Department of Agriculture, Food and the Marine
An Roinn Talmhaíochta, Bia agus Mara

Research Stimulus Fund

Final Report

'Sustainable nitrogen fertiliser Use and Disaggregated Emissions of Nitrogen (SUDEN)'

DAFM Project Reference No: 11-S-138

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End Date: 30/06/2016

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Please place *one* "x" below in the appropriate area on the research continuum where you feel this project fits

Basic/Fundamental ⟶ Applied ⟶ Pre Commercial

1	2	3	4 X	5	6	7

Please specify priority area(s) of research this project relates to from the National Prioritisation Research Exercise* (NRPE) report;

Priority Area (s)	**Priority Area I - Sustainable Food Production and Processing**

Key words: *(max 4)*
Agronomy, Nitrogen, Ammonia, Nitrate Leaching

1. Rationale for Undertaking the Research

This section should outline the rationale for carrying out the research and identify the need / problem to be addressed

Ireland's growing agriculture industry is utilising our national soil and climate resources to produce high quality foods. The production of these foodstuffs underpins an export business worth €10.8 billion in 2015 (Bord Bia, 2016). The sustainability of our production systems are an important point for differentiating our exports from competitors through the efforts of the Bord Bia Origin Green programme for example. Fertiliser nitrogen is a cornerstone input of many of our production systems. However, fertiliser nitrogen application is associated with emissions of the greenhouse gas (GHG) nitrous oxide (N_2O) and the air pollutant ammonia (NH_3). Ireland has committed to making significant reductions in both of these gaseous emissions in the coming years. As agriculture accounts for c. 33% of GHG emissions and c. 98% of ammonia emissions agriculture must play a role in meeting these targets to achieve reductions and to demonstrate contribution to increased sustainability. Fertiliser nitrogen along with dung and urine deposited at pasture are sources of both gases. In the present work ammonia was measured along with yield, N efficiency and nitrate leaching. The greenhouse gas nitrous oxide was measured as part of the sister AGRI-I project, also funded under the Research Stimulus Fund.

2. Research Approach

Specify the research methodologies employed, emphasising novel techniques and also outline any modifications from the original approved project proposal

To measure the effect of fertiliser N type on grass yield, NH_3 and soil mineral N, replicated field experiments were conducted at three grassland sites in Ireland (Figure 1) in 2013 and 2014 (six site-years). The locations were Johnstown Castle, Co. Wexford, Moorepark, Co. Cork and Hillsborough, Co. Down. The sites were chosen to represent a range of soil and geo-climatic conditions across intensively managed agricultural areas in Ireland. The experimental design was a randomised complete block with five replicates at each site-year. The CAN, urea and urea+NBPT fertiliser treatments were applied at annual N rates of 100, 200, 300, 400 and 500 kg/ha in five equal split applications between March and September. Urea+DCD and urea+NBPT+DCD were applied at the 200 kg N/ha rate only. In addition there was a zero N control treatment. Plots received a basal application of P, K, and S in line with soil test recommendations. Yield and N uptake was measured by harvesting dedicated agronomic plots (2 m x 10-12 m at the end of each grass growth cycle. Soil mineral N was measured by sampling the dedicated soil sampling area of the plots. Ammonia emissions were measured from each of the fertiliser treatments at the Johnstown Castle and Hillsborough sites during 2014 using a system of wind tunnels (Lockyer, 1984; Meisinger *et al.*, 2001). Leaching was measured using the lysimeter facility at Johnstown Castle. Gross N transformations were measured using a ^{15}N stable isotopes coupled with an isotope tracing model. A new model was created joining the Moorepark

dairy simulation model with an environmental model to predict the impacts of FW2025 on Nitrogen emissions.

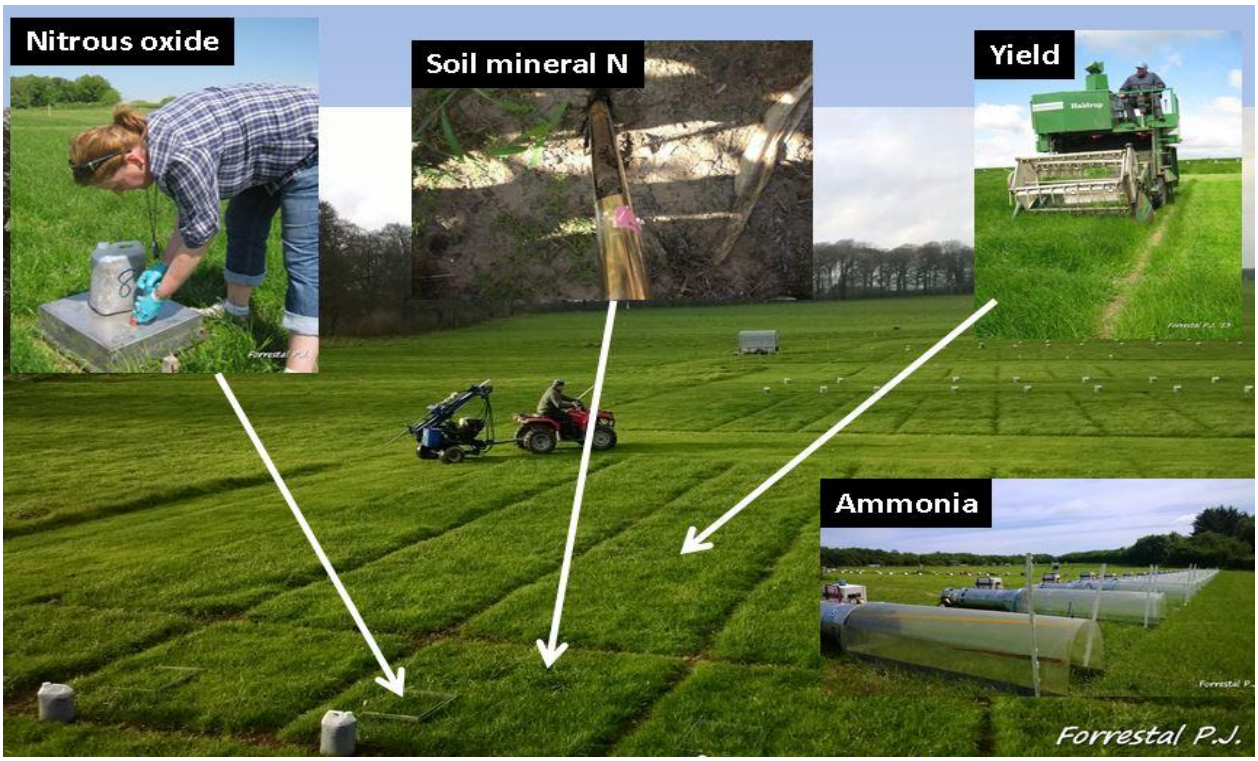

Figure 1 Experimental setup of one of the three sites in the project.

The spring barley trial was conducted on one free-draining loam site located in Marshalstown and Johnstown Castle Co. Wexford over three years. The experimental design was a randomised complete block with five replicates. The layout of each experimental unit was similar to the grassland sites (Figure 2) with a dedicated N_2O, soil mineral N and yield measurement area. The same fertilisers used in the grassland experiment were applied in two split applications. Yield and N uptake was measured by harvesting barley at maturity. Soil mineral N was measured by sampling the dedicated soil sampling area of the plots. Ammonia emissions were measured using a system of luening shuttles.

Ammonia emissions from dung and urine deposition was carried out across three seasons, at the Teagasc Johnstown Castle in Wexford using a system of wind tunnels (Meisinger *et al.*, 2001).

3. Research Achievements/Results

Outline main results achieved

Agronomic Yield

- The yield of CAN and urea was not significantly different in these trials.
- Urea treated with the urease inhibitor NBPT consistently yielded as well as CAN.

- The use of the nitrification inhibitor DCD alone decreased grassland yields relative to CAN.
- Addition of NBPT to urea treated with DCD recovered the yield lag caused by the nitrification inhibitor.

Efficiency: apparent fertiliser nitrogen recovery (AFR)

- Urea has the potential for lower (AFR) compared to CAN particularly at higher nitrogen rates.
- Use of the urease inhibitor NBPT ensured that the AFR of urea was consistently at least equal to CAN.
- The nitrification inhibitor DCD used alone had a pronounced negative effect on AFR at the inclusion rate tested in these trials. However, inclusion of NBPT with DCD treated urea increased yields to similar levels to yield from plots fertilised with CAN or urea treated with NBPT alone.

Ammonia

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

Nitrate leaching

- There was no significant effect of fertilizer formulation on nitrate leaching under grazing conditions. On average there was 43 kg NO_3-N ha^{-1} leached in the conventional urea and CAN systems and 37 kg NO_3-N ha^{-1} leached from the urea with NBPT. There were significant differences in N leaching between soils.

Modelling

- Milk production could be increased by 44% in the high profit grass system compared to the baseline resulting in a farm net profit of €1589 ha^{-1}.
- Incorporation of inhibitors in the high profit grass maintained yield increases of 44% but represented an additional cost of €74 ha^{-1}.
- Increasing milk production increased total N loss to the environment from 107 kg N ha^{-1} (baseline scenario) to a maximum of 162 kg N ha^{-1} for the high profit grass based system.
- Incorporation of inhibitors in the high profit grass system resulted in the lowest total N loss of 122 kg N ha^{-1}, a 44% increase in milk production and increased farm net profit of €1,515 ha^{-1}.

The present study found that the fertiliser N form applied along with enhanced efficiency technologies such as urease and nitrification inhibitors are tools which can help to address

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

Urea holds a significant cost advantage per kg DM produced because urea is considerably less expensive than either CAN or urea + NBPT. Although less tangible to farmers there was an efficiency penalty, particularly at higher rates, when using urea compared with using CAN or Urea + NBPT. The efficiency disadvantage for urea compared to CAN or urea + NBPT ranged from 4 to 7.6%, a difference likely to be primarily associated with ammonia loss from urea. However, as yield and cost rather than ammonia emissions are currently more pertinent to on farm decisions the yield results of the current study and associated implications for cost per tonne DM production will promote additional urea usage amongst farmers. Such additional usage without a urease inhibitor such as NBPT will present a challenge for national governments committed to reducing national ammonia emissions. Urea + NBPT substitution for CAN is likely to create a small cost saving however there will be a net cost when urea + NBPT is substituted for urea.

4. Impact of the Research

A summary of the tangible impact of the research project should be provided under the outcomes' and 'outputs' heading below. In addition, please provide a short narrative synopsis of the benefits / improvements the research has made to the area under investigation particularly as regards end users, e.g. industry, consumers, regulatory authorities, policymakers, the scientific community, etc

This research has identified that farmers can maintain yields and reduce nitrogen loss to the environment by switching from CAN to urea protected with NBPT. This new technology, widely available on the market, offers farmers a cost effective fertiliser that improves on farm sustainability. For the first time this research has generated Irish specific emission factors for dung and urine deposited by grazing cows. The modelling has highlighted that milk production can be increased dramatically through the high profit grass system. Nitrogen loss to the environment can be reduced substantially by integrating inhibitors within the high profit grass system. This research has added to the international scientific community through the publication of a 11 papers and this continues to increase.

4(a) Summary of Research Outcomes

(i) Collaborative links developed during this research

The research team deepened research collaborative linkages between the partners and also with ADAS and Rothamsted Research in the U.K. The research team have developed links with several fertiliser companies producing enhanced efficiency fertilisers. There is on-going work at Johnstown Castle evaluating new urease inhibitors.

(ii) Outcomes where new products, technologies and processes were developed and/or adopted

At the beginning of the project urea protected with a urease inhibitor was not available on the Irish market. In 2016, based on the results of the project there has been adoption of this technology with 194 tonnes of protected urea being sold on the Irish market. The results of the project are being adopted as Tier 2 emissions factors for Ireland by the EPA in the national IPCC reporting.

(iii) Outcomes with economic potential

Urea protected with a urease inhibitor offers a small cost saving to farmers vs the standard CAN fertiliser. However, the results showing comparable yields for urea could lead farmers to pursue these substantial cost savings. This could lead to increased national ammonia emissions.

(iv) Outcomes with national/ policy/social/environmental potential

This project has important national implications. Changing fertiliser N source from CAN to urea protect with a urease inhibitor will sustain yield and efficiency and reduce national greenhouse gas emissions without increasing national ammonia emissions substantially. Increased milk production required by Food Wise 2025 can be achieved through the high profit grass system and nitrogen loss to the environment can be substantially reduced with the incorporation of inhibitors.

4 (b) Summary of Research Outputs

(i) Peer-reviewed publications, International Journal/Book chapters.

1. Forrestal, P.J., Murphy, J.B., Fenton, O. and Richards, K.G. (In Review) Fertiliser formulation and soil type effects on reactive nitrogen leaching in intensive grassland.
2. Hoekstra, N.J., Schulte, R.P.O., Forrestal, P.J., Hennessy, D., Lalor, S.T.J., Lanigan, G., Müller, C., Shalloo, L., Wall, D., Richards, K.G. (In Review) Modelling the effect of sustainable dairy intensification on farm scale nitrogen flows and economic performance.
3. Burchill, W., Lanigan, G.J., Forrestal, P.J., Misselbrook, T., Richards, K. (In Press) Ammonia volatilisation from cattle urine patches, urea and the combination of urine patches with urea and stabilised urea in temperate grassland. *Nutrient Cycling in Agroecosystems*

4. Burchill, W., Lanigan, G.J., Forrestal, P.J., Reville, F., Misselbrook, T., and Richards, K.G. (2016). A field based comparison of ammonia emissions from six Irish soil types following urea fertiliser application. Irish Journal of Agriculture and Food Research 55: 152-158.
5. Forrestal, P.J., Wall, D.P., Carolan, R., Harty, M.A. Roche, L.M, Krol, D.J. Watson, C.J., Lanigan, G.J. and Richards, K.G. 2016. Effects of urease and nitrification inhibitors on yields and emissions in grassland and spring barley. *Proceedings of the International Fertiliser Society, Cambridge, U.K. 9th December, 2016. Proceeding no. 793, ISBN 978-0-85310-430-8.*
6. 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 (in press).*
7. Harty, M.A., McGeough, K.L., Carolan, R., Muller, C., Laughlin, R.J., Lanigan, G.J., Richards, K.G. and Watson, C.J. 2017. Gross nitrogen transformations in grassland soil react differently to urea stabilisers under laboratory and field conditions. Soil Biology and Biochemistry 109 23-34.
8. Harty, M.A., Forrestal, P.J., Carolan, R., Watson, C.J., Hennessy, D., Lanigan, G.J., Wall, D.P and Richards, K.G. 2017. Temperate grassland yields and nitrogen uptake are influenced by fertilizer nitrogen source. *Agronomy Journal*. 109: 1-9. doi:10.2134/agronj2016.06.0362.
9. 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. doi: 10.1111/sum.12232
10. Fischer, K., Burchill, W., Lanigan, G.J., Kaupenjohann, M., Chambers, B., Richards, K.G. and Forrestal, P.J. 2016. Ammonia emissions from cattle dung, urine and urine with dicyandiamide. *Soil Use and Management*. 32: 83-91. doi: 10.1111/sum.12203
11. Krol, D.J., P.J. Forrestal, Lanigan, G.J. and Richards, K.G. 2015. In situ N_2O emissions are not mitigated by hippuric and benzoic acids under denitrifying conditions. *Science of the Total Environment* 511:362-368. doi:10.1016/j.scitotenv.2014.12.074

(ii) Popular non-scientific publications and abstracts including those presented at conferences

Contributed paper - international conference

2016

1. Forrestal, P.J., Wall, D.P., Carolan, R., Harty, M.A. Roche, L.M, Krol, D.J. Watson, C.J., Lanigan, G.J. and Richards, K.G. 2016. Effects of urease and nitrification inhibitors on yields and emissions in grassland and spring barley. *Proceedings of the International Fertiliser Society, Cambridge, U.K. 9th December, 2016. Proceeding no. 793, ISBN 978-0-85310-430-8.*
2. Harty, M., Forrestal, P.J., Carolan, R., McGeough, K.L., Watson, C.J., Laughlin, R.J., Krol, D.J., Richards, K.G. and Lanigan, G. 2016. Fertiliser nitrogen source and stabiliser effects on nitrous oxide emissions in temperate grassland *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February.*

3. Richards, K., Harty, M., Forrestal, P.J., Carolan R.C., McGeough, K.L., Krol D., Minet E., Laughlin, R.L., Watson, C.J. and Lanigan, G.J. 2016. Disaggregated N_2O emissions from Irish Agriculture. Burchill, W., Fischer, K., Forrestal, P.J., Minet, E., Krol, D., Lanigan, G., Kaupenjohann, M. Richards, K.G. 2016. Ammonia and indirect N_2O emissions from cattle dung, urine and urine in combination with fertiliser N coated with/without N inhibitors on temperate grassland. *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February*.
4. Krol, D., Carolan, R., Minet, E., McGeough, K., Watson, C., Forrestal, P.J., Lanigan, G. and Richards, K. 2016. Nitrous Oxide Emissions from Urine and Dung Patches: Estimation of National Emission Factors and Possibilities for Mitigation. *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February*.
5. Minet, E.P., Ledgard, S.F., Lanigan, G., Murphy, J.B., Hennessy, D., Lewis, E., Forrestal, P.J. and Richards, K. 2016. Mixing dicyandiamide (DCD) with cattle feeds: an effective method to deliver a nitrification inhibitor to urine patches. *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February*.
6. Forrestal, P.J., Krol, D., Lanigan, Gary and Richards, K. 2016. Chamber size effects on nitrous oxide emissions from simulated urine patches. *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February*.
7. Lanigan, G., Burchill, W., Forrestal, P.J., Minet, E., Bourdin, F., Meade, G., Brennan, R., Cahalane, E., Watson, C., Fenton, O., Curran, T., Richards, K. 2016. Reducing gaseous emissions from manure management in Ireland. *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February*.
8. Harty, M., McGeough, K.L., Roche, L., Carolan, R., Forrestal, P.J., Richards, K., Watson, C.J. and Lanigan, G. 2016. Proposed improvements to static chamber determinations of N_2O emission factors. *Greenhouse Gases in Animal Agriculture, Melbourne, Australia, 14-18 February*.
9. Watson C.J., Harty M.A., Carolan R., McGeough K.L., Forrestal P.J., Richards K.G. and Lanigan G.L. 2016. Minimising the environmental footprint of nitrogen fertilisers. *Global Farm Platform Conference, University of Bristol, 12-15 January.*

2015

10. Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., McNeill, G. and Richards K.G. 2015. Fertiliser N formulation: effects on ammonia loss in temperate grassland. International Fertiliser Society annual meeting, Cambridge, U.K.
11. Roche, L., Forrestal, P.J., Richards, K.G., Lanigan, G.J., Shaw, L.J., Hackett, R., Wall, D.P. 2015. The effect of fertiliser nitrogen source and N stabilisers on spring barley grain yield. *International Fertiliser Society annual meeting, Cambridge, U.K.*
12. Roche, L., Forrestal, P.J., Richards, K.G., Lanigan, G.J., Gooding, M.J., Shaw, L.J., Hackett, R., Wall, D.P. 2014, Effect of nitrogen source and inhibitors on spring barley grain yield. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Minneapolis, MN, U.S.A.*
13. Roche, L., Forrestal, P.J., Richards, K.G., Lanigan, G.J., Gooding, M.J., Shaw, L.J., Hackett, R., Wall, D.P. 2015, Effect of nitrogen source on nitrous oxide emissions in spring barley. *American Society of Agronomy, Crop Science Society of America and*

Soil Science Society of America Joint International Meetings, Minneapolis, MN, U.S.A.

14. Harty, M., Forrestal, P.J., Lanigan, G.J., McNeill, G., Carolan, R., McGeough, K., Laughlin, R., Elliot C., Watson, C.J. and Richards, K.G. 2015. Calcium Ammonium Nitrate, Urea or Stabilised Urea: The Impact on Yield and Apparent Fertiliser Recovery in Intensive Grassland. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Minneapolis, MN, U.S.A.*
15. Vero, S., Creamer, R., Healy, M., Henry, T., Forrestal, P.J., Richards, K. and Fenton, O. 2015. Achieving equilibrium in the soil water characteristic curve: an 'effective' approach. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Minneapolis, Minnesota, U.S.A.*
16. Harty, M., Forrestal, P.J., Lanigan, G.J., Carolan, R., McGeough, K., Laughlin, R., Elliot C., Watson, C.J. and Richards, K.G. 2015. Effect of fertiliser form on yield and gaseous emissions in grassland. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Minneapolis, MN, U.S.A.*
17. *Forrestal, P.J., Harty, M., Carolan, R., Lanigan, G.J., Watson, C.J., Laughlin, R.J., McNeill, G. and Richards K.G. 2015. Ammonia emissions from stabilised urea fertiliser formulations in temperate grassland. American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Minneapolis, MN, U.S.A.*
18. *Krol, D.J., Forrestal, P.J., Lanigan, G.J. and Richards, K.G. 2015. Can manipulation of the constituents of ruminant urine reduce N_2O emissions from urine patches? American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Minneapolis, MN, U.S.A.*
19. Roche, L., Lanigan, G.J., Forrestal, P.J., Richards, K.G., Shaw, L.J., Gooding, M.J., Hackett, R., Wall, D.P. 2015. Effect of fertiliser nitrogen source on nitrous oxide emissions and yield in spring barley. *Catchment Science Conference, Wexford, Ireland.*
20. Harty, M., Forrestal, P.J., Krol, D., Lanigan, Gary, Carolan, R., McGeough, K.L., Laughlin, R.J., Hennessy, D., Elliot, C., Watson, C.J. and Richards, K. 2015. Nitrogen fertiliser formulation: The impact on yield and gaseous emissions in temperate grassland. *12th British Grassland Society Conference, September 2015.*
21. Harty, M., Mueller, C., Laughlin, R., Watson, C., Richards, K., Lanigan, G., Forrestal, P.J., and McGeough, K. 2015. The effect of urea fertiliser formulations on gross nitrogen transformations in a permanent grassland soil. *European Geosciences Union meetings, Vienna, Austria.*
22. Harty, M., Krol, D., Carolan, R., McNeill, G., McGeough, K., Laughlin, R., Watson, C., Richards, K., Lanigan, G., and Forrestal, P.J. 2015. Nitrogen fertiliser formulation: The impact on N_2O emissions. *European Geosciences Union meetings, Vienna, Austria.*
23. Minet, E., Janangir, M.M.R., Krol, D., Rochford, N., Forrestal, P.J., Fenton, O., Rooney, D., Lanigan, G and Richards, K. 2015. Environmental benefits of amending cow slurry

with the nitrification inhibitor dicyandiamide. *Ramiran 2015 - 16th International Conference Rural Urban Symbiosis, Hamburg, Germany, 8-10 Sept.*

24. Healy, M.G., Morrison, L., Forrestal, P.J., Peyton, D., Fleming, G., Danaher, M., Wall, D., Cormican, M. and Fenton, O. 2015. Characterisation of metal concentrations in treated municipal sludge in Ireland and impacts on runoff water quality following land application. *International Conference on Solid Wastes, Hong Kong, Hong Kong SAR of China, 19-23 May.*
25. Forrestal, P.J., Krol, D.J., Lanigan, G.J., and Richards, K.G. 2015. Urine patch simulation approach: effects on nitrous oxide emissions. *N_2ORA – ICOS trace gas flux measurement workshop, University of Gothenburg, Sweden.*
26. Roche, L., Forrestal, P.J., Lanigan, G.J., Richards, K.G., Shaw, L.J., Gooding, M.J., Hackett, R., Wall, D.P. 2015. Managing the soil nitrate pool in arable systems. *British Soil Science society early career research conference. University of York, York, U.K.*

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27. Forrestal, P.J., M. Harty, C.J. Watson, G.J. Lanigan, K.G. Richards, R. Carolan. Grassland nitrogen uptake and use efficiency as affected by fertiliser nitrogen source and inhibitors. *International Fertiliser Society Annual Conference, Cambridge, U.K., December 2014.*
28. Roche, L., P.J. Forrestal, K.G. Richards, G.J. Lanigan, L.J. Shaw, M.J. Gooding, R. Hackett, D.P. Wall. Evaluating the effect of fertiliser nitrogen source on grain yield in spring malting barley. *International Fertiliser Society Annual Conference, Cambridge, U.K., December 2014.*
29. Harty, M., P.J. Forrestal, D.J. Krol, G.J. Lanigan, G. McNeill, K. McGeough, R. Laughlin, C. Elliot, C.J. Watson, K.G. Richards. Fertiliser nitrogen formulation affects nitrous oxide emissions from grassland. *7th International Symposium on Non-CO_2 Greenhouse Gases, Amsterdam, Netherlands, November 2014.*
30. Forrestal, P.J., D.J. Krol, G.J. Lanigan, K.G. Richards. Urine patch simulation approach affects quantification of nitrous oxide emissions. *7th International Symposium on Non-CO_2 Greenhouse Gases, Amsterdam, Netherlands, November 2014.*
31. Harty, M., P.J. Forrestal, D.J. Krol, G.J. Lanigan, G. McNeill, K. McGeough, R Laughlin, C. Elliot, C.J. Watson, K.G. Richards. Fertiliser nitrogen formulation affects nitrous oxide emissions from grassland. *7th International Symposium on Non-CO_2 Greenhouse Gases, Amsterdam, Netherlands, November 2014.*
32. Forrestal, P.J., J.J. Meisinger, R.J. Kratochvil. A preplant soil nitrate test for site-specific starter nitrogen management in humid region winter wheat production. 2014. *American Society of Agronomy. American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Longbeach, California, U.S.A., November 2014*.
33. Roche, L., P.J. Forrestal, K.G. Richards, G.J. Lanigan, M. Gooding, L. Shaw, R. Hackett, D.P. Wall. Nitrous oxide emissions in spring barley production as influenced by fertiliser nitrogen source and inhibitor selection. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Longbeach, California, U.S.A., November 2014*.
34. Forrestal, P.J., M. Harty, G.J. Lanigan, R. Laughlin, C.J. Watson, K.G. Richards. Assessing ammonia volatilization as influenced by fertilizer nitrogen source, urease,

and nitrification Inhibitors. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Longbeach, California, U.S.A., November 2014*.

35. Harty, M., P.J. Forrestal, D.J. Krol, G.J. Lanigan, S. Lalor, D. Hennessy, C.J. Watson, K.G. Richards. Fertilizer nitrogen source and inhibitor approaches for sustaining agronomic productivity and mitigating nitrous oxide emissions in intensively managed grassland. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Longbeach, California, U.S.A., November 2014*.
36. Forrestal, P.J., L. Roche, M. Harty, G.J. Lanigan, D.J. Krol, K.G. Richards, D.P. Wall. Managing the Soil Nitrate Pool in Intensive Grassland and Arable Systems. 18th International Nitrogen Workshop, Lisbon, Portugal, July 2014.
37. Krol. D.J., P.J. Forrestal, G.J. Lanigan, K.G., Richards. Potential of hippuric acid and benzoic acid to mitigate nitrous oxide emissions from urine patches. 18th International Nitrogen Workshop, Lisbon, Portugal, July 2014.
38. Harty, M., P.J. Forrestal, J.B. Murphy, D.J. Krol, K.G. Richards, G. McNeill, B. McCarney, K. McGeough, R. Laughlin, C. Elliot, C.J. Watson. Nitrous oxide emissions from grassland as impacted by fertiliser nitrogen formulation. 18th International Nitrogen Workshop, Lisbon, Portugal, July 2014.
39. Roche, L., K.G. Richards, P.J. Forrestal, L.J. Shaw, M.J. Gooding, R. Hackett, D.P. Wall. Reducing nitrous oxide emissions from spring barley in Ireland. 18th International Nitrogen Workshop, Lisbon, Portugal, July 2014.

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40. Forrestal, P.J., M. Harty, S. Lalor, D. Hennessy, G.J. Lanigan, K.G. Richards, D.J. Krol. Evaluating fertilizer nitrogen source and inhibitors for gaseous nitrogen loss mitigation and increased nitrogen use efficiency in temperate humid region grassland. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America Joint International Meetings, Tampa, Florida, U.S.A., November 2013*.
41. Richards, K., G.J. Lanigan, R.J. Laughlin, C.J. Watson, M. Harty, D.P. Wall, L. Roche, C. Elliot, L. Shaw, D. Krol, and P.J. Forrestal. Quantification of specific nitrous oxide emission factors and the assessment of fertiliser mitigation options for grassland and spring barley. *Greenhouse Gases and Animal Agriculture, Dublin, Ireland, June 2013.*

Paper/summary in proceedings of national conference

2015

1. Roche, L., Forrestal, P.J., Richards, K., Lanigan, Gary, Shaw, L.J., Hackett, R. and Wall, D. 2015. Selecting nitrogen fertiliser sources for improved yield and reduced gaseous emissions in spring barley production systems. *Teagasc Walsh Fellowship Seminar Annual Meeting, Dublin, 01 December.*
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3. Forrestal, P.J., Harty, M., Lanigan, G. and Richards, K. Fertiliser technologies for improved efficiency and reduced gaseous emissions. *Advances in Knowledge and Technologies for Agriculture Conference, Tullamore, Co. Offaly, Ireland, June 2015*
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6. Forrestal, P.J., Lanigan, G., Harty, M., Roche, L., Krol, D., Wall, D., Minet, E., Carolan, R., Laughlin, R., McGeough, K., Watson, C., and Richards, K. 2015. Ireland - AGRI-I grassland and spring barley N2O, NH3 and yield. U.K. Agricultural GHG PLATFORM and Agricultural greenhouse gas initiative for Ireland joint meeting, Dublin, Ireland.
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10. Harty, M., Krol, D., Carolan, R., McNeill, G., McGeough, K., Laughlin, R., Watson, C., Richards, K., Lanigan, Gary and Forrestal, P.J. 2014. Nitrogen Fertiliser Formulation: The impact on NUE and gaseous N emissions. Teagasc Walsh fellowship seminar.
11. Harty, M., P.J. Forrestal, D.J. Krol, S. Lalor, G. McNeill, K.L. McGeough, R.J. Laughlin, C. Elliot, D. Hennessy, C.J. Watson, K.G. Richards. 2014. Nitrogen fertiliser formulation: the impact on agronomic performance in grassland. Agricultural Research Forum, Tulamore, Offaly, Ireland. March 2014.
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13. Wall, D., Forrestal, P.J., Harty, M., Lanigan, G. and Richards, K. 2014. The effect of N fertiliser formulation and inhibitors on N efficiency and GHG emissions. National Agri-Environmental Conference, Tullamore, 14-Nov-2014.
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Belfast, Northern Ireland. May 2014.

15. Roche, L., K.G Richards, P.J. Forrestal, G.J. Lanigan, L.J. Shaw, M. Gooding, R. Hackett, D.P. Wall. Evaluating the effect of N fertiliser type on nitrous oxide emissions from spring barley. Agricultural Research Forum, Tulamore, Offaly, Ireland. March 2014.

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2. Forrestal, P.J., Harty, M, Murphy, J., Krol, D., McGeough, K., McNeill, G., B., Laughlin, R., Elliot, E., Hennessy, D., Lalor, S., Watson, C. and Richards, K. Fertiliser Nitrogen Formulation: Trends in Grassland Yield Performance. *United Kingdom, Greenhouse gas joint platform meeting, Edinburgh, Scotland, December, 2013.*

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17. Roche, L., Richards, K.G., Forrestal, P.J., Shaw, L.J., Gooding, M.J., Maddock, C., Krol, D., Murphy, J.B, Hackett, R., Wall, D.P. 2013. Evaluating the effect of N fertiliser type on N2O emissions from spring barley. United Kingdom, Greenhouse gas joint platform meeting, Edinburgh, Scotland, December, 2013.
18. Richards, K., Forrestal, P.J., Harty, M, Murphy, J., Krol, D., McGeough, K., McNeill, G., B., Laughlin, R., Elliot, E., Hennessy, D., Lalor, S. and Watson, C. 2013. Nitrous Oxide Emission Update. Gaseous Emissions - Agriculture and Land Use Network Meeting, Redcow, Dublin, December, 2013.
19. Forrestal, P.J., Harty, M, Murphy, J., Krol, D., McGeough, K., McNeill, G., B., Laughlin, R., Elliot, E., Hennessy, D., Lalor, S., Watson, C. and Richards, K. 2013. Sustainable Use and Disaggregated Emissions of Nitrogen (SUDEN) update. Gaseous Emissions - Agriculture and Land Use Network Meeting, Redcow, Dublin, December, 2013.

(iii) National Report

20. Lanigan, G.J., Donnellan, T., Burchill, W., Forrestal, P.J., McClutcheon, G., Crosson, P., Hanrahan, K., Schulte, R., Richards K.J. and Browne. P. 2015. A Cost-Benefit Analysis for the Abatement of Ammonia Emissions. Teagasc submission to the Department of Agriculture, Food and the Marine.

(iv) Workshops/seminars at which results were presented

1. Final Project Stakeholder meeting. "Latest research on reconciling agronomic and greenhouse gas targets", The College of Amenity Horticulture, National Botanic Gardens, Glasnevin, Dublin 9, Friday June 10th 2016.

5. Scientists trained by Project

Total Number of PhD theses: 2

1. Harty. M.A. 2016. Queen's University, Belfast, Northern Ireland. Ph.D. thesis. Evaluation of fertiliser formulation on grassland nitrogen use efficiency and N2O emissions from soil.
2. Roche, L. 2017. University of Reading, Reading, United Kingdom. Ph.D. thesis. Fate and transport of fertiliser nitrogen under spring barley cultivation on contrasting soils.

Total Number of Masters theses: 1

1. Fischer, K. 2015. Technische Universität Berlin, Germany. M.Sc. thesis. Ammonia emissions from bovine dung and urine in temperate maritime grassland.

6. Permanent Researchers

Institution Name	Number of Permanent staff contributing to project	Total Time contribution (person years)
Teagasc Johnstown Castle	5	1.96
AFBI	14	3.02
UCD	1	0.00
Teagasc Moorepark	1	0.06
Total	**21**	**5.04**

7. Researchers Funded by DAFM

Type of Researcher	Number	Total Time contribution (person years)
Post Doctorates/Contract Researchers	0	0
PhD students	2	3.75
Masters students	0	
Temporary field assistants	8	2.5
Research Technician	1	3
Total	**11**	**9.25**

8. Involvement in Agri Food Graduate Development Programme

Name of Postgraduate / contract researcher	Names and Dates of modules attended
Leanne Roche	Information for hot topics in agri-food research – professional skills for the early career agri-food researcher – September 2013
Mary Harty	Science Writing - Sept 2014
Mary Harty	Career Management Skills for the Agri-Food Researcher - Nov 2015
Dominika Krol	Information for Hot Topics in Agri Food Research - Professional skills for the early-career Agri-Food Researcher

9. Project Expenditure

Total expenditure of the project:	€635,197.94
Total Award by DAFM:	€639,106.01
Other sources of funding including benefit in kind and/or cash contribution(specify):	€

Breakdown of Total Expenditure

Category	Teagasc Johnstown Castle	Teagasc Moorepark	AFBI	UCD	Total
Contract staff	54,395.40	55,909.85	92,316.75	20,454.03	223,076.03
Temporary staff	30,506.53				30,506.53
Post doctorates					
Post graduates	11,000				11,000
Consumables	107,543.95		68,870.43		176,414.38
Travel and subsistence	15,520.41	4,119.87	5,096.32		24,736.60
Sub total	**218,966.29**	**60,029.72**	**166,283.50**	**20,454.03**	**465,733.54**
Durable equipment	19,472.47		10,271.87		29,744.34
Other					
Overheads	65,689.89	18,008.92	49,885.05	6,136.21	139,720.06
Total	**304,128.65**	**78,038.64**	**226,440.42**	**26,590.24**	**635,197.94**

10. Leveraging

Summarise any additional resources'/funding leveraged by this award from other sources e.g. Additional Staff, National/EU funding secured, EI Commercialisation Fund, etc.

Through this project we leverage funds from the Teagasc Walsh Fellowship scheme to support the two PhD students who worked on both this project and AGRI-I. The project led to the successful funding of a Enterprise Ireland Enterprise Post-Doctoral research grant with BASF as the industrial partner. There has also been interest from a number of other large fertiliser manufacturers and there is potential funding in that area in the future. Finally this research has led to involvement in 1 horizon 2020 funding application, one EU ERA-net proposal and one Global Research Alliance funding proposal.

11. Future Strategies

Outline development plans for the results of the research.

There are plans to investigate a number of other advanced fertiliser formulations to assess the potential benefits to optimise production while reducing emissions. There is a need to urgently address the potential issue of residue traces in milk, meat or the

environment. This was beyond the scope of the current project but needs to be addressed to ensure there is no risk to the global marketing of Irish agricultural produce. The model developed in the project will be used in the future for assessment of agronomic and nitrogen losses to the environment.