the island of Ireland, covering a range of soils and climatic conditions. Results showed that CAN, urea+NBPT, urea+NBPT+DCD and urea had equal annual DM yield. Urea+DCD had lower DM yield than CAN for 3 site-years. Calcium ammonium nitrate and urea+NBPT consistently had the same N uptake, and urea+DCD had lower N uptake than CAN in 4 of 6 site-years, urea had lower N uptake than CAN in two site-years and urea+NBPT+DCD had lower N uptake than CAN in one site-year. Urea+NBPT is a cost-effective alternative to CAN, which is consistently equal in terms of both yield and N uptake in temperate grassland.

Urea is the most concentrated solid N fertilizer (46% N), is cheaper to manufacture, more economical to transport and less expensive than other solid forms of fertilizer N. Consequently, urea is the leading N fertilizer product used globally; however, in the UK and Ireland, ammonium nitrate (AN) based fertilizers are the dominant form of N fertilizer applied to grassland, whereas in New Zealand, 93.7% of the total fertilizer N used in grasslands in 2013 was urea (IFADATA, 2013). Differences in N sources may be related to the influence of local conditions (Watson et al., 1990a). In some studies, nitrogen applied initially as urea may be less susceptible to denitrification losses than calcium ammonium nitrate (CAN), especially in wet conditions and in high organic matter soils (Clayton et al., 1997, Dobbie and Smith, 2003, Jones at al., 2007). Research has shown urea to be a useful tool for reducing N_2O emissions in practice without reducing fertilizer N input as N in urea undergoes two transformations before it is vulnerable to denitrification loss as NO_3^- (Dobbie and Smith, 2003; Harty et al., 2016). However, in Ireland, farmers are concerned about the influence on variability on crop yields This variability is attributed related to the loss of ammonia (NH_3) through volatilization (Watson et al., 1990a). Ammonia losses from urea in temperate grasslands (Forrestal et al., 2016, Chambers and Dampney, 2009) averaged higher than from CAN/AN, however, N losses from urea can be highly variable. Urea is vulnerable to NH_3 loss through volatilization because hydrolysis of urea induces a short-duration pH increase around the fertilizer granule to increase the proportion of NH_3-N in the soil solution, thereby promoting NH_3 volatilization (Mikkelsen, 2009). Urease or nitrification inhibitors may reduce these losses.

Urease inhibitors (UI) have been available on the US market since the mid 1990's. Agrotain®, the most common product, (Koch Agronomic Service, Wichita, Kansas, USA) (Chien et al., 2009) has the active ingredient, N-(n-butyl) thiophosphoric triamide (NBPT), which inhibits the hydrolytic action of soil urease by blocking the active site of the enzyme.

N-(n-butyl) thiophosphoric triamide, or specifically its oxygen analog (NBPTo) (Engel et al., 2015), delays the rate of urea hydrolysis to NH_4^+-N and moderates the localised zones of high pH and NH_4^+-N concentrations and reduces NH_3 volatilization (Watson et al., 1990b; 1994). **Nitrification inhibitors** (NIs) are compounds that delay the bacterial oxidation of NH_4^+ by inhibiting soil-nitrifying bacteria (Subbarao et al., 2012). Reduction in NO_3^- denitrification and leaching potentially increasing the efficiency of the applied N. Nitrification inhibitors include 3, 4-dimethylpyrazole phosphate (DMPP), nitrapyrin (N-Serve), 2-amino-4-chloro-6-methyl pyrimidine (AM) is dicyandiamide (DCD) which has been used in agriculture for many years (Fox and Bandel,1989) because of its low cost, solubility, and low volatility. **Combined nitrification and urease inhibitors** (CIs) the partial calcium salt of maleic–itaconic copolymer (MIP) has been marketed globally as both a urease and nitrification inhibitor under the trade name Nutrisphere®. Maleic–itaconic copolymer claims to reduce urea hydrolysis and nitrification, thereby reducing both NH_3 volatilization and increasing the agronomic efficiency of urea-based N fertilizers; however, Goos (2008) found MIP had no effect on either hydrolysis or nitrification levels compared to urea in either a sandy loam or clay loam.

No studies have compared the yield performance of CAN with an extensive suite of urea-based formulations incorporating UIs, NI’s, and CI’s such as NBPT, DCD, and MIP, as well as a 50/50 blend of CAN and Urea in temperate grasslands over a range of soils and climatic conditions. The objective of this study was to determine how different urea based formulations would perform relative to CAN, in terms of grass DM yield and N uptake.

MATERIALS AND METHODS

Experimental sites

Experiments were conducted at permanent pasture sites at three locations in Ireland during the 2013 and 2014 growing seasons, giving 6 site-years in total. Perennial ryegrass (*Lolium perenne* L.) was the dominant species in the swards. The locations were Johnstown Castle, Co. Wexford (JC13 and JC14) (52°18'27"N, 6°30'14"W and 52°17'32", 6°30'7"), Moorepark, Co. Cork (MP13 and MP14) (52°9'27"N, 8°14'42"W and 52°9'33"N, 8°14'43"W) and Hillsborough, Co. Down (HB13 and HB14) (54°27'83"N, -6°04'58"W and 54°45'31"N, -6°08'18"W). Site details and soil characteristics are provided in Table 1. More detailed site characteristics as well as the soil mineral N concentrations, (NO_3^- and NH_4^+) for the growing season for each of the six site years are available in Harty et al. (2016). A new experimental site was used at each location in each year to avoid N carryover between years. These locations covered a range of soils and climatic conditions in which grass is grown in Ireland. Perennial ryegrass and Italian ryegrass account for nearly all of the agricultural grass sown in Ireland (DAFM, 2015). The experimental design was the same at all three sites, a randomised complete block with five replicates. Each experimental unit (plot) measured 2 × 8 m at HB and 2 × 10 m at JC and MP. The experimental treatments were a selection of N fertilizers applied in five equal splits to total 200 kg ha^{-1} yr^{-1}. The N fertilizer treatments were CAN, urea, urea+NBPT, urea+DCD, urea+NBPT+DCD, and a control (zero N) treatment. Two additional treatments were applied at the MP14 and JC14 sites, which were urea+MIP (Maleic-Itaconic Copolymer) and CAN/urea blend which was a combination of 50% urea-N and 50% CAN-N (giving 25% NH_4-N and 25% NO_3-N). The same source of urea was used across all sites and years (except urea+MIP). The DCD was incorporated into the urea melt as part of the manufacturing process, at a rate of 1.6% on a urea weight basis, giving a DCD rate of 1.39 kg DCD ha^{-1} $application^{-1}$ or 6.96 kg DCD ha^{-1} yr^{-1}. The Urea+MIP was a commercially available product purchased for the study. The source of the urease inhibitor NBPT was Agrotain®, which was coated onto the urea granules at 660 mg NBPT kg^{-1} urea. Plots received a basal dressing of P, K, and S in line with soil test recommendations. Although soil pH was below the recommended level, no lime was applied to avoid confounding effects on the performance of the urea fertilizer which is susceptible to NH_3 volatilization.

Following each fertilizer application, a 1.5m wide strip was cut through the centre of each grass plot to a height of approximately 5cm using a Haldrup harvester (Haldrup, Løgstor, Denmark) and the grass was removed from the plot. The period between fertilizer application and harvest varied from 4 to 9 weeks (Table 1) to reflect the change in grass growth rates over the growing season in response to environmental conditions as characterized previously by Humphreys et al. (2004). To account for changes over the growing season, regrowth was measured during mainly vegetative growth phases and to limit the period of growth during reproductive growth phases. As a consequence, the period of regrowth chosen varied over the course of the growing season. Fresh weight was recorded at each harvest and a 200 g subsample collected to determine DM and N content using a C and N analyser (Leco Corporation, St. Joseph, Michigan, USA).

Apparent fertilizer N recovery (AFR) was calculated as:

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

Urea relative yield (URY) was calculated as:

$$\text{URY (\%)} = (\text{Yield}_{\text{urea\_product}} / \text{Yield}_{\text{CAN}}) * 100$$

Grass Growing degree days (GDD) was calculated as:

$$\text{GDD} = (\text{DailyTemp}_{\max} + \text{DailyTemp}_{\min}/2 - T_{\text{base}}) \ (T_{\text{base}} = 6°\text{C for grass})$$

Climatic measurements included daily air temperature (°C), atmospheric pressure (mbar), rainfall (mm), and soil temperature (°C) at 5- and 10-cm below ground level measured by a weather station that was within 1 km of field sites. Soils were sampled to a depth of 10 cm weekly for mineral N and gravimetric water content during the growing season and fortnightly in winter. Separate volumetric soil moisture measurements were measured at each gas sampling occasion using a hand held ML2x Theta Probe (Delta-T Devices Ltd., HH2, UK). Hourly volumetric moisture measurements were recorded on a CR10X Data logger (Campbell Scientific) with a minimum of four CS-625 Water Content Reflectometer (WCR) probes. The stone free bulk density at each site was used to calculate WFPS from the volumetric moisture content. Volumetric soil moisture data was first calculated from the gravimetric measurements and this was supplemented with theta probe and WCR volumetric data to provide better temporal resolution. Soil Moisture Deficit (SMD) was calculated based on the SMD hybrid model for Irish grassland (Schulte et al., 2005). The soil lime requirement was determined using Shoemaker, McKleen and Pratt (1996) lime buffer test. This was performed to provide information on the pH buffer capacity of each soil across the different site-years. The surface soil texture at HB is a clay loam whereas at the other two sites the surface soil texture is a sandy loam. The HB site has the highest organic matter, cation exchange capacity (CEC) and buffering capacity.

Statistical analysis

The effect of fertilizer N treatment on the dependent variables of grass yield and N uptake were tested using the general linear mixed model for all site-years using the PROC GLIMMIX procedure of SAS (© 2002-2010, SAS Institute Inc., Cary, NC, USA). The factors in the model were site-year and fertilizer N and their interactions as fixed effects and block as a random effect. Least significant differences are presented along with the pooled standard error of the mean. The effect of fertilizer N treatment on apparent fertilizer recovery (AFR) was tested for each site-year using PROC GLIMMIX. The factors in the model were site-year and fertilizer N and their interactions as fixed effects and block as a random effect. Inferences were made using the 5 percent level of significance which is shown along with the standard error of the mean.

RESULTS

Environmental and soil variables

Precipitation during the main growing season (Mar-Sept) was above the 30 yr average at HB13 and similar to the long term average at HB14 (Table 1). Growing season rainfall was below the long-term average for JC and MP in both years: for JC13 and MP13 by 53 and 198 mm, respectively, and for JC14 and MP14 by 93 and 53mm, respectively. This variation in precipitation resulted in the lowest SMD at HB13 and highest SMD at JC13 and MP13 (Figure 1). Soil moisture deficit increased above zero at HB13 between 12th and 24th July and at HB14 from 11th June to 30th September. In contrast a SMD occurred in all months of the growing season at MP and JC, the greatest in July, and both sites had a greater SMD in 2013 compared to 2014. The average annual soil temperature (surface 5cm) was lower for HB than MP and JC, by approximately 1ºC in 2013 and between 1.7 and 2ºC, respectively, in 2014, which resulted in less grass growing degree days (Thom, 1954) (Table 1). During the growing season this temperature difference was greater at HB14 with an average difference of 2.5ºC at MP and 2.7 ºC at JC (data not shown).

N Response and growing season yield

The production potential of individual site-years differed; the highest treatment and control yields were produced at MP 2014, followed by JC 2014. The HB site-years produced the lowest yield. The 200 kg N ha^{-1} yr^{-1} rate used was on a responsive part of the N yield response curve. There was an interaction between site-year and fertilizer N type on total annual yield ($P < 0.05$) (Table 4). Urea relative yield (URY) for urea+DCD was always less than 100% indicating numerically lower yield than CAN at all site-years while yield was lower than CAN in three site-years (MP13, HB13 and JC14) (Table 2). Urea + DCD produced lower yield than urea in two site-years. There was no yield difference between

CAN and untreated urea, urea+NBPT or urea+DCD+NBPT in any site-year. In addition, the yield of urea+MIP was not different from CAN, but it was lower than urea at MP in 2014. The yield with CAN/Urea treatment was not different to CAN in the two site-years where it was tested (Table 2).

Growing season N uptake and recovery

There was a site-year by fertilizer type interaction on total N uptake (P = 0.005) (Table 4). Urea+DCD had lower N uptake than CAN in four site-years at the MP and JC sites (Table 3) while urea+DCD had less N uptake than urea at MP14 only. There was no difference in N uptake between CAN and urea+NBPT in six site-years while urea+NBPT+DCD had lower N uptake than CAN at one site-year and urea had lower N uptake than CAN at two site-years. Of the two site-years CAN/urea treatment and urea+MIP had lower N uptake than CAN and urea at one site-year. At the other site-years, where these treatments were included (JC14), these treatments and untreated urea were not different to CAN. There was greater N uptake in the control plots in both site-years at MP and at JC13 relative to JC14, which itself had greater N uptake relative to the HB site. Urea+DCD had lower AFR than both CAN and Urea+NBPT at two site-years (JC14, MP13) (Table 3), and was lower than urea at two site-years (HB13 and MP14). The lowest individual AFR and lowest average treatment AFR was with the Urea+DCD treatment (39% and 62% respectively) and the highest was for Urea+NBPT (103% and 75% respectively).

Individual harvests

A harvest x site–year x fertilizer interaction was detected for both DM yield and N uptake (Table 4). A review of the individual site-year DM yield and N uptake data for each harvest showed that urea+DCD was the treatment which showed reduced performance relative to other treatments, and these occurred predominately in the summer. No other treatment exhibited this level of reduced yield or N uptake compared to all of the other treatments. As the N uptake is product of yield and grass N content, the results for the individual site-year responses for each harvest for N uptake only are presented in Table 5. Dry matter yield was similar for all N fertilizers except for urea+DCD which had reduced yield (relative to the standard CAN) on 71% of applications in summer (data not shown).

Urea+DCD reduced N uptake on eight occasions relative to urea+NBPT, on six occasions relative to urea and on five occasions relative to CAN. The reduced N uptake of urea+DCD was more pronounced at JC compared to other sites, urea+DCD reduced uptake: compared to urea+NBPT at JC on four occasions and twice each at HB and MP; compared to urea at JC on three occasions, twice at HB and once at MP; and compared to CAN at JC on four occasions and once at HB. The reduced N uptake of urea+DCD occurred most frequently in summer: urea+DCD reduced uptake on eight harvests compared to urea+NBPT and all reductions except one in summer; on six harvests compared to urea with all reductions except one in summer and on five occasions compared to CAN with all five occasions in summer

DISCUSSION

The key factors affecting grassland yield and N uptake were fertilizer N type, harvest timing, site-year differences and soil conditions.

Fertilizer type effects on annual yield and N uptake

Although urea can be vulnerable to NH_3 loss, especially during summer, annual yields from the urea treatment were neither consistently lower, nor different to CAN at any site-year. Consequently, it follows that the yield from treatments containing MIP and NBPT, which claim to reduce NH_3 loss were not lower than CAN, in fact they were not different from CAN. The similarity in the pattern of AFR from each of the individual harvests (data not shown) indicated the lowest average AFR was in early spring (37% in harvest 1) followed by in late summer (64% in harvest 5). The highest AFR was in late spring (95% in harvest 2) followed by early and mid-summer (harvest 3, 86% and harvest 4, 78%).The consistency of total growing season yield from urea, urea+NBPT and urea+NBPT+DCD relative to CAN over the six site-years (Table 3), suggests that there is little yield implication for production at least in the short term by switching from CAN to one of these formulations. This is noteworthy as the applied N rate was on the responsive part of the N response curve; consequently, any N deficiency would be expected to be expressed in yield at this rate. This N deficiency compared to CAN was observed for urea+DCD in three site-years in contrast to urea or urea+NBPT, both of which generated yield levels not different to CAN in all site-years.

Despite similar yield performance relative to CAN, N uptake from urea was lower at two of six site-years (JC13 and MP13) (Table 4), a reflection of the NH_3 loss vulnerability of urea. At these two sites, the addition of NBPT improved N uptake to levels not different to CAN. Urea+DCD treatments had lower N uptake compared to CAN in four site-years and urea in one site-year. The poorer performance compared with untreated urea maybe be a result of DCD enhancing NH_3 loss from urea (Kim et al., 2012; Forrestal et al., 2016). As the proportion of NH_3 volatilization loss from urea relative to CAN is higher at higher rates of application (Forrestal et al., 2016), this enhancement of NH_3 loss from urea with the addition DCD may be even higher at higher N application rates. The addition of NBPT (i.e. urea+NBPT+DCD) provided a technical solution by closing the N uptake gap of urea+DCD such that urea+NBPT+DCD had a lower yield than CAN at only one of the 6 site-years tested. The role of NBPT in maintaining yield and N uptake of urea at levels comparable to CAN is in agreement with results from Watson et al., (1990b). While leaching losses were not measured, N_2O and NH_3 emissions (measured in parallel experiments) support the switch to urea+NBPT. In addition to producing yield and N uptake comparable to CAN, N_2O emissions from urea+NBPT were significantly lower compared to CAN (Harty et al., 2016) and the addition of NBPT to urea reduced NH_3 emissions by on average 78.5% compared to urea alone (Forrestal et al., 2016). These results provide a promising strategy for the mitigation of GHG emissions without compromising production especially in higher precipitation environments such as temperate maritime grassland.

Harvest Differences

While the results of the present study found only one harvest each (from 29 harvest occasions) where urea yield and N uptake was lower than CAN (Table 5), there was a trend for reduced URY (Table 2). This supports the findings of Forrestal et al. (2016); Watson et al. (1990a); Chambers and Dampney (2009) where reduced performance of urea in summer relative to CAN/AN in temperate grasslands is accounted for by NH_3 losses, which were higher more highly variable from urea. In contrast, urea+DCD reduced N uptake compared to CAN on five occasions. The reduced urea+DCD performance were in contrast with a number of studies where DCD increased grassland yield (Di and Cameron 2002; Zaman et al., 2009; Moir et al, 2012 and Delgato and Mosier 1996). However, yield increases were observed at irrigated sites, while the present study was entirely rain-fed. Precipitation could have contributed to an unequal distribution of moisture which could have resulted in N leaching although leaching was not measured in the present study. The yield results are in agreement with Abalos et al., (2014) who found inhibitors (nitrification and urease) increased yields more consistently in irrigated than rain-fed systems. Where DCD reduced yield relative to urea, the soil WFPS was low and reducing (data not shown). DCD retained more N as NH_3 higher in the soil profile and as the soil dried this may have contributed to enhanced NH_3 volatilization. This supports the findings that NIs have been shown to increase NH_3 loss from urea during conditions conducive to NH_3 volatilisation (Kim et al., 2012 and Lam et al., 2016).

Site-year differences

The differences in N uptake observed across site-years in the control plots support the findings that N mineralization rates that vary seasonally and between soils (Nunan et al., 2000; Herlihy, 1979; McDonald et al., 2014) and can contribute a considerable proportion of N grass growth (Humphreys et al., 2008). In addition, AFR for urea at MP14 was 103% of fertilizer applied indicating that fertilizer N may be priming additional mineralization over the control (Gioacchini et al., 2002; Murphy et al., 2015). Immobilization of applied N fertilizer may have contributed to the lower AFR rate at HB which has a high soil organic matter content and cooler, wetter weather conditions than the other two sites. The higher clay content at HB may also have been a contributing factor as Hassink (1994) found a negative relationship between the percentage of soil N mineralizing and the clay and silt content of the soil.

The treatment with most variable performance, urea+DCD, reduced yield compared to all other treatments most frequently at JC (11 occasions) and most frequently in the summer (100%, 100% and 64% in summer at JC, MP and HB, respectively). The yield reduction was also more pronounced at JC13 (reduced yield on seven occasions, compared to JC14 four occasions). All of these yield reductions occurred for summer fertilizer N applications in 2013. This coincided with highest SMD conditions in the study at JC13 (117 days) followed by 85 days at MP13, 69 days at JC14, and 41 days at MP14. Urea+DCD also reduced N uptake compared to all other treatments most frequently at JC (19 occasions), compared to HB (5 occasions) and MP (4 occasions). This reduction was greater at JC14 (12 occasions) than JC13 (7 occasions). All of these uptake reductions also occurred in summer. Conditions in 2014 were more favourable for grass growth than in 2013 when more extreme SMD conditions were encountered (Fig. 1) and all three sites generated greater yields in 2014 (Table 2). Urea AFR was lowest in the drier conditions at JC13 and MP13, relative to CAN. This result supports Morrisson (1980) who found that yield was positively related ($r^2 = 0.75$) to water availability during the growing season.

Soil Conditions

Differences in soil properties between sites, particularly CEC and buffering capacity, may have also contributed to reduced N uptake performance of urea+DCD in the JC site. DCD slows nitrification, resulting in higher NH_3 concentration in the soil solution. Nitrification lowers pH, so adding DCD slows nitrification and results in a higher pH in the soil solution. A higher pH and a larger NH_3 pool could contribute to higher volatilization rates (Singh et al., 2008) above those produced by urea (Asing et al., 2008). This effect may be moderated in soils with higher CEC (Kim et al, 2012) (as more NH_3 is locked up on the exchange sites) and higher buffering capacity (smaller pH spikes driving lower levels of volatilization). This supports the findings of Stevens et al, (1989) who found that the lowest rates of NH_3 volatilization will occur from soils with low buffering capacity and van Burg et al., (1982) who found the highest efficiency of urea compared to AN occurred in well buffered soils. Urea+DCD uptake performance relative to urea was lowest in JC14 (lower uptake in two harvests) compared to any other site-year. This site-year had both the lowest CEC (15.5 $cmol^+ kg^{-1}$) and lowest buffering capacity in the study.

Economics and implications for policy

Based on average 2015 prices (CSO, 2016), the cost per tonne of grass grown, net of the control yields, using CAN had a cost of US$49.07 (€43.97) and using urea had a cost of US$37.51 (€33.61). So there is an economic advantage for a farmer to switch from CAN to urea. However, substitution with urea would have implications for national NH_3 emissions and fertilizer efficiency. Measurements by Forrestal et al., (2016) showed that on average NH_3 emissions from urea were higher than CAN. The more environmentally friendly urea formulation, urea+NBPT, reduced average NH_3 emissions from urea by 78.5% (Forrestal et al., 2016) of N applied, delivered consistent yield and N uptake efficiency results to CAN (present study) and successfully reduced N_2O emissions compared to CAN (Harty et al., 2016). Based on the results of the present study, CAN cost over US$11 (€10) more per tonne of grass grown than urea; and urea+NBPT offers the potential to generate the yield and N uptake performance of CAN at a lower cost than CAN. Urea+NBPT is currently marketed at between 5% and 10% cheaper than CAN resulting in a US$2 to $4.50 (€2 to €4) T^{-1} DM gain for a farmer. However, there is a risk that farmers may elect to apply urea over urea+NBPT as the inclusion of NBPT could increase costs over urea by almost US$8 (€7) T^{-1} DM.

CONCLUSION

The results of this study showed there was no reduction in annual yield in the short term if farmers switched fertilizer from CAN to urea, urea+NBPT or urea+NBPT+DCD. However, urea+DCD had lower yield than CAN in three site-years and reduced N uptake in four site-years. Although urea generated the same yields as CAN, and was the least expensive, increased application of urea, could increase NH_3 emission levels and reduce system N use efficiency. Urea+NBPT consistently delivered equal yields and N uptake compared to CAN. Urea+NBPT provides farmers with a cost effective alternative to CAN, which is agronomically comparable but has potential environmental advantages in terms of nitrous oxide emissions. As urea treated with NBPT is more expensive than urea some form of incentive may be needed to encourage farmers to use of urea+NBPT over in place of urea, a switch which will reduce ammonia emissions.

ACKNOWLEDGEMENTS

The authors would like to thank the laboratory and field staff at Teagasc Johnstown Castle, Teagasc Moorepark and Agri-Food and Biosciences Institute with their assistance on this project. The authors would also like to thank Koch Agronomic Services for the supply of fertilizer products. This research was financially supported under the National Development Plan, through the Research Stimulus Fund, administered by the Department of Agriculture, Food and the Marine (Grant numbers RSF10-/RD/SC/716 and RSF11S138) and from the Department of Agriculture and Rural Development for Northern Ireland. The first author gratefully acknowledges funding received from the Teagasc Walsh Fellowship Scheme.

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Figure Captions, Tables, and Figures.

Figure Captions

Figure 1: Soil Moisture Deficit for the three sites from 1 March to 30 September.

Tables

Table 1. Experimental site locations, soil characteristics and rainfall 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	5.6	5.7
Drainage †	Imperfectly	Imperfectly	Well	Well	Well	Moderate
Soil texture ‡	Clay Loam	Clay Loam	Sandy loam	Sandy loam	Sandy loam	Sandy Loam
TN (%)	0.6	0.5	0.3	0.3	0.3	0.3
Soil LOI (%)	14.3	12.5	7.4	7.9	7.3	7.0
CEC (cmol($^+$) kg^{-1})	28.5	25.4	16.7	18.4	15.6	15.5
Lime Req. (tonnes ha^{-1})	9.5	10	3	5	5	1.5
GSR § (mm)	560	459	407	459	336	441
30 avg. GSR (mm)	478	478	509	512	534	534
Age of sward (years)	23	24	3	4	3	1
Grass growing degree days ¶	1192	1330	1396	1411	1377	1472
Average annual soil temp (5cm) (°C)	10.2	9.9	11.2	11.6	11.1	11.9

†Drainage Classification was based on the soil associations from the Soil map of Ireland (Gardiner and Radford, 1980)

‡Soil texture classification determined using LandIS portal © Cranfield University, UK.

§GSR: Growing Season Rainfall (1March- 30 September)

¶Grass growing degree days from first fertilizer application to final harvest

Table 2. The effect of fertilizer type on total Dry Matter (DM) yield.

Site-year	**JC 2013**	**MP 2013**	**HB 2013**	**JC 2014**	**MP 2014**	**HB 2014**	**Avg**
Fertilizer				**Grass DM yield (kg ha^{-1})**			**URY(%)**
Control	6801 b[†]	7470 c	6362 c	7395 d	8105 c	6561 b	
CAN	11862 a (100)	12254 a (100)	10819 a (100)	13575 ab (100)	14209 ab (100)	12354 a (100)	100%
Urea	11027 a (93)[‡]	12425 ab (101)	11062 a (102)	13112 ab (97)	14566 a (103)	12342 a (100)	99%
Urea+NBPT	11329 a (96)	12947 a 106)	11139 a (103)	12787 bc (94)	13828 ab(97)	12702 a (103)	100%
Urea+NBPT+DCD	11369 a (96)	12541 ab (102)	11262 a (104)	13309 ab (98)	13764 ab (97)	12222 a (99)	99%
Urea+DCD	10418 a (88)	12042 b (98)	10147 b (94)	12133 c (89)	13706 b (96)	12178 a (99)	94%
CAN/Urea				13775 a (101)	13558 b (95)		
Urea+MIP				12998 abc (96)	13682 b (96)		

Pooled standard error of the mean 344 kg N ha^{-1}

[†] Within columns yields with different lower case letters are significantly different. Mean comparison by F-protected LSD test (P<0.05).

[‡] Urea relative yield (URY) in brackets (urea product yield expressed as a % of CAN yield)

Table 3 Total N uptake as affected by fertilizer N source

Site-year	**JC 2013**	**MP 2013**	**HB 2013**	**JC 2014**	**MP 2014**	**HB 2014**	**Avg**
Fertilizer			**Grass N uptake (kg ha^{-1}) and AFR (%)**				**AFR(%)**
Control	166 c[†]	184 c	107 c	120 c	194 c	117 b	
CAN	313 a (74[‡])	358 a (87)	202ab (48)	265 a (72)	384 a (95)	256 a (70)	74
Urea	280 b (57)	342 b (79)	208 ab (51)	249 ab (64)	400 a (103)	262 a (72)	71
Urea+NBPT	297 a (66)	377 a (96)	217 a (55)	261 a (71)	376 a (91)	262 a (72)	75
Urea+NBPT+DCD	296 a (65)	334 b (75)	215 a (54)	249 ab (64)	372 a (89)	257 a (70)	70
Urea+DCD	267 b (51)	329 b (72)	184 b (39)	223 b (51)	367 b (86)	263 a (73)	62
CAN/Urea				264 a (72)	362 b (84)		
Urea+MIP				243 ab (61)	363 b (84)		

Pooled standard error of the mean 13 kg N ha^{-1}

[†] [e]Within columns uptake with different lower case letters are significantly different. Mean comparison by *F*-protected LSD test (*P*<0.05).

[‡] Apparent fertilizer recovery value (%) in brackets

Table 4- Analysis of variance of fixed effects harvest, site-year and fertilizer and interactions for annual Dry Matter (DM) yield and N uptake and repeated measures analysis of individual harvests of DM yield and N uptake for each site-year

	Annual DM yield	**Annual N Uptake**		**Individual harvest DM Yield Repeated measures analysis**	**Individual harvest N Uptake Repeated measures analysis**
Effect	**Pr > F**	**Pr > F**	**Effect**	**Pr > F**	**Pr > F**
Site-year	***	***	Harvest	***	***
Fertilizer	***	***	Site-year	***	***
Site-year x Fertilizer	*	***	Harvest x Site-year	***	***
			Fertilizer	***	***
			Harvest x Fertilizer	***	***
			Site-year x Fertilizer	n.s[†].	n.s.
			Harvest x Site-year x Fertilizer	***	**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

[†] n.s. = not significant

Table 5: Effect of harvest, fertilizer type and site-year on N uptake kg N ha^{-1} harvest $^{-1}$

Site-year / fertilizer type	**Spring Applications Harvest 1**	**Harvest 2**	**Summer Applications Harvest 3**	**Harvest 4**	**Harvest 5**
HB13			**N uptake kg N ha^{-1} harvest $^{-1}$**		
Control		25.7 c[†]	27.9 b	19.4 c	29.3 c
CAN		45.5 b	56.3 a	35.1 b	58.2 b
Urea		55.9 b	47.9 a	45.2 ab	52.9 a
Urea + NBPT		59.6 a	50.0 a	46.7 a	53.4 ab
Urea + NBPT+DCD		53.8 b	52.6 a	52.5 a	48.1 a
Urea + DCD		49.2 b	45.3 a	41.7 c	42.6 b
HB14			**N uptake kg N ha^{-1} harvest $^{-1}$**		
Control	11.1 b	29.6 b	35.2 b	17.2 b	22.4 b
CAN	19.4 ab	61.8 a	69.8 a	41.2 a	60.6 a
Urea	22.4 a	71.4 a	60.7 ab	40.6 a	61.7 a
Urea + NBPT	26.9 a	61.2 a	57.1 b	44.6 a	63.0 a
Urea + NBPT+DCD	21.9 ab	62.2 a	60.0 a	44.6 a	61.8 a
Urea + DCD	27.9 a	68.5 a	63.3 a	42.9 a	55.7 a
JC13			**N uptake kg N ha^{-1} harvest $^{-1}$**		
Control	16.6 a	14.8 b	27.3 a	24.4 c	28.1 b
CAN	19.4 a	44.6 a	62.1 a	63.5 a	57.8 a
Urea	21.5 a	37.4 a	54.1 a	51.9 ab	52.0 a
Urea + NBPT	22.7 a	43.8 a	56.2 a	58.2 a	54.9 a
Urea + NBPT+DCD	20.5 a	38.2 a	57.6 a	57.8 a	53.4 a
Urea + DCD	22.5 a	39.8 a	48.5 b	45.9 b	50.2 a
JC14			**N uptake kg N ha^{-1} harvest $^{-1}$**		
Control	25.8 b	32.2 b	16.3 c	16.3 c	22.5 b
CAN	41.5 a	67.7 a	46.6 a	46.1 a	49.8 a
Urea	41.3 ab	65.6 a	46.8 a	38.6 a	45.7 a
Urea + NBPT	40.9 ab	69.6 a	50.7 a	42.1 a	47.8 a
Urea + NBPT+DCD	37.5 ab	68.3 a	49.4 a	39.2 a	44.0 a
Urea + DCD	37.7 ab	65.3 a	35.1 b	34.4 b	40.9 a
CAN/Urea	44.5 a	70.2 a	49.0 a	44.7 a	43.9 a
Urea + MIP	40.1 ab	66.1 a	47.9 a	40.3 a	39.6 a
MP13			**N uptake kg N ha^{-1} harvest $^{-1}$**		
Control	6.8 a	24.7 b	33.4 c	57.5 b	26.7 a
CAN	15.3 a	83.1 a	88.1 ab	98.0 a	46.8 a
Urea	16.1 a	79.8 a	78.2 b	93.8 a	46.2 a
Urea + NBPT	17.5 a	81.9 a	95.3 a	98.1 a	53.4 a
Urea + NBPT+DCD	14.4 a	79.4 a	74.7 b	91.4 a	49.0 a
Urea + DCD	12.7 a	74.5 a	76.0 b	91.8 a	47.0 a
MP14			**N uptake kg N ha^{-1} harvest $^{-1}$**		
Control	21.1 c	31.4 d	29.1 b	26.5 c	44.4 c
CAN	47.3 ab	84.7 ab	77.8 a	65.1 ab	77.5a
Urea	57.8 a	87.5 a	75.0 a	68.2 ab	74.4 a
Urea + NBPT	43.9 b	77.5 bc	76.0 a	76.1 a	68.8 a
Urea + NBPT+DCD	52.6 ab	76.0 bc	74.2 a	69.8 ab	67.5 a
Urea + DCD	46.7 ab	75.2 bc	69.3 a	61.6 b	73.6 a
CAN/Urea	47.3 ab	75.2 bc	75.4 a	65.4 ab	68.5 a
Urea + MIP	47.4 ab	72.1 c	75.1 a	69.5 ab	65.5 b

Pooled standard error of the mean 5.7 kg N ha^{-1}

[†] Within column and site-year values with different lower case letters are significantly different. Mean comparison by *F*-protected LSD test (*P*<0.05).

Figures.

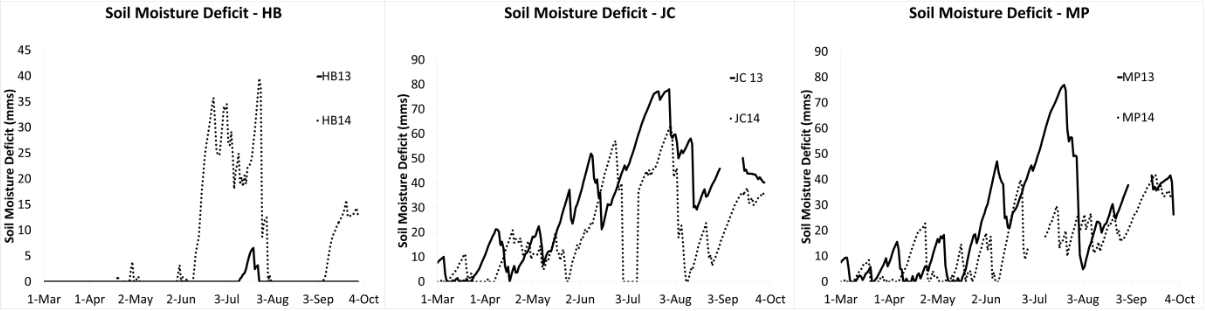

Figure 1: Soil Moisture Deficit for the three sites from 1 Mar – 30 Sept.