



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

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

2

3

4 **Abstract**

5 In temperate grassland N source influences greenhouse gas emissions (GHG). Nitrification  
6 and urea hydrolysis inhibitors can reduce these losses. The objective of this study was to  
7 evaluate the impact of N source, urease inhibitors and nitrification inhibitors on temperate  
8 grassland yields and N uptake. Experiments were conducted at three locations over two years  
9 (6 site-years) on the island of Ireland, covering a range of soils and climatic conditions.  
10 Results showed that CAN, urea+NBPT, urea+NBPT+DCD and urea had equal annual DM  
11 yield. Urea+DCD had lower DM yield than CAN for 3 site-years. Calcium ammonium nitrate  
12 and urea+NBPT consistently had the same N uptake, and urea+DCD had lower N uptake than  
13 CAN in 4 of 6 site-years, urea had lower N uptake than CAN in two site-years and  
14 urea+NBPT+DCD had lower N uptake than CAN in one site-year. Urea+NBPT is a cost-  
15 effective alternative to CAN, which is consistently equal in terms of both yield and N uptake  
16 in temperate grassland.  
17

18 Urea is the most concentrated solid N fertilizer (46% N), is cheaper to manufacture, more  
19 economical to transport and less expensive than other solid forms of fertilizer N.  
20 Consequently, urea is the leading N fertilizer product used globally; however, in the UK and  
21 Ireland, ammonium nitrate (AN) based fertilizers are the dominant form of N fertilizer  
22 applied to grassland, whereas in New Zealand, 93.7% of the total fertilizer N used in  
23 grasslands in 2013 was urea (IFADATA, 2013). Differences in N sources may be related to  
24 the influence of local conditions (Watson et al., 1990a). In some studies, nitrogen applied  
25 initially as urea may be less susceptible to denitrification losses than calcium ammonium  
26 nitrate (CAN), especially in wet conditions and in high organic matter soils (Clayton et al.,  
27 1997, Dobbie and Smith, 2003, Jones et al., 2007). Research has shown urea to be a useful  
28 tool for reducing N<sub>2</sub>O emissions in practice without reducing fertilizer N input as N in urea  
29 undergoes two transformations before it is vulnerable to denitrification loss as NO<sub>3</sub><sup>-</sup> (Dobbie  
30 and Smith, 2003; Harty et al., 2016). However, in Ireland, farmers are concerned about the  
31 influence on variability on crop yields. This variability is attributed related to the loss of  
32 ammonia (NH<sub>3</sub>) through volatilization (Watson et al., 1990a). Ammonia losses from urea in  
33 temperate grasslands (Forrestal et al., 2016, Chambers and Dampney, 2009) averaged higher  
34 than from CAN/AN, however, N losses from urea can be highly variable. Urea is vulnerable  
35 to NH<sub>3</sub> loss through volatilization because hydrolysis of urea induces a short-duration pH  
36 increase around the fertilizer granule to increase the proportion of NH<sub>3</sub>-N in the soil solution,  
37 thereby promoting NH<sub>3</sub> volatilization (Mikkelsen, 2009). Urease or nitrification inhibitors  
38 may reduce these losses.

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

43 N-(n-butyl) thiophosphoric triamide, or specifically its oxygen analog (NBPT<sub>o</sub>) (Engel et al.,  
44 2015), delays the rate of urea hydrolysis to NH<sub>4</sub><sup>+</sup>-N and moderates the localised zones of high  
45 pH and NH<sub>4</sub><sup>+</sup>-N concentrations and reduces NH<sub>3</sub> volatilization (Watson et al., 1990b; 1994).

46 **Nitrification inhibitors** (NIs) are compounds that delay the bacterial oxidation of NH<sub>4</sub><sup>+</sup> by  
47 inhibiting soil-nitrifying bacteria (Subbarao et al., 2012). Reduction in NO<sub>3</sub><sup>-</sup> denitrification  
48 and leaching potentially increasing the efficiency of the applied N. Nitrification inhibitors  
49 include 3, 4-dimethylpyrazole phosphate (DMPP), nitrapyrin (N-Serve), 2-amino-4-chloro-6-  
50 methyl pyrimidine (AM) is dicyandiamide (DCD) which has been used in agriculture for  
51 many years (Fox and Bandel,1989) because of its low cost, solubility, and low volatility.

52 **Combined nitrification and urease inhibitors** (CIs) the partial calcium salt of maleic–  
53 itaconic copolymer (MIP) has been marketed globally as both a urease and nitrification  
54 inhibitor under the trade name Nutrisphere®. Maleic–itaconic copolymer claims to reduce  
55 urea hydrolysis and nitrification, thereby reducing both NH<sub>3</sub> volatilization and increasing the  
56 agronomic efficiency of urea-based N fertilizers; however, Goos (2008) found MIP had no  
57 effect on either hydrolysis or nitrification levels compared to urea in either a sandy loam or  
58 clay loam.

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

64

## 65 MATERIALS AND METHODS

### 66 Experimental sites

67 Experiments were conducted at permanent pasture sites at three locations in Ireland during  
68 the 2013 and 2014 growing seasons, giving 6 site-years in total. Perennial ryegrass (*Lolium*  
69 *perenne* L.) was the dominant species in the swards. The locations were Johnstown Castle,  
70 Co. Wexford (JC13 and JC14) (52°18'27"N, 6°30'14"W and 52°17'32", 6°30'7"), Moorepark,  
71 Co. Cork (MP13 and MP14) (52°9'27"N, 8°14'42"W and 52°9'33"N, 8°14'43"W) and  
72 Hillsborough, Co. Down (HB13 and HB14) (54°27'83"N, -6°04'58"W and 54°45'31"N, -  
73 6°08'18"W). Site details and soil characteristics are provided in Table 1. More detailed site  
74 characteristics as well as the soil mineral N concentrations, ( $\text{NO}_3^-$  and  $\text{NH}_4^+$ ) for the growing  
75 season for each of the six site years are available in Harty et al. (2016). A new experimental  
76 site was used at each location in each year to avoid N carryover between years. These  
77 locations covered a range of soils and climatic conditions in which grass is grown in Ireland.  
78 Perennial ryegrass and Italian ryegrass account for nearly all of the agricultural grass sown in  
79 Ireland (DAFM, 2015). The experimental design was the same at all three sites, a randomised  
80 complete block with five replicates. Each experimental unit (plot) measured  $2 \times 8$  m at HB  
81 and  $2 \times 10$  m at JC and MP. The experimental treatments were a selection of N fertilizers  
82 applied in five equal splits to total  $200 \text{ kg ha}^{-1} \text{ yr}^{-1}$ . The N fertilizer treatments were CAN,  
83 urea, urea+NBPT, urea+DCD, urea+NBPT+DCD, and a control (zero N) treatment. Two  
84 additional treatments were applied at the MP14 and JC14 sites, which were urea+MIP  
85 (Maleic-Itaconic Copolymer) and CAN/urea blend which was a combination of 50% urea-N  
86 and 50% CAN-N (giving 25%  $\text{NH}_4\text{-N}$  and 25%  $\text{NO}_3\text{-N}$ ). The same source of urea was used  
87 across all sites and years (except urea+MIP). The DCD was incorporated into the urea melt as  
88 part of the manufacturing process, at a rate of 1.6% on a urea weight basis, giving a DCD rate  
89 of  $1.39 \text{ kg DCD ha}^{-1} \text{ application}^{-1}$  or  $6.96 \text{ kg DCD ha}^{-1} \text{ yr}^{-1}$ . The Urea+MIP was a

90 commercially available product purchased for the study. The source of the urease inhibitor  
91 NBPT was Agrotain<sup>®</sup>, which was coated onto the urea granules at 660 mg NBPT kg<sup>-1</sup> urea.  
92 Plots received a basal dressing of P, K, and S in line with soil test recommendations.  
93 Although soil pH was below the recommended level, no lime was applied to avoid  
94 confounding effects on the performance of the urea fertilizer which is susceptible to NH<sub>3</sub>  
95 volatilization.

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

107 Apparent fertilizer N recovery (AFR) was calculated as:

108 
$$\text{AFR (\%)} = ((\text{N off-take}_{\text{treatment}} - \text{N off-take}_{\text{control}}) / \text{N rate}) * 100$$

109 Urea relative yield (URY) was calculated as:

110 
$$\text{URY (\%)} = (\text{Yield}_{\text{urea\_product}} / \text{Yield}_{\text{CAN}}) * 100$$

111 Grass Growing degree days (GDD) was calculated as:

112 
$$\text{GDD} = (\text{DailyTemp}_{\text{max}} + \text{DailyTemp}_{\text{min}} / 2 - T_{\text{base}}) (T_{\text{base}} = 6^{\circ}\text{C for grass})$$

113

114

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

133

#### 134 **Statistical analysis**

135 The effect of fertilizer N treatment on the dependent variables of grass yield and N uptake  
136 were tested using the general linear mixed model for all site-years using the PROC  
137 GLIMMIX procedure of SAS (© 2002-2010, SAS Institute Inc., Cary, NC, USA). The  
138 factors in the model were site-year and fertilizer N and their interactions as fixed effects and  
139 block as a random effect. Least significant differences are presented along with the pooled

140 standard error of the mean. The effect of fertilizer N treatment on apparent fertilizer recovery  
141 (AFR) was tested for each site-year using PROC GLIMMIX. The factors in the model were  
142 site-year and fertilizer N and their interactions as fixed effects and block as a random effect.  
143 Inferences were made using the 5 percent level of significance which is shown along with the  
144 standard error of the mean.  
145

## 146 **RESULTS**

### 147 **Environmental and soil variables**

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

161

### 162 **N Response and growing season yield**

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

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

175

### 176 **Growing season N uptake and recovery**

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

191

### 192 **Individual harvests**

193 A harvest x site-year x fertilizer interaction was detected for both DM yield and N uptake  
194 (Table 4). A review of the individual site-year DM yield and N uptake data for each harvest  
195 showed that urea+DCD was the treatment which showed reduced performance relative to

196 other treatments, and these occurred predominately in the summer. No other treatment  
197 exhibited this level of reduced yield or N uptake compared to all of the other treatments. As  
198 the N uptake is product of yield and grass N content, the results for the individual site-year  
199 responses for each harvest for N uptake only are presented in Table 5. Dry matter yield was  
200 similar for all N fertilizers except for urea+DCD which had reduced yield (relative to the  
201 standard CAN) on 71% of applications in summer (data not shown).

202 Urea+DCD reduced N uptake on eight occasions relative to urea+NBPT, on six occasions  
203 relative to urea and on five occasions relative to CAN. The reduced N uptake of urea+DCD  
204 was more pronounced at JC compared to other sites, urea+DCD reduced uptake: compared to  
205 urea+NBPT at JC on four occasions and twice each at HB and MP; compared to urea at JC  
206 on three occasions, twice at HB and once at MP; and compared to CAN at JC on four  
207 occasions and once at HB. The reduced N uptake of urea+DCD occurred most frequently in  
208 summer: urea+DCD reduced uptake on eight harvests compared to urea+NBPT and all  
209 reductions except one in summer; on six harvests compared to urea with all reductions except  
210 one in summer and on five occasions compared to CAN with all five occasions in summer  
211

212 **DISCUSSION**

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

215

216 **Fertilizer type effects on annual yield and N uptake**

217 Although urea can be vulnerable to NH<sub>3</sub> loss, especially during summer, annual yields from  
218 the urea treatment were neither consistently lower, nor different to CAN at any site-year.

219 Consequently, it follows that the yield from treatments containing MIP and NBPT, which  
220 claim to reduce NH<sub>3</sub> loss were not lower than CAN, in fact they were not different from

221 CAN. The similarity in the pattern of AFR from each of the individual harvests (data not

222 shown) indicated the lowest average AFR was in early spring (37% in harvest 1) followed by

223 in late summer (64% in harvest 5). The highest AFR was in late spring (95% in harvest 2)

224 followed by early and mid-summer (harvest 3, 86% and harvest 4, 78%).The consistency of

225 total growing season yield from urea, urea+NBPT and urea+NBPT+DCD relative to CAN

226 over the six site-years (Table 3), suggests that there is little yield implication for production at

227 least in the short term by switching from CAN to one of these formulations. This is

228 noteworthy as the applied N rate was on the responsive part of the N response curve;

229 consequently, any N deficiency would be expected to be expressed in yield at this rate. This

230 N deficiency compared to CAN was observed for urea+DCD in three site-years in contrast to

231 urea or urea+NBPT, both of which generated yield levels not different to CAN in all site-

232 years.

233 Despite similar yield performance relative to CAN, N uptake from urea was lower at two of  
234 six site-years (JC13 and MP13) (Table 4), a reflection of the NH<sub>3</sub> loss vulnerability of urea.

235 At these two sites, the addition of NBPT improved N uptake to levels not different to CAN.

236 Urea+DCD treatments had lower N uptake compared to CAN in four site-years and urea in

237 one site-year. The poorer performance compared with untreated urea maybe be a result of  
238 DCD enhancing NH<sub>3</sub> loss from urea (Kim et al., 2012; Forrestal et al., 2016). As the  
239 proportion of NH<sub>3</sub> volatilization loss from urea relative to CAN is higher at higher rates of  
240 application (Forrestal et al., 2016), this enhancement of NH<sub>3</sub> loss from urea with the addition  
241 DCD may be even higher at higher N application rates. The addition of NBPT (i.e.  
242 urea+NBPT+DCD) provided a technical solution by closing the N uptake gap of urea+DCD  
243 such that urea+NBPT+DCD had a lower yield than CAN at only one of the 6 site-years  
244 tested. The role of NBPT in maintaining yield and N uptake of urea at levels comparable to  
245 CAN is in agreement with results from Watson et al., (1990b). While leaching losses were  
246 not measured, N<sub>2</sub>O and NH<sub>3</sub> emissions (measured in parallel experiments) support the switch  
247 to urea+NBPT. In addition to producing yield and N uptake comparable to CAN, N<sub>2</sub>O  
248 emissions from urea+NBPT were significantly lower compared to CAN (Harty et al., 2016)  
249 and the addition of NBPT to urea reduced NH<sub>3</sub> emissions by on average 78.5% compared to  
250 urea alone (Forrestal et al., 2016). These results provide a promising strategy for the  
251 mitigation of GHG emissions without compromising production especially in higher  
252 precipitation environments such as temperate maritime grassland.

253

#### 254 **Harvest Differences**

255 While the results of the present study found only one harvest each (from 29 harvest  
256 occasions) where urea yield and N uptake was lower than CAN (Table 5), there was a trend  
257 for reduced URY (Table 2). This supports the findings of Forrestal et al. (2016); Watson et al.  
258 (1990a); Chambers and Dampney (2009) where reduced performance of urea in summer  
259 relative to CAN/AN in temperate grasslands is accounted for by NH<sub>3</sub> losses, which were  
260 higher more highly variable from urea. In contrast, urea+DCD reduced N uptake compared to  
261 CAN on five occasions. The reduced urea+DCD performance were in contrast with a number

262 of studies where DCD increased grassland yield (Di and Cameron 2002; Zaman et al., 2009;  
263 Moir et al, 2012 and Delgato and Mosier 1996). However, yield increases were observed at  
264 irrigated sites, while the present study was entirely rain-fed. Precipitation could have  
265 contributed to an unequal distribution of moisture which could have resulted in N leaching  
266 although leaching was not measured in the present study. The yield results are in agreement  
267 with Abalos et al., (2014) who found inhibitors (nitrification and urease) increased yields  
268 more consistently in irrigated than rain-fed systems. Where DCD reduced yield relative to  
269 urea, the soil WFPS was low and reducing (data not shown). DCD retained more N as NH<sub>3</sub>  
270 higher in the soil profile and as the soil dried this may have contributed to enhanced NH<sub>3</sub>  
271 volatilization. This supports the findings that NIs have been shown to increase NH<sub>3</sub> loss from  
272 urea during conditions conducive to NH<sub>3</sub> volatilisation (Kim et al., 2012 and Lam et al.,  
273 2016).

274

#### 275 **Site-year differences**

276 The differences in N uptake observed across site-years in the control plots support the  
277 findings that N mineralization rates that vary seasonally and between soils (Nunan et al.,  
278 2000; Herlihy, 1979; McDonald et al., 2014) and can contribute a considerable proportion of  
279 N grass growth (Humphreys et al., 2008). In addition, AFR for urea at MP14 was 103% of  
280 fertilizer applied indicating that fertilizer N may be priming additional mineralization over  
281 the control (Gioacchini et al., 2002; Murphy et al., 2015). Immobilization of applied N  
282 fertilizer may have contributed to the lower AFR rate at HB which has a high soil organic  
283 matter content and cooler, wetter weather conditions than the other two sites. The higher clay  
284 content at HB may also have been a contributing factor as Hassink (1994) found a negative  
285 relationship between the percentage of soil N mineralizing and the clay and silt content of the  
286 soil.

287 The treatment with most variable performance, urea+DCD, reduced yield compared to all  
288 other treatments most frequently at JC (11 occasions) and most frequently in the summer  
289 (100%, 100% and 64% in summer at JC, MP and HB, respectively). The yield reduction was  
290 also more pronounced at JC13 (reduced yield on seven occasions, compared to JC14 four  
291 occasions). All of these yield reductions occurred for summer fertilizer N applications in  
292 2013. This coincided with highest SMD conditions in the study at JC13 (117 days) followed  
293 by 85 days at MP13, 69 days at JC14, and 41 days at MP14. Urea+DCD also reduced N  
294 uptake compared to all other treatments most frequently at JC (19 occasions), compared to  
295 HB (5 occasions) and MP (4 occasions). This reduction was greater at JC14 (12 occasions)  
296 than JC13 (7 occasions). All of these uptake reductions also occurred in summer. Conditions  
297 in 2014 were more favourable for grass growth than in 2013 when more extreme SMD  
298 conditions were encountered (Fig. 1) and all three sites generated greater yields in 2014  
299 (Table 2). Urea AFR was lowest in the drier conditions at JC13 and MP13, relative to CAN.  
300 This result supports Morrisson (1980) who found that yield was positively related ( $r^2 = 0.75$ )  
301 to water availability during the growing season.

302

### 303 **Soil Conditions**

304 Differences in soil properties between sites, particularly CEC and buffering capacity, may  
305 have also contributed to reduced N uptake performance of urea+DCD in the JC site. DCD  
306 slows nitrification, resulting in higher  $\text{NH}_3$  concentration in the soil solution. Nitrification  
307 lowers pH, so adding DCD slows nitrification and results in a higher pH in the soil solution.  
308 A higher pH and a larger  $\text{NH}_3$  pool could contribute to higher volatilization rates (Singh et  
309 al., 2008) above those produced by urea (Asing et al., 2008). This effect may be moderated in  
310 soils with higher CEC (Kim et al, 2012) (as more  $\text{NH}_3$  is locked up on the exchange sites)  
311 and higher buffering capacity (smaller pH spikes driving lower levels of volatilization). This

312 supports the findings of Stevens et al, (1989) who found that the lowest rates of NH<sub>3</sub>  
313 volatilization will occur from soils with low buffering capacity and van Burg et al., (1982)  
314 who found the highest efficiency of urea compared to AN occurred in well buffered soils.  
315 Urea+DCD uptake performance relative to urea was lowest in JC14 (lower uptake in two  
316 harvests) compared to any other site-year. This site-year had both the lowest CEC (15.5  
317 cmol<sup>+</sup> kg<sup>-1</sup>) and lowest buffering capacity in the study.

318

### 319 **Economics and implications for policy**

320 Based on average 2015 prices (CSO, 2016), the cost per tonne of grass grown, net of the  
321 control yields, using CAN had a cost of US\$49.07 (€43.97) and using urea had a cost of  
322 US\$37.51 (€33.61). So there is an economic advantage for a farmer to switch from CAN to  
323 urea. However, substitution with urea would have implications for national NH<sub>3</sub> emissions  
324 and fertilizer efficiency. Measurements by Forrestal et al., (2016) showed that on average  
325 NH<sub>3</sub> emissions from urea were higher than CAN. The more environmentally friendly urea  
326 formulation, urea+NBPT, reduced average NH<sub>3</sub> emissions from urea by 78.5% (Forrestal et  
327 al., 2016) of N applied, delivered consistent yield and N uptake efficiency results to CAN  
328 (present study) and successfully reduced N<sub>2</sub>O emissions compared to CAN (Harty et al.,  
329 2016). Based on the results of the present study, CAN cost over US\$11 (€10) more per tonne  
330 of grass grown than urea; and urea+NBPT offers the potential to generate the yield and N  
331 uptake performance of CAN at a lower cost than CAN. Urea+NBPT is currently marketed at  
332 between 5% and 10% cheaper than CAN resulting in a US\$2 to \$4.50 (€2 to €4) T<sup>-1</sup> DM gain  
333 for a farmer. However, there is a risk that farmers may elect to apply urea over urea+NBPT  
334 as the inclusion of NBPT could increase costs over urea by almost US\$8 (€7) T<sup>-1</sup> DM.

### 335 **CONCLUSION**

336 The results of this study showed there was no reduction in annual yield in the short term if  
337 farmers switched fertilizer from CAN to urea, urea+NBPT or urea+NBPT+DCD. However,  
338 urea+DCD had lower yield than CAN in three site-years and reduced N uptake in four site-  
339 years. Although urea generated the same yields as CAN, and was the least expensive,  
340 increased application of urea, could increase NH<sub>3</sub> emission levels and reduce system N use  
341 efficiency. Urea+NBPT consistently delivered equal yields and N uptake compared to CAN.  
342 Urea+NBPT provides farmers with a cost effective alternative to CAN, which is  
343 agronomically comparable but has potential environmental advantages in terms of nitrous  
344 oxide emissions. As urea treated with NBPT is more expensive than urea some form of  
345 incentive may be needed to encourage farmers to use of urea+NBPT over in place of urea, a  
346 switch which will reduce ammonia emissions.

347

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503 **Figure Captions, Tables, and Figures.**

504 **Figure Captions**

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

506

507 **Tables**508 **Table 1.** Experimental site locations, soil characteristics and rainfall details

	<b>HB 2013</b>	<b>HB 2014</b>	<b>MP 2013</b>	<b>MP 2014</b>	<b>JC 2013</b>	<b>JC 2014</b>
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 <sup>-1</sup> )	28.5	25.4	16.7	18.4	15.6	15.5
Lime Req. (tonnes ha <sup>-1</sup> )	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

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

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

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

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

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514

515 **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 <sup>-1</sup> )						URY(%)
Control	6801 b <sup>†</sup>	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<sup>-1</sup>

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

<sup>‡</sup> Urea relative yield (URY) in brackets (urea product yield expressed as a % of CAN yield)

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517

518 **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 <sup>-1</sup> ) and AFR (%)						AFR(%)
Control	166 c <sup>†</sup>	184 c	107 c	120 c	194 c	117 b	
CAN	313 a (74 <sup>‡</sup> )	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<sup>-1</sup>

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

<sup>‡</sup> Apparent fertilizer recovery value (%) in brackets

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520

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

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

524 \* Significant at the 0.05 probability level.

525 \*\* Significant at the 0.01 probability level.

526 \*\*\* Significant at the 0.001 probability level.

527 <sup>†</sup>n.s. = not significant

528

**Table 5: Effect of harvest, fertilizer type and site-year on N uptake kg N ha<sup>-1</sup> harvest<sup>-1</sup>**

Site-year / fertilizer type	Spring Applications			Summer Applications	
	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 5
<b>HB13</b>					
	N uptake kg N ha <sup>-1</sup> harvest <sup>-1</sup>				
Control		25.7 c <sup>†</sup>	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
<b>HB14</b>					
	N uptake kg N ha <sup>-1</sup> harvest <sup>-1</sup>				
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
<b>JC13</b>					
	N uptake kg N ha <sup>-1</sup> harvest <sup>-1</sup>				
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
<b>JC14</b>					
	N uptake kg N ha <sup>-1</sup> harvest <sup>-1</sup>				
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
<b>MP13</b>					
	N uptake kg N ha <sup>-1</sup> harvest <sup>-1</sup>				
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
<b>MP14</b>					
	N uptake kg N ha <sup>-1</sup> harvest <sup>-1</sup>				
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<sup>-1</sup>† Within column and site-year values with different lower case letters are significantly different. Mean comparison by *F*-protected LSD test (*P*<0.05).

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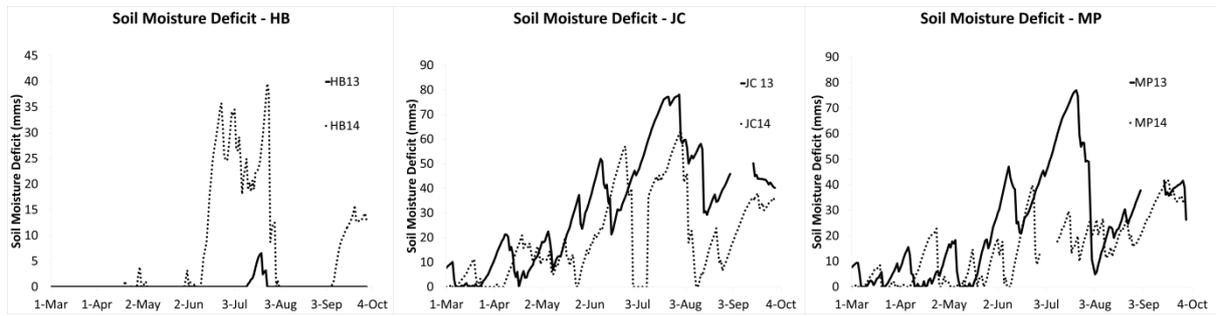
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537 **Figures.**

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

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