Response to Letter from Yara: Irish First National Mitigation Plan – Climate Action and Low Carbon Development Act 2015 – submissions and proposals.

Background

Food Harvest 2020 (FH 2020) and the subsequent Food Wise 2025 strategies are industry led initiatives that have been endorsed by the Irish Department of Food, Agriculture and the Marine. The principal targets of Food Wise include a) increasing the value of agri-food exports by 85% to €19 billion, b) increasing value added in the agri-food, fisheries and wood products sector by 70% to in excess of €13 billion, c) increasing the value of Primary Production by 65% to almost €10 billion and d) creating an additional 23,000 direct jobs in the agri-food sector. Simultaneously national greenhouse gas (GHG) emissions targets set under the EU Effort Sharing Decisions (Decision No 406/2009/EC and COM/2016/482) require GHG reductions of 20% by 2020 and propose 30% by 2030. In addition, new Clean Air targets will require a 5% reduction in ammonia from 2030 onwards. Significantly, Ireland is unique among the EU countries in that one-third of national greenhouse gas (GHG) emissions originate from agriculture. Indeed, amongst the developed economies, only New Zealand has a higher proportion of national GHG emissions associated with agriculture. Mineral fertiliser-based nitrous oxide (N_2O) emissions currently comprise 8.5% of agricultural emissions based on default (Tier 1) N_2O emission factors set by the Intergovernmental Panel on Climate Change (IPCC 2006). However, these default emission factors do not account for differences based on N source or impacts of other factors, such as soil type or climate which are known to impact substantially on N_2O loss (Davidson and Swank, 1986, Davidson et al., 2000, Shelton et al., 2000) and the IPCC recommends that countries should move to country-specific (Tier 2) emission factors.

Irish agriculture contributes virtually all (98%) of Ireland’s national ammonia emissions, an acidifying gas (Hyde et al., 2003; Duffy et al., 2016). In 2014 dairy and non-dairy bovines comprise 76.9% of agricultural ammonia, with these emissions arising principally from animal housing and storage (41.4%) and the landspreading of manures (28.6%). Manure emissions from pig and poultry systems comprise the bulk of the remaining emissions, followed by fertiliser-based emissions (8%).

Increased agricultural activity resultant from Food Wise 2025 is forecast to require an increase in mineral fertiliser usage. Whilst increasing nitrogen use efficiency improvements can mitigate this increase, there is a requirement to reduce the absolute amount of GHG emissions per unit N applied in order to help achieve emissions reductions targets. However, this must be achieved without exacerbating ammonia emissions or negatively impacting on yield. As a result, DAFM provided funding to assess the impacts of fertilisers on GHG emissions, ammonia losses and yields on both grassland and croplands (RSF 10/RD/SC/716 and RSF 11/S/138, see www.agri-i.ie).

Recently, a number of issues about the use of urea plus urease inhibitor in place of Calcium Ammonium Nitrate have been raised by Yara Ltd. in a submission released on 13 April 2017. We recognise that Yara are a leading manufacturer with a) a long track record in the development of fertilisers and b) a long record of both innovation and development of low GHG technologies associated with the manufacture of fertiliser as well as the development of life cycle analysis to quantify and verify these emissions. In the sections below, we address several issues raised.

1. CO_2 emissions from urea have not been considered.

The impact of both Food Wise and the EU Climate and Energy Framework Effort Sharing Proposals are currently being addressed via an updating of the 2012 Marginal Abatement Cost Curve for Irish Agriculture (Schulte et al. 2012), which Teagasc is currently in the process of finalising and which is due to be published in May 2017. This analysis is assessing the impact of Food Wise on agricultural activity, while simultaneously assessing the potential benefits and costs of a range of mitigation options for reducing methane, nitrous oxide and enhancing carbon sequestration. While Harty et al. (2016) only specifically addressed N_2O emissions, it is recognised that there are CO_2 emissions associated upon the application of urea to soils and these have been factored into the overall analysis. Current greenhouse gas (GHG) emissions associated with CAN and CAN-based compounds and urea applied to grassland soils along with the impact of replacing 50% of CAN with either urea or urea plus a urease inhibitor such as the compound assessed by Harty et al. (2016) i.e. N-(n-butyl) thiophosphoric triamide (NBPT) are shown in supplementary Figures 1 and 2. Currently the Tier 2 N_2O EFs are being combined in a marginal abatement cost curve analysis of potential mitigation options to reduce agricultural GHG emissions. The fertiliser form measure is only considered on managed grasslands and excludes arable sites as the reduction in N_2O emissions are small (e.g. Roche et al., 2016) and total GHG emissions are superseded once CO_2 emissions are included. This analysis is being conducted using the Tier 2 IPCC calculation methodology (IPCC 2006) and therefore includes the calculation of N_2O emissions from indirect sources and CO_2 emissions from urea use.

GHG emissions from fertiliser use in 2014 was 1869 kT CO_2-e, using Tier 2 emission factors (Harty et al. 2016), with grassland usage comprising 10% urea and the remainder principally comprising CAN and AN-based compounds. If 50% of CAN and AN –based compounds were replaced by untreated urea, the net GHG emissions reduction (accounting for direct, indirect N_2O and CO_2 emissions) would be **-471 kT CO_2-e** (total emissions = 1398 kT CO_2-e) , but with a substantial increase in ammonia loss (see below and Supplementary Figure 2). If 50% were replaced with urea+NBPT, the net GHG reduction is **-428 kT CO_2-e** (1441 Kt CO_2-e**)**, with direct N_2O higher than untreated urea, but indirect N_2O lower due to reduced volatilisation. Using 2030 projections of the impacts of FoodWise 2025 on GHG emissions, higher fertiliser use is predicted. In a scenario, whereby 50% of CAN/compounds are replaced by urea+NBPT, GHG emissions would reduce by 550 kT CO_2-e.

2. Recommendation based on limited data set. A series of experimental trials on grassland and spring barley sites were conducted to produce and publish country specific N_2O and NH_3 emission factors and to investigate mitigation options to reduce emissions. These experiments build on previous research conducted by Teagasc and university partners on two grassland sites under silage cutting that investigated the effect of CAN, urea and urea + NBPT on N_2O emissions and agronomic yield (Higgins et al. In Prep).

The most recent trials carried out consisted of the following treatments:

- CAN (commercially available)
- straight urea (commercially available)
- urea+urease inhibitor (NBPT, now commercially available in Ireland and in many other markets including New Zealand)
- urea+nitrification inhibitor (DCD, experimental)
- urea+urease+nitrification inhibitor (NBPT+DCD commercially available in US).

The urease inhibitor reduces ammonia volatilisation loss of ammonia from urea and the nitrification inhibitor prevents nitrification of ammonium to nitrate (the nitrogen form susceptible to leaching and/or denitrification resulting in emissions of nitrous oxide, a GHG).

The trial also investigated the effect of fertiliser rate for the CAN, urea and urea+urease inhibitor treatments (as these products are commercially available) at 0, 100, 200, 300, 400 and 500 kg N ha^{-1} for grassland (applied in 5 splits) and 0, 125, 150, 175 and 200 kg N ha^{-1} for spring barley (applied in 2 splits). The grassland trails were performed over two years at on a well-drained (Moorepark), well/moderately-drained (Johnstown) and imperfectly-drained (Hillsborough) soil. The arable trials were on a medium-drained (Johnstown) and well-drained (Marshallstown) site. Each treatment had 5 replicates.

Key Results

Agronomic results:

- Arable and Grassland: No difference in yield across all fertiliser types with the exception of urea with the nitrification inhibitor DCD alone which had lower yield than the other four fertiliser types in grassland (Harty et al., 2017). Urea + urease inhibitor consistently yielded as well as the standard which is CAN (Forrestal et al., 2017, Harty et al., 2017, Roche et al., 2017, Roche et al., 2015).
- There was a reduction in fertiliser N recovery (the total amount of N in the yield of crop or sward harvested) for the untreated urea treatment compared to CAN and urea + urease inhibitor particularly at higher N rates (Forrestal et al., 2017), indicating that urea has lower fertiliser recovery efficiency compared with both CAN and urea + urease inhibitor, both of which consistently had the highest fertiliser N recovery (Forrestal et al., 2017, Harty et al., 2017, Roche et al., 2015).

Gaseous results:

- **Grassland:** N_2O emissions were on average across all sites three times higher for CAN compared to other fertilisers and much more variable for CAN across soil types (Harty et al., 2016, Carolan et al., In Prep; Higgins in Prep, Hyde et al., 2016, Krol et al., in review). On all occasions the N_2O emissions for CAN were higher than for urea+NBPT in grassland.
- In grasslands, soil type had a large impact on emissions with the range in emission factors (%N_2O per kg N applied) for WELL drained compared to POOR drained as follows: CAN (0.58% to 3.81%), urea (0.1% to 0.49%) and urea+urease inhibitor (0.21% to 0.69%, Harty et al. 2016, Higgins et al., In prep, Hyde et al., 2016, Krol et al., In review)
- **Arable:** N_2O emissions were lower than on grassland. There was no significant difference between CAN and other fertiliser types in terms of N_2O emissions, although the trend was for higher N_2O from CAN (Roche et al., 2016).
- Ammonia loss from urea was significantly higher than for CAN. When urea was treated with the urease inhibitor NBPT, urea ammonia loss was reduced by 79%. Urea treated with the urease inhibitor NBPT was not significantly different to CAN (Forrestal et al., 2016).

In arable sites there were no significant difference of fertiliser type of N_2O and our data would conclude that ***based on a need to reduce ammonia emissions***, only untreated urea on arable land should be replaced with treated urea (urea+NBPT) or CAN (Roche et al., 2016). For grasslands, particularly on moderate to poorly drained soils, where denitrification dominates, our data supports a large body of data in the literature (see Table 1) which confirms that urea-based fertilisers (treated or untreated) have substantially lower N_2O emissions compared to CAN. In addition, Harty et al. 2016 highlight the variability in CAN emissions across soil type was considerably higher than urea and urea+NBPT with observed coefficients of variation of 61% (CAN), 14% (urea) and 29% (urea+NBPT). The UK GHG Platform InveN$_2$Ory project has also reported similar ranges of results to our experiments with N_2O emissions for AN >1% and urea fertilisers <1% but no difference between fertiliser types on arable sites. Previous research by Teagasc (Hyde et al., 2016), reported a N_2O emission from CAN of 2.15% for a single N application. Other research in the final stage of review by Krol et al. (in review) shows an emission of 2.39% of CAN vs 0.17% for urea treated with NBPT on a grassland site. In summary on grassland sites which are typically wetter soils CAN has a higher EF than urea and urea NBPT fertilisers, and these published data have been used to establish a new Tier 2 country specific EF for fertiliser formulation in Ireland. In contrast on the drier free draining soils,

N_2O emissions are low for all fertiliser types and there is no significant effect of fertiliser formulation on N_2O emissions.

Yield response

In terms of yield, previous studies in the UK found that yields from urea were lower than those from ammonium nitrate (Devine & Holmes, 1963; Chaney & Paulson, 1988). However, our findings are not unprecedented in Irish temperate grassland as Keane et al. (1974) also reported no significant difference between CAN and urea in terms of grass yield. There was consistently no yield difference between straight urea and CAN either for grass or spring barley. This finding does contrast with the idea that urea will result in poorer yields than CAN and it could urge farmers to use urea which is circa 20% cheaper than CAN. This question of yield differentials between CAN and urea underlines the importance of long-term trials, a public good Teagasc is in a unique position to provide. The long term question was highlighted as a caution in our paper (Forrestal et al., 2017) published on the 23th March 2017. At Johnstown Castle long-term plots are in place in which plots are now in their fourth year receiving the same type of fertiliser N.

3. Reducing greenhouse gasses but increasing ammonia emissions. *(Reference:Annex 5)*

Ammonia emissions

Ammonia emissions associated with fertilizer applications are dependent on fertilizer type, weather and soil conditions. Currently Ireland's proportion of ammonia per kg agricultural N is low compared to most EU countries (13%) due to a) the relatively short housing periods, b) long grazing periods and c) comparatively low levels of untreated urea usage. Emissions from urea-based fertilizers are much greater than from ammonium or nitrate fertilisers because rapid hydrolysis of urea will cause localised increases in pH. Our studies did not indicate significant variations in ammonia loss due to differences in soil drainage class (Burchill et al. 2017). As the Yara group point out, replacing 50% of CAN with straight urea will substantially increase agricultural ammonia emissions by up to 11% relative to 2005 and this would increase to over 14% by 2030 when emissions are required to decrease by 5% relative to 2005 (Supplementary Figure 3). This could be problematic for Ireland nationally both in terms of reaching targets and impacts on eutrophication of low nutrient ecosystems. However, as of yet it would not affect the individual farmer who is primarily focused on yield and cost effectiveness. Our studies have indicated that replacing urea with urea+NBPT will decrease ammonia losses by 79% (Forrestal et al. 2016). While replacing 50% CAN with urea+NBPT results in a marginal increase in ammonia relative to CAN only, this would be more than compensated by the replacement of untreated urea with urea treated with a urease inhibitor. It should also be noted that the two years (2013 and 2014) that measurements were made across all sites were dry with very dry summers. These should have provided the most challenging conditions for urea in terms of ammonia emissions.

4. Inhibitors yet again introducing another chemical in agriculture. *(Reference:Annex 6 and 7)*

As with any chemical compound added to agriculture a caution is of course needed with regard to their potential for negative eco-toxological, environmental, trade or reputational impacts. It is for these reasons that there are certification processes in place for chemicals. To our knowledge and as mentioned by Yara, NBPT has passed registration and is an approved agricultural chemical within the EU.

The New Zealand experience where a specific nitrification inhibitor, dicyandiamide (DCD), was found in milk powder has been cited. In this case DCD was sprayed onto grass in single applications of c. 10 kg DCD/ha. This is a very different use case to the inclusion of an inhibitor on or in a fertiliser granule where the inhibitor is delivered in a very targeted manner and at a relatively low rate. Yara are no doubt aware DCD and NBPT are very different compounds working on different processes. The application methods differ in that NBPT coats the urea prill and thus hits the soil surface whereas DCD is sprayed to both the grass and soil. The persistence of NBPT and it oxygen analogue NBPTo in the environment is much shorter than for DCD. NBPT has a half-life as low as < 1 day (Engel et al., 2013) compare to 37 days for DCD (McGeough et al., 2016). The application rate of NBPT 0.29 kg ha^{-1} compares to 20 kg ha^{-1} for DCD (Table 2). The group of compounds broadly referred to as inhibitors need to be looked at on their own individual merits/demerits. It is worthwhile to note that in New Zealand where the DCD residue issue arose, urea+NBPT continues to be used commercially on farms and has not been detected in New Zealand milk.

Table 2 Comparison of DCD and NBPT in terms of the process inhibited, the application method, the inhibitor half-life and the inhibitor application rate.

	DCD		**NBPT**
Process inhibited	nitrification		Urea hydrolysis
Application method	Sprayed on grass/soil	In the fertiliser granule	On the urea fertiliser granule
Inhibitor Half-life	Mean 37 days[1]		<1 day[2]
Inhibitor application rate (kg ha^{-1})	20[#]	7*	0.29*

[1] McGeough et al., 2016

[2] Engel et al., 2015

[#] DCD is typically applied in two 10 kg ha^{-1} splits in autumn and spring.

* Based on the 200 kg N/ha in Teagasc studies, which was applied in 5 splits.

In 2015 Teagasc (Forrestal et al., in prep) conducted a small study to test for uptake of NBPT and its oxygen analogue (NBPTo) in grass. Urea+NBPT was applied to cut plots and the grass regrowth was cut at 2, 5 and 20 days. In all cases the sum of NBPT and NBPTo was below 0.01 ppm (the maximum residue level for pesticides). The measurement methodology was capable of lower detection and for one replicate sample harvested 2 days after fertiliser application an NBPTo detection at 0.001 ppm was made. There were no other detections of NBPT on days 2, 5 and 20 after application. Typically the shortest period between fertiliser application and animal grazing in Ireland varies between 21 and 28 days. The perception of a risk that NBPT might appear as a residue in agricultural products does warrant further research.

The use of urease inhibitors can indeed result in *short-term* urease inhibition in plant shoots, although the impact may be species specific and effects only occur at high rates of NBPT application (orders of magnitude higher than the rates applied in our studies). With reference to the studies cited in the Yara letter, low levels of NBPT were detected in *Pisum sativum* (pea) which displayed higher foliar urease inhibition compared to *Spinacea oleracea* (spinach) with a concomitant build-up of endogenous foliar urea, although inhibition lasted only nine days (Cruchaga et al. 2011). Similar impacts were also observed in maize although this was hypothesised to be due to NBPT binding to a urea transporter protein *DUR3* which reduced urea uptake (Zanin et al. 2015). Miller & Watson (1996) observed transient leaf tip scorch 7–15 days after nBTPT + urea application and was greatest with high concentrations of nBTPT and high urea-N application rates. Whilst there was a shift in amino acid composition, total water soluble carbohydrate and protein content was unaffected. They conclude ‘The previously reported benefit of nBTPT in reducing NH_3 volatilization of urea would appear to far outweigh any of the observed short-term effects, as dry-matter production of ryegrass is increased.’ This agrees with our findings that there was no difference in dry matter yield or total foliar N content between CAN and urea+NBPT. Importantly, both mode of NBPT delivery and application rates were very different across studies. The Teagasc studies were made using urea coated with **660ppm** (w/w) NBPT and applied to soil. The plants in both the Zanin and Cruchaga studies were grown hydroponically with NBPT delivered in solution at a rate of **0.5%** (w/w). This is several orders of magnitude higher than our application rate. At lower rates (0.01% and lower), no impacts have been observed (Watson & Millar 1996).

Summary

There is robust evidence from our and associated studies that on wet poor to moderately well drained grassland soils greenhouse gas emissions can be reduced by switching from nitrate based fertilisers to non-nitrate based fertilisers. Switching fertiliser formulation needs to take account of the indirect effects such as increased CO_2 and NH_3 emissions and this has been done in the current marginal abatement cost curve exercise for the evaluation of potential mitigation measures for agriculture. Using urea protected with NBPT offers a solution to reduce N_2O emissions and reduce NH_3 emissions to levels similar to CAN. There is a need for a greater focus on long term studies and one is in place at Johnstown Castle. The residue issue that arose relating to DCD in New Zealand is important and highlights the need to ensure that all agrochemicals do not negatively impact food quality. The direct comparison of NBPT and DCD is not useful as these are very different products in persistence, application method and application rate. There is a need for further research to ensure that Irish food products meet current and future quality demands.

References:

Irish publications relating to fertiliser form:

1. Burchill W.T., Lanigan G.J., Forrestal P.J, Misselbrook T., Richards K.G. (2017) Ammonia emissions from urine patches amended with N stabilized fertilizer formulations. Nutrient Cycling in Agroecosystems. In Press.
2. Burchill, W., Lanigan, G.J., Forrestal, P.J., Reville, F. and Richards, K.G (In Prep) A field based comparison of ammonia emissions from six Irish soil types following urea fertiliser application Irish Journal of Agricultural and Food Research 55 (2), 152-158
3. Carolan R. et al. (In Prep) The effect of nitrogen fertiliser form and application rate on N_2O emissions under simulated grazing.
4. Forrestal P.J., Harty M., Carolan R., Lanigan G.J., Watson C.J., Laughlin R.J., McNeill G., Chambers B.J., Richards K.G. (2016) Ammonia emissions from stabilised urea fertiliser formulations in temperate grassland. Soil Use and Management 32, Issue Supplement S1, 92-100.
5. Forrestal, P.J., Harty, M.A., Carolan, R., Watson, C.J., Lanigan, G.J., Wall, D.P., Hennessy, D., Richards, K.G. 2017. Can the agronomic performance of urea equal calcium ammonium nitrate across nitrogen rates in temperate grassland? Soil Use and Management. DOI: 10.1111/sum.12341.
6. Forrestal, P.J., Lanigan, G.J., Richards, K.G. (in prep). Uptake of the urease inhibitor NBPT and NBPTo by grass.
7. Harty M (2016) PhD thesis
8. Harty, M.A., Forrestal, P.J., Watson, C.J., McGeough, K.L., Carolan, R., Elliot, C., Krol, D.J., Laughlin, R.J., Richards, K.G.*, and Lanigan, G.J. Reducing nitrous oxide emissions by changing N fertiliser use from calcium ammonium nitrate (CAN) to urea based formulations. 2016. *Science of the Total Environment*. 563-564: 576-586. http://dx.doi.org/10.1016/j.scitotenv.2016.04.120
9. Harty, M.A., Forrestal, P.J.,Carolan, R., Watson, C.J., Hennessy, D., Lanigan, G.J., Wall, D.P and Richards, K.G. (2017) Fertiliser N type affects temperate grassland yield and N recovery. Journal of Agronomy 109, 1-9.

10. Higgins et al. (In Prep) The effect of fertiliser rate and form on N2O emisisons from silage production.
11. Hyde, B.P., Forrestal, P.J.*, Jahangir, M.M.R., Ryan, M., Fanning, A.F., Carton, O.T., Lanigan, G.J. and Richards, K.G. 2016. The interactive effects of fertiliser nitrogen with dung and urine on nitrous oxide emissions in grassland. *Irish Journal of Agriculture and Food Research*. 55: 1-9. doi: 10.1515/ijafr-2016-0001
12. Krol, D.J., Minet, E.P, Forrestal, P.J., Lanigan, G.J. and Richards, K.G. *(in review).*The effects of various nitrogen fertiliser formulations applied to urine patches on nitrous oxide emissions in grassland.
13. Lanigan, G.J., Donnellan, T., Hanrahan, K., Gultzer, C., Forrestal, P., Farrelly, N., Shalloo, L., O'Brien, D., Ryan, M., Murphy, P., Schulte, R.P.O., Finnan, J.P., Boland, A., Richards, K.G., and Browne P. (in review). A Revised Marginal Abatement Cost Curve for Irish Agriculture: 2021-20130. Teagasc, Oak Park, Carlow Ireland
14. Lanigan, G.J., Donnellan, T., Hanrahan, K., Burchill, W., Forrestal, P., McCutcheon, G., Crosson, P., Murphy, P., Schulte, R.P.O Richards, K.G., and Browne P. (in press) An Analysis of the Cost of the Abatement of Ammonia Emissions in Irish Agriculture from 2030 onwards. Teagasc, Oak Park, Carlow Ireland.
15. Roche, L. , Forrestal P.J., Lanigan G.J.*, Richards, K.G., Shaw, L. and Wall, D.P. (2016) Impact of fertiliser nitrogen formulation, and N stabilisers on nitrous oxide emissions in spring barley. Agriculture, Ecosystems and Environment 233 (2016) 229–237
16. Roche, L., Forrestal, P.J., Lanigan, G.J., Richards, K.G., Shaw, L.J., Wall, D.P. (In Prep) Effect of N fertiliser formulation on spring barley grain yield and crop N uptake: CAN versus urea with and without N stabilisers
17. Roche L, Forrestal PJ, Lanigan GJ, Richards KG, Shaw LJ, Gooding MJ, Hackett R, Wall DP (2015) Evaluating the effect of fertiliser nitrogen type on grain yield in spring malting barley. In: Proceedings of the Agricultural Research Forum, Tullamore, 9th-10th March 2015
18. Roche L. (2017) Ph.D thesis Fate and transport of fertiliser nitrogen under spring barley cultivation on contrasting soils

International fertiliser N nitrous oxide grassland:

Bell, M., Hinton, N., Cloy, J., Topp, C., Rees, R., Cardenas, L., Scott, T., Webster, C., Ashton, R., Whitmore, A., 2015. Nitrous oxide emissions from fertilised UK arable soils fluxes, emission factors and mitigation. Agric. Ecosys. Environ. 212, 134–147.

Davidson, E.A., Swank, W.T., 1986. Environmental parameters regulating gaseous nitrogen losses from two forested ecosystems via nitrification and denitrification. Appl. Environ. Microbiol. 52, 1287–1292 0099-2240/86/121287-06$02.00/0.

Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V., Veldkamp, E., 2000. Testing a conceptual model of soil emissions of nitrous and nitric oxides: using two functions based on soil nitrogen availability and soil water content, the hole-in-the-pipe model characterizes a large fraction of the observed variation of nitric oxide and nitrous oxide emissions from soils. Bioscience 50, 667–680. http://dx.doi.org/10.1641/ 0006-3568(2000)050[0667:TACMOS]2.0.CO;2.

Dobbie, K.E., Smith, K.A., 2003. Impact of different forms of N fertilizer on N2O emissions from intensive grassland. Nutr. Cycl. Agroecosyst. 67, 37–46. http://dx.doi.org/10.1023/A:1025119512447

Jones, S.K., Rees, R.M., Skiba, U.M., Ball, B.C., 2007. Influence of organic and mineral N fertiliser on N2O fluxes from a temperate grassland. Agric. Ecosyst. Environ. 121 (1–2), 74–83. http://dx.doi.org/10.1016/j.agee.2006.12.006.

Kuikman, P.J., van der Hoek, K.W., Smit, A., Zwart, K., 2006. Update of emission factors for nitrous oxide from agricultural soils on the basis of measurements in the Netherlands. Alterra Report 1217, p. 40 (ISSN 1566–7197).

Shelton, D.R., Sadeghi, A.M., McCarty, G.W., 2000. Effect of soil water content on denitrification

during crop cover. Soil Sci. 165, 365–371.
Stehfest, E., Bouwman, L., 2006. N2O and NO emission from agricultural fields and soils under natural vegetation. Nutr. Cycl. Agroecosyst. 74 (3), 207–228. http://dx.doi.org/10.1007/s10705-006-9000-7.

Impact on ammonia emissions

Chambers, B., Dampney, P.2009. Nitrogen efficiency and ammonia emissions from urea-based and ammonium nitrate fertilizers. Proc No. 657. Internat Fert Soc, York, UK.
Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., McNeill, G., Chambers, B. and Richards, K.G. (2016). Ammonia emissions from urea, stabilised urea and calcium ammonium nitrate: insights into loss abatement in temperate grassland. Soil Use and Management . 32, 92-100.
Watson, C.J. & Miller, H. 1996. Short-term effects of urea amended with the urease inhibitor N-(n-butyl) thiophosphoric triamide on perennial ryegrass. Plant and Soil, 184, 33–45.
Watson, C.J., Stevens, R.J. & Laughlin, R.J. 1990. Effectiveness of the urease inhibitor NBPT (N-(n-butyl) thiophosphoric triamide) for improving the efficiency of urea for ryegrass production. Fertilizer Research, 24, 11–15.

Papers on N metabolism and detection of NBPT

Cruchaga S., Artola E., Lasa B., Ariz I., Irigoyen I., Moran J. F., et al. (2011). Short term physiological implications of NBPT application on the N metabolism of Pisum sativum and Spinacea oleracea. J. Plant Physiol. 168 329–336.
Engel, R.E., B.D. Towey and E. Gravens. 2015. Degradation of the urease inhibitor NBPT as affected by soil pH. Soil Science Society of America journal 79: 1674-1683.
Kawakami, E.,M.,, Oosterhuis, D.M., Snider, J.L., Mozaffari, M. (2012) Physiological and yield responses of field-grown cotton to application of urea with the urease inhibitor NBPT and the nitrification inhibitor DCD. European Journal of Agronomy 43: 147-154
Watson C. J., Miller H. (1996). Short-term effects of urea amended with the urease inhibitor N-(n-butyl) thiophosphoric triamide on perennial ryegrass. Plant Soil 184 33–45.
Zanin L., Tomasi N., Pinton R. (2015) The Urease Inhibitor NBPT Negatively Affects DUR3-mediated Uptake and Assimilation of Urea in Maize Roots. Front Plant Sci. 2015; 6: 1007.doi: 10.3389/fpls.2015.01007

Supplementary Tables/Figures:

Table 1. Summary of fertiliser type direct N_2O emissions factors

		Direct fertiliser type N_2O Emission Factor (%)				
Study	**Landuse**	**CAN**	**urea**	**urea+ NBPT**	**urea+NBPT+ DCD**	**urea+ DCD**
Harty et al. 2016	Grassland	0.58-3.81	0.1-0.49	0.21-0.69	-0.05-0.27	-0.08-0.25
Krol et al. (in review)	Grassland	2.39	0.25	0.17	0.06	0.02
Higgins et al (In Prep)	grassland	0.44-3.81	0.3-0.49	0.25-0.43		
Hyde et al 2016	grassland	2.15				
Dobbie and Smith 2003	grassland	2.75 (0.56)	2.12 (0.44)			
Jones et al 2007	grassland	0.1-1.4	0.1-0.4			
Clayton et al 1997	grassland	0.4-1.2	0.8-1.4			

Eichner 1990	arable & grassland	0.04-1.71	0.08-0.18

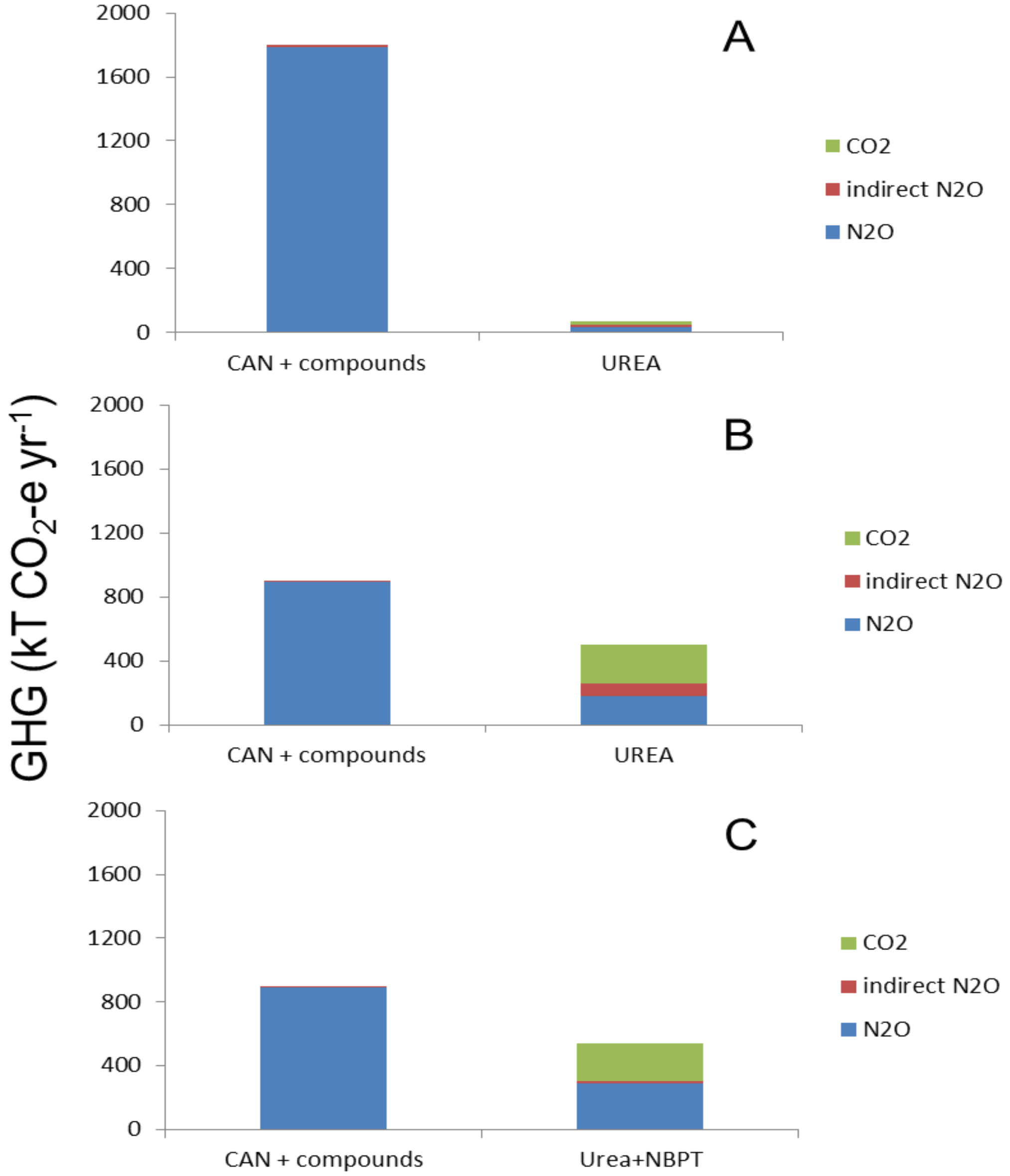

Figure 1: Total grassland-based GHG fertiliser emissions from a) current usage, b) replacing 50% of CAN with urea and c) replacing 50% of CAN with urea+NBPT. Data based on Lanigan et al. 2017 (in review)

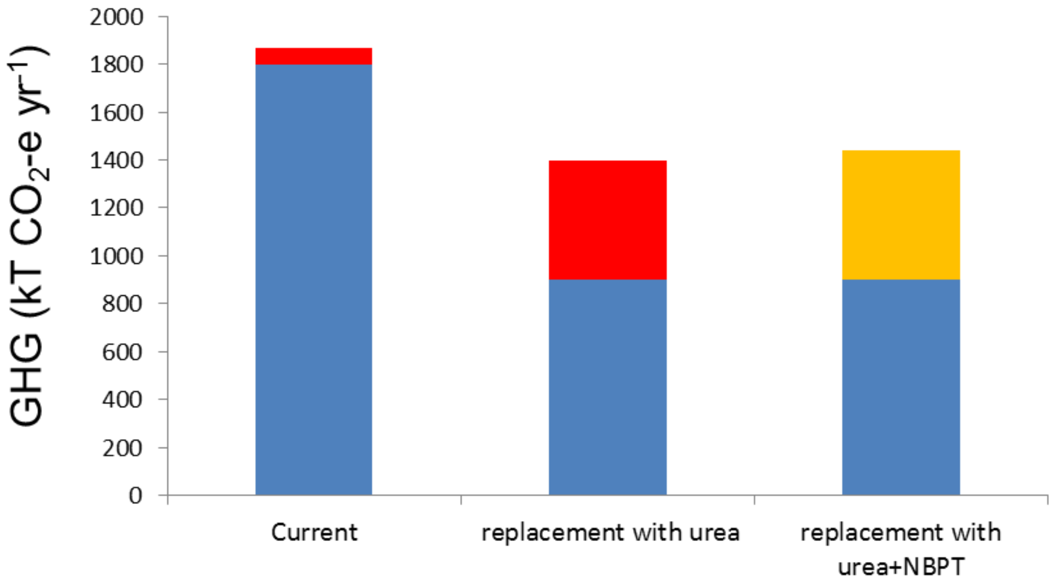

Figure 2: Impact of replacing 50% CAN with urea on GHG emissions and 50% CAN+ all untreated urea with urea+NBPT

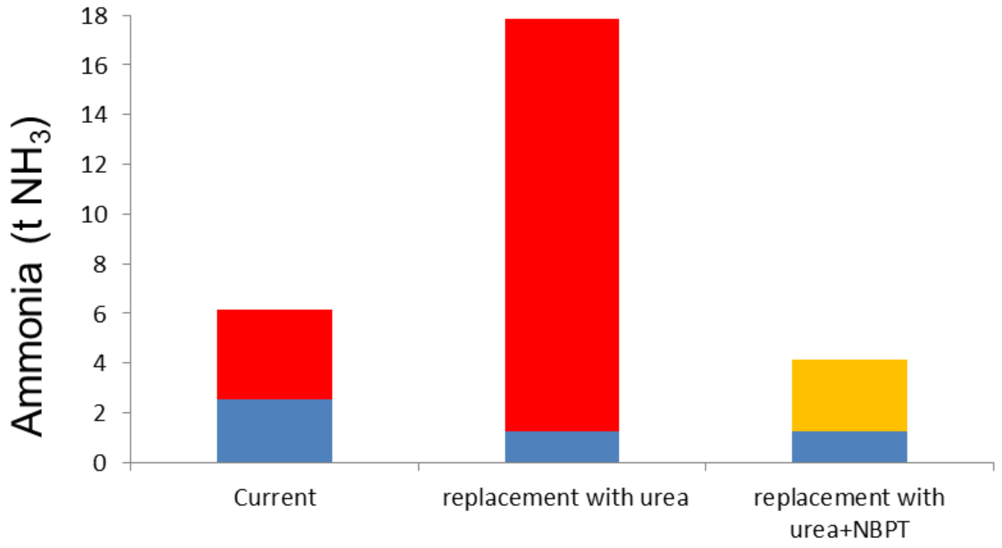

Figure 3: Current fertiliser-based ammonia emissions (CAN =blue, urea = red), theoretical ammonia loss based on 50% replacement of CAN and AN compounds (blue) with untreated urea (red) and theoretical ammonia emissions where 50% CAN replacement and 100% untreated urea is replaced with urea+NBPT (orange). Data derived from Lanigan et al. 2017 (in press)