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Minimising nitrous oxide intensities of arable crop products (MIN-NO)

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1. Abstract

The MIN-NO project (2009 to 2014) used multi-site industry data, field experiments and modelling to improve estimates of nitrous oxide (N_2O) emissions associated with major UK arable crops and their products. Of 24 field experiments conducted in widely contrasting rainfall, soil and crop conditions, 21 showed direct N_2O emissions due to fertiliser nitrogen (N) to be less than the 1% default emission factor (EF) assumed by the Intergovernmental Panel on Climate Change. A simple model summarising these emissions predicted a 30-year average EF for arable land across the UK of only 0.46% of N applied.

A set of 'smart' EFs was devised for consideration by UK stakeholders, based on the MIN-NO model, other MIN-NO results and associated evidence[1]. The smart EF for fertiliser N predicted a decrease in emissions of almost 10% of the previously estimated total N_2O-N emission from UK agriculture (which excludes fertiliser manufacture). The greenhouse gas (GHG) intensity estimated with the MIN-NO smart EFs (which include reduced GHG from fertiliser manufacture) expressed as emissions per tonne of UK feed wheat was 20% less than the 'benchmark' GHG intensity using a current default methodology. Smart EFs also gave reduced GHG intensities for harvested rapeseed, similar intensities for sugar beet and increased intensities for vining peas. Thus most UK arable food products are likely to have smaller GHG intensities than are being estimated at present. Also, biofuels made from N-fertilised crops could be considered more effective in reducing GHG emissions than is currently assumed.

However, prospects for mitigation of N_2O emissions associated with UK arable cropping are less than was thought previously. Farmers already using abated N fertilisers and following good practice lack any easy means of further mitigation. Feasible approaches tend to have economic costs, so further mitigation depends on the arable industry finding ways of capturing financially some of the value. Four feasible options were identified and, if all of these were aggregated, a combined GHG emissions mitigation potential of around -30% was estimated for the harvested produce of most crops, and from -5% to -25% for their food or fuel products. The best mitigation options appeared to lie in employing more sophisticated crop nutrient supply systems, and / or growing more N-efficient crops through better-informed selection of species and varieties. Other options, such as cultivation strategies to improve soil conditions, cannot be advocated without further research.

[1] Note that final EFs adopted for use in the UK agricultural GHG inventory and for GHG accounting by other stakeholders may differ from these values. For example, data from additional field trials are being taken into account in the Defra-funded GHG Research and Development Platform.

3. Executive summary

Approach and the 'State of Play'

A collaborative project was conducted from 2009 to 2014 involving 23 partners from government, industry and academia. The project aimed to improve estimates of N_2O emissions associated with production of major UK arable crops (cereals, sugar beet, oilseeds and pulses) and their products, so as to help improve estimates of greenhouse gas (GHG) emissions reported in the UK's inventory and in commercial GHG accounting (carbon footprinting) procedures. It provided evidence of direct nitrous oxide (N_2O) emissions due to major UK arable crops and suggested better means of estimating and mitigating these and other GHG emissions associated with arable crop production and products. The project involved (i) sensitivity analysis of existing GHG accounting procedures for crops and their products, (ii) field experiments to measure N_2O emissions associated with manufactured nitrogen (N) fertiliser use, cultivation of pulses and soil incorporation of crop residues, and (iii) modelling to generalise the findings for all UK crops and crop products, and for the National GHG Inventory.

Based on national statistics, 'Benchmark' crops of winter wheat (both for animal feed and breadmaking), winter oilseed rape (OSR), sugar beet and vining peas were defined with typical yields and input levels. GHG emissions for the N fertilised benchmark crops ranged from 2.5 to 3.5 t CO_2e ha^{-1}, as estimated using 'Standard' GHG accounting procedures based on emission factors (EFs) defined by the Intergovernmental Panel on Climate Change (IPCC, 2006). Estimated emission intensities of harvested produce were 443, 518, 974, 45 and 294 kg CO_2e $tonne^{-1}$ respectively, of which from 43% to 79% was related to fertiliser N use or N_2O emissions.

An extensive sensitivity analysis used farm-level yield and husbandry data provided by industry relating to 880 fields of wheat, 350 of OSR, 510 of sugar beet and 34 of vining peas; this showed wide ranges in GHG intensities. The main causes of variability were fertiliser N rate and yield, but fertiliser choice, soil organic matter (SOM) levels and crop residue removals were also important. Further industry data showed contributions of crop-related emissions to the GHG footprints of food products (bread, chicken meat, cooking oil, frozen peas, sugar and whisky) estimated with the methodology set out under Publicly Available Specification 2050 (PAS2050; British Standards Institution, 2011) and fuel products (bioethanol from wheat and sugar beet, and biodiesel from OSR) estimated with the Renewable Energy Directive approach (RED; European Commission, 2009) ranged from 20% to >80%. Variability in GHG due to crop production thus affected GHG intensities for crop products accordingly.

Experimentation

Twenty four experiments tested the effects on crop yield and direct N_2O emissions of five rates of manufactured fertiliser N from nil to 160% (or more) of recommended levels over three seasons, involving feed and breadmaking wheat varieties, spring and winter barley, winter OSR, and sugar beet. Three further experiments compared crop yields and N_2O emissions associated with winter and spring beans, vining and dry-harvested peas, with wheat having no N applied as the control. The same experiments also tested effects on N_2O emissions of removing crop residues of all these pulse crops as well as fertilised wheat, OSR, and sugar beet.

The fertiliser experiments largely supported the assumption that, excluding a background emission, direct soil N_2O emissions relate directly to fertiliser N rate; they did not generally support the hypothesis that annual cumulative direct soil N_2O emissions might relate better to the N-balance (N applied less N uptake). About half of the responses in emissions ha^{-1} were non-linear, and about half the responses in emissions t^{-1} (intensity of crop produce) showed minima as N rate increased. However, soil mineral N data and N_2O emissions measured through the weeks following N applications showed these to be largely an artefact of some N rates being confounded with different N timings – small N rates were applied on one date, whereas large N rates were applied on two dates.

The N_2O emissions associated with pulses were small during crop growth but larger emissions occurred, probably due to premature death of root nodules e.g. after harvest of immature peas for vining. Removal of ‘dead’ crop residues (<2%N) after harvest of cereals, OSR or pulses caused no significant effects on N_2O emissions; however, removal of green residues (>2%N), e.g. sugar beet tops, reduced emissions in two of three experiments, on average by 1.2% of the N removed.

Modelling

The simulation model, DNDC, did not predict measured emissions satisfactorily so a statistical model (‘the MIN-NO model’) was developed that related the natural logarithm of observed total annual direct soil N_2O emissions to the fertiliser N applied, annual rainfall and soil clay content. Crop type or SOM effects were not significant. When extrapolated nationally (using 5 km grid scale activity data), this model predicted (i) background emissions ranging from 0.2 to >1.5 kg N_2O-N ha^{-1}, (ii) a weighted UK average EF for N_2O-N from applied fertiliser N of 0.46% (SD 0.07%), and (iii) a total annual UK fertiliser N-related direct N_2O emission from all arable land of 1.7 Mt CO_2e.

Taking into account other recent UK research on N_2O emissions and GHG accounting, a set of ‘smart’ EFs was proposed for UK Tier 2 GHG accounting and life cycle assessment (LCA) to best represent key causes of arable N_2O emissions, and the most obvious opportunities for mitigation. These included EFs relating applied fertiliser N due to its manufacture (3.52 kg CO_2e kg^{-1} N) and to direct soil N_2O emissions (the UK weighted average being 0.46% of N applied), a ‘background’ emission (UK weighted average, 0.69 kg N_2O N ha^{-1} $year^{-1}$) in place of emissions previously related to some crop residues (those considered to be ‘dead’), and an indirect emission from leached nitrate that was crop-type-related rather than related to applied N, as by IPCC. Compared to using standard EFs, smart EFs predicted reduced GHG intensities for the harvested produce of wheat and OSR, similar intensities for sugar beet and increased intensities for vining peas.

Key conclusions

- Based on multiple robust measurements, a simple statistical model (the ‘MIN-NO model’), and comprehensive data on annual cropping in the UK, it is clear that N_2O emissions averaged across arable land in the UK are less than are predicted by IPCC guidelines: the new estimate for just direct soil emissions is 1.7 Mt CO_2e smaller than that previously estimated by IPCC EFs (Table 46).
- Compared to the default IPCC EF of 1%, direct N_2O emissions from soil due to fertiliser use on arable crops across the UK were estimated to average at 0.46% of the N applied. This was unaffected by crop type but subject to interacting effects of rainfall and soil type (% clay), such that fertiliser-induced emissions could be larger than the default IPCC EF in the wetter regions of the UK.
- Compared to the default IPCC EF of 1%, direct N_2O emissions from soil due to returned and incorporated crop residue N (from straw, haulm and leaves) were negligible over the first 12 months, except where these residues contained more than 2% N (e.g. sugar beet leaves).
- All arable land emitted significant additional N_2O, unrelated to recent N additions as fertiliser or crop residues. These N_2O emissions were estimated to range from 0.2 kg ha^{-1} N in the drier East and South to 1.5 kg ha^{-1} N in the wetter West and North; they are likely to arise from SOM and be influenced by many factors, including levels of organic N inputs over recent years and soil cultivations that cause soil N to mineralise. After comparison with smaller ‘background’ emissions from unfertilised, undisturbed land e.g. grassland, it is suggested that these emissions could be attributed in GHG accounting schemes to arable land, perhaps best defined as ‘cultivable land that annually has a period without crop cover’.
- The abatement of N_2O emissions from manufacture of N fertilisers used in the UK has reduced GHG intensities of arable food and biofuel products substantially: for bread by 7%, bioethanol from wheat by 15%, and biodiesel from OSR by 16%.
- Compared with the ‘benchmark’ GHG intensity of 445 kg CO_2e t^{-1}, estimated for grain from an average UK crop of feed wheat using PAS 2050 methodology, the equivalent GHG intensity based on smart EFs was ~350 kg CO_2e t^{-1} – a reduction of over 20%.

Messages for industry and policy

- Most arable food products have significantly smaller GHG footprints than are being estimated by or on behalf of industry at present.
- Biofuels made from N-fertilised crops grown in the UK are more effective in reducing GHG than was previously thought. The impact of this finding will be enhanced further if the UK defines NUTS2 regional emission estimates for biofuels in a similar way to that suggested by the MIN-NO model e.g. depending on regional rainfall.
- Mitigation of arable GHG emissions by reduced use of fertiliser N was estimated to be largely ineffective if indirect effects on land uses elsewhere were acknowledged.
- As proposed in recent UK reviews, many potential GHG mitigation methods may be applicable to arable crops; these can be classed into four distinct themes,
  1. Fertiliser systems (methods of manufacture, formulation, application and timing) with low GHG emissions per kg nutrient. (These should probably include the use of chemical inhibitors of soil processes, but exclude 'clever' fertiliser timing because this was judged to be impractical.)
  2. Selection of species, varieties and / or fertiliser systems that convert soil and fertiliser N more efficiently into harvestable biomass.
  3. Sourcing of crop produce from regions with low rainfall and light soils hence low N_2O emissions. (Whilst having benefits to individual businesses, global benefits of this approach might be near-neutral, due to displacement effects.)
  4. Removal of crop residues, if green; this applies to a minority of crops.

  Individually these approaches were estimated to have maximum mitigation potentials (on GHG intensities of crop produce) of -25%, -23%, -23% and approximately -16%.
- The maximum GHG mitigation potential derived by aggregating all four mitigation approaches was around -30% for the harvested produce of most crops (grain, seed or root), hence from -5% to -25% for their food or fuel products, depending on the contribution of crop produce to total GHG footprint of the product.
- Thus there are opportunities for industry to help further mitigate the GHG footprints of arable products through improved fertiliser systems (better regarded as 'crop nutrient supply systems') e.g. incorporating chemical inhibitors within fertiliser products, but their exploitation will depend on finding means of capturing some of the value e.g. through economic incentives offered by the supply chain.
- Any improvements that the plant breeding industry can make in the N Use Efficiency of crop varieties will prove beneficial to GHG mitigation, but the scope will be modest, especially if further progress is made in fertiliser technology, because mitigation is multiplicative, not additive.
- The main opportunities for farmers to mitigate N_2O emissions lie in selecting crop species and fertiliser systems. Unfortunately farmers using abated N fertilisers and following best

practice have few other means of effective N_2O mitigation at present (at least that could affect calculated GHG emissions). Even under-fertilising with N is counter-balanced by GHG effects through indirect land use change (ILUC).

- Thus the scope for the UK arable industry to further mitigate GHG intensities of its products is less than previously estimated, and GHG mitigation maxima could only be achieved if adequate and sustained incentives became available to support development and use of all the appropriate technologies.

Project achievements and highlights

- Through a combination of design and luck, the MIN-NO project has quantified N_2O emissions across extreme contrasts in growing conditions, particularly rainfall, so in predicting emissions across the UK it largely proved possible to generalise by interpolation rather than extrapolation. The main conditions untested here are the combination of high rainfall and light soil.
- The hypothesis that direct N_2O emissions should have a non-linear relationship with N applied was not universally upheld; many relationships were linear, and occurrence of non-linear relationships was more easily explained by these arising as artefacts of N rate treatments being confounded with N timing differences, than by any biological explanation.
- However, frequent measures of soil mineral N (SMN) soon after N applications have revealed large perturbations in available N that may help to explore the causes of the high variation commonly seen in recovery of applied N by crops.
- This Project did not test nitrification inhibitors. However, Defra Project AC0213 (‘Potential for nitrification inhibitors and fertiliser nitrogen application timing strategies to reduce direct and indirect N_2O emissions from UK agriculture’) has shown positive results and with this knowledge, we were able to explore (‘theoretical’) mitigation practices that might halve direct N_2O emissions from soil.
- The LCA review showed that most elements of a footprint have similarly large uncertainties and that sensitivities of estimated GHG intensities to uncertainties are largely predictable from knowing crop contributions to the full product footprint. The LCA review confirmed the importance of fertiliser N, and quantified the extent to which fertiliser N mitigations have already reduced GHG footprints (through manufacturing improvements) and might reduce these further. The LCA review also revealed boundary problems with some of the larger contributors to the footprint e.g. current classification of soils according to their organic matter content is clearly inadequately crude; the soils classes of mineral, organic or peaty need to be replaced by a continuous scale relating emissions to SOM content. Note that there are multiple technical benefits to farmers of knowing topsoil organic matter contents, so this information should become commonly available.

- The simulation model DNDC proved unfit for the purposes intended in this project. This finding should have positive influences on both science (because the limits to understanding have been thrown into closer focus) and practice (because the adoption of inaccurate GHG estimates has been avoided). A more generic benefit is that simulation models should attract closer scrutiny before being adopted for use in practice.
- The consortium successfully brought together scientists and practitioners concerned with both GHG inventory reporting and carbon footprinting of food and fuel products. Members of the consortium have engaged comprehensively and actively with the work of the project. Attendance at six-monthly steering meetings has been excellent, with additional meetings arranged to satisfy their wish to engage with the technical findings. Consortium members have engaged actively with the preparation of this report.

Opportunities for further progress through research

Whilst this Project successfully improved UK estimates of N_2O emissions associated with arable crop production, and its products, its conclusions were reached with varying levels of certainty. Thus further research on various aspects of arable N_2O emissions would be beneficial. The most important opportunities for progress are listed at the end of this report (Section 11). In summary, research funders could benefit from better understanding of soil N dynamics; this could lead to improved management of cultivations, crop residues and irrigation according to climate and soil characteristics (especially SOM and texture) so as to maximise crop productivity whilst reducing both direct and background N_2O emissions.