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# SID 5 Research Project Final Report

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## Project identification

1. Defra Project code: AC0221
2. Project title: Scoping the potential to reduce GHG emissions associated with N fertiliser applied to arable crops
3. Contractor organisation(s):

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4. Total Defra project costs (agreed fixed price): £ 80,000
5. Project: start date................. 1 December 2009

   end date.................. 20 August 2010

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# Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Introduction

In 2007 the greenhouse gas (GHG) emissions associated with UK agriculture (including fuel use) was 47.9 Mt CO2e, with 29.6 Mt CO2e associated with English agriculture. The Low Carbon Transition Plan white paper published in 2009 targets a reduction in English agricultural greenhouse gas (GHG) emissions, of more than 3 Mt CO2e per annum by 2020 compared with their current projected levels. Nitrous oxide (N2O) emissions make up approximately half of the GHG emissions associated with agriculture (25 Mt CO2e), of which the most important sources are fertiliser nitrogen (N) applications, grazing (urine) returns and manure applications to land. It is important to recognise that GHG emissions from fertiliser or agro-chemical manufacture are not included in the agricultural sector in the UK GHG emissions inventory and nor are emissions associated with agricultural land use change (LUC). This study estimates the total GHG savings possible through N management and, where necessary, estimates the savings relevant to the agriculture GHG inventory.

Aim and objectives

The aim of this project was to estimate the extent to which GHG emissions associated with N fertiliser use on the main arable crops in England (winter wheat, winter oilseed rape, winter barley and spring barley) could be reduced through optimal N timing, improving the prediction of N requirement and the development of longer-term technologies. This was achieved through the following objectives.

1. Estimate the potential to increase yield and reduce GHG emissions through altering N timing and assess whether this is influenced by factors such as region.
2. Estimate the level of imprecision in N fertiliser use and the effect on GHG emissions.
3. Evaluate the scope for altering N timing towards the optimum for minimising GHGs, identify barriers for change and assess whether these are influenced by factors such as region.
4. Evaluate the scope for minimising imprecision of fertiliser use and identify barriers for change.
5. Assess the potential for minimising fertiliser N requirement through the development of N efficient varieties and low N bread technology.
6. Estimate realistic changes to N use and GHG emissions that could be achieved with timescales.

Methods

The current farm practices for the amount and timing of N fertiliser were summarised using information collected within the British Survey of Fertiliser Practice. Published literature and unpublished datasets were reviewed to quantify the potential for GHG emissions to be reduced by altering the timing of N applications from that currently used. Hypotheses tested included a) N2O emissions may be minimised by improving the synchrony between N application and crop N uptake, b) it is possible to increase yield for a given amount of N by optimising N timings thereby reducing GHGs per tonne and indirect GHGs through land use change, and c) it may be possible to minimise N2O emissions by avoiding N applications when environmental factors favour the release of N2O. Datasets (189) describing the response of crop yields to N fertiliser were compared with the amount of N recommended by fertiliser guidelines to estimate the level of error associated with N recommendations and the effect of this on GHGs and profit. A survey of 300 farmers and four focus groups with agronomists and farmers were used to understand the extent to which farmers could alter N fertiliser practice towards the optimum practice for minimising GHGs defined in objectives 1 and 2. The potential to reduce GHGs through breeding N efficient varieties was assessed by reviewing published literature and analysing data collected in two key LINK projects (LK0959 and LK0979) for which the main objective was to facilitate breeding wheat and oilseed rape varieties with a low requirement for N. A focus group was used to assess the potential to develop technologies for making bread from grain with low N and potential GHG savings associated with this were estimated. All GHG savings were estimated for the main arable crops in England only and were expressed as a percentage of both the UK and English agriculture GHG inventories.

Results

Overall, N2O emissions from soils were estimated to account for more than 50% of GHG emissions from UK agriculture, on a CO2e basis. Variation in environmental conditions, mainly temperature and soil moisture, cause a wide range of N2O emissions, of at least ten-fold in England. There is evidence that altering N timings to avoid warm temperatures and wet soil can help to reduce N2O emissions, and although dedicated experiments are required to accurately quantify the effects of these changes in N management on N2O emissions, some estimates can be made using data from a series of 8 experiments in England which measured N2O emissions following three sequential N applications (known in the industry as split timings). If the 3rd N split on all feed wheat crops in England (applied in May) could be shifted about 30 days earlier, it is estimated that direct N2O emissions from applied N could be reduced by 20%, which would reduce GHG emissions across England by 165 kt CO2e (Table A). Much smaller potential reductions are possible in other crops because they receive proportionally less N in May. Results from the farmer survey and focus groups indicated that there is scope to alter N timings from current practice (e.g. apply in cooler conditions). Unsuitable weather and soil conditions for applying N are likely to prevent realisation of the full potential savings from applying N earlier. If 75% of the estimated savings could be achieved then direct GHG reductions would amount to 124 kt for winter wheat (Table A), all of which would be relevant for the agriculture GHG inventory. This is equivalent to 0.26% of the UK agriculture GHG inventory and 0.42% of the English agriculture GHG inventory in 2007.

It is likely that autumn N applications can be avoided on a proportion of oilseed rape crops without reducing yield, but further work is required to show that this can be done in all situations, particularly where large amounts of straw are incorporated at establishment. There also appears to be scope to reduce GHGs through earlier applications to winter barley and delaying N applications to oilseed rape crops with large canopies. These changes could be made now, although more experiments may be required on winter barley to give farmers enough confidence to change practice. The size of the reduction in GHGs depends upon whether the optimal timings lead to farmers maintaining yields while applying less N, or whether yields are increased leading either to less pressure to change land use for more crop production, or to more idle land. Further research is required to evaluate which scenario is most likely. It is estimated that by a combination of avoiding autumn N and reducing N fertiliser rates applied to oilseed rape and winter barley through better N timing, could reduce the UK agriculture GHG inventory by 0.16% and the English agriculture GHG inventory by 0.25% (Table A).

It was estimated that 72% of farms use a fertiliser prediction tool (mainly RB209) when estimating N fertiliser requirements. On average, RB209 was shown to recommend similar or smaller amounts of N compared with the true economic optimum N rate for wheat, oilseed rape and barley. This indicates that the amount of N applied to these crops across the country is not excessive. Using RB209 often resulted in large errors from the true optimum N rate on individual fields and it is clear that fertiliser prediction systems need to be improved. Improving precision by which N requirement is estimated will reduce GHG emissions because under- or over-applications lead to extra GHG emissions. Improving accuracy of the average recommendation will lead to more N being recommended for some crops and greater GHG emissions nationally. However the greater yields that would result from greater N use are likely to either reduce pressure to convert uncropped land to arable or increase the amount of idle land that can sequester carbon. Aside from the effects of land use change, it is estimated that realistic savings of 48 kt CO2e could be made by increasing the proportion of farmers using SMN testing with RB209, equivalent to 0.10% of the UK agriculture GHG inventory and 0.16% of English agriculture GHG inventory (Table A). It should be recognised that improving the prediction of N fertiliser requirement will require a concerted research effort because elements such as mineralisation and crop growth are currently difficult to predict.

Growing triticale, or other N efficient cereal species, in place of 2nd wheat crops (wheat crop following a wheat crop) potentially offers a relatively quick way of achieving moderate to large reductions in GHGs, because triticale has a lower N requirement than wheat and is tolerant to root take-all disease which affects 2nd wheats. It is estimated that GHGs could be reduced by 88 kt CO2e if triticale replaced a modest proportion of 2nd wheats (12% of non-first wheats), equivalent to 0.18% or 0.30% of UK and English agricultural GHG inventories, respectively (Table A).

It has been estimated that breeding new crop varieties with a lower N requirement could produce very large reductions in N requirement and GHG emissions of up to 1,258 kt CO2e for wheat and oilseed rape together (3.15 and 5.10% of the UK and English Agriculture GHG inventories respectively). It is likely that larger and faster reductions in GHGs could be made by employing GM technology. Major barriers to developing N efficient varieties are identifying which traits plant breeders should select, methods for rapid trait selection and developing testing systems for identifying the best varieties. Moderate varietal differences in N requirement have already been detected, and if methods of quantifying differences in N requirement between varieties can be improved then reductions in GHGs could occur relatively quickly.

It is estimated that the additional N applied to bread-making wheats to help them achieve grain protein specification (compared with feed wheats) leads to emission of 137 kt CO2e (0.29% and 0.46% of UK and English agriculture GHG inventories respectively). The relevant industries are willing to investigate the possibility of making bread from lower N grain, but several potential barriers exist including; maintaining the nutritional quality of bread, altering existing bread making plants and compatibility with current variety testing systems.

Table A Summary of how changes in N fertiliser management may reduce GHG emissions for crops grown in England (kt CO2e per annum), where calculations include only N2O emissions and direct fuel use, for comparison with GHG inventory figures (Total agricultural emissions in 2007 of 29.6 Mt CO2e in England and 47.9 Mt CO2e in the UK). Figures in parenthesis represent the reduction from the English Agriculture GHG inventory. Note that GHG savings from fertiliser manufacture would be additional to those described below.

| Change in N management | | Winter wheat | Oilseed rape | Winter barley | Spring barley |
|---|---|---|---|---|---|
| Changing N timing to reduce N rate or increase yield | Potential | 0 | 47 (0.16%) | 47 (0.16%) | 0 |
| | Realistic | 0 | 24 (0.08%) | 35 (0.12%) | 0 |
| Avoid autumn N | Potential | 0 | 33 (0.11%) | 0 | 0 |
| | Realistic | 0 | 16 (0.06%) | 0 | 0 |
| Reduce N2O through altering N timing | Potential | 165 (0.55%) | 4 (0.01%) | 7 (0.02%) | 11 (0.04%) |
| | Realistic | 124 (0.42%) | 3 (0.01%) | 5 (0.02%) | 8 (0.03%) |
| Improve estimate of N requirement from RB209 (FAM) to true optimum | Potential | 0 | -110 (-0.37%) | ? | ? |
| | Realistic | 0 | 0 | ? | ? |
| Improve estimate of N requirement RB209 (FAM) to RB209 (SMN) | Potential | 212 (0.71%) | 59 (0.19%) | ? | ? |
| | Realistic | 42 (0.15%) | 6 (0.02%) | ? | ? |
| Breeding N efficient varieties | Potential | 1258 (4.26%) | 252 (0.86%) | ? | ? |
| | Realistic | 629 (2.12%) | 126 (0.42%) | ? | ? |
| Breeding N efficient varieties Including GM technology | Potential | 1572 (5.31%) | 485 (1.64%) | ? | ? |
| | Realistic | 786 (2.66%) | 242 (0.83%) | ? | ? |
| Low N bread technology | Potential | 137 (0.47%) | NA | NA | NA |
| | Realistic | 69 (0.23%) | NA | NA | NA |
| Use of N efficient species Triticale to replace non-first wheats | Potential | 176 (0.60%) | NA | NA | NA |
| | Realistic | †† 88 (0.29%) | NA | NA | NA |

† Estimate based on the 3rd N split being shifted 30 days earlier, causing a 20% reduction in direct N2O emissions.

†† Assume triticale replaces 12% of non-first wheat, requires 44 kg N/ha less and yields 0.5 t/ha more.

Conclusions

- This study has estimated that there is scope to reduce GHG emissions associated with the English agriculture GHG inventory by almost 4% by using N fertiliser more efficiently. This would represent more than one third of the targeted reduction. However it is clear that there are no easy wins and progress would need to be made on several fronts to achieve a significant reduction in GHG emissions.
- It should also be recognised that the changes proposed would reduce GHGs in sectors other than the agriculture inventory (primarily by affecting fertiliser manufacture and LUC). If these are included then the GHG savings described for the English agriculture GHG inventory (Table A) increase by approximately 70%.
- The quickest savings could be made by altering N timings to winter barley and oilseed rape and replacing non-first wheats with triticale. These have estimated savings of 0.55%, but would require some further evidence of their effects to hasten uptake by the industry.
- Breeding for lower N requirement offers the greatest potential savings in GHG emissions. If methods of testing current and new varieties for N requirement can be developed then progress may be made quite quickly, although the scale of such a variety testing system should not be under-estimated. Identification and rapid screening of traits for low N requirement will take longer to develop.
- It is not possible to quantify the true potential for reducing N2O emissions because there is insufficient evidence on how factors influence emissions. The potential savings estimated here could be greater if it is shown that avoiding wet soil, extra splits and using nitrification inhibitors have a significant effect.

- N fertiliser recommendations from RB209 were generally similar or smaller than the true economic optimum of the crop, which indicates that N applications on farms are not excessive.

The GHG mitigation potentials for N fertiliser use on arable crops estimated in this report have been used in a parallel project (AC0222: 'Agriculture greenhouse gas mitigation feasibility study') to estimate wider GHG mitigation potentials for agriculture.

AC0221 should be referenced as 'Berry, P.M., Wiltshire, J.J.J., Roques, S., Clarke, S., Thorman, R., Jones, G., Simpson, D. (2010). Scoping the potential to reduce greenhouse gas emissions associated with N fertiliser applied to arable crops. Defra Project No AC0221, 34pp.'

## Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

# Introduction

In 2007 the GHG emissions associated with UK agriculture (including fuel use) was 47.9 Mt CO2e, with 29.6 Mt CO2e associated with English agriculture. The Low Carbon Transition Plan white paper published in 2009 targets a reduction in English agriculture greenhouse gas (GHG) emissions, of more than 3 Mt CO2e per annum by 2020 compared with their current projected levels. The predicted value for emissions from UK agriculture in 2020 is 47 Mt CO2e (Low Carbon Transition Plan, Annex A, Table A9). A significant proportion of greenhouse gas (GHG) emissions associated with the production of arable crops result from the use of nitrogen (N) fertiliser. For example N fertiliser has been estimated to contribute 75 to 79% of the GHG emissions associated with wheat and oilseed rape production respectively (Berry et al., 2008a; Mahmuti et al., 2009). Greenhouse gas emissions associated with N fertiliser are in the form of nitrous oxide (N2O) and carbon dioxide (CO2) released during the manufacture and application processes. It is important to recognise that GHG emissions from fertiliser or agro-chemical manufacture are not included in the agricultural sector in the GHG emissions inventory and nor are emissions associated with agricultural land use change. These emissions are included within the energy and land use, land use change and forestry sections respectively. The current UK GHG emissions inventory (MacCarthy et al., 2010, inventory year 2008) estimates that N2O emissions make up approximately half of the GHG emissions associated with agriculture (25 Mt CO2e), of which the most important sources are fertiliser N applications, grazing (urine) returns and manure applications to land. It is not possible to calculate exactly how much of these emissions are associated with the production of arable crops because some of the breakdown figures encompass arable and grassland. The arable source sector (mainly crop residues) is estimated at 3.2 Mt, synthetic fertiliser (5.8 Mt), leaching/runoff (6.3 Mt), N deposition (1.5 Mt), and manure as organic fertiliser (2.3 Mt). If the proportion of total synthetic fertiliser emissions attributable to arable is the same as the proportion of total fertiliser used for arable (0.59), and the proportion of leaching, deposition and manure use emissions attributable to arable is the same as the proportion of the total grass and arable area that is arable (0.41), then the emissions associated with arable cropping are estimated to be approximately 10.8 Mt CO2e.

Greenhouse gas emissions associated with N fertiliser use may be reduced by simply reducing N rates, but it is recognised that this would reduce crop yields and transfer GHG emissions to wherever the yield shortfall is made up, and may even increase GHG emissions as a result of greater indirect land use change (ILUC) (Kindred et al., 2008). There are three broad methods by which changes to crop management may reduce the GHG emissions associated with N fertiliser without reducing yield including; i) reducing the N rate required to achieve a given yield, ii) increasing yield for a given N rate and iii) reducing the N2O emissions for a given rate of N. Methods i and iii will reduce the GHGs included in the UK inventory of GHG emissions, whilst method ii will reduce GHGs per tonne of produce and reduce GHG release through ILUC.

Previous research (AC0206, RMP4950), has identified optimising N timing and avoiding excess N as possible methods for reducing GHGs within a short time-scale. The rationale behind optimising N timing is that a) N2O emissions may be minimised by improving the synchrony between N application and crop N uptake, b) it may be possible to increase yield for a given amount of N by optimising N timings to maximise yield and c) it may be possible to minimise N2O emissions by avoiding application when environmental factors favour the release of N2O. The issue of avoiding excess N may be better defined as improving the prediction of N requirement because this also encompasses under-fertilisation which, as described above, may also lead to greater indirect GHG emissions. Methods for predicting N requirement exist (e.g. Fertiliser Recommendations for Agricultural and Horticultural crops, Defra RB209), but there is significant scope for improvement both in terms of increasing use of existing prediction methods and by improving the methods themselves. Improving the precision of fertiliser applications offers a route to reducing GHG emissions in the short-term. However, it is clear that there is much greater potential for reducing GHGs through breeding N efficient varieties and through developing end-use technology that minimises the requirement for nitrogen in the grain in the form of protein.

The aim of this project was to estimate the extent to which GHG emissions associated with N fertiliser use on arable crops in England could be reduced through optimal N timing, improving the prediction of N requirement and the development of longer-term technologies. Published literature and existing datasets were used to quantify the optimum N timings for minimising GHG emissions, together with the maximum level of precision that fertiliser requirements may be predicted using current technology. Existing survey information, a telephone survey with farmers and focus groups with farmers and agronomists were then used to gauge the extent to which farmers can practically alter N timing towards the optimum and improve the prediction of fertiliser requirement. Barriers that may constrain improvement and potentially influencing factors were identified. Information from current Defra LINK projects was analysed to assess the potential and identify barriers for reducing N requirement and GHG emissions by breeding N efficient crop varieties. An expert group approach was used to assess the potential to develop technologies for making bread from wheat with low protein and to estimate the consequent reduction in fertiliser N. Finally the project estimated realistic changes to N use and GHG emissions that could be achieved with timescales.

# Scientific Objectives

The aim of this project was to estimate the extent to which GHG emissions associated with N fertiliser use on the main arable crops in England (winter wheat, winter oilseed rape, winter barley and spring barley) could be reduced through optimal N timing, improving the prediction of N requirement and the development of longer-term technologies. This was achieved through the following objectives.

1. Estimate the potential to increase yield and reduce GHG emissions through altering N timing and assess whether this is influenced by factors such as region.
2. Estimate the level of imprecision in N fertiliser use and the effect on GHG emissions.
3. Evaluate the scope for altering N timing towards the optimum for minimising GHGs, identify barriers for change and assess whether these are influenced by factors such as region.
4. Evaluate the scope for minimising imprecision of fertiliser use and identify barriers for change.

5. Assess the potential for minimising fertiliser N requirement through the development of N efficient varieties and low N bread technology.
6. Estimate realistic changes to N use and GHG emissions that could be achieved with timescales.

# The extent to which the objectives have been met

All objectives have been fully met.

# Methods

1) Estimate the potential to increase yield and reduce GHG emissions through altering N timing and assess whether these are influenced factors such as region (Objective 1 linked to milestone 1).

Published literature and unpublished datasets were reviewed to identify the optimum timing of N applications for maximising yield for a given amount of N for winter wheat, winter barley, spring barley and oilseed rape. These were then compared with current practice (British Survey of Fertiliser Practice) and with recommended practice (RB209) to estimate the scope for increasing yields. Effects of N timing on end product quality (e.g. protein content in wheat) were also reviewed. Nitrous oxide literature was reviewed to identify the important environmental and crop factors involved and the direction in which they affect N2O emissions. The project group involved in the LINK project LK9128 'Minimising nitrous oxide emissions' was consulted in order to get an expert view of the optimum fertiliser N timings for minimising N2O emission, and approximate ranges in N2O emissions that may result from applying fertiliser in different environmental conditions. The potential reduction in GHG emissions (both direct and indirect through maximising yield) that may be achieved by altering N timings from current practice to the optimum N timings were estimated by using GHG calculation methods (e.g. Berry et al., 2008a; Kindred et al., 2008). Due to the uncertainty associated with estimating N2O emissions that result from different fertiliser N timings GHG emissions were calculated for several scenarios each assuming a different percentage saving in N2O emissions.

2) Estimate the level of imprecision in N fertiliser use and the effect on GHG emissions (Objective 2, linked to Milestone 2).

True economic optimum N rates calculated from N response experiments described in Sylvester-Bradley et al. (2008) (wheat and spring barley) and Berry and Spink (2009) (oilseed rape), and unpublished datasets on winter barley were used to estimate the level of error in N rate resulting from using existing schemes for estimating fertiliser requirement including RB209 (forthcoming 8th edition, 2010) with and without a measurement of soil mineral N. Effects of applying the wrong N rate on yield, gross margin and GHGs were estimated. See Annex 4 for full details of methodology.

3) Evaluate the scope for altering N timing to the optimum for minimising GHGs and identify barriers for change and assess whether these are influenced by factors such as region (Objective 3, linked to Milestone 3).

The rationale behind the decision on N timings, the scope for altering N timing towards the optimum defined in (1) and the identification of any barriers against changing practice were ascertained from a telephone survey with a broad cross-section of farmers together with focus groups with farmers and agronomists. The survey was designed and managed by ADAS in conjunction with a market research specialist (DS Research Ltd), working to the MRS code of conduct. The interviews were conducted by a specialist interviewing agency, the Hill Taylor Partnership, and were conducted via CATI (computer assisted telephone interviewing). In line with the requirements of Defra survey control, the survey was preceded by a mailing that allowed farmers to opt out of the survey. The survey obtained information from 300 farmers covering all regions of England, the main soil types and Defra robust farm types 1 (cereals), 2 (general cropping) and 3 (mixed). Quotas were applied to the interview sample to ensure that it reflected the proportion of each farm type within the farming population. Interlocking quotas were also applied within farm type to reflect the farming population in terms of region and SLR size bands. Four focus groups were conducted to understand as fully as possible barriers against altering N timing practice. One group was conducted amongst agronomists and three amongst farmers. The groups were conducted in Lincoln (1 agronomist and 1 farmer group), Huntingdon, Cambridgeshire and Thirsk, North Yorkshire. Each focus group comprised 7-8 respondents from a mix of cereal, general cropping and mixed farm types across a range of farm sizes and followed a pre-agreed topic guide (see appendix to this report). An estimate of how much N fertiliser timings could be realistically changed towards the optimum described in (1) and an estimate of the associated GHG savings was made. A cost benefit analysis was carried out to assess the impact of different N timing strategies, together with the potential cost of mitigating GHG emissions.

4) Evaluate the scope for minimising imprecision of fertiliser use and identify barriers for change (Objective 4, linked to Milestone 4).

Information from the survey described in (3) together with information from the Farm Practice Survey and information gathered from soil testing labs was used to estimate the number of farmers who use guides and soil/crop N measurement to predict the N fertiliser requirement. The potential for improving N precision through greater use of existing guides and technology was then assessed. The focus groups set up in (3) were used to identify barriers against using fertiliser guides, soil analysis and other techniques. The amount by which the accuracy of estimating fertiliser N requirement may be realistically improved after taking account of barriers against uptake was then estimated together with the GHG savings. A cost benefit analysis of using different N prediction schemes was carried out, together with the potential cost of mitigating GHG emissions.

5) Assess the potential for minimising fertiliser N requirement through the development of N efficient varieties and low N bread technology (Objective 5, linked to Milestone 5).

Information from published literature and from Defra LINK projects LK0959 (wheat) and LK0979 (oilseed rape) was used to assess the potential for reducing N requirement and GHG emissions through breeding. Changes required to breed N efficient varieties were considered including the type of crop traits that breeders must select, changes to the variety testing system, methods of quantifying the reduction in N requirement and changes to growing practices and end uses. Potential technical barriers to developing and using N efficient varieties were identified through the focus groups. The potential reduction in N requirement from developing technologies to make bread of acceptable quality to consumers using wheat with a low grain protein content was assessed by consulting with industry experts. Research to develop the necessary technology and mitigating factors were identified through the industry consultation.

6) Estimate realistic changes to N use and GHG emissions that could be achieved with timescales (Objective 6, linked to Milestone 6).

Results from objectives 1 to 5 were used to estimate the likely reduction in GHG emissions associated with N fertiliser that could practically be achieved on-farm. The focus groups were used to estimate how quickly the changes could be made and included potential GHG reductions from developing N efficient varieties and low N bread technologies.

# Estimation of GHG emissions

Greenhouse gas emissions have been calculated that are directly associated with growing a crop and indirectly as a result of land use change due to changes in crop productivity. GHGs associated with growing the crop have been calculated using the method of Berry et al. (2008a). This method includes direct and indirect N2O emissions from soil following the application of N fertiliser and following the incorporation of crop residues, and emissions associated with seed production, fertiliser manufacture, pesticides, field operations (fuel and machinery manufacture), and grain drying. Standard figures for seed, phosphorus, potassium, sulphur and lime inputs, pesticides, energy associated with field operations and grain drying were used, whilst crop yield and N rate were varied. GHG emissions were calculated per hectare and per tonne of grain and expressed as kg of CO2 equivalent (CO2e) after accounting for the different global warming potentials of the greenhouse gases. GHG emissions associated with the manufacture, packaging and transport of ammonium nitrate fertiliser were assumed to be 7.11 kg CO2e per kg N (Anon. 2007). Direct and indirect N2O emissions from soil were calculated following the IPCC methods detailed by MacCarthy et al. (2010). Soil emissions of N2O following the application of fertiliser N were assumed to be linearly related to N fertiliser rate as per IPCC Tier 1 methodology given in the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997), with 0.0177 kg N2O per kg N from direct emissions; plus 0.0105 kg N2O per kg N indirect emissions from leaching and 0.0016 kg N2O per kg N from volatilisation, giving a total of 0.030 kg N2O per kg N, or 9.215 kg CO2e per kg N. The global warming potential (GWP) used for N2O is 310 kg CO2e per kg N2O, from IPCC (1997). Emissions associated with crop residues were linearly related to crop yield as per IPCC Tier 1 methodology, at 0.327 kg N2O per t/ha for wheat, 0.322 kg N2O per t/ha for oilseed rape and 0.302 kg N2O per t/ha for winter and spring barley.

Changes to GHG emissions were calculated for England using average crop areas and yields from 2007 to 2009, from Defra statistics. These areas were 1,772,000 ha wheat at 7.81 t/ha, 340,000 ha winter barley at 6.29 t/ha, 333,000 ha spring barley at 5.37 t/ha and 533,000 ha winter oilseed rape at 3.32 t/ha. Changes are reported in kt (thousand tonnes) CO2e.

Increases in crop productivity (yield per ha) may affect GHG emissions via several mechanisms; i) national production is maintained with the use of less N fertiliser, ii) greater production reduces pressure for uncropped land to be converted to arable with a consequent reduction in GHGs, or iii) previously cropped land is left idle and sequesters carbon. For scenario (i) the GHG model described above is used to estimate the effect on GHG emissions. For scenario (ii) the method of Kindred et al. (2008) was used as follows. The yield foregone compared with the N management option with the greatest yield was calculated. It was assumed that all of the foregone yield was produced on land converted from temperate grassland. The area of LUC to meet this production was obtained by dividing the foregone yield by the expected yield on the newly cropped land, taken as the yield of the particular N management option in question. Over a 30 year period the GHG emissions resulting from converting temperate grassland to arable crop land have been estimated at on average 6 t CO2 e per ha per year (Anon., 2006; Searchinger et al., 2008). For scenario iii) the amount of land required to maintain the original national productivity has been calculated based on the higher crop yields and the remaining land area that once grew the crop is assumed to become idle. It is then assumed that this land sequesters 0.33 t C per ha per year (1.21 tCO2e per ha per year) for grassland establishment (Post & Kwon, 2000).

In order to estimate the effects of changes in N management on the UK GHG inventory, only the GHG savings included within the inventory were used including N2O emissions and direct fuel use, and excluding emissions associated with fertiliser manufacture, machinery manufacture, pesticides and land use change. These figures are reported as a percentage of UK and England agricultural emissions in 2007 (47.9 Mt CO2e and 29.6 Mt CO2e, respectively, including fuel use).

# Results and Discussion

Sections 1 to 5 are used to estimate the potential and realistic GHG savings possible from changes to N management, breeding and low bread N technologies. Section 6 then estimates the amount of these GHG savings that are relevant to the UK Agriculture GHG inventory.

# Estimate the potential to increase yield and reduce GHG emissions through altering N timing and assess whether these are influenced factors such as region (Objective 1 linked to milestone 1)

## Summary

- Evidence from the British Survey of Fertiliser Practice indicates that farming practice follows RB209 recommendations for all crops in terms of the timing and number applications with which N fertiliser is applied.
- Recent research indicates that N timings recommended by RB209 for oilseed rape and winter barley are not optimal for gross margin with yield increases of about 0.4 t/ha possible.
- For oilseed rape and winter barley, the greatest potential decrease in GHG emissions from optimising N timing is from cutting N rates whilst maintaining yield per hectare and avoiding autumn N on oilseed rape. These amount to potential savings of 225 kg CO2e including the costs of fertiliser manufacture.
- No systematic N timing experiments have been carried out on winter wheat since the trials done in 1980s to develop RB209, so it is not possible to conclude whether N timings can be optimised for this crop.
- Variation in environmental conditions (mainly temperature and soil moisture) has been shown to cause a wide variation in N2O emissions measured at more than ten-fold.
- A preliminary analysis indicated that applying in cooler conditions may reduce N2O emissions. It was estimated that bringing May N applications forward by 30 days could reduce GHG emissions of relevance to the UK Agriculture GHG inventory by 165 kg CO2e. Greater reductions may be possible if it is shown that applying in dry soil and using extra splits are beneficial.

## Introduction

This section first describes the best practice guidelines for fertiliser N timing as described in RB209 (Anon, 2000) and, where different in the revised edition about to be published (Anon. 2010). Published and unpublished literature describing how changes in N timing affect yield and crop quality are reviewed followed by an assessment of the scope for increasing yield by altering N timings from those currently recommended in RB209 guidelines. Effects of environmental factors on N2O emissions are described together with a consideration of how changes in N timing may affect N2O emissions. The current practice of N fertiliser use is summarised from both published and unpublished information collected in the British Survey of Fertiliser Practice (BSFP). Potential reductions in GHG emissions that may result from altering N timings from current practice are estimated.

## Optimal N application timings for maximising yield and grain quality

Full details about recommended and optimal N timings are described in Annex 1. Winter wheat: Defra RB209 guidelines recommend that N should be applied from just before the start of stem extension (Mid February to mid March) until mid-stem extension (early May), with later amounts recommended for milling wheat to increase grain protein. Three splits are recommended for total rates above 160 kg N/ha. This guidance is based on studies done in the 1980s and no systematic N timing studies have been carried out since then, so it is not possible to conclude whether the current advice on timings is optimal or not. Certainly there appears to be a requirement to re-test the optimum timings due to significant changes in average wheat yields and farming practices in the last 20 years, including the end of stubble burning, increase in straw incorporation and reduction in tillage. From the published research that has been done on N timing in wheat it seems likely that current RB209 guidelines are correct in that N for yield should not be applied after the end of leaf production (GS39), however evidence is conflicting about whether or not yields may be reduced by applying a significant amount of N before the start of stem extension (Petersen, 2004; Howard et al., 2002; Kindred et al., 2009). Research carried out to identify the optimum N management for wheat grown as a bioethanol feedstock has shown that total N rates recommended by RB209 should be reduced by 10-12% to optimise ethanol yield/ha, as high grain protein concentrations reduce ethanol yield/t (Clarke et al., 2008), and there is likely to be some benefit from applying a greater proportion of N in mid-February to mid-March. However, more evidence is needed to confirm that this change to N timings will be effective.

Winter oilseed rape: RB209 guidelines recommend that 30 kg N/ha may be applied in autumn to fields with a low or moderate SNS. The main N applications are recommended to be split equally between mid February to early March and late March to mid April. Two splits are recommended for total rates above 100 kg N/ha. Published literature and unpublished data indicate that the RB209 recommendation of 30 kg N/ha applied in autumn may be unnecessary for most crops, apart from possibly crops with a large amount of straw incorporated from the previous crop and which have undergone minimal soil cultivations during establishment. Evidence suggests that crops can take up sufficient N from spring applications to achieve the optimal canopy size for yield, and that spring applications of N are taken up more efficiently than autumn or winter applications. Currently autumn N is applied to 29% of oilseed rape crops and while further research is required to test the value of autumn N in different situations, it seems likely that autumn N could be applied to fewer crops without reducing yield. RB209 guidelines for oilseed rape could also be improved by applying spring N later to crops with large canopies following winter (Berry and Spink, 2009). Delaying the first split until the start of stem extension (late March to early April) and delaying the 2nd split until yellow bud/early flowering (mid April to early May) has been shown to increase yield by up to 0.36 t/ha, or reduce N application rate by up to 50 kg N/ha while maintaining yield. However, it should be recognised that these gains will only apply to a proportion of crops which will vary by season.

Winter barley: RB209 guidelines recommend that a small proportion of the N may be applied before the start of stem extension between mid February and mid March with the bulk applied by early stem extension (GS31) in April. Two splits are recommended for total rates above 100 kg N/ha. As with wheat the field experiments used to develop these guidelines were carried out in the 1980s (Lord & Vaughan, 1987) and few experiments have been carried out on N timings since then. Recent experiments funded by GrowHow UK Ltd and carried out by ADAS have shown that both yield and quality can be improved by applying N earlier than is recommended by RB209. Trials have shown that applying 50% of the N between late February and early March and 50% in mid to late March improves yield by an average of 0.3-0.5 t/ha and reduces grain N concentration by 0.07-0.1% (which is important for malting quality), compared with RB209 timings. Alternatively, the earlier timings can allow the use of 30 kg/ha less N to achieve the same yield as with RB209 timings. These trials also showed that the optimum N rates were 40 to 80 kg N/ha greater than recommended by RB209, which may be due to the higher yield potential of modern varieties. Further work is ongoing to investigate whether these earlier timings increase the risk of lodging or nitrate leaching, and to confirm whether there are differences for the optimal N strategy between 2-row and 6-row barley.

Spring barley: RB209 guidelines recommend that N should be applied between drilling and early stem extension (between early April and early May). All N applied to malting barley should be applied by the end of March to minimise grain protein. Two splits are recommended for total rates above 70 kg N/ha. Overthrow (2005) showed that on average, the highest yields were achieved by applying N in two equal splits (seedbed and three-leaf stage). This gave an average yield increase of 0.11 t/ha across all N rates, and 0.19 t/ha at the highest N rate (200 kg N/ha), relative to a single application at the one-leaf stage. This indicates that yield increases could be achieved by applying N earlier than recommended in RB209, however, results from this study and McTaggart & Smith (1995) showed that changes in timing and the number of splits produced inconsistent effects on yield. Other studies outside the UK suggest that N may be applied at any time between sowing and tillering without impacting yield or quality. It has also been shown that RB209 recommendations underestimate the optimum N rate of modern spring barley varieties (Overthrow, 2005; Sylvester-Bradley et al., 2008). There is no strong evidence that the RB209 recommended timings for N application can be improved for yield or grain quality.

# Effect of N timing on N2O emissions

The current UK greenhouse gas (GHG) emissions inventory (MacCarthy et al., 2010, inventory year 2008) estimates that 75% of nitrous oxide (N2O) is produced from agriculture, amounting to 82,070 t N2O (25,443,160 t CO2e). Approximately 60% of the N2O produced from agriculture is directly emitted from agricultural soils. Less than 10% of agricultural N2O is emitted from manure management and c.30% is emitted indirectly from soils from two mechanisms, namely:

i) following N loss via ammonia (NH3) volatilisation/NOx emission (c.20%),

ii) nitrate ($NO3-$) leaching (c.80%).

It has been estimated that arable crop production may contribute approximately 10,800,000 t CO2e of the total N2O emissions associated with UK agriculture (see Introduction for calculation), with N2O emissions from fertiliser N applications representing by far the most important source.

Nitrous oxide emissions from agricultural soil are predominately produced via the microbially mediated processes of nitrification and denitrification (Firestone and Davidson, 1989). The key factors which control the magnitude of N2O emission include; soil moisture content, soil temperature and soil mineral nitrogen content (particularly soil nitrate) (Dobbie & Smith, 2001; Dobbie & Smith, 2003).

Davidson (1991) suggests that the greatest N2O emissions occur at a water filled pore space (WFPS) of 60%. Other research, however, has shown that the WFPS for maximum emissions can vary with soil type and conditions. Notably, UK studies have indicated that the maximum N2O emissions frequently occur under more anaerobic conditions i.e. at a WFPS >60% (Dobbie et al. 1999; Dobbie & Smith, 2001; Dobbie & Smith, 2003). For example, in a laboratory study using arable soil, Dobbie & Smith (2001) measured an approximate 30 fold increase in N2O emissions as the WFPS increased from 60 to 80%. Similarly, Defra project CC0223 showed for a grassland site that N2O emissions increased about 10-fold when water table depth decreased from 40cm to 20cm, although it is difficult to distinguish the effects of water table depth and water-filled pore space. The WFPS of the soil is controlled by the water addition processes of rainfall and irrigation, and the water removal processes of evapotranspiration and drainage. Consequently, the amount and distribution of rainfall is frequently considered to be a strong driver of N2O loss, particularly during the crop growing season.

In a laboratory study using soil cores taken from arable fields in Scotland, Dobbie & Smith (2001) demonstrated the importance of soil temperature in controlling N2O emissions. They reported that, increasing temperature caused a very large increase in the size of the mean N2O emissions, particularly over the 5-12°C range.

Previous work has shown that under certain conditions there is a good relationship between soil mineral N surpluses at the field (and farm) level and N2O emissions (Schils et.al., 2008; van Groenigen et al., 2008). Applications of fertiliser N in excess of crop requirement will lead to increased N2O emissions, particularly, as discussed above, if applied under conditions conducive to elevated emissions i.e. ‘wet’ and warm soil conditions (e.g. Chantigny et al., 1998). Immediately following N fertiliser application N2O emission from soil is unlikely to be limited by the mineral N content and, therefore, temperature and moisture are likely to be more critical in influencing the magnitude of loss. Farmers have little control over these conditions, other than by changing the timing of N application in relation to current and forecast soil conditions or investing in drainage, e.g. mole drains or subsoiling. Given that drainage schemes are already installed on the majority of arable land in England, altering application timing may be the more promising of these options.

To our knowledge there are no experiments that have been carried out in England specifically designed to examine the effect of N fertiliser application timing to arable (or grassland) crops on N2O fluxes. Experiments have, however, been carried out to quantify the effect of contrasting slurry application timings on N2O losses.

Results from Defra project ES0115 (OPTI-N), where direct and indirect N2O losses were measured following the application of slurry to free draining arable land or grassland showed that generally the highest N2O losses were associated with slurry applications in October, November and December, when temperatures were relatively warm, soils were moist and crop growth (and nitrogen uptake) was slow. The lowest N2O losses (≤ 0.20% of total N applied) were generally associated with slurry applications during periods of active crop growth (i.e. spring and early autumn for oilseed rape), where crop N uptake reduced the soil mineral N pool potentially available for loss as N2O and when the soil was either dry and/or relatively cold. In order to fully account for total N2O emissions following fertiliser/manure application it is necessary to not only consider direct losses of N2O, but to also include losses that occur indirectly following application as a result of nitrate leaching and as ammonia volatilisation. In situations where nitrate leaching was high following slurry applications it was shown that indirect emissions could be two times greater than direct emissions (See Annex 2 for more details).

It has been possible to analyse data from previous studies, which may provide some limited evidence to begin to develop N fertiliser application timing recommendations aimed at minimising direct N2O emissions. Nitrous oxide emission factors (EFs), calculated as a percentage of N2O-N out of the total N applied at a given split, were collated in an IPCC compliant database using the results of field studies from Defra-funded projects NT2605 and AC0101 where manufactured N fertiliser was applied to winter cereals in England. Data from the two experiments were only included in the dataset if the fertiliser applied was ammonium nitrate and if the fertiliser application rate followed recommended practice (Anon, 2000). This resulted in a database containing 23 N2O measurements which is summarised in Table 1 and full details given in Annex 2.

Table 1 Summary of N2O-N emission factors (EF) following the application of ammonium nitrate fertiliser to winter cereals in England

| Application date | 1st fertiliser split<br>Early to mid March | 2nd fertiliser split<br>Early to mid April | 3rd fertiliser split<br>End April to mid May | Total over 12 months<br>March to May |
|---|---|---|---|---|
| Mean measurement period (days) | 34 | 25 | 30 | 365 |
| Mean EF (% of total N applied) | 0.21 | 0.13 | 0.62 | 1.04 |
| Standard error of the mean | 0.08 | 0.04 | 0.14 | 0.20 |
| Median EF (% of total N applied) | 0.14 | 0.10 | 0.63 | 0.81 |
| Maximum EF (% of total N applied) | 0.71 | 0.31 | 1.19 | 3.17 |
| Minimum EF (% of total N applied) | 0.00 | 0.04 | 0.05 | 0.23 |
| Number of measurements | 8 | 7 | 8 | 8 |

Analysis of the database shows that over a c.30 day measurement period following ammonium nitrate application significantly greater (P<0.01) emissions of N2O occurred after the 3rd split (0.62% total N applied) than from the 1st (0.21% total N applied) or 2nd (0.13% total N applied) splits. Over 12 months the EFs ranged from 0.23% to 3.17% of total N applied, with an average of 1.04%. This compares with the IPCC (1997) range for N2O emissions of 0.25% to 2.25% of total N applied, with a default value of 1.25%. Plotting the split EFs against the mean air temperature calculated over a 4-week period from 1 week before fertiliser application to 3 weeks after the N application and total rainfall calculated over 7 days after application (Figure 1) showed that with heavy rainfall, if the temperature was <10°C, generally large emissions did not occur, which was a combination routinely observed following the first 2 split applications. Similarly, even with temperatures >10°C, if the total rainfall was <c.20 mm large emissions also were not generally measured. Similar relationships were also found when WFPS calculated over a 4-week period from 1 week before fertiliser application to 3 weeks after was plotted against temperature (see Annex 2 for details). It must be recognised generally that all of the application splits with a high EF were the 3rd N split. This means that the conclusions drawn about the influence of temperature and rainfall on EFs must be treated with caution because these environmental factors are confounded with the split number. Nonetheless, Clayton et al. (1997) also reported the existence of threshold levels of soil temperature and WFPS following the application of N fertiliser to grassland in Scotland and reported a steep rise in N2O emissions with temperature where WFPS or mineral N values were not limiting.

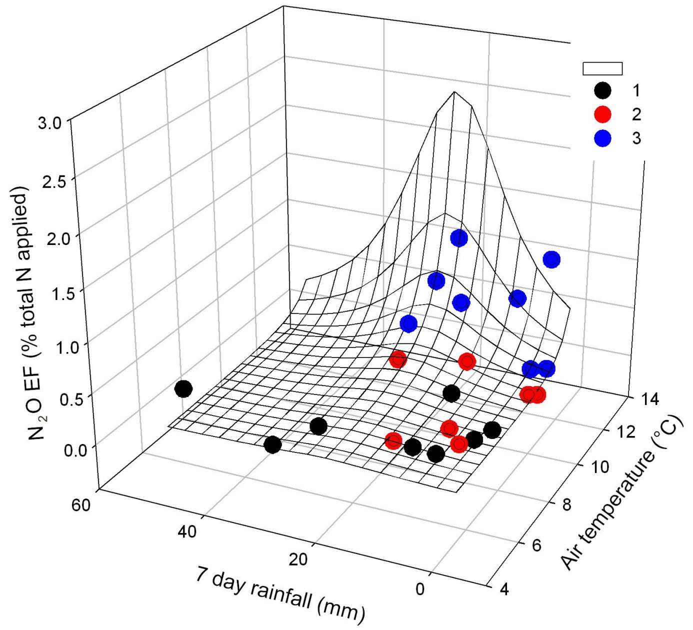

Figure 1. Relationship between N2O emission factors (EF) (% of total N applied lost as N2O) calculated over c.30 d following the application of ammonium nitrate fertiliser to winter cereals and, mean air temperature calculated over a 4-week period from 1 week before fertiliser application to 3 weeks after and cumulative rainfall calculated over 7 days after application. Black dots represent data from the 1st fertiliser split; Red dots represent data from the 2nd fertiliser split; Blue dots represent data from the 3rd fertiliser split. (R2 = 0.60, P<0.01).

The review of N2O literature and data described above indicate that adjusting the timing of N applications and the frequency of splits could help to reduce N2O emissions. Applying more N early when temperatures are low would help to minimise N2O emissions, but this approach would need to be balanced against the greater risk of nitrate leaching before the crop is able to take it up or excessive early crop growth leading to lodging and reduced yields, and trafficability. It may also be possible to apply more N in drier soil conditions, but this strategy relies on being able to accurately forecast rainfall events and it may restrict crop N uptake if soils are very dry. More frequent applications of smaller amounts of fertiliser N in close synchrony with crop requirements would minimise soil mineral N levels at risk from elevated N2O losses at any point in time, including those when conditions are conducive to high N2O emissions. Modelling studies predict that such a strategy would increase N recovery and decrease gaseous N and leaching losses (e.g. del Grosso et al., 2002; del Prado et al., 2004). However, no UK data exists to validate these predictions and very few literature data exist from elsewhere; Sitthaphanit et al. (2009) reported that increasing the number of split fertiliser N applications increased N use efficiency in maize (Thailand) and Burton et al. (2008) showed that split N application timings could reduce N2O emissions from potatoes (Canada), but this was not consistent over all years. Experiments currently being carried out within Defra project AC0213 will assess the potential for optimising fertiliser N application timings (i.e. “little and often” policies) to reduce N2O emissions from cereal crops and grassland under UK conditions.

# Current N fertiliser practice

Across all tillage crops in England and Wales, overall N application rates rose steadily from around 90 kg N/ha in the early 1970s to over 160 kg N/ha by 1985. Since 1985, the overall N rate for oilseed rape has fallen from around 270 kg N/ha to 190 kg N/ha, but N application rates to winter wheat, winter barley and spring barley have not changed aside from small fluctuations. This is despite significant increases in the yield potential of both wheat and barley over this period.

Between 2006 and 2008, for all four of these major crops, the majority of fertiliser N (55% to 67%) was applied as ammonium nitrate. Other major N sources were urea (8% to 18%) and urea ammonium nitrate (10% to 17%), although the relative importance of these varied with crop species.

For winter wheat, 25% of the total N was applied in March, 46% in April and 23% in May. This spread of N application timings is consistent with RB209 recommendations which advise beginning N applications between mid February and mid March until early May. For winter oilseed rape, 11% of the total N was applied in February, 44% in March and 36% in April. These applications are consistent with RB209 recommendations which recommend, but are generally earlier than the results of more recent research recommends (Berry and Spink, 2009). For winter barley, 40% of the total N was applied in March and 47% in April. This is consistent with RB209 recommendations, but later than more recent research recommends. For spring barley, 28% of the total N was applied in March, 51% in April and 16% in May. This appears to be consistent with RB209 recommendations.

Autumn applications were most common for oilseed rape, with negligible amounts for the other crops. Even for oilseed rape autumn applications have become less common over the last 25 years, dropping from over 80% of the area receiving 52 kg N/ha in 1985 to 29% of the area receiving 37 kg N/ha between 2006 to 2008. Winter wheat received the highest average number of nitrogen applications, at 2.66, with 50% of the wheat area receiving 3 applications. The most common number of N applications to winter oilseed rape, winter barley and spring barley was two. The number of N splits is consistent with RB209 recommendations for all crops.

For winter wheat crops receiving three N splits the final split had been applied by the end of March on 4% of fields, by the end of April on 38% of fields and by the end of May on 93% of fields. For oilseed rape crops receiving two splits the final split had been applied by the end of March on 26% of fields and by the end of April on 96% of fields. For winter barley crops receiving two splits the final split had been applied by the end of March on 11% of fields and by the end of April on 86% of fields. For spring barley crops receiving two splits the final split had been applied by the end of March on 9% of fields, by the end of April on 61% of fields and by the end of May on 96% of fields. Full details of current fertiliser practices are described in Annex 3.

Table 2 Average spring N application rates, numbers of N applications and most common timings for applications for the major arable crops in England from 2006-2008.

| | Winter wheat | Winter barley | Spring barley | Winter oilseed rape |
|---|---|---|---|---|
| Overall N application rate (kg N/ha) | 190 | 138 | 105 | 194 |
| Mean number of applications | 2.66 | 1.96 | 1.56 | 2.55 |
| Most common timings for applications (% N applied in month) | Feb (3%)<br>Mar (25%)<br>Apr (46%)<br>May (23%) | Feb (4%)<br>Mar (40%)<br>Apr (47%)<br>May (8%) | Feb (3%)<br>Mar (28%)<br>Apr (51%)<br>May (16%) | Feb (11%)<br>Mar (44%)<br>Apr (36%)<br>May (3%) |
| Percentage of fields receiving all N by the end of March, April or May for wheat receiving 3 N splits and other crops receiving 2 splits. | Mar (4%)<br>Apr (38%)<br>May (93%) | Mar (11%)<br>Apr (86%)<br>May (99%) | Mar (9%)<br>Apr (61%)<br>May (96%) | Mar (26%)<br>Apr (96%)<br>May (100%) |

# Potential to reduce GHG emissions by altering current N timing practice

In this section the GHG savings of relevance to the UK Agriculture GHG inventory are calculated. Additional calculations include the total GHG savings that also take account of N manufacture and any possible land use change effects.

## Winter wheat

It appears that current farm practice is consistent with the N timings recommended by RB209. No systematic N timing trials have been carried out on winter wheat since the trials used to develop the current RB209 guidelines in the 1980s, so it is not possible to conclude whether yields could be increased or N use reduced by adopting different N timings to those recommended by RB209. There is therefore no evidence to suggest that GHG emissions associated with winter wheat can be reduced by this route, although this may change if new research shows that optimum N timings differ from current practice.

## Winter oilseed rape

Currently autumn N is applied to 29% of winter oilseed rape crops at a rate of 37 kg N/ha and while further research is required to test the value of autumn N in different situations, it seems likely that autumn N could be applied to fewer crops. If autumn N was avoided completely and this resulted in a net reduction in N use of 23 kg N/ha, then this would result in a total reduction in N use of 3.56 kt for the UK (based on an average winter oilseed rape area in England of 533,000 ha between 2007 and 2009). This would equate to a reduction in GHG emissions (including N manufacture) of 58 kt CO2e per annum assuming GHG efficiency factors described in the methods section. It is probably more realistic to assume that half of the crops that receive autumn N do not require it because autumn N may be shown to be beneficial in some situations. If this is shown to be the case then total GHG savings amount to 29 kt CO2e.

Delaying N applications to oilseed rape crops with large canopies following winter has been shown to increase yield by up to 0.36 t/ha, or reduce N application rate by approximately 32 kg N/ha while maintaining yield, compared with N timings recommended by RB209. It is estimated that this size of effect will reduce the GHG emissions of cropping by 114 kg CO2e/t (8.8%) relative to RB209 timings. Use of the canopy management timings to cut N application rates whilst maintaining yield would have cut GHG emissions by 522 kgCO2e/ha (12.4%) or 157 kgCO2e/t (12.1%). It should be recognised that these gains will only apply to the proportion of crops which have large canopies which will vary by season. It has been estimated that crops with a green area index (GAI) of at least 1.5 will yield more in response to later N applications (Berry and Spink, 2009). Surveys of oilseed rape canopy size carried out by BASF showed that in 2006 (a year with large canopies following winter) 50% of crops had a GAI of 1.5 or more. In 2009 (a year with small canopies) 18% of crops had a GAI of 1.5 or more. If on average 30% of crops respond positively to delayed N and the average reductions in GHG emissions described above apply then reducing total N use by 5.12 kt and maintaining current productivity would equate to a reduction in total GHG emissions of about 84 kt CO2e per annum.

Alternatively, if fertiliser rates remain unchanged oilseed rape productivity will be increased by 58 kt (a 3.3% increase), assuming an oilseed rape area of 533,000 ha. This could reduce pressure on land use change and reduce indirect GHG emissions. If a specific scenario of increasing productivity caused a reduction in the amount of temperate grass converted to arable is assumed (see methods section for details) then it is estimated that indirect GHG emissions could be reduced by 88 kt CO2e. Alternatively current production could be maintained using 16,800 ha less land area which would save GHGs that would have been associated with growing a crop and in addition could be used to sequester carbon, saving a total of 85 kt CO2e.

## Winter barley

Recent experiments have shown that applying N earlier than recommended by RB209 improves yield by an average of 0.3-0.5 t/ha or can allow the use of 30 kg/ha less N to achieve the same yield as with RB209 timings. It has been estimated that use of the earlier N timings could reduce the GHG emissions by 27 kg CO2e/t (4.4%) relative to RB209 timings. Use of the earlier timings to cut N application rates whilst maintaining yield would cut GHG emissions by 490 kgCO2e/ha (13.2%) or 73 kgCO2e/t (12.7%). Current practice of N timings appear to be consistent with farmers following RB209 guidelines. If the lower range of the yield improvements described above applied to 50% of the winter barley crop (note that N is generally applied early to malting barley) then reducing total N use by 5.1 kt and maintaining productivity would equate to a reduction in GHG emissions of approximately 83 kt CO2e per annum.

Alternatively, if fertiliser rates remain unchanged winter barley productivity will be increased by 51 kt (a 2.4% increase), assuming a winter barley area of 340,000 ha. If a specific scenario of increasing productivity causes a reduction in the amount of temperate grass converted to arable is assumed (see Annex 4 for methods) then it is estimated that indirect GHG emissions could be reduced by 42 kt CO2e. Alternatively current production could be maintained using 7,900 ha less land area which would save GHGs that would have been associated with growing a crop and in addition could be used to sequester carbon, saving 34 kt CO2e.

## Spring barley

Current farm practice appears to be consistent with RB209 guidelines. There is some evidence that greater yields could be achieved if N was applied earlier than RB209 recommends, but this evidence is not consistent enough to conclude with confidence that yield could be increased or N use reduced if N timings were altered from current practice. There is therefore little evidence currently to support reducing GHG emissions of spring barley by altering N timings. However, as with winter wheat there has been no recent systematic N timing study and until this is carried out it is possible that N timings could be further optimised.

## Nitrous oxide emissions

The default emissions factor from IPCC for direct N2O emissions as a consequence of N fertiliser application remaining after N volatilisation losses is 0.0125 kg N2O–N per kg N (IPCC, 1997). [NB this equates to direct emissions of 0.0177 kg N2O per kg N applied]. This value is given an uncertainty range of 0.0025 to 0.0225 kg N2O–N per kg N applied, reflecting the large variation in N2O emissions that can occur, even in the context of average values for national inventory reporting. N2O emission data from 8 experiments carried out in England (Table 1) has shown that N2O emissions for a typically fertilised wheat crop range from 0.0023 to 0.0317 kg N2O–N per kg N applied with an average of 0.0104 kg N2O–N per kg N applied. This large range in N2O emissions was caused by variation in environmental factors, mainly temperature and soil moisture, with direct emissions being highest from the 3rd split timing, applied between the end of April and mid-May. To estimate the effects of altered N timings, it was assumed that the 3rd N split could be moved to a timing more similar to the first two timings, and that in the absence of unseasonably warm and wet conditions, this would give a consequent reduction in direct N2O emissions. Direct emissions from 30 days after this split to the end of the year were raised in proportion to the extended length of this period. The measured emissions factors were applied to N splits of 51, 76 and 63 kg N/ha, using the average N rate applied to wheat of 190 kg N/ha and the proportional N splits calculated from BSFP data. The resulting annualised direct emissions were reduced by 20% by this timing change. This indicates that the IPCC default figure for direct emissions of 0.0177 kg N2O per kg N would reduce to 0.0142 kg N2O per kg N. It must be emphasised that this is a maximum possible reduction based on shifting the 3rd application about 30 days earlier and also assumes that the emission factors are not affected by more frequent early N applications. It is crudely estimated from the BSFP that 62% of wheat crops receive N in May or after (Table 2). It is unlikely that N could be applied earlier to bread wheats because of the need to achieve high protein through later N applications. Since 2006, bread wheats have made up 27% of the total wheat area. Therefore, if the N2O savings described above were applied to 62% of the feed wheat area this could give a reduction of 165 kt CO2e. This assumes there are no adverse effects on crop growth from bringing forward N applications (e.g. increased crop lodging). Potential savings for oilseed rape, winter barley and spring barley are less because only 4%, 14% and 29% of crops receive N in May (Table 2). It is not possible to translate the effects of N timing on N2O emissions from wheat to other crops directly because; 1) N2O measurements have not been carried out for these crops and 2) the 20% reduction in direct N2O emissions estimated for wheat relates to a specific quantity of N applied in May. Therefore the following estimates should be treated with caution. If it is assumed that bringing May N applications forward reduced direct N2O emissions by 20% then the GHG reductions would amount to 4 kt CO2e for oilseed rape, 7 kt CO2e for winter barley and 11 kt CO2e for spring barley.

The potential to reduce N2O emissions may be greater if future work quantifies a soil moisture threshold which has a large effect on N2O emissions and shows that more frequent N splits are beneficial. Nitrification inhibitors may also provide a means of reducing N2O emissions and further work is required assess the benefits against the costs. There is no strong evidence to suggest that N2O emissions may be reduced by applying urea rather than ammonium nitrate. Taking all the full-season EFs for AN and urea from both the NT2603 and NT2605 results together (12 experiments), the overall mean EFs were 2.02% for AN and 1.51% for urea. However, the difference in mean EF for direct emissions from AN and urea was more than cancelled out by taking account of associated indirect emissions (mainly volatilised/redeposited N being converted to N2O), and the overall EF for both direct and indirect pathways was not significantly different. Brentrup and Palliere (2008) estimated that the GHG emissions upon application were 9.33 kg CO2e per kg N for urea and 5.62 kg CO2 per kg of N for ammonium nitrate. When the manufacturing costs were included the GHG costs were 10.91 kg CO2e per kg N for urea and 11.82 kg CO2 per kg of N for ammonium nitrate.

# Estimate the level of imprecision in N fertiliser use and the effect on GHG emissions (Objective 2, linked to Milestone 2).

## Summary

- Conclusions can be drawn with most confidence for winter wheat and winter oilseed rape because these crops had the largest datasets.
- Using RB209 with direct measurements of soil mineral N and crop N resulted in the least error from the true economic optimum N rate, except for spring barley. Using RB209 with the field assessment method (look up tables for soil N supply) often gave a similar error to using the same fixed N rate for each crop.
- The RB209 systems generally predicted similar or smaller N rates compared with the true optimum N rate, which means that improving the N recommendation systems will potentially increase GHG emissions across England by up to 340 kt CO2e for wheat or oilseed rape, but this will also increase productivity by 3-5% and reduce pressure of land use change (LUC).
- Improving N recommendation systems is predicted to increase GHG emissions relevant to the UK Agriculture GHG inventory. However GHG reductions are predicted if indirect effects of LUC are accounted for, e.g. if production is maintained and the cropped area reduced then a large proportion of the increased GHG emissions associated with the increased N use described above would be offset due to the effects of LUC.
- If the same crop area is grown then over-applying N increases GHG emissions because the GHG cost of N outweighs the benefit from higher yield. Under-fertilising by a small amount (20-40 kg N/ha) reduces GHG emissions and has little effect on gross margin. Under-fertilising by more reduces gross margins and under-fertilising by more than 50 kg N/ha increases net GHG emissions for oilseed rape.
- After accounting for a specific LUC scenario it was estimated that achieving the true optimum N on all wheat fields (i.e. raising production) will reduce GHG emissions by 269 kt CO2e compared with using RB209 with look-up tables, but would increase emissions by 75 kt CO2e compared with using RB209 with soil and crop measurements, due to higher N rates. For oilseed rape, the same changes would increase emissions by 64 and 188 kt CO2e, respectively.
- Using RB209 with soil and crop N measurements compared with RB209 and look-up tables is estimated to reduce total GHG emissions by 376 kt CO2e for wheat and 104 kt CO2e for oilseed rape. These effects result from applying less N, and whilst this increases the gap from the true optimum N rate, the reduction in error means that yields are unchanged and profit is greater than with the RB209 look-up tables.

## Introduction

Data from a total of 189 Nitrogen (N) response experiments carried out in England since 2003 on modern varieties of winter wheat, winter oilseed rape, and winter and spring barley were analysed. The aim was to estimate the level of imprecision in N fertiliser use that result from using RB209 recommendations (Anon., 2010) and other N recommendation systems. Each N response experiment was used to calculate the economic optimum N rate (Nopt) and this was taken as the true optimum N rate for the field. Estimating the soil N supply (SNS) is a key input that the RB209 guidelines use to estimate fertiliser requirement. SNS can either be estimated using look-up tables which take account of previous crop soil type and rainfall and is referred to as the field assessment method (FAM), or SNS can be measured directly by measuring the soil mineral N (SMN) and the crop N in autumn or early spring. Both methods of estimating SNS have been used to evaluate RB209 recommendations. The effects of imprecision on yields, margin over N costs and greenhouse gas (GHG) emissions taking account of indirect effects of land use change (LUC) have been estimated. The LUC scenario assumed that any reduction in potential yield was made up by converting temperate grass land to arable which resulted in additional GHG emissions. An alternative scenario of applying the same fixed rate of N to each crop was also tested. The fixed rate was the average rate of N applied to crops over the last 3 seasons, taken from the British Survey of Fertiliser Practice. See Annex 4 for full details of the methodology used.

## Winter wheat

For winter wheat, RB209 gave similar recommendations to the average economic (or true) optimum N rate (Nopt). The range of true Nopts was greater than the range that could be estimated using RB209 (Table 3) which automatically indicates a source of imprecision. There was no relationship between the amount of N recommended using RB209 with FAM and the true Nopts. However the amount of N recommended by RB209 with SMN was significantly related to the true Nopts (R2 = 0.15; Figure 2a). A Friedman's non-parametric ANOVA showed a significant difference (P = 0.014) between the size of errors associated with the three methods (RB209+SMN, RB209+ FAM and fixed rate). Using RB209 with SMN resulted in the lowest average error in N fertiliser requirement of +/-54 kg/ha compared with +/- 59 kg/ha for RB209 with FAM or +/- 61 kg/ha when always using a fixed N rate of 180 kg N/ha (Table 3). These errors are due to a combination of inaccuracy (difference between the Nopt and average recommended N rate) and imprecision (the error when the Nopt and average recommended N rate are the same). These levels of error reduced yield by on average 0.22 to 0.25 t/ha and gross margins over N costs by £15/ha for RB209 with SMN to £21/ha for RB209 with FAM. Under-fertilisation led to significant reductions in yield, whereas over-fertilisation led to only slight yield increases (Figure 2b). Margins over N costs were reduced compared to those at the true Nopt whether crops were under- or over-fertilised (Figure 2c; Table 3). Under-fertilisation led to low yields and so lower margins over N costs, whereas although over-fertilisation led to slightly higher yields, the yield increases did not compensate for the extra N costs, and so margins again decreased.

If the true Nopt could be achieved across the England winter wheat area of 1.77 million ha (average of 2006 to 2008) then at the simplest level there would be an increase in GHG emissions of 337 kt CO2e and 288 kt CO2e compared with using RB209 with SMN or using a fixed N rate of 180 kg N/ha respectively, with little change from using RB209 with FAM. The increases described here are due to the greater N use associated with Nopt. But it should be recognised that the greater N use together with the greater precision associated with achieving the Nopt would also result in a production increase of approximately 420 kt, which equates to approximately 3% of total production in England. If production is maintained by leaving 3% of the wheat area idle (approximately 53,000 ha) then the reduction in GHG emissions associated with less wheat production would be 251 kt CO2e, and it is estimated that an additional 64 kt CO2e could be saved through carbon sequestration on this land. However, the effects of carbon sequestration are more uncertain, could be reversed in the event of a change in land use, and will eventually cease as soil carbon levels reach equilibrium. Alternatively, as well as increasing farmer profits the extra productivity may reduce pressure to convert uncropped land to arable with a consequent reduction in GHG emissions as described below.

When the possible effects of LUC are accounted for then it is estimated that achieving true Nopt would reduce GHG emissions per tonne of grain by 16 kg CO2e compared to the fixed N rate, by 10 kg CO2e compared to RB209 with SMN and by 28 kg CO2e compared to RB209 with FAM (Table 3). Where RB209 N recommendations or the fixed N rate were higher than the true Nopt, GHG emissions per tonne of grain increased significantly. This was because N fertiliser, the biggest contributor to emissions, was increasing with little associated increase in yield. The small increase in yield above the true Nopt meant there was little or no effect of indirect LUC. At N levels below the true Nopt, GHG emissions tended to decrease slightly and level off for winter wheat (Figure 2c). Here, although N was decreasing, the yield foregone by using lower N levels meant that more non-arable land would have to be converted to arable to make up the shortfall in production, resulting in further indirect GHG emissions. [In the case of other crops, below a difference in N applied from Nopt of approximately -50kg N/ha, GHGs increased to levels higher than at Nopt]. If the true Nopt could be achieved across the England winter wheat area then it is estimated that GHG emissions could be reduced by 388 kt CO2e compared to using RB209 with FAM, reduced by 221 kt CO2e compared to using a fixed N rate on all fields of 180 kg N/ha, and reduced by 138 kt CO2e compared with using RB209 with SMN.

Using RB209 with soil and crop N measurements compared with RB209 and FAM is estimated to reduce total GHG emissions by 376 kt CO2e for wheat. These effects result from applying less N, and whilst this increases the gap from the true optimum N rate, the reduction in error means that yields are unchanged and profit is greater than with the RB209 land FAM.

Table 3 Optimum N rate for economic return (Nopt), grain yield at Nopt, N application rates for three recommendation systems (fixed N rate, RB209 with FAM and RB209 with SMN) and, for each recommendation system compared with Nopt, changes in N applied, yield, margin and greenhouse gas (GHG) emissions.

| | Units | Winter wheat | Winter oilseed rape | Winter barley | Spring barley |
|---|---|---|---|---|---|
| Nopt at BER 5:1 or 2.5:1 for OSR | kg/ha | 189 | 204 | 213 | 126 |
| Grain yield at Nopt | t/ha | 9.44 | 4.36 | 8.31 | 5.72 |
| Fixed N rate | kg/ha | 180 | 192 | 144 | 96 |
| N recommended by FAM | kg/ha | 191 | 183 | 172 | 123 |
| N recommended by SMN | kg/ha | 178 | 171 | 190 | 140 |
| N difference at fixed N rate * | kg/ha | 61 | 55 | 72 | 40 |
| N difference at Nrec by FAM * | kg/ha | 59 | 60 | 45 | 37 |
| N difference at Nrec by SMN * | kg/ha | 54 | 40 | 32 | 40 |
| Yield change at fixed N rate | t/ha | -0.25 | -0.11 | -0.84 | -0.28 |
| Yield change at Nrec by FAM | t/ha | -0.22 | -0.15 | -0.41 | -0.10 |
| Yield change at Nrec by SMN | t/ha | -0.23 | -0.14 | -0.22 | -0.08 |
| Margin change at fixed N rate | £/ha | -17.95 | -20.89 | -24.48 | -4.21 |
| Margin change at Nrec by FAM | £/ha | -20.99 | -25.17 | -7.88 | -5.92 |
| Margin change at Nrec by SMN | £/ha | -14.75 | -15.51 | -3.71 | -13.90 |
| GHGs change at fixed N rate | kg CO2 e/t | 16 | 35 | 0 | 6 |
| GHGs change at Nrec by FAM | kg CO2 e/t | 28 | 22 | -13 | 32 |
| GHGs change at Nrec by SMN | kg CO2 e/t | 10 | -39 | -9 | 80 |

BER – Break even ratio is the quantity of grain (kg) required to pay for 1 kg of fertiliser N.

* Means of differences between N applied and Nopt, calculated with all differences as positive values.

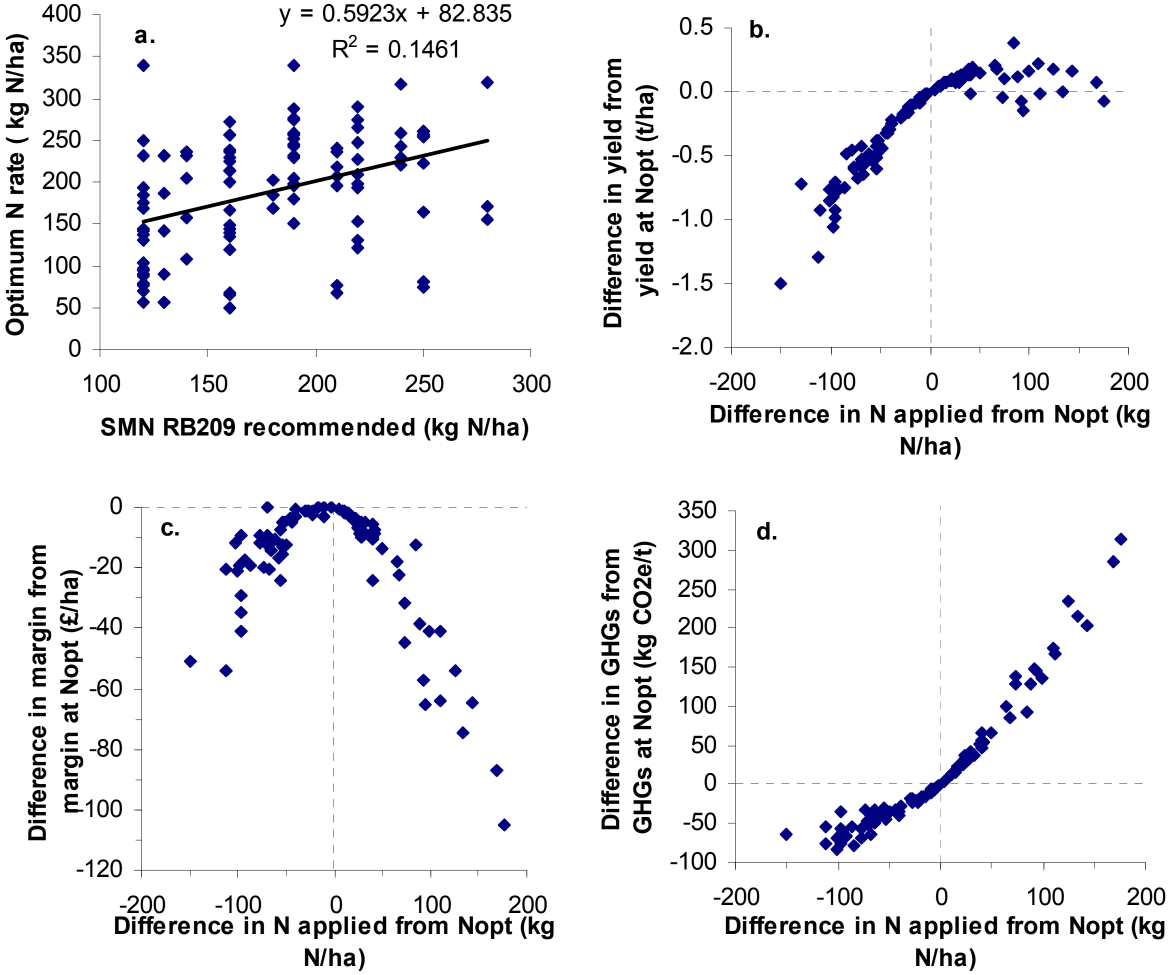

Figure 2. Using N recommendations for winter wheat generated using the RB209 Soil Mineral N measurement method (SMN) compared to calculated economic optimum N rate (Nopt): a. relationship between the actual Nopts and SMN recommendations, and the effects of applying N rates different to Nopt on: b. yield (t/ha at 15% moisture content); c. margin over N costs (£/ha); and d. Greenhouse Gas (GHG) emissions taking account of indirect land use change (LUC).

## Winter oilseed rape

For winter oilseed rape, using a fixed N rate of 192 kg N/ha, RB209 with FAM or RB209 with SMN recommended 12, 21, or 31 kg N/ha less than the true Nopt respectively (Table 3). As with winter wheat the range of true Nopts was greater than the range that could be recommended by RB209. There was no relationship between the RB209 with FAM recommendations for OSR and the true Nopts. However, there was a significant relationship between the recommendations from the RB209 with SMN and the true Nopts (R2 = 0.56), although a Friedman's non-parametric ANOVA did not show a significant difference between the magnitudes of the errors associated with the three methods (RB209+SMN, RB209+ FAM and fixed rate). It seems likely that the accuracy of the RB209 with SMN measurement was due to a combination of measuring both SMN and crop N in early spring. Crop N can vary significantly in oilseed rape and is therefore an important factor to consider when estimating the SNS. Using RB209 with SMN resulted in the lowest average error in N fertiliser requirement of +/-40 kg/ha compared with +/- 60 kg/ha for RB209 with FAM or +/- 55 kg/ha when always using a fixed N rate of 192 kg N/ha (Table 3). These levels of error reduced yield by on average 0.11 to 0.15 t/ha and gross margins over N costs by £16/ha for RB209 with SMN to £25/ha for RB209 with FAM. The data included 48 response curves over 14 site seasons, encompassing several soil types. This is a reasonably large and representative dataset, but it should be recognised that more sites are probably required to produce firm conclusions.

If the true Nopt could be achieved across the England winter oilseed rape area of 533,000 ha (average of 2006 to 2008) then at the simplest level there would be an increase in GHG emissions of 110, 195 or 296 kt CO2e compared with using either a fixed N rate of 192 kg/ha or RB209 with FAM or RB209 with SMN respectively. The increases described here are due to the greater N use associated with Nopt. But it should be recognised that the greater N use together with the greater precision associated with achieving the N opt would also result in a production increase of approximately 60,000 to 81,000 t, which equates to approximately 3-5% of total production in England. If production is maintained by leaving 4% of the oilseed rape area idle then the reductions in GHG emissions associated with growing less oilseed rape and carbon sequestration are estimated to be 90 and 26 kt CO2e, respectively. Alternatively, as well as increasing farmer profits this extra productivity may reduce pressure to convert uncropped land to arable with a consequent reduction in GHG emissions, as described below.

When the possible effects of LUC are accounted for then it is estimated that achieving Nopt would reduce GHG emissions per tonne of seed by 35 kg CO2e compared to the fixed N rate, reduce emissions by 22 kg CO2e compared to RB209 with FAM and increase emissions by 39 kg CO2e compared to RB209 with SMN (Table 3). The increase in GHG emissions associated with using RB209 with SMN was because this system recommended significantly less N (33 kg N/ha) than the true Nopt and the reduction in GHGs associated with the lower N use outweighed the increase in GHGs associated with the greater LUC resulting from the lower yield of 0.14 t/ha. If the true Nopt could be achieved across the England winter oilseed rape area then it is estimated that GHG emissions would be reduced by 62 kt CO2e compared with using a fixed N rate of 192 kg N/ha, reduced by 39 kt CO2e compared with using RB209 with FAM or increased by 69 kt CO2e compared with using RB209 with SMN, although the gross margins would also increase by £21/ha, £25/ha or £16/ha, respectively.

Using RB209 with soil and crop N measurements compared with RB209 and FAM is estimated to reduce total GHG emissions by 104 kt CO2e for wheat. These effects result from applying less N, and whilst this increases the gap from the true optimum N rate, the reduction in error means that yields are unchanged and profit is greater than with the RB209 land FAM.

## Winter barley

For winter barley, significantly fewer N response experiments were available to study than wheat or oilseed rape experiments (10 compared with 112 and 48), therefore the summary described below should be treated with less confidence. Using a fixed N rate of 144 kg N/ha, RB209 with FAM or RB209 with SMN recommended 69, 41, 23 kg N/ha less than the true Nopt respectively. It is likely that the N response experiments, carried out between 2007 and 2009, had higher N opts than recommended because the yields were 2 to 3 t/ha greater than the yields of the trials used to develop the RB209 guidelines in the 1980s. As with winter wheat and oilseed rape the range of true Nopts was greater than the range that could be recommended by RB209. In fact the highest N rate recommended by the latest version of RB209 of 210 kg N/ha (Anon., 2010) is lower than the true Nopt in half of the experiments studied here. Using RB209 with SMN resulted in lowest average error in N fertiliser requirement of +/-32 kg/ha compared with +/- 45 kg/ha for RB209 with FAM or +/- 75 kg/ha when always using a fixed N rate of 144 kg N/ha. These levels of error reduced yield by on average 0.22, 0.41, 0.84 t/ha for RB209 with SMN, RB209 with FAM and the fixed N rate respectively. Gross margins over N costs were reduced by £4/ha for RB209 with SMN to £8/ha for RB209 with FAM and £24/ha for the fixed N rate.

If the true Nopt could be achieved across the England winter barley area of 340,000 ha (average of 2006 to 2008) then at the simplest level there would be an increase in GHG emissions of 411, 242 or 136 kt CO2e compared with using either a fixed N rate of 144 kg/ha or RB209 with FAM or RB209 with SMN respectively. The increases described here are due to the greater N use associated with Nopt. But it should be recognised that the greater N use together with the greater precision associated with achieving the N opt would also result in a production increase of approximately 76 to 286 kt, which amounts to approximately 3 to 14% of total production in England. If production is maintained by leaving 4% of the winter barley area idle then the reductions in GHG emissions associated with less barley production and carbon sequestration are estimated to be 50 and 16 kt CO2e, respectively. Alternatively, as well as increasing farmer profits this extra productivity is likely to reduce pressure to convert uncropped land to arable with a consequent reduction in GHG emissions, as described below.

When the possible effects of LUC are accounted for then it is estimated that achieving Nopt would not change the GHG emissions per tonne of grain compared to the fixed N rate but would increase emissions by 13 kg CO2e/t or 9 kgCO2e/t respectively compared with using RB209 with FAM or with SMN, because the GHGs resulting from the higher Nopt outweigh the decrease in GHGs from LUC. If the true Nopt could be achieved across the England winter barley area then it is estimated that GHG emissions could be increased by 28 kt CO2e or 19 kt CO2e respectively compared with using RB209 with FAM or with SMN, although gross margins would be improved by up to £24/ha (Table 3).

## Spring barley

For spring barley, significantly fewer N response experiments were available to study than wheat or oilseed rape experiments (12 compared with 112 and 48), therefore the summary described below should be treated with less confidence. Using a fixed N rate of 96 kg N/ha, RB209 with FAM or RB209 with SMN recommended 30 less, 3 less or 14 more kg N/ha less than the true Nopt respectively. As with the other crops the range of true Nopts was greater than the range that could be recommended by RB209. The average error in N fertiliser requirement was similar for either the fixed N rate of 96 kg N/ha, RB209 with FAM or RB209 with SMN at between +/- 37 and 40 kg N/ha. These levels of error reduced yield by on average 0.08, 0.10, 0.28 t/ha for RB209 with SMN, RB209 with

FAM and the fixed N rate respectively. Gross margins over N costs were reduced by £4/ha for RB209 with SMN, £6/ha for RB209 with FAM and £14/ha for the fixed N rate.

If the true Nopt could be achieved across the England spring barley area of approximately 333,000 ha (average of 2006 to 2008) then at the simplest level there would be an increase in GHG emissions of 175 kt CO2e compared with using a fixed N rate of 96 kg/ha, an increase of 20 kt CO2e compared with using RB209 with FAM and a decrease of 71 kt CO2e compared to RB209 with SMN. The higher GHG emissions associated with using RB209 with SMN resulted from the higher N rate recommended by this system. The greater N use together with the greater precision associated with achieving the N opt compared with using a fixed N rate would also result in a production increase of approximately 94 kt, which amounts to approximately 5% of total production. If production is maintained by leaving 5% of the spring barley area idle then the reductions in GHG emissions associated with less spring barley production and carbon sequestration are estimated to be 51 and 20 kt CO2e, respectively. Alternatively, this is likely to reduce pressure to convert uncropped land to arable with a consequent reduction in GHG emissions, as described below.

When the possible effects of LUC are accounted for then it is estimated that achieving Nopt would reduce GHG emissions per tonne of grain by 6 kg CO2e compared with the fixed N rate, reduce by 32 kg CO2e compared to RB209 with FAM and reduce by 80 kg CO2e compared to RB209 with SMN. If the true Nopt could be achieved across the England spring barley area then it is estimated that GHG emissions could be reduced by 11 kt CO2e compared with using a fixed rate, or 57 kt CO2e compared with using RB209 with FAM, or by 143 kt CO2e compared with using RB209 with SMN.

# Evaluate the scope for altering N timing to the optimum for minimising GHGs and identify barriers for change and assess whether this influenced by factors such as region (Objective 3, linked to Milestone 3).

## Summary

- The general period of N application was mainly determined by growth stage but the actual date of application was overwhelmingly determined by weather and to a lesser extent soil conditions (which were less critical in the South).
- 71% of surveyed farmers were likely (31% very likely) to apply nitrogen in one additional split, but focus groups highlighted significant barriers to this change, suggesting the likelihood may not be so high.
- Reasons for not applying more splits were lack of time (33%), cost (25%), lack of belief it would reduce pollution (25%) and insufficient days when the weather was right (22%).
- 78% of the surveyed farmers would be fairly or very likely to avoid N fertiliser use during 5 days after heavy rainfall, with less in North or on shallow soils over chalk. Some have to wait 5 days before land is trafficable
- 59% of the farmers who were unlikely to avoid the 5 day period stated there was insufficient time to spread on all fields
- Focus groups indicated that farmers would find it difficult to delay N applications after they would normally apply mainly because of a lack of confidence in weather forecasts and the concern over missing a period of suitable weather for spreading.
- There is likely to be sufficient flexibility in timing to reduce GHG emissions by applying earlier to winter barley and delaying N on oilseed rape crops with large canopies.
- There appears to be moderate scope for increasing split number by one, but farmers would need strong evidence, including benefits to yields as well as the environment.
- Realistic decreases in GHG emissions associated with altering N timing to wheat, oilseed rape and barley have been estimated at 273 kt CO2e (including the manufacture of fertilisers).

## Introduction

This objective aims to evaluate the scope for farmers to change N timings towards the optimum timings identified in Objective 1. This was achieved through a telephone interview with 300 farmers (Annex 5) and four focus groups with farmers and agronomists (Annex 6). Only statistically significant differences at the 95% level of probability are described for region, farm type, farm size or soil type from the telephone survey.

# Telephone survey & Focus groups

## Application practice

79% of the telephone survey sample applied N fertiliser to winter feed wheat, 56% to winter oilseed rape, 49% to winter barley, 38% to spring barley and 34% to winter bread wheat. It can be assumed that these proportions equate to the proportion of farms growing those crops. Winter barley was most common on mixed farms (64%), whilst winter bread wheat (45%) and oilseed rape (70%) were most common on cereal farms. Nitrogen fertiliser was most often applied in solid form on 88% of farms; results from the British Survey of Fertiliser Practice show that ammonium nitrate (AN) is the main form of solid N fertiliser used on British farms. Liquid fertiliser was more often the main form used on cereal farms (18%) than elsewhere. Liquid N is applied at a range of growth stages with early applications often in the form of urea ammonium nitrate (UAN) which are taken up by the plant via the soil and late applications (post ear emergence for wheat) usually in the form of urea which is taken up through the foliage and as a result are often referred to as foliar N applications (see section 5, low N bread making technologies for more information). These are commonly used on bread making wheat to help increase grain protein to achieve bread making specification and some foliar N is applied to oilseed rape post-flowering. The farmer was the main person to apply the nitrogen fertiliser on 88% of the farms, with 11% using a contractor.

Single or twin disc spreaders were predominantly used to spread the fertiliser (78%). 9% used a sprayer, 6% an oscillating spout and 2% a pneumatic spreader. The single or twin disc spreader was most commonly used on large farms, whilst a sprayer was more likely to be used on cereal farms than the other farm types, and an oscillating spout more common on small farms. 91% of the farms had had their fertiliser spreader calibrated either within the last year or about a year ago. Mixed farms were the least likely to do so (66%).

On average N was applied to winter bread wheat in 3.1 splits (range of 1 to 5), to winter feed wheat in 2.6 splits (range of 1 to 4), winter oilseed rape in 2.6 splits (range of 1 to 4), winter barley in 2.0 splits (range of 1 to 4) and spring barley in 1.5 splits (range of 1 to 3). The most common number of splits for winter bread wheat was 3-4, compared to 2-3 for winter feed wheat and winter oilseed rape. Two splits were most often used for winter barley, whilst 1-2 were used for spring barley. These split numbers were similar to those found by BSFP. Cereal farms applied 2.7 splits to winter feed wheat compared with 2.4 splits on mixed farms, and farms in north England applied 2.4 splits to winter feed wheat compared with 2.6 in other regions. Slightly fewer splits in the north may reflect fewer days when the weather and soil conditions are appropriate spreading. This small difference is not necessarily due to rainfall as the west has as much, or more, rain than the north, but may reflect a longer period required for the soil to dry due to lower temperatures in the north.

## Decision making – timing of application

The farmer was the main person who decided when to apply the nitrogen fertiliser, either alone (47%) or jointly with an agronomist (36%). On 14% of farms an agronomist made the decision alone, whilst on 3% the contractor made the decision. The agronomist was more likely to make the decision alone on the large farms (21%).

82% of the sample had an idea when the nitrogen fertiliser would be applied well ahead of the application, the farmers who made a joint decision with an agronomist being the most likely to plan ahead (91%) compared with 74% of the farmers who made the decision alone. Farms in the south (95%) were more likely to plan ahead than in other regions. Crop growth stage appeared to be the main driver for when to apply the fertiliser (crop growth stage 54%, time period 8%, both crop growth stage and time period 37%). Small farms were more likely to consider only time period. The time period was defined by the weather in 53% of cases, by a ‘latest date for application’ in 19% of cases and within a specific week in 14% of cases. In fact, 95% of farms indicated that the weather was a main factor in deciding the actual day of application. 68% mentioned the planned time period/growth stage as a main influence and 66% mentioned the soil conditions, whilst 13% identified workload as a key factor. 75-78% of farms in the East and Midlands took account of soil conditions compared with 51% in the South. No clear differences in the factors affecting application timings were evident by soil type.

## Potential to change farm practice

The telephone survey showed that 71% of farmers were likely (31% very likely) to apply nitrogen in one additional split if it reduced air pollution and reduced the farm’s carbon footprint. The cereal farms were the most likely to be very likely to do so (37%), whilst the mixed farms were the least likely to be very likely (19%). However, the survey data suggests that cereal farms already apply a greater number of splits than mixed farms. Farms growing winter bread wheat were the most likely to add an extra split whilst farms growing spring barley were the least likely. The farmers attending the focus groups were more resistant to the idea of increasing the number of splits and there was a perception that the number of splits used had already increased and that they were now at the optimum number that was practical for their business. The key reasons for not being likely to increase the number of splits were lack of time (33%), cost (25%), lack of belief it would reduce air pollution (25%) and insufficient days when the weather would be appropriate (22%). The focus groups largely concurred with the telephone survey regarding barriers and emphasised that additional splits could mean applying the fertiliser every 2 or 3 weeks, which may not be practical. The smaller and mixed farms particularly had issues over lack of time. The concern over cost could be overcome if the cost of the application was less than the increase in yield. The conclusion from the focus groups was that if sound scientific evidence showed that adding another split was beneficial to yield it is possible that some farms could adapt, at least in favourable weather conditions.

78% of the telephone survey sample said would be likely to follow advice not to apply N fertiliser during 5 days after heavy rainfall in order to reduce air pollution (33% would be very likely to do so). Only 67% of farms in the North would be fairly or very likely to avoid this period compared with 77% to 87% for other regions. 56% of farms with shallow soil over chalk would be fairly or very likely to avoid this period compared with 76% to 84% for other soil types. Shallow soils are likely to be trafficable soonest after rainfall, therefore the respondents to this question may have viewed a 5 day period after heavy rain as unnecessary before the soil dried sufficiently to travel. 59% of the farmers who stated that they were unlikely to avoid the 5 day period because of insufficient time to spread on all fields, 15% stated that the soil would still be too wet to travel and 13% stated that it would depend on the weather. Results from the focus groups indicated that a proportion of farms would need to wait for 5 days after heavy rain anyway before the land was trafficable. The focus groups therefore investigated the potential to delay applications for at least a day after they would normally apply in order to gauge the degree of flexibility over timing. A major barrier for delaying N applications was lack of confidence in weather forecasts, and as a result farmers felt they could not afford to miss a suitable weather window. Encouraging farmers to apply in more splits would seemingly increase the problem of finding suitable weather windows and reduce the chance farmers could wait for longer before application. In order to encourage any change in practice it is likely that farmers would again need sound scientific evidence that nitrogen uptake would improve and GHGs decrease. They would also need clear guidance on what a suitable soil moisture level would be which itself caused concern that assessing this would entail additional work for farmers.

Most farmers in the focus groups had very little knowledge of the nitrous oxide emissions associated with nitrogen fertiliser, and few understood its potency compared to carbon dioxide or methane. GHGs were not currently a deciding factor when making decisions regarding nitrogen fertiliser application, primarily due to lack of information and knowledge about the nature and source of the emissions, but also as maximising yields and profit were the farmers' main priority. It was apparent that any potential change in practice needed to have at least a neutral impact on the farm business but most likely provide a benefit to the farm business, with sound scientific evidence to prove the need for change. Many of the farmers considered that their current farm practices aimed at maximising yields and minimising costs were consistent with reducing GHG emissions, e.g. applying the fertiliser in several splits, avoiding application on to wet soil, applying when the crop is growing and not applying more than the crops can take up. Farmers were aware of loss of nitrogen from leaching and run off and took action to avoid this, motivated by the need to reduce loss to maximise yields and profit and comply with NVZ regulations.

## Scope for optimising N timings

It was concluded in objective 1 that yields could be increased and GHG savings made by delaying N to oilseed rape crops with a large canopy and applying N earlier to winter barley. The results of the telephone survey and focus groups indicate that most farmers do have some flexibility in when they apply N fertiliser which suggests that these changes are possible. Appropriate weather and soil conditions for spreading are likely to be the main limiting factors. Scope for delaying applications will be constrained by confidence in weather forecasts. Unsuitable weather and soil conditions for applying N are likely to prevent the full potential savings from applying N earlier to winter barley from being realised. If it is estimated that 75% of the potential savings estimated for winter barley could be achieved then direct GHG reductions resulting from applying less N and maintaining yield would amount to 62 kt CO2e. If N rates remained the same and yields increased then savings associated with LUC would be 26-32 kt CO2e. It is unlikely that the potential reduction in GHGs associated with delaying N to oilseed rape could be achieved due mainly to uncertainty in weather forecasts. If it is estimated that 50% of the potential could be achieved then direct GHG reductions resulting from applying less N and maintaining yield would amount to 42 kt CO2e. If N rates remained the same and yields increased then savings associated with LUC would be 42-44 kt CO2e.

It is also possible that N2O emissions can be reduced primarily by applying in cooler conditions, by applying when the soil is dry and possibly by applying in more frequent splits. Section 1 estimated the potential reduction from shifting any May applications at least 30 days earlier when the soil is cooler. Unsuitable weather and soil conditions for applying N are likely to prevent the full potential savings from applying N earlier from being realised. If it is estimated that 75% of the potential savings estimated could be achieved then direct GHG reductions would amount to 124 kt for winter wheat, 3 kt for oilseed rape, 5 kt for winter barley and 8 kt for spring barley. The phone survey and focus groups indicated that farmers have some flexibility to delay applying N until soils become dryer but that in practice this will be limited by lack of confidence in weather forecasts. The majority of farmers indicated that they could add an additional split suggesting that this could be a useful strategy if further research demonstrates that an additional split will reduce N2O emissions. However, farmers would also require evidence of increased yields before making these changes, particularly since the cost of an additional split has been estimated at £13/ha.

# Evaluate the scope for minimising imprecision of fertiliser use and identify barriers for change (Objective 4, linked to Milestone 4).

## Summary

- It is estimated that 72% of farms use some sort of fertiliser prediction tool and 62% use RB209/PLANET.
- It is likely that a substantial proportion use RB209 and experience together and 37% of farmers who did not use agronomists relied solely on experience.
- Focus groups confirmed that for many, RB209 is only used as a rough guide and to demonstrate compliance with regulations. Many farmers expressed a lack of confidence in the accuracy of RB209 guidelines.
- 70 to 80% of farms accounted for soil N, of which it is estimated that 50 to 60% measured it on some fields. Reasons for not measuring were lack of confidence in how to do it, and in the results, together with expense. 88% of agronomists accounted for soil N.
- 92% of farmers accounted for manure N and 82% accounted for N in oilseed rape crop, although again this was sometimes by visual estimation rather than by sampling and measuring.
- Using RB209 with SMN rather than RB209 with look-up tables gives the potential to reduce GHG emissions. However, uptake is likely to be low due scepticism of soil N tests. Realistic savings from measuring soil N and crop N more frequently are estimated to be 75 kt CO2e for wheat and 10 kt CO2e for oilseed rape.

## Introduction

Objective 2 demonstrated that in general, reducing the level of error associated with estimating the true economic N fertiliser requirement will reduce GHG emissions and maximise gross margin. This section investigates how farmers calculate the N fertiliser requirement of their crops and assesses the scope for using fertiliser prediction systems that reduce error.

## Telephone survey & Focus groups

### Decision making

Both the agronomist and farmer played a key role in deciding how much N fertiliser to apply (agronomist decided alone 21%, farmer alone 28%, joint farmer and agronomist 47%). In the North of England 40% of farmers decided alone compared with 21 to 27% elsewhere. The focus groups indicated that the decisions were often made jointly between the agronomist and farmer, as the farmer felt he knew the needs of his land much better than the agronomist. The mixed farms appeared less likely to use an agronomist for fertiliser decisions, even though they used one for advice on pesticides etc., the reasons being that they were concerned about additional costs, did not feel an agronomist could add to their knowledge and a feeling that perhaps an agronomist would not consider that a small farm or mixed farm was a viable proposition for them.

In total 63% of the farmers who jointly or solely made the decision as to how much N fertiliser to apply used a specific tool or system, the majority making use of RB209 or PLANET (55%) with 8% using other tools. 62% responded that they relied on experience, so there must be a substantial proportion of farmers who use a combination of experience and prediction tools. 37% relied solely on experience or used the same amount as in a previous year. Use of RB209/PLANET was lowest on mixed farms: 35% compared with 59% to 65% on cereal and general cropping farms. In the North 39% used RB209 and 70% relied on experience compared with the east where 76% used RB209 and 57% relied on experience. The farmers responded that 80% of agronomists were known to use RB209 (69%) or another system (11%).

The Farm Practice Survey (FPS) 2007, using a larger sample size than the survey in this study, estimated that 36% of farmers use RB209 or PLANET and that 63% seek professional advice which may indicate that RB209 is used to recommend N on more than 36% of farms. Fewer mixed (24%) and small farms (30%) used RB209/PLANET compared with cereal (58%) and large farms (51%). 40% used own knowledge (e.g. crop appearance) and 64% farm experience (e.g. normal practice), so it is clear from this survey that a combination of recommendation tools and experience were used.

The focus groups showed that although many of the farmers and agronomists used RB209, there was evidence that this was sometimes simply to comply with regulations, rather than because it offered a benefit. RB209 received a number of criticisms in that it underestimated the N requirement of modern crops, the data was inaccurate and not sensitive to different soil types. As a result many farmers used RB209 as a guide but still heavily relied on their own knowledge of the land and previous cropping.

66% of farmers always took the soil N into account when deciding how much N to apply, whilst 14% did so most of the time, 7% some of the time, 3% rarely and 10% never. Mixed farms were most likely not to take the soil nitrogen into account (20%). The soil nitrogen was equally likely to be measured (42%) or estimated from look up tables (41%). 16% did neither, suggesting they used their own experience or judgement. The small farms were the most likely to use their own experience or judgement (23%) compared with 7% of large farms. The main reasons for not measuring the soil nitrogen were a lack of confidence that it would improve the nitrogen prediction (39%), expense (31%) and insufficient time (14%). 55% of general crop farmers who did not measure soil N cited lack of confidence as the main reason compared with 19% of mixed farmers and 37% of cereal farmers. These telephone survey results were supported by the focus groups which revealed uncertainty about what methods were best for measuring soil N, how to store and transport it and a lack of confidence in the results. The farmers explained that sound evidence is required about the benefits of measuring soil N before they will use it more regularly.

Agronomists were more likely than farmers to take the soil N into account: 88% always and 6% most of the time. The agronomist was also more likely than the farmer to actually measure the soil nitrogen (69%) than use look up tables (21%). A small proportion of agronomists (3%), were not thought to take soil nitrogen into account or estimate or measure its content. The two major soil analysis labs were asked how many soil samples are processed for mineral N per year. NRM labs process approximately 5,100 sample and Hill Court Farm processed approximately 5,500 samples per year. If it is assumed that the vast majority of samples are from arable fields, an average field size of 10 ha and an arable area in England of approximately 3.8 million ha then this indicates that 2-3% of arable fields are tested for mineral N. This maybe a slight over-estimate since some fields with have samples from more than one depth, but this may be counter-balanced by samples analysed by other labs. It is likely that this estimate of the number of fields on which soil N is measured is significantly less than estimated from the farmer survey because farmers who say they measured soil N will only have measured a proportion of fields and may not have measured soil N every year.

The proportion of farms that applied manure who always took manure nitrogen into account when estimating fertiliser requirements (92%) was higher than the proportion who always took soil nitrogen into account (66%). Where manure N was taken into account, this was most often done through nutrient analysis (48%), with 35% using look up tables. 15% appeared to take it into account based on their own knowledge as they neither undertook an analysis nor used look up tables. The Farm Practice Survey of 2009 using a larger sample size found that 54% of farms using manure assessed/calculated the nutrient content of the manure. This is not the same as whether manure N is accounted for when calculating fertiliser requirements, but may indicate that fewer than 92% of farms take account of manure N. The focus groups revealed that poultry manure was most likely to be tested due to the high nitrogen content with less attention paid to cattle manure as this contains less N. Uncertainty about how to measure manure N and lack of confidence in results were expressed.

84% of those who grew oilseed rape always took the crop nitrogen into account when deciding how much nitrogen to apply, whilst a further 4% did so most of the time. These figures were even higher on farms where an agronomist decided how much nitrogen to apply (always: 95%). 7%, however, never considered the crop nitrogen. A lack of time was the main reason for not always taking the crop nitrogen into account, followed by lack of confidence (26%) and cost (22%). Although the sample size is small there was an indication that the mixed farms were the least likely to take the crop nitrogen into account (68%) compared 84 to 90% for other cropping types. The focus groups revealed that many but not all farmers appeared to be taking the crop nitrogen into account and showed that the methods of assessing the nitrogen varied from measuring it by cutting and weighing a metre squared of crop, using satellite technology or sending a picture of the canopy to the BASF website in order to obtain a green area index. Other farmers observed plant growth or used past experience.

# Scope for minimising imprecision

Objective 2 estimated the levels of error associated with always using a fixed N rate, RB209 with FAM and RB209 with SNS, compared with the true Nopt. This showed that the majority of N fertiliser systems predicted a similar or smaller N rate than the true N opt which indicates that improving the prediction of N fertiliser requirement will often increase direct GHG emissions. However, a large proportion of these increases would be countered if the LUC effects of greater yield were taken into account. In the short term there is little prospect of a new system becoming available for predicting N requirement more accurately. Therefore the chance of realising these greater N opts is low. For wheat and oilseed rape it was shown that using RB209 with SNS measurements reduced direct GHG emissions by 376 and 104 kt CO2e respectively compared with RB209 with FAM, due to predicting a lower N requirement. Even though this increased the yield gap between the true Nopt and the predicted N requirement, the lower error resulted in a similar yield and greater profit, compared with RB209 with FAM. Therefore, in the short term there may be scope to maintain yield, increase profit and reduce GHGs by measuring soil N and crop N more frequently.

Based on the balance of farmers and agronomists making the decision about how much to apply, together with the proportion of each group that uses RB209/PLANET or other tools, it is estimated that 72% of farms use some sort of fertiliser prediction tool either directly by the farmers themselves or indirectly through their agronomists (62% use RB209/PLANET). 37% of farmers relied solely on experience or used the same amount as in a previous year. On the same basis as described above, it was also estimated that 70% to 78% of farms accounted for soil N, of which 50% to 60% measured it. Therefore the proportion of farms that measure soil N may range from 35% to as much as 47%. This percentage seems high compared with the 2-3% of fields estimated from the lab analysis numbers, but focus groups confirmed that each farm usually only measures a proportion of the fields. The Focus groups revealed a lot of scepticism about the reliability and value for money of soil N tests. Table 3 shows that the increase in gross margin resulting from soil testing may be £6/ha for wheat and £10/ha for oilseed rape. This means that the cost benefits of measuring soil N on all fields will be marginal at current prices, which will limit the number of farmers willing to use this technology (the cost benefits are likely to be more favourable if farmers concentrated soil measurements on the fields for which the SNS was uncertain, e.g. recently ploughed grassland). Furthermore, 82% of farms already estimate the amount of N in the oilseed rape canopies which is likely to be responsible for much of the variation in SNS in this crop. It is therefore estimated that the realistic improvement may be 20% of the potential for wheat and 10% of the potential for oilseed rape resulting in a reduction in GHGs of 75 kt CO2e for wheat and 10 kt CO2e for oilseed rape. There were insufficient datasets to carry out similar exercises for barley.

It is clear that current fertiliser recommendation systems must be improved to help farmers get closer to the true economic optimum N rate. However, it is recognised that this will require long-term effort because elements which determine fertiliser N requirement are difficult to predict, particularly mineralisation and crops growth which are strongly influenced by weather. Work to improve fertiliser recommendations have been ongoing for at least 50 years and it is clear that moderate or long time scales may be required to achieve significant progress. Ongoing research by HGCA project 3425 aims to improve understanding about how to predict SNS. It is also clear that retrospective monitoring of how accurate the estimate of N requirement has been should have a much greater role in determining N rates for following years. It has been shown that for feed wheats a grain protein of 11.5% indicates that the crop has been fertilised at close to the economic optimum (Sylvester-Bradley et al., 2009). Grain with more protein has been over-fertilised and grain with less protein under-fertilised. Currently it is recommended that this system is employed across a farm or group of fields. Further work should assess whether it can be developed to work for individual fields and to account the seasonal differences, as well as developing similar systems for other species.

# Assess the potential for minimising fertiliser N requirement through the development of N efficient varieties and low N bread technology (Objective 5, linked to Milestone 5).

## Summary

- It is estimated that in the long term the N requirement of wheat and oilseed rape could be reduced by 40% (2198 kt CO2e) and 26% (439 kt CO2e) respectively, of which half could be achieved by 2020. The use of GM technology would hasten and increase these potential gains, particularly for oilseed rape.
- Methods for quantifying the difference in N requirement between varieties must be developed together with tools that plant breeders can use to select for low N requirement.
- Triticale is a potential alternative to non-first wheats as it requires less N and produces higher yields. There are possible savings of up to 440 kt CO2e.
- Developing technology to produce bread from low N grain would achieve reductions in GHG emissions of up to 242 kt CO2e.

## Potential for minimising fertiliser N requirement through breeding N efficient varieties and low N bread technology

### N efficient varieties

Nitrogen use efficiency (NUE) (kg of yield per kg of available N) is the product of two components: nitrogen uptake efficiency (NUpE), the proportion of available N which is taken up by the crop, and nitrogen utilisation efficiency (NUtE), the grain yield (kg/ha at 100% dry matter) achieved per unit of N taken up by the crop (kg N/ha). From the perspective of minimising GHG emissions associated with crop production it is important that varieties with a high NUE also have a high yield for them to be commercially viable. As a result of this it is important to measure NUE at the economic N rate, but very few studies have done this.

Studies have estimated the amount by which N requirement may be reduced by through breeding and are described in Annex 7. The Green Grain LINK project (LK0959) (Sylvester-Bradley et al., 2010) formulated a model to explain NUE in terms of N capture, N distribution between stem, leaf and ear, and N redistribution to grain (i) as is normally observed for high-yielding wheat crops in the UK, (ii) as was proposed for the GREEN grain ideotype at the outset of the project, and (iii) according to genetic variation in key traits as observed through the project. From this analysis it appears possible to increase N capture by 10%, reduce canopy N by ~40 kg/ha and grain N by 30-40 kg/ha, with a net effect of reducing requirements for applied N by 80 kg/ha, or 40%. This should have equivalent large effects on growing costs, on direct N emissions of nitrate, ammonia and nitrous oxide, and thus on GHG emissions. Advantages are also expected from the increased grain starch and reduced gliadin in the grain when it is used for feed, for seed and for distilling, but these are relatively small compared to effects on growing costs. Two other studies have estimated that the NUE of UK wheat could be improved by up to 20%. The crop which stands out for having a low NUE is oilseed rape. Ongoing 'Green Oil' LINK project (LK0979), has estimated the potential for improving the NUE of oilseed rape, using genetic variation found in modern varieties. This project estimates that as a result of reducing the N concentration of stems and pod walls and increasing N capture by increasing root length density at depth, the typical fertiliser application rate could be decreased from 191 to 142 kg N/ha (26% reduction) without reducing yield (Berry et al., 2008b). Greater reductions may be achieved using GM technology, e.g. promoting activity of the enzyme alanine aminotransferase enhances N assimilation in plants and has been shown to reduce the fertiliser N requirement of oilseed rape by 50% (Good et al., 2007). Potential greater and faster gains could be achieved using GM technology which by increasing N uptake efficiency would be complementary to the conventional breeding approaches proposed by LK0959 and LK0979 projects for wheat and oilseed rape respectively which predicted modest improvements in N uptake. This GM approach would also help reduce the N requirement of bread wheats for which the GREEN grain ideotype is not compatible (assuming high grain N is required). It seems reasonable to estimate that in the long term the potential for reducing the fertiliser N requirement of wheat and oilseed rape could be 40% and 26% respectively using conventional breeding techniques. This would equate to GHG savings of 2198 kt CO2e for wheat and 439 kt CO2e for oilseed rape. Progress by 2020 is estimated to be half of these amounts, and the saving of relevance to the UK Agriculture GHG inventory would be 629 kt CO2e for wheat and 126 kg CO2e for oilseed rape. If GM technology is also used then the long-term potential reduction in N requirement could be as much as 50% for both species, with possibly half of this achievable by 2020.

It has been shown for both wheat and barley that modern varieties have higher NUE than historic varieties. However, yields under low N conditions have improved by only a small amount, relative to yields under high N conditions, probably because most breeding programmes have taken place at moderate to high N levels. It should be noted that the NUE of spring barley has increased more than in wheat in the last 30 years of breeding, which may be partly because spring barley breeding trials are generally conducted at sub-optimal N levels for yield in order to achieve low grain N for malting. This resulted in spring barley yield increases without an increase in fertiliser requirement (Sylvester-Bradley et al., 2008). Very little is known about the potential to reduce the N requirement of winter barley and further work is required to reduce its N requirement. Studies have found that the relative importance of the two components of NUE (NUpE and NUtE) varies with N supply, so selection for NUE at one extreme of N supply would be likely to limit the type of traits which are being selected for. Researchers at CIMMYT have trialled a range of breeding strategies and found the most effective to be alternating high and low N regimes; a system which has the advantage of not increasing the scale of breeding trials, unlike the use of parallel trials at different N rates. It is also likely that different breeding and variety testing approaches will be required to reduce the N requirement of feed wheat varieties compared with bread wheat varieties due to the different requirements for grain protein (also see section below on prospects for making bread with low N wheat).

Although NUE can be assessed simply by measurement of yield at known available N levels, the components of NUE and associated traits are more challenging to assess. Distinguishing between NUpE and NUtE requires measurement of whole plant N content, which is a relatively time-consuming process, and the key traits for NUpE include aspects of root morphology, which are also difficult to assess. One of the most efficient genetic tools used in breeding is marker-assisted selection. However, relatively few genetic markers have been established for traits associated with high NUE, many of which are likely to be controlled by multiple genes. A review of candidate traits for reducing N requirement and progress which has been made with improving them is described in Annex 7.

Breeding for low N requirement may also benefit from crosses involving more exotic varieties, from regions where N stress is more common than in the UK. The use of alternative species should also be considered, such as triticale as an alternative to feed wheat. National statistics show that the NUE of triticale in the UK is typically 24% higher than that of feed wheat, and in a recent ADAS trial following a wheat crop, triticale out-yielded feed wheat by 1.5 to 2 t/ha at a range of levels of N fertilisation and was found to have an economically optimum N rate of 44 kg N/ha less than wheat. Further work is required to test the relative performance of triticale and wheat over a greater range of sites and seasons. If reduction in N requirement is shown to be consistent over several experiments and triticale replaces all non-first wheats destined for feed (estimated at 24% of the wheat area) then this would reduce GHG emissions by 307 kt CO2e. If the average yield increase is about 0.5 t/ha then the additional reduction in GHG emissions associated with less pressure to convert uncropped land would amount to 133 kt CO2e; alternatively if production was maintained and more land was left idle then the total savings would be approximately 425 kt CO2e, including the effects of C sequestration in the idled land. Triticale has a perception within the agriculture industry of being a low input crop that performs well on poor soils. The focus groups indicated that growers would be willing to grow triticale if evidence was provided of its benefits. Nonetheless, this general perception may limit uptake in the short term and realistic GHG savings are estimated to be 50% of the potential described above with 154 kg CO2e saved from reduced N.

### Low N bread making technology

Increasing yield and NUtE often involves reducing grain N concentration. This a major issue for milling wheats, for which UK bread-makers generally specify a minimum protein concentration of 13%. Already, many crops of milling wheat fail to meet this specification and late N applications aimed at raising protein concentrations over the 13% threshold achieve this aim in only 1 in 4 cases. A current LINK project (LK0927) is investigating how crop samples taken at or soon after ear emergence can be used to predict the likelihood that the grain protein specification will be achieved and whether it is justified to apply liquid foliar N after ear emergence. Looking further ahead, it is estimated that if current rates of yield increase continue, protein concentrations of wheat will be approximately 0.6% lower in 10 years time. This means that either changes to the current baking processes or improvements in grain protein quality will be required to meet this challenge. Over the last three years milling wheats have received 31 kg N/ha more than feed wheats and in 2008 were grown on approximately 27% of the total wheat area. The majority of the extra N that bread wheats receive is in the form of liquid N applied after ear emergence which has been shown to have a lower rate of crop uptake than solid N fertiliser applied at the beginning of stem extension (Dampney et al., 2006). However, liquid N applied after ear emergence has been shown to be more effective at increasing grain protein than solid N fertiliser applied at flag leaf emergence (approximately mid to late stem extension) (Dampney et al., 2006). If low N bread technology can be developed then this would potentially reduce N use by 15 kt, which would equate to 242 kt CO2e.

A workshop was recently convened to discuss these issues. It involved representatives of the wheat breeding, farming, milling and baking industries as well as researchers in relevant fields. The millers emphasised their commitment to using UK-grown wheat, and pointed out that to an extent they are already buying for protein quality, or ‘functionality’ when they choose particular varieties because of the knowledge they have about the performance of that variety. However, protein functionality is still not well understood and is difficult to assess and explain, hence the use of protein concentrations, which is generally a good indicator of quality. Both millers and bakers were willing to investigate the use of lower protein wheat as long as varieties could be bred with good protein functionality at a range of protein concentrations. However, barriers to this included: the breeding and variety testing systems which are not designed to test this; commercial considerations including the long life of a baking plant which means it would be difficult to change current baking processes quickly; the nutritional properties of the bread which would be reduced if protein concentration was lower; and constraints to, for example, ingredients in bread required by the food standards agency. If a concerted effort was made to reduce the requirement for high N bread then it may be possible to achieve half of the potential GHG savings described above by 2020. This would represent total GHG savings of 121 kt CO2e.

## Estimate realistic changes to N use and GHG emissions that could be achieved with timescales (Objective 6, linked to Milestone 6).

Variation in environmental conditions, mainly temperature and soil moisture, causes a wide range of N2O emissions measured to be at least ten-fold in England. It is unlikely that these N2O emissions can be reliably altered to this extent through changes in N fertiliser management alone because N2O emissions are influenced so strongly by uncontrollable environmental factors. There is evidence indicating that altering N timings to avoid warm temperatures and wet soil can help to reduce N2O emissions, and although dedicated experiments are required to accurately quantify the effects of these changes in N management on N2O emissions, some estimates can be made using data from a series of 8 experiments in England which measured N2O emissions from 3 N split timings. If the 3rd N split on feed wheat crops in England could be shifted 30 days earlier, it is estimated that direct N2O emissions from applied N could be reduced by 20%, which would reduce GHG emissions across England by 165 kt CO2e, assuming that conditions at this earlier application are not unseasonably warm. Results from the farmer survey and focus groups indicated that there is scope to alter N timings from current practice (e.g. apply in cooler conditions) and if 75% of the potential savings described above could be achieved then this would give savings of 124 kt CO2e (Table 5), all of which would be relevant for the UK Agriculture GHG inventory. This is equivalent to 0.26% of UK and 0.42% of England agricultural emissions in 2007.

It seems likely that autumn N applications can be avoided on a proportion of oilseed rape crops without reducing yield, but further work is required to show that this can be done in all situations, particularly where large amounts of straw are incorporated at establishment. Realistic savings are estimated to be 29 kt CO2e (Table 5) of which 16 kt CO2e would be relevant for the UK Agriculture GHG inventory (Table 5). There also appears to be scope to reduce GHGs through earlier applications to winter barley and delaying N to oilseed rape crops with large canopies. These changes could be employed now, although more experiments may be required on winter barley to give farmers enough confidence to change practice. The size of the reduction in GHGs depends upon whether the optimal timings lead to farmers maintaining yields by applying less N or whether yields are increased leading either to less pressure to convert uncropped land to arable or to more idle land which can sequester carbon. Further research is required to evaluate which scenario is most likely. If it is assumed that N applications are reduced then realistic GHG savings are estimated to be 104 kt CO2e of which 59 would be relevant to the UK Agriculture GHG inventory (Table 5). It is estimated that the changes in N timing described in this paragraph could reduce the UK GHG inventory by 0.15% and the English GHG inventory by 0.25%.

Improving the precision with which fertiliser N requirement is estimated is likely to increase the amount of N applied because current N fertiliser prediction schemes generally underestimate the economic optimum N requirement. However using more N and improving precision will increase yields which will either reduce pressure for converting uncropped land or increase the amount of idle land. When these scenarios are considered then improving the estimate of N requirement will lead to reductions in GHG emissions when the most commonly used method of estimating fertiliser requirement (RB209 with Field Assessment Method – look-up tables) is compared with the true economic optimum. However, these GHG savings will not count towards the UK Agriculture GHG inventory. For wheat and oilseed rape using a direct measurement of soil N (currently done on about one third of farms and a much smaller proportion of fields) will reduce GHG emissions compared with using RB209 with Field Assessment Method. This is as a result of reducing the amount of N recommended which, although widening the gap from the true economic optimum, results in a similar yield and greater profit because the level of error is reduced. Realistic estimates for the GHG savings that could be achieved if soil and crop N was measured on more fields amount to 85 kt CO2e for wheat and oilseed rape of which 48 kt CO2e would be relevant to the UK Agriculture GHG inventory (Table 5). These savings equate to a reduction in the UK GHG inventory by 0.10% and the English GHG inventory by 0.16%.

It has been estimated that breeding new crop varieties with a lower N requirement could produce very large reductions in N requirement and GHG emissions (Table 4). This would be achieved by increasing the proportion of N that the crop retrieves from the soil and by reducing the requirement that the crop requires to intercept light and carry out photosynthesis. A major barrier towards developing N efficient varieties is identifying which traits plant breeders should select. Moderate varietal differences in N requirement have already been detected, so if methods of quantifying differences in N requirement between varieties can be developed then reductions in GHGs could occur relatively quickly. Realistic savings for wheat and oilseed rape are estimated at 1319 kt CO2e, of which 755 kt CO2e would be relevant to the UK Agriculture GHG inventory (Table 5). These savings equate to a reduction in the UK GHG inventory by 1.5% and the English GHG inventory by 2.6%. Larger and faster reductions in N requirement could be made by employing GM technology, equating to 2.1% of UK emissions and 3.5% of English emissions.

Replacing non-first wheats (wheat crops following wheat crops) with triticale offers a potentially quick route for saving GHGs because triticale has been shown to require less N fertiliser and achieve greater yields particularly in situations where the root fungus Take-all has infected non-first wheats. Realistic savings have been estimated at 307 kt CO2e, of which 88 kt CO2e would be relevant to the UK Agriculture GHG inventory (Table 5). These savings equate to a reduction in the UK GHG inventory by 0.18% and the English GHG inventory by 0.30%.

It is estimated that the additional N applied to bread making wheats (compared with feed wheats) to help them achieve grain protein specification amounts to an additional 242 kt CO2e. The relevant industries are willing to investigate the possibility of making bread from lower N grain, but several potential barriers exist including; maintaining the nutritional quality of bread, altering existing bread making plants and compatibility with current variety testing systems. Realistic savings by 2020 are estimated at 139 kt CO2e, of which 69 kt CO2e would be relevant to the UK Agriculture GHG inventory (Table 5). These savings equate to a reduction in the UK GHG inventory by 0.14% and the English GHG inventory by 0.23%.

If all realistic savings (not including GM technology) could be made as described in Table 4, then the total savings would amount to 1970 kt CO2e, of which 1175 kt CO2e would be relevant to the UK Agriculture GHG inventory (Table 5). These savings equate to a reduction in the UK GHG inventory by 2.44% and the English GHG inventory by 3.96%. A summary of the main barriers against achieving the potential GHG is given in Table 6.

Table 4 Summary of how changes in N fertiliser management may reduce total GHG emissions for crops grown in England (kt CO2e per annum), where calculations include direct and indirect N2O emissions from soil following the application of N fertiliser and following the incorporation of crop residues, and emissions associated with seed production, fertiliser manufacture, pesticides, field operations (fuel and machinery manufacture), and grain drying. Figures in parenthesis include the effects of LUC, where changes in management cause increased yields.

| Change in N management | | Winter wheat | Oilseed rape | Winter barley | Spring barley |
|---|---|---|---|---|---|
| Changing N timing to reduce N rate | Potential | 0 | 84 (85-88) | 83 (34-42) | 0 |
| or increase yield | Realistic | 0 | 42 (42-44) | 62 (26-32) | 0 |
| Avoid autumn N | Potential | 0 | 58 | 0 | 0 |
| | Realistic | 0 | 29 | 0 | 0 |
| Reduce N2O through | Potential | † 165 | 4 | 7 | 11 |
| altering N timing | Realistic | 124 | 3 | 5 | 8 |
| Improve estimate of N requirement | Potential | 0 (315-388) | -195 (39-111) | ? | ? |
| RB209 (FAM) to true optimum N | Realistic | 0 | 0 | ? | ? |
| Improve estimate of N requirement | Potential | 376 (250) | 104 (108) | ? | ? |
| RB209 (FAM) to RB209 (SMN) | Realistic | 75 (50) | 10 (11) | ? | ? |
| Breeding N efficient varieties | Potential | 2198 | 439 | ? | ? |
| | Realistic | 1099 | 220 | ? | ? |
| Breeding N efficient varieties | Potential | 2748 | 844 | ? | ? |
| Including GM technology | Realistic | 1374 | 422 | ? | ? |
| Low N bread technology | Potential | 242 | NA | NA | NA |
| | Realistic | 139 | NA | NA | NA |
| Use of N efficient species | Potential | 307 (440) | NA | NA | NA |
| Triticale to replace non-first wheats | Realistic | †† 154 (220) | NA | NA | NA |

† Estimate based on the 3rd N split being shifted 30 days earlier, causing a 20% reduction in direct N2O emissions.
†† Assume triticale replaces 12% of non-first wheat, requires 44 kg N/ha less and yields 0.5 t/ha more.

Table 5 Summary of how changes in N fertiliser management may reduce GHG emissions for crops grown in England (kt CO2e per annum), where calculations include only GHG emissions relevant to the agriculture GHG inventory, i.e. N2O emissions and direct fuel use, for comparison with GHG inventory figures (Total agricultural emissions in 2007 of 29.6 Mt CO2e in England and 47.9 Mt CO2e in the UK). Figures in parenthesis represent the reduction from the England agriculture GHG inventory.

| Change in N management | | Winter wheat | Oilseed rape | Winter barley | Spring barley |
|---|---|---|---|---|---|
| Changing N timing to reduce N rate | Potential | 0 | 47 (0.16%) | 47 (0.16%) | 0 |
| or increase yield | Realistic | 0 | 24 (0.08%) | 35 (0.11%) | 0 |
| Avoid autumn N | Potential | 0 | 33 (0.11%) | 0 | 0 |
| | Realistic | 0 | 16 (0.05%) | 0 | 0 |
| Reduce N2O through | Potential | † 165 (0.55%) | 4 (0.01%) | 7 (0.02%) | 11 (0.04%) |
| altering N timing | Realistic | 124 (0.42%) | 3 (0.01%) | 5 (0.02%) | 8 (0.03%) |
| Improve estimate of N requirement | Potential | 0 | -110 (-0.37%) | ? | ? |
| from RB209 (FAM) to true optimum | Realistic | 0 | 0 | ? | ? |
| Improve estimate of N requirement | Potential | 212 (0.71%) | 59 (0.19%) | ? | ? |
| RB209 (FAM) to RB209 (SMN) | Realistic | 42 (0.15%) | 6 (0.02%) | ? | ? |
| Breeding N efficient varieties | Potential | 1258 (4.26%) | 252 (0.86%) | ? | ? |
| | Realistic | 629 (2.12%) | 126 (0.42%) | ? | ? |
| Breeding N efficient varieties | Potential | 1572 (5.31%) | 485 (1.64%) | ? | ? |
| Including GM technology | Realistic | 786 (2.66%) | 242 (0.83%) | ? | ? |
| Low N bread technology | Potential | 137 (0.47%) | NA | NA | NA |
| | Realistic | 69 (0.23%) | NA | NA | NA |
| Use of N efficient species | Potential | 176 (0.60%) | NA | NA | NA |
| Triticale to replace non-first wheats | Realistic | †† 88 (0.29%) | NA | NA | NA |

† Estimate based on the 3rd N split being shifted 30 days earlier, causing a 20% reduction in direct N2O emissions.
†† Assume triticale replaces 12% of non-first wheat, requires 44 kg N/ha less and yields 0.5 t/ha more.

Table 6 Summary of potential and realistic GHG savings as a percentage of the UK and English (Eng) agriculture GHG inventories, together with the main barriers against uptake.

| Change in N management | | % saving UK (Eng) | Barriers to uptake |
|---|---|---|---|
| Changing N timing to reduce N rate or increase yield | Potential<br>Realistic | 0.20 (0.32)<br>0.12 (0.20) | More evidence to prove benefit of earlier applications to barley. Inability to alter N timings due to wet soil or lack of confidence in weather forecasts |
| Avoid autumn N | Potential<br>Realistic | 0.07 (0.11)<br>0.03 (0.05) | More evidence to show autumn N is not required on oilseed rape |
| Reduce N2O through altering N timing | Potential<br>Realistic | 0.37 (0.63)<br>0.30 (0.47) | Potential may be greater if evidence for benefit of avoiding wet soil or more splits Suitable spreading conditions and crop requirements restrict earliness of N |
| Improve estimate of N requirement from RB209 (FAM) to true optimum | Potential†<br>Realistic | -0.23 (-0.37)<br>0 (0) | More accurate N prediction would increase N use and yields, and reduce N error. Effect of extra N on GHGs countered by LUC. No new prediction system |
| Improve estimate of N requirement RB209 (FAM) to RB209 (SMN) | Potential<br>Realistic | 0.56 (0.92)<br>0.10 (0.16) | Measuring soil/crop N reduces N applied and reduces error. Barriers include costs, and perceived lack of reliability (soil test). |
| Breeding N efficient varieties | Potential<br>Realistic | 3.16 (5.10)<br>1.57 (2.55) | Identify important traits for breeders, develop methods of rapidly assessing traits, and methods of testing for suitable varieties. |
| Breeding N efficient varieties Including GM technology | Potential<br>Realistic | 4.29 (6.95)<br>2.15 (3.47) | Will GM technology be adopted by 2020? |
| Low N bread technology | Potential<br>Realistic | 0.29 (0.46)<br>0.14 (0.23) | Will the bread making industry be willing to develop new technology? Consumer acceptance of different bread |
| Use of N efficient species Triticale to replace non-first wheats | Potential<br>Realistic | 0.37 (0.59)<br>0.18 (0.30) | More evidence to prove benefits of triticale and to overcome some negative perceptions of the crop |
| Total (not including GM or improve N requirement to true optimum ) | Potential<br>Realistic | 5.02 (8.13)<br>2.44 (3.96) | |

† This estimate only includes GHGs associated with N use relevant to the UK Agriculture GHG inventory and does not include GHG savings that will result from effects of greater yields on LUC.

# Main implications

- This study has estimated that there is scope to reduce GHG emissions associated with the English agriculture GHG inventory by almost 4% by using N fertiliser more efficiency. This would represent more than one third of the targeted reduction. However it is clear that there are no easy wins and progress would need to be made on several fronts to achieve a significant reduction in GHG emissions.
- It should also be recognised that the changes proposed would reduce GHGs in sectors other than the agriculture inventory (primarily by affecting fertiliser manufacture and LUC). If these are included then the GHG savings described for the UK inventory increase by approximately 70%.
- The quickest savings could be made by altering N timings to winter barley and oilseed rape and replacing non-first wheats with triticale. These have estimated savings of 0.55%, but would require some further evidence of their effects to hasten uptake by the industry.
- Breeding for lower N requirement offers the greatest potential savings in GHG emissions. If methods of testing current and new varieties for N requirement can be developed then progress may be made quite quickly, although the scale of such a variety testing system should not be under-estimated. Identification and rapid screening of traits for low N requirement will take longer to develop.
- It is not possible to quantify the true potential for reducing N2O emissions because there is insufficient evidence on how factors influence emissions. This study estimates the savings from avoiding applications in warm conditions and these have the potential to reduce GHG emissions on the English agriculture inventory by 0.63%. The potential savings could be greater if it is shown that avoiding wet soil, extra splits and using nitrification inhibitors have a significant effect. However, farmers' ability to alter N timings will be barrier for realising these potential savings.
- It was estimated that 72% of farms use a fertiliser prediction tool (mainly RB209) when estimating N fertiliser requirements. On average, RB209 was shown to recommend similar or smaller amounts of N compared with the true economic optimum N rate for wheat, oilseed rape and barley. This indicates that the amount of N applied to these crops across the country is not excessive.
- Using RB209 often resulted in large errors from the true optimum N rate on individual fields and it is clear that fertiliser prediction systems need to be improved. It should be recognised that this will require a long-term and concerted research effort which will result in incremental improvements. Improving precision by which N requirement is estimated will reduce GHG emissions. Improving accuracy will lead to more N being recommended for some crops and greater GHG emissions nationally. However the greater yields are likely to either reduce pressure to convert uncropped land to arable or increase the amount of idle land that can sequester carbon. When the GHG emissions from land use change are accounted for it was shown that improving fertiliser prediction systems are likely to reduce GHGs.
- There is limited potential to reduce GHGs by encouraging farmers to use existing fertiliser prediction systems because a large proportion already uses them. It seems likely that encouraging more farmers to measure the amount of N in the soil and crop before spring in wheat and oilseed rape will result in a modest reduction in GHGs. The perceived lack of reliability of soil tests is a barrier against uptake. Greater reduction in GHGs will be achieved by improving the prediction systems.
- Winter wheat covers a greater arable area than any other crop, but no systematic N timing trials have been carried out on this crop since the trials used to develop the current RB209 guidelines in the 1980s, so it is not possible to conclude whether, for winter wheat, yields could be increased, N use reduced or GHGs reduced by adopting different N timings.

# Future work and recommended actions

- Quantify the effect of weather, soil conditions, the number of N splits and nitrification inhibitors on N2O emissions before a realistic estimate of GHG savings can be made.
- Identify crop variety traits associated with low N requirement and develop methods by which plant breeders can rapidly select for low N requirement. This work has been started for wheat and oilseed rape by 2 LINK projects which are now coming to an end. Very little work has been done in this area on barley.
- Develop variety testing systems to quantify varietal differences in N requirement.
- It is clear that current fertiliser recommendation systems must be improved as far as possible to help farmers get closer to the true economic optimum N rate. In particular estimates of the amount of N supplied by the soil together with predictions of crop growth must be improved.
- Methods to retrospectively monitor of how accurate the estimate of N requirement has been should be improved for feed wheat and developed for other crops.
- Investigate whether N timing guidelines are appropriate for modern wheat varieties.
- Investigate how increases in yield resulting from changes in N fertiliser management will affect land use change (LUC) and consequent GHG emissions. Assess which LUC scenario is most likely.
- Investigate whether autumn N can be avoided on all oilseed rape crops, including those which have had large amounts of straw incorporated.
- Develop technologies for producing bread from low N grain.

- Investigate the extent to which other species with a low N requirement (e.g. triticale or oats) can be used in place of current crop species.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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