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NEWS & VIEWS

GREENHOUSE GAS AND AMMONIA EMISSION MITIGATION PRIORITIES FOR UK POLICY TARGETS

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KEYWORDS

agriculture, ammonia, greenhouse gas, mitigation, net zero

HIGHLIGHTS

- An expert survey highlighted the most effective strategies for GHG and ammonia mitigation.
- Interventions considered to have the highest mitigation potential are discussed.
- Experts agreed that no single mitigation measure can uniquely deliver GHG and ammonia mitigation.
- Experts noted a need for further investment in research, knowledge exchange, education and to develop implementation pathways.
- There is a need for more data to better quantify mitigation potentials and implement effective management strategies.

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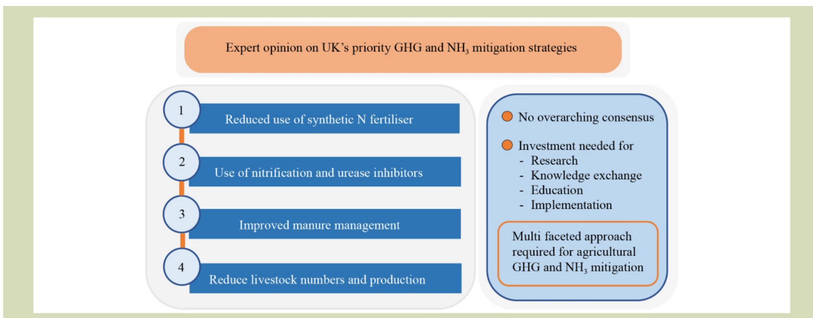
GRAPHICAL ABSTRACT



ABSTRACT

Agriculture is essential for providing food and maintaining food security while concurrently delivering multiple other ecosystem services. However, agricultural systems are generally a net source of greenhouse gases and ammonia. They, therefore, need to substantively contribute to climate change mitigation and net zero ambitions. It is widely acknowledged that there is a need to further reduce and mitigate emissions across sectors, including agriculture to address the climate emergency and emissions gap. This discussion paper outlines a collation of opinions from a range of experts within agricultural research and advisory roles following a greenhouse gas and ammonia emission mitigation workshop held in the UK in March 2022. The meeting identified the top mitigation priorities within the UK's agricultural sector to achieve reductions in greenhouse gases and ammonia that are compatible with policy targets. In addition, experts provided an overview of what they believe are the key knowledge gaps, future opportunities and co-benefits to mitigation practices as well as indicating the potential barriers to uptake for mitigation scenarios discussed.

1 INTRODUCTION

Agricultural land use is a significant source of greenhouse gas (GHG) emissions arising largely as a result of methane from livestock, and nitrous oxide from fertilizers and organic N containing materials applied to soils. In 2020, the agriculture sector is estimated to have been responsible for 11% of UK emissions (46.4 Mt CO_2 equiv.) where methane accounted for 55% of agricultural GHGs, 32% came from nitrous oxide and 12% was from carbon dioxide (mostly related to agricultural machinery)[1]. The UK has set an ambitious target to reduce GHG emissions to net zero by 2050[2]. The UK's Climate Change Committee, an independent body set up to advise the government on its climate change mitigation targets, suggests emissions from UK land use can be reduced by 64% to around 21 Mt CO_2 equiv. by 2050[3]. This would require a 54.7% (25.4 Mt CO_2 equiv.) reduction from the UK's 2020 agricultural GHG emissions of 46.4 Mt CO_2 equiv.

It has been reported that there is the potential to reduce emissions by 7.1 Mt CO_2 equiv. by 2035 using available cost-effective mitigation strategies across all agricultural emissions[4]. However, this is only 28% of the 25.4 Mt CO_2 equiv. reduction needed to achieve the Climate Change Committee's target of 21 Mt CO_2 equiv. by 2050, leaving 72% of emission reduction still to be achieved between 2035 and 2050. In addition, activities outlined within the land use, land use change and forestry (LULUCF) sector show that for cropland and grasslands land classes (4B and 4C, respectively) 10.5 Mt CO_2 equiv. was sequestered by land converted to grassland and land remaining grassland[5]. However, these GHG removals are offset by activities associated with cropland, in particular land conversion to cropland and the drainage of organic soils. When all activities within LULUCF land classes 4B and 4C are considered, there are net emissions of 11.5 Mt CO_2 equiv. from land associated with cropland and grasslands[5]. This highlights a significant contribution to agriculturally related GHG emissions reported under LULUCF, which needs to be considered in mitigation strategies to achieve net zero.

It is recognized that agriculture and aviation are two sectors of the economy from which it is most difficult to mitigate GHG emissions[6]. In addition, according to the Climate Change Committee, it is estimated that by 2050 there would still be approximately 21 Mt CO_2 equiv. emissions from agriculture in a scenario that is consistent with net zero. This would require offsetting of residual emissions by a range of carbon removal technologies to achieve the net-zero target[6]. The potential for carbon offsetting remains highly uncertain and hence maximizing mitigation of non-CO_2 GHG emissions from agriculture is an urgent priority. The Climate Change Committee commented in a recent report that there is "a lack of progress in low carbon farming and productivity measures needed to decarbonize the agriculture sector" and that there are "major risks to delivering the necessary emissions reductions from agriculture and to freeing up land needed for UK-based GHG removals"[7]. The lack of progress is partly because the overall priorities among various mitigation strategies are not well-understood. This is because (among other reasons), while a financial optimum can be derived using marginal abatement cost curves, some mitigation options are more difficult to implement due to the initial financial commitments, lack of knowledge or skepticism among farmers, and other factors leading to a low uptake rate.

In addition to GHG mitigation, there is also a need to reduce ammonia emissions from agriculture due to its polluting effects. Ammonia is a pollutant which can have significant effects on both human health and the natural environment, and is considered to be an indirect GHG. The agricultural sector is the main contributor (87% in 2020) to UK NH_3 emissions and associated pollution[8]. Ammonia emissions from UK agriculture for 2020 were 226 kt NH_3, representing a substantial decrease of 12.9 kt from the previously reported estimate (2021 submission) for 2019 and overall agricultural emissions have decreased by 21% over the time period 1990–2020 and by 3.3% since 2005[8]. The most significant causes of reductions between 1990 and 2005 were decreases in pig numbers, decreased use of nitrogen fertilizers and the banning of crop residue burning[9]. The government has agreed to reduce NH_3 emissions by 16% in 2030, compared to 2005 levels[10] highlighting the need to consider NH_3 emissions in agricultural N management.

Against this background, this paper provides a synthesis of expert opinions regarding which GHG and NH_3 mitigation strategies they thought should take priority within the UK agricultural sector for meeting policy targets. Experts also provide viewpoints on where there are gaps in our quantification and/or understanding of these strategies, suggest insights to future opportunities and indicate the potential barriers to uptake for mitigation scenarios discussed.

2 METHODS

Between 22 and 24 March 2022, 59 experts in UK GHG and NH_3 emissions, comprising a mixture of agricultural scientists (ranging in specialization including soil and animal scientists), environmental modelers, life cycle assessment experts, consultants and agricultural advisors gathered in Edinburgh (UK) for the Association of Applied Biologist's workshop, "Agricultural greenhouse gases and NH_3 mitigation: solutions, challenges, and opportunities". To collate the views and opinions of delegates regarding UK agricultural GHG and NH_3 mitigation priorities, a survey was circulated to workshop delegates. The survey was also circulated to a wider group of 35 key invited colleagues who are considered experts in this field but were not present at the workshop, with all those completing the survey being authors of this paper.

The survey template involved the following open-ended questions:

(1) Please state three GHG and/or NH_3 mitigation strategies that you think offers the largest mitigation potential.
a. Are your choices based on a holistic view or specific to your area of expertise?
b. By how much do you think your chosen mitigation potential will contribute to GHG and/or NH_3 reduction in agriculture?

(2) In relation to your chosen mitigation strategies, what do you think are the main gaps in knowledge that needs to be addressed?

(3) In relation to your chosen mitigation strategies, what do you think are the main challenges and barriers for uptake?

(4) What do you think are the main opportunities that your chosen strategies bring in addition to GHG mitigation and/or NH_3 reduction (e.g., synergies and trade-offs with other environmental and/or financial benefits).

Following the completion of the survey, the answers to each question were collated and merged to formulate this opinion-based report. It is worth noting that the following discussion is a collation of the various views provided in the survey and not a blended, overarching consensus from those that completed the survey and coauthored this report.

3 SURVEY RESULTS

The survey was completed by 28 researchers and two agricultural advisors/consultants from organizations across the UK and Ireland. Table 1 highlights that there are many options available for GHG and NH_3 mitigation and that expert opinion differs in terms of what these priority strategies should be. Authors were asked to provide their top three strategies to prioritize and to be the focus of this report. Therefore, based on the counts given in Table 1, the top strategies proposed by the authors were: (1) management practices which focus on the reduction of synthetic N-fertilizer use and/or the optimization of N application including the use of legumes and cover crops to offset the dependence on synthetic N use (n = 14); (2) use of nitrification and urease inhibitors (n = 9); (3) reduction in livestock numbers through decreased production and consumption of meat and dairy products (n = 8); and (4) improved slurry and manure management including the use of anaerobic digestion and NH_3 capture in manure storage (n = 8).

The following sections provide short descriptions of the mitigation strategy followed by the opinions and views taken directly from the survey.

3.1 Reduced use or optimization of synthetic N application, including an increased reliance on legumes and cover crops

This mitigation scenario includes the direct reduction in the use of synthetic N-fertilizers, optimizing fertilizer management as well as an increased reliance on legumes. Optimizing N application rates by using the best estimate of economic optimum N rate, growing crops with lower N requirement and ensuring accurate application, such as calibrating application machinery, can result in increased efficiency and a decrease in N application. Discussion points provided by experts, outlined below, are primarily focused on grassland systems.

Table 1 Ranking of GHG mitigation strategies suggested by the survey respondents

Mitigation strategy	Count
Reduction of synthetic N input and/or optimisation of N application (& legume and cover crop incorporation)	14
Use of nitrification and urease inhibitors	9
Reduction in livestock numbers or production (reduced consumption).	8
Livestock manure management (slurry and anaerobic digestion, and ammonia capture)	8
Livestock feed management (including supplements, sward/fodder composition and extension of grazing season)	6
Improved animal health and breeding	5
Soil carbon sequestration	3
Agroforestry, moving farming off peatlands and fossil fuel substitution	2
Better monitoring (soil testing & N use efficiency), data recording and reporting	2

The optimization and/or reduction of N fertilizer applications will reduce N fertilizer application rates, which has the potential to be compensated for through increased incorporation of legumes in grasslands and arable rotations[11,12]. Legumes can fix N biologically (e.g., clover can fix up to 80–200 kg·ha^{-1}·yr^{-1} N[13,14]) and subsequently the requirement for fertilizer is reduced, which leads to reductions in CO_2, N_2O and NH_3 emissions associated with fertilizer manufacture, transport and application[15]. It is worth noting that the IPCC Inventory methodology for reporting agricultural GHGs[16] assumes that biologically-fixed N does not directly result in emissions, particularly N_2O, although legumes will contribute to direct 'crop residue' N_2O emissions following incorporation if they are used in a ley or as a cover crop[17]. Research has highlighted that fertilizer rates could be reduced by up to 70% in grasslands without impacting yield or grass quality[18]. Therefore, there is potential to reduce N fertilizer inputs to grasslands and arable rotations through the use of legumes and multispecies swards, and through improved management. Using legumes in ruminant feeding systems (e.g., forage and fodder) can reduce overall GHG emissions due to decreased N fertilizer use and related emissions[19], such as reduced urine N excretion and reduction in enteric methane emissions driven by plant secondary metabolites[20].

Reduced synthetic N-fertilizer use can also be achieved through improving soil fertility via management practices, such as liming and phosphorus application (as well as the incorporation of clover with multispecies swards). Achieving optimum pH through liming can contribute to improved N use efficiency through better macro- and micronutrient regulation and reduced use of N-based fertilizers. For example, optimizing pH via liming can increase soil N supply through organic matter mineralization processes by approximately 70 kg·ha^{-1}·yr^{-1} N[21], meaning that fertilizer-N use can be reduced accordingly. It has also observed that higher soil pH levels can reduce the emissions of N_2O[22]. However, there is an environmental cost associated with applying lime with up to 12% of the mass of limestone potentially emitted as CO_2-C[16]. Nevertheless, the potential reduction in N_2O losses are likely to outweigh this carbon cost. In addition, increasing soil phosphorus to the agronomic optimum improves N use efficiency and has been shown to reduce fertilizer derived N_2O emissions[23] with the potential for substantial improvements in land use efficiency and phosphorus uptake obtained by cereal/legume intercropping[24].

3.1.1 Knowledge gaps in relation to reduced synthetic N-fertilizer application as a mitigation option

The complexity of soil dynamics and nutrient interactions makes predicting GHG reduction potential challenging. Questions still exist in relation to best practice to minimize potential production losses with reduced synthetic N-fertilizer application. The use of increased liming with clover and legume-based multispecies swards (as alternatives to synthetic N-fertilizers) are both mature technologies, but there are still uncertainties regarding optimum agronomic practices for multispecies grasslands under various farming practices (including inclusion in arable rotations, cutting and grazing management) in various climatic conditions and soil types and the long-term effects on soil fertility. There is a lack of knowledge quantifying the impact of legume inclusion in grass swards and arable leys on GHG emissions, carbon sequestration and nitrate leaching, and more research is needed on how to integrate legumes into arable rotations as well as understanding the persistency, ease of establishment and providing advice for weed control. Knowledge gaps in emission estimates from legume-based systems are likely due to a lack of understanding of the mechanisms driving changes to N cycling, biological fixation and changes to the microbial community under multispecies swards. There is a need to further develop knowledge relating to the optimal grazing management for multispecies swards and leys to achieve maximum persistence of species and to better understand the legacy effects on N cycling and carbon sequestration including soil carbon stability and permanence. A recent review highlighted that there is little evidence demonstrating the effects of increased species richness on carbon stocks to fully quantify its potential in terms of GHG mitigation[25]. Quantifying full GHG (N_2O, CO_2 and CH_4), NH_3 emissions and soil carbon sequestration potential from grazing animals in relation to sward composition would contribute to holistic GHG mitigation knowledge.

Therefore, the potential to reduce N fertilizer through optimization of soil fertility and substitution by legume fixed N such as clover would need to be estimated more precisely to determine best practice. Crucially there is a need for further environmental and economic assessments of how reductions in certain inputs might offset potential reduction in gaseous outputs alongside productivity and the cost of adapting management practices (e.g., whether different machinery is required). Further advice is needed in terms of how to match the most appropriate cover crops with existing farming types and systems across the UK while considering soil and climatic differences. In addition, more research is required to look at novel and alternative fertilizers (e.g., reuse of phosphorus sources, enhanced efficiency fertilizers, organomineral fertilizers, biosolids and other alternative organic materials) as well as fertilizer optimization which will all be key strategies in agricultural GHG and NH_3 emissions reductions.

3.1.2 Expert opinion on the potential barriers to uptake of reducing reliance on synthetic N-fertilizers

Planting cover crops to provide soil cover between the harvest of one crop and the planting of the next, reduces the duration and area of bare soil. This contributes to the reduction of GHG emissions, nitrate leaching, potential soil erosion and soil carbon losses[26] but may impact on seed eating winter birds[27]. According to the experts surveyed, there are three key barriers to uptake of these strategies.

(1) Changes in management practices. There may be limited opportunity to move toward the replacement of synthetic N-fertilizer application with undersown, rotational or catch crop legumes, and multispecies swards as these can be more difficult to manage. The management of soil N within multispecies swards to ensure production of high-quality silages for feed and fodder is more complex than in standard monocultures and leads to reluctance by dairy farmers to include legumes in their swards.

(2) Risk to productivity and cost. Due to the uncertainty in persistency, establishment costs and how to manage multispecies swards contributes to poor farmer adoption. It is felt that growers are wary of adjusting their normal N application rates through fear of reductions in yield and quality. Multispecies swards or direct reduction in N fertilizer require careful planning and tailoring to specific farm conditions to obtain best results without loss of output (economic loss). Introducing cover crops into a farming system may create additional upfront costs, labor and time for farmers. If the benefits are not clear, then there will be a barrier to taking on this measure.

(3) Market fluctuations. Market fluctuations in demand need to be considered as this influences which crop species and cultivars are grown, some of which may not favor legume-based, multispecies sward systems. Depending more on synthetic N-fertilizer input compared to legume-based systems does offer more flexibility in the short-term.

Therefore, there needs to be incentives for farmers to plant more legumes and include them in grasslands and/or arable rotations (e.g., Agri-Environment Climate Scheme[27]). More research is needed to establish recommendations for N rates that achieve optimum yield and environmental outcomes. Survey responses showed that experts felt that there is a lack of advisory information on establishment, nutrient management and grazing management of multispecies swards compared to legume-based swards. Therefore, more guidance, advice and demonstration for farmers on how best to use cover crops and legumes would be beneficial.

3.1.3 Potential opportunities for co-benefits and trade-offs with reducing synthetic N-fertilizer reliance

Inclusion of legume-based grassland swards and leys can have multiple benefits including a reduced reliance on fossil fuel derived fertilizers and reduced fertilizer costs as well as improved soil health through increased soil cover resulting in reduced soil erosion, reduced runoff and higher protein content silage[28]. The introduction of multispecies swards, cover crops and undersown legumes creates benefits for future crops as well as improving system biodiversity through increasing habitat for wildlife. It can also improve soil structure and the deeper rooting species can lead to greater drought and flooding resilience[28].

Increased reliance on sward composition rather than synthetic N application may also contribute to a reduced housing period in animal management because of improvements to soil structure, with increased trafficability leading to longer outdoor grazing, reduction in GHG and NH_3 from indoor housing, health and livestock performance, and thereby lower NH_3 emissions.

3.2 Use of nitrification and urease inhibitors

Nitrification inhibitors (NIs) slow the microbial conversion of ammonium-N to nitrate-N (nitrification), which can reduce the risk of loss through leaching or denitrification and thereby increasing the N use efficiency of fertilizers[29]. Within soils, slowing nitrification using inhibitors can allow for the extension of N availability from 6 to 8 to 8–16 weeks while reducing N losses[30]. The use of mineral fertilizers in agriculture contributes to around 17% of agricultural NH_3 emissions, with a large proportion of this coming from urea fertilizers. The addition of urease inhibitors (UIs) to urea fertilizer has the potential to greatly reduce NH_3 emissions from these applications. Urease is an enzyme contributing to the breakdown of urea to ammonium, which can be readily volatilized to NH_3 and so UIs contribute to the reduction of NH_3 emissions. In addition to a reduction in NH_3 and N_2O emissions, the use of NIs and UIs lowers the degree to which N is leached to surface and ground waters, contributing to a reduction of indirect emissions[31]. UIs also improve the efficiency of urea, bringing it in line with N-fertilizers (such as ammonium nitrate), which can either improve yield due to better N use or allow for reduced N application rates. The inhibitors, dicyandiamide (DCD) and N-(n-butyl) thiophosphoric triamide (NBPT), have been shown to have a sizable impact on N_2O emissions when applied in combination with both ammonium nitrate and urea fertilizers, reducing emissions considerably[32]. In the case of urea treated with both DCD and NBPT, a report (collating data from 21 studies) showed an emission factor (i.e., the proportion of N fertilizer applied emitted as N_2O-N) of 13 kg N_2O-N per kg N (8–21 kg N_2O-N per kg N), the lowest emission factor of all treatments[32]. It is important that this mitigation measure is considered as a whole farm approach. To be most effective, it should be combined with careful planning of fertilizer applications, soil testing, nutrient management and fertilizer application plans. The 4R fertilizer strategies (right type, right rate, right timing and right placement) are recommended to improve N use efficiency and associated NH_3 losses.

3.2.1 Knowledge gaps in relation to the use of NIs and UIs as a mitigation option

There were many knowledge gaps highlighted by experts in relation to the use of NIs and UIs, particularly in relation to understanding and quantifying the long-term effects of inhibitors on soil health (notably soil microbial biodiversity) and efficacy to reduce N_2O and NH_3 across different soil, management, and climatic types. There is some evidence showing an interaction between temperature, soil clay content and soil organic matter, which govern the efficacy of DCD[33]. However, experts highlight a lack of UK field data on the effectiveness of inhibitors to reduce soil N_2O emissions (particularly from peat and silt soils) and emission reduction potential of inhibitors when used together with manure application, or when using NIs and UIs in combination. Other knowledge gaps include identifying the optimal rate of fertilizer product versus the rate of applied NIs or UIs, and how efficacy is affected across various soil types, soil properties and climatic (variable rainfall) conditions. In addition, there is still a lack of knowledge in relation to quantifying emissions for NI and UI manufacturing which could affect farm carbon footprints.

Knowledge on the long-term efficacy of NIs and UIs in soil and the potential uptake in grass and crop systems is poorly understood. More research is needed to provide guidance on best practice when using inhibitors; for example, the delivery method (e.g., differences for targeting different N sources such as fertilizers, manure and urine patches), optimal rates of application (appropriate to N loading rates) and accounting for pollution swapping (e.g., trade-offs with increased NH_3 volatilization). Another knowledge gap is the effect of UI additives to urea fertilizers on optimum fertilizer application rates. There have been many questions relating to the persistence of NIs and UIs within soils and subsequent food chains and whether there are any long-term safety concerns with associated food products, for example trace amounts of DCD have been found in some New Zealand dairy product exports[34,35] and the impact of inhibitors on the soil microbiome. There are very few ecological studies on the long-term impacts of fertilizer-applied inhibitors, however a 5-year study found that there was no impact of either UI or NI use on non-target microbial community composition or abundance with a significant impact of fertilization and fertilizer type (i.e., calcium ammonium nitrate or urea) on the fungal community structure but no impact on bacterial community structure[36]. In addition, results of a 7-year study supports the hypothesis that DCD is a specific enzyme inhibitor for NH_3 oxidation and does not affect other non-target microbial and enzyme activity[37].

Further research is needed to ensure that appropriate residue limits are set for these compounds based on risk assessments. In addition, more research into potentially new and novel natural UIs such as garlic and onion extracts[38] and biological NIs[39] is needed. Newer technologies to improve N use efficiency from fertilizers might include nanotechnology and more research and development might provide more options in the future[40].

3.2.2 Expert opinion on the potential barriers to uptake of using NIs and UIs

According to experts surveyed, there are four key barriers to uptake.

(1) **Financial implications.** The additional cost of using fertilizers with added inhibitors have been approximately 3% to 10% more expensive (depending upon location, fertilizer type and energy costs) than traditional fertilizers with little evidence that effects on productivity can offset the difference.

(2) **Confidence in inhibitor efficacy.** The efficacy of inhibitors is highly variable depending on environmental conditions, such as soil type and temperature, and therefore requires knowledge of local soil conditions. Nutrient management plans and soil testing will improve the efficacy of inhibitors.

(3) **Safety concerns.** The addition of chemicals within food production requires robust data and confidence in the safety of food products produced. Concerns about potential food chain contamination (or agreeing internationally acceptable levels of contamination) in relation to human health have been raised when DCD appeared as a residue in milk[35]. The potential effects of leaching of NIs on soil and water quality over the long-term are unknown. Human health concerns have led to an increase in the potential for biological NIs to reduce direct and indirect N_2O emissions from soil[39]. In addition, polymer coatings raise concerns over the contribution to microplastic pollution in the surrounding environment, although there is limited evidence quantifying this.

(4) **Lack of communication, guidance and advice.** Communications around inhibitor use is not always clear. Stakeholder engagement with farmers in a UK study found knowledge was a barrier to uptake for inhibitors as farmers felt the effectiveness was not fully proven or understood[41]. Therefore, it can be challenging to advise farmers to use inhibitors and explain the reasons why. This is due to the lack of perceived benefits and uncertainties around the long-term impacts on soil quality and productivity as well as the financial burden. Many practitioners are still skeptical or unaware of benefits of switching to low emission fertilizer formulations, therefore more communication and education is needed. Parts of the Industry have been slow to embrace the change to fertilizer formulations with inhibitors as this requires shifts in supply chains and fertilizer pricing structure.

3.2.3 Potential opportunities for co-benefits and trade-offs with the use of NIs and UIs

If the fertilizer industry can adapt to include inhibitors and meet demand it means large reductions in pollution can be achieved without changing current business practice, particularly as their inclusion has little effect on the overall carbon footprint of fertilizer production. As inhibitors release available fertilizer-N more slowly, there is a steady supply of N for crop growth which may contribute to better N use efficiency, potential biomass gains and reduced surplus N. A key benefit of reduced surplus N is the reduction of direct and indirect N_2O and NH_3 emissions. Co-benefits would be obtained by using NIs and UIs simultaneously to reduce N_2O and NH_3 emissions at the same time[42]. In northwest Europe, urea-based products are generally cheaper and are more effective compared to hugely popular ammonium nitrate-based products and therefore offer additional financial benefits. There is some evidence[43] of UIs increasing yields, however, results are variable depending on soil type and temperature.

Using a fertilizer with an inhibitor retains more N, which leads to a reduction in the number or application rate of fertilizer required leading to reduced inputs, which is particularly important considering the uncertainties of the fertilizer market. Fewer applications require less tractor passes (and therefore less fuel and machinery use), which can improve soil structure and overall soil health leading to more resilient systems. Lower quantities of synthetic N-fertilizer applied will also cause a reduction in GHGs from fertilizer manufacturing. There is a potential for increased NH_3 loss when NIs and UIs are used in combination due to the buildup of soil ammonium[31]. In addition, there are potential mitigation gains with minimal negative trade-offs with natural alternatives to chemical UIs[39] which still need to be explored.

3.3 Improved livestock manure management

Slurry, farmyard manure and poultry manure are an inevitable consequence of livestock production as housed animals, which are recycled back to the land for plants to use the nutrients they contain[44]. However, this practice contributes to N_2O and CH_4 emissions due to the inorganic N and microbially available C they contain. These GHGs can be produced and emitted at each stage of the manure management continuum, being the livestock building, manure stores, manure treatment and manure spreading on cropland[44]. Slurry application methodology and associated slurry amendments can result in less reactive N emissions, but it is unclear what impact this would have on overall inventory reporting. Depending on the manure management strategy, anaerobic digestion and low emission slurry spreading (LESS) may reduce GHG emissions associated with slurries as discussed below.

3.3.1 Knowledge gaps in relation to improved livestock manure management

Anaerobic digestion at the center of these systems would enable a circular economy of N use on a farm in which synthetic fertilizer can be further reduced by, for example, using such digestates to fertilize field crops. However, there is a need to better understand the microbial dynamics in terms of useful or detrimental microbes that may be enriched or impoverished[45] following application to optimally use digestate products and minimize and detrimental effects on soil health. This is important within large anaerobic digesters where a relatively homogenous and consistent source of feedstock is vital. Significant and/or frequent changes in the composition of the feedstock may lead to frequent adaptations by the microbial community reducing biogas production.

There is a need for improvement to manure management systems, to allow for the preservation of biogas methane value of the manure feedstock, while also offsetting GHG losses[44]. LESS is a mature technology widely used in most European countries, however, data on its efficacy is still relatively imprecise, that is, in Ireland, where one efficacy value is used per technology regardless of soil and weather conditions. Ideally, this should be refined to provide better spatially and temporally disaggregated data aiding improved quantification of emissions. In relation to slurry application methods and associated slurry management, there is a lack of information on the long-term impact on soil compaction, soil health, soil carbon sequestration and wider pollution swapping potential. Ammonia can easily be removed (stripped) from air and into solution, but there needs to be a purpose for the end product, such as fertilizer contributing to circular economy goals. Current stripping systems flush the NH_3 a lot of the time. It can be used as a fertilizer, mixed with nitric acid to form ammonium nitrate or applied directly to mimic urea. More research is needed to find economically feasible ways to do this in the local surrounding to the point source.

3.3.2 Expert opinion on the potential barriers to uptake of manure management strategies

Experts highlight three main barriers to uptake.

(1) Financial implications. While many farmers are open to adoption of optimized slurry application method and associated slurry management, the initial investment and technology costs are seen as a major barrier. There are large capital costs to effectively implement optimal manure management strategies. For example, the large expense in relation to building, operating and maintaining an anaerobic digestion facility is a significant problem for the industry and presents a large financial risk for the operator. The main challenge is to create the market environment where the organic material is sufficiently valued to justify the cost of the transportation of the material, including the reduction in the liquid fraction to ensure efficient transport.

(2) Legislative support. There is also a lack of legislative support and government incentives with only a few programs that promote implementation of anaerobic digesters. Technical issues are also given as a deterrent, such as blockages occurring when spreading slurry with a high dry matter content, LESS machinery having slower working rate than fertilizer broadcasting, the need for a more powerful tractor and potential risk of soil compaction due to machinery weight. Clear and straightforward government support is essential.

(3) Advice and knowledge for land practitioners. Another barrier is a lack of knowledge and advice available for farmers in terms of how best to manage manures without incurring an additional financial burden.

3.3.3 Potential opportunities for co-benefits and trade-offs with the use livestock manure management strategies

In combination with soil and slurry testing there is great potential for farmers to target application to where the nutrients are needed most. LESS can contribute to a reduction in NH_3 emissions from slurry and can lead to higher N utilization and lower requirement for synthetic N-fertilizer use (as can slurry acidification). Coupling the use of LESS with reduced synthetic N-fertilizer applications should also reduce synthetic N-fertilizer manufacturing emissions. Additionally, using LESS reduces odor and sward contamination in grasslands, therefore potentially shortening the grazing rotation and allowing a greater opportunity for slurry spreading compared to surface broadcasting. Savings can be made through better N retention and recycling of NH_3 into useful products. As a result, this will lead to better N use efficiency while maintaining (or increasing) crop yields, favoring soil quality (nutritionally), less pollution, less emissions and reduced use of mineral fertilizers, leading to financial benefits.

Electricity production via combined heat and power systems or supplementation of natural gas with biomethane could be an additional opportunity arising from optimal manure management. Nutrient rich digestate when spread to land leads to better agronomic performance due to higher nutrient availability, leading to less reliance on synthetic fertilizers[46]. Digestate from many waste streams outside of agriculture, including food, municipal, landfill, aquaculture waste streams may potentially be processed, stabilized and blended for the production of digestate-based fertilizers with specific chemical profiles of particularly useful elements such as N, P and K.

3.4 Reduced livestock production

This mitigation option includes the reduction in livestock production and subsequent adaptation by food consumers in terms of quantity of meat consumption and dietary habits. This section also includes discussion regarding a transition from intensive livestock production toward practices in line with regenerative agricultural systems. This may include land-use change, via reduction in herd numbers, to an alternative synergistic (i.e., compatible with emissions reduction) land use, such as reafforestation. However, such changes can lead to increased emission intensities despite lower emissions per unit area, which are outlined below.

3.4.1 Knowledge gaps in relation to reduced livestock production

A reduction in livestock production can contribute to net-zero targets, however, such changes to agricultural systems will lead to many secondary effects across the industry, many of which are poorly understood or quantified. These secondary effects may be both positive and negative, all of which need to be considered and researched in more detail to fully understand and evaluate the net gains and losses in terms of net-zero targets alongside the socioeconomic implications of such changes. For example, reductions in livestock numbers will have a negative impact on business viability and employment within the agricultural sector, including supporting services, such as feed suppliers, veterinarians, abattoirs and processing facilities[47]. Generally, there needs to be more research on nutrient biogeochemistry, land use and public attitudes in relation to the potential reduction in livestock production. A reduction in livestock numbers would lead to reduced manure availability for fertilizing soils, particularly in organic crop production, which will have implications for soil health. However, the extent of the impact is largely unknown, particularly with growing interests in alternative fertilizer options being researched and produced.

Experts within the survey raised concerns regarding the inclusion of numerous subjective assumptions of some current scenario testing within the literature leading to unreliable predictions. It was felt that substantially more robust analyses of industry-wide environmental and economic impacts is required, such as scenario iterations, to provide a range of possible outcomes related to changes in meat consumption nationally as well as globally. World trade is complicated, and as a result there is considerable scope to fill a gap within the literature with respect to more robust scenario analyses using a combination of economic modeling and forecasting in conjunction with consequential life cycle analyses (which considers changes in supply and demand rather than focusing solely on a snapshot in time relating to a specific product or service). Knowledge gaps also exist in understanding how best to incentivize or influence behavior in terms of dietary change among consumers with there being many suggestions ranging from education[48] to enforcing meat taxation[49]. With the promotion of dietary change there needs to be support available for farmers moving away from livestock production.

There is still a debate about meat quantity requirements in the human diet. Many believe lean, unprocessed meat is a highly nutritious food needed to achieve recommended daily intake of all nutrients in a well-balanced diet and so should not be eliminated completely. Conversely, recent reports such as Eat-Lancet suggest that a shift toward more plant-based diets would improve human health and environmental outcomes[50]. This argument is based on the findings that within Europe, the consumption of protein in the human diet is considerably higher than that recommended by WHO guidelines[51]. There is however no clear consensus as to an optimal level of meat consumption across the range of human dietary needs that can inform a robust strategy for a reduction in the livestock production and supporting sectors. In relation to GHG emissions and achieving net zero, there is also a concern that if consumer demand does not match decreased in livestock production within the UK, then there is the risk of effectively outsourcing the nation's emissions via increased imports of meat from other countries, which can potentially cause higher net global GHG emissions compared to that if livestock rearing continued within the UK.

3.4.2 Expert opinion on the potential barriers to reducing livestock production

Proposing industry shrinkage, which would be a consequence of reduced consumption and production (unless meat exports are increased), will likely be a significant barrier to the uptake of this strategy by farmers. Experts highlighted three other key barriers to uptake.

(1) Cultural and traditional barriers. A key barrier for uptake is related to social aspects (e.g., cultural traditions and habits) which may restrict, if not prevent entirely, a widespread reduction in meat consumption. Despite the efforts of governments and nutritional groups across the globe, getting populations to eat a well-balanced diet has proven difficult, and this will become even more of a challenge as the global population grows. Therefore, there appears to be some inertia to change within public attitudes, potentially due to cultural and nutritional requirements.

(2) Considerable efforts required. Despite the potential gains in GHG mitigation, the reduction of livestock numbers will have significant economic and cultural trade-offs, as such, a considerable care is needed in this debate, which must focus on an equitable transition. Given the sensitivity surrounding potential economic and cultural transitions, political will (or lack thereof) along with entrenched institutional ideals, can all be significant barriers. Some experts felt that across the agricultural sector there are strong vested interests (such as the meat and livestock industry, farmers and farming unions) in maintaining the status quo and show a reluctance to change. In addition, some experts suggested that current policies are inadequate due to government and related agencies not being sufficiently committed to direct and lead change. This, however, may be due to the complexities that industry shrinkage would bring and disentangling the secondary effects is a sizable and difficult challenge. As highlighted in the knowledge gaps, there could be many currently undefined factors contributing to low and slow uptake of reduced livestock production as a mitigation option. On a global scale, there are long-term concerns around food security in light of political unrest and financial difficulties. Therefore, any changes within the UK agricultural sector should focus on future self-sufficiency and resilience to market fluctuations.

(3) Knowledge of alternative land uses and long-term investment. Further education regarding the impacts of diets upon GHG emissions and climate change is needed. It is felt that education is key to promoting change among farmers but also that this would be beneficial across all sectors of the food industry to seek opportunities to mitigate or offset GHG emissions, where possible. Getting farmers to switch to regenerative agricultural practices should be achievable over time, however, there needs to be a phased change and farmers need to be convinced about the benefits (especially short-term tenant farmers that may not have a vested interest in mitigating GHG emissions and/or improving soil health and the legacy of current management approaches). While reafforestation brings added benefits of co-products (e.g., timber and paper pulp), the returns from these would take many years to materialize. Changes to ecosystem services via expansion of greenery (i.e., trees in this instance) and potential rewilding bring numerous benefits. However, they also present risks which need to be assessed in terms of rural economies and associated workforce.

3.4.3 Potential opportunities for co-benefits and trade-offs with the reduction of livestock production

Overall, reducing livestock production would reduce GHG emissions within the agricultural sector as well as alleviate pressure on land currently related to livestock production. Reviewing dietary consumption in terms of type and quantity of foods can contribute to reduced food wastes, energy and water demands in food production, and can be beneficial to human health[52]. There is scope to provide policymakers with novel options to address the trade-offs for livestock-farmer livelihoods within this mitigation scenario, but high levels of creativity and innovation are required. The careful reallocation of spared land area can increase both environmental and economic sustainability with improved efficiency in use of nutritional and water resources. Increasing forested areas, for example, can sequester carbon, while forest outputs can be used in the production of harvested wood products for energy, building materials and agricultural inputs[3]. Regarding synergies, given the predominance of agricultural land use in the UK (and across the world), the sector arguably possesses the potential to offset emissions in other sectors (e.g., transport). While farmers do not currently get credited for woodland under the GHG National Inventory system, there is a need for the reduction of emissions within individual activities but also to consider entire cross-sector economic activities to target synergistic GHG reductions and offsetting potential.

4 CONCLUSIONS

A survey of agricultural scientists and advisors was conducted to determine opinions on the most effective mitigation strategies that should be prioritized for GHG mitigation within the UK's agricultural sector. Results showed that the following four strategies were the priorities identified by the experts.

(1) Reduction of synthetic N-fertilizer use with the transition to more reliance on legumes, cover crops and multispecies swards as the primary source of N for soil fertility.

(2) Adoption of NIs and UIs alongside synthetic N-fertilizer use.

(3) Improved livestock manure management.

(4) Reduction in livestock production.

As anticipated, there was no consensus on the priority interventions that could be used for GHG and NH_3 mitigation, although there is a widespread view that the application of a range of interventions applied simultaneously could lead to a significant contribution to mitigation. An interesting consideration is that if there was a reduction in synthetic N-fertilizer use then there will be less need for the adoption of NIs. In addition, with a potential decrease in livestock production, there will be less GHG emissions from manures and therefore potentially more opportunity to manage these manures more effectively.

All experts noted the need for further investment into research on mitigation options, education, knowledge exchange and developing pathways to implementation. There are still great uncertainties in GHG emission quantification and so there is scope for further research to better capture the full potential for GHG reduction within the agricultural sector. Quite often research studies are limited to a single GHG gas or may assess soil C sequestration potential without including GHG emissions. Therefore, there is limited quantification of the net effects of mitigation strategies across all GHGs alongside the potential removals (e.g., via soil carbon sequestration) across mitigation scenarios. In addition, it is often unclear what the combined effects will be when implementing multiple mitigation scenarios across different farm enterprises. The effectiveness of measures will be dependent on the scale and efficacy of implementation. Evidence for mitigation potential from individual measures, often comes from evidence with limited experimental data. Therefore, monitoring and assessment of measures that are developed will be important as no single mitigation measure can be uniquely effective. In many instances, improved communication and better support within the industry could result in better environmental outcomes, especially with the adoption of new management practices. Measures must also be practical, cost-effective and relatively speaking easy to implement for the farmer, while also increasing farm resilience and benefiting the whole supply chain and the environment.

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Compliance with ethics guidelines

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