NITROUS OXIDE AND METHANE EMISSIONS FROM AGRICULTURE AND APPROACHES TO MITIGATE GREENHOUSE GAS EMISSIONS FROM LIVESTOCK PRODUCTION

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This published work was carried out
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This work or any part thereof has not previously been presented in any form to the University or to any other body whether for the purposes of assessment, publication or for any other purpose (unless otherwise indicated). The individual publications on which this work is based have been published in Peer-reviewed Journals. Save for any express acknowledgments, references and/or bibliographies cited in the work, I confirm that the intellectual content of the work is the result of my own efforts and of no other person.

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Abstract

This thesis links papers reporting field measurements, modelling studies and reviews of greenhouse gas (GHG) emissions and their abatement from agriculture, in particular from livestock production. The aims of the work were to: quantify GHG emissions from litter-based farmyard manures; evaluate means by which GHG emissions from agricultural production may be abated; assess synergies and conflicts between the abatement of other N pollutants on emissions of nitrous oxide (N_2O); analyse two records of soil temperature from 1976-2010 from Wolverhampton (UK) and Vienna (Austria).

Agricultural emissions of GHGs are not readily abated by ‘end of pipe’ technologies. Large decreases in agricultural GHG emissions may require changes in the production and consumption of food that could have unwelcome impacts on both consumers and producers. However, identifying and prioritizing both modes and locations of production, together with utilizing inputs, such as N fertilizer and livestock feeds, more efficiently can reduce GHG emissions while maintaining outputs. For example, GHG emissions from livestock production may be lessened by increasing the longevity of dairy cows, thereby decreasing the proportion of unproductive replacement animals in the dairy herd. Sourcing a larger proportion of calves from the dairy herd would decrease emissions of GHGs from beef production.

The distance between the region of food production to that of consumption has relatively little impact on total GHG emissions per tonne of food product. Due to greater productivity or lesser energy inputs, importing some foods produced in other parts of the world may decrease GHG emissions per tonne compared with UK production, despite the additional emissions arising from long-distance transport.

Manure application techniques to abate ammonia (NH_3) emissions do not axiomatically increase emissions of N_2O and may decrease them.

Soil temperature measurements from 1976 to 2010 were consistent with the warming trends reported over the last 40 years.

Title

Nitrous oxide and methane emissions from agriculture and approaches to mitigate greenhouse gas emissions from livestock production

Table of contents

Structure of thesis

This thesis links together published papers which evaluate means to use inputs to agriculture more efficiently, thereby decreasing emissions of greenhouse gases (GHG). The work reported focuses mainly on the livestock sector and, in particular, non-carbon dioxide (non-CO_2) GHG emissions from livestock manure and how these can be reduced. The work includes field experiments, modelling studies and reviews.

The first section of the thesis is an account of work carried out to better quantify estimates of GHG emissions from solid (i.e. litter-based) manures. The main aims of the first study were to describe the major processes driving emissions from solid manures and to assess whether the empirical data were sufficient to support a recommendation for an emission factor (EF) for each non-CO_2-GHG for each type of solid manure. The section continues with the findings of a field study of the impact on nitrous oxide (N_2O) emissions of incorporating solid livestock manures to land immediately after application, in order to abate ammonia (NH_3) emissions.

The second section reports a study to model strategies to abate GHG emissions from livestock production and other UK agriculture sectors. This work was carried out using the Cranfield University Life Cycle Assessment (LCA) Model to determine whether different modes of production within the UK can be utilized to decrease total GHG emissions from livestock production by concentrating production in those current management systems that emit the least per tonne of product. The section continues with a review of N_2O emissions from liquid manures applied to land by techniques designed to abate ammonia NH_3 emissions.

Work on the impacts of policy on GHG emissions from agriculture are included in the next section which reports two papers on the consequences of the EU Nitrates Directive on GHG emissions.

The Cranfield University LCA Model was used to assess whether there are locations of production that require significantly fewer inputs, and hence cause less pollution, than others. The production of seven foods, grown either in the UK or another country, was assessed to determine the GHG emissions beginning with on-farm emissions and subsequent emissions from each stage of the supply chain to the retail distribution centre in the UK.

A study is reported which attempted to account for the fate of N applied to land in solid manures by measuring or modelling losses as NH_3-N, N_2O-N, dinitrogen (N_2), nitrate (NO_3^-) leaching, crop N uptake and addition of N to soil organic matter (SOM).

The final section reports 35 years of measurements of soil temperature at the University of Wolverhampton meteorological station from its inception to closure and measurements of soil temperature at a site near Vienna, Austria. These results provide an example of data indicating the scale of recent warming. This dataset begins in August 1975 and ends in December 2010.

The thesis ends with a discussion of how the findings may be used by policy-makers and farmers to reduce GHG emissions from agriculture, how measures to reduce GHG emissions from agriculture interact with other forms of agricultural pollution and how potential conflicts between GHG mitigation and other pollutant emissions may be resolved.

Introduction

Gases in the atmosphere trap infrared radiation (IR) reflected from the Earth's surface thereby increasing the temperature of the Earth's biosphere. Water vapour and CO_2 are particularly effective in absorbing IR. Hydrocarbons, such as methane (CH_4), are even more effective at trapping IR, as is N_2O. Each molecule of CH_4 has a warming potential equivalent to 25 molecules of CO_2 (CO_2-eq), while N_2O has a CO_2-eq of 298 (IPCC 2006). These four gases are the main 'greenhouse gases.' In the UK, agriculture is the major source of the GHGs CH_4 and N_2O, accounting for 79% of CH_4 emissions, 89% of N_2O emissions and 7% of total UK GHG emissions in 2014 (Anon., 2016).

Between 1970 and 2000 temperatures increased at a rate far greater than found in records of climate data, persuading observers that the biosphere was warming and the cause was increased concentrations of GHGs (IPCC, 2001). In 2005 the UK Government appointed Sir Nicholas Stern, formerly Chief Economist at the World Bank, to chair an independent review of climate change and its likely impacts. The conclusions of the review were unequivocal: "*The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response*" (Stern, 2006). Climate change was due to anthropogenic activities and it would be cost effective to act now to mitigate the emissions leading to a warmer climate, rather than to have to adapt to a changed climate later.

The Climate Change Act (2008) requires the UK to reduce GHG emissions by 80% from 1990 levels by 2050. The agriculture sector will need to reduce annual emissions in England by $3 * 10^6$ t of CO_2-eq by the third carbon budget period (2018-2022) under the Government's 2009 Low Carbon Transition Plan. Hence, there is a need to quantify GHG emissions from agricultural sources and evaluate means to abate those emissions.

The thesis begins with the estimation of non-CO_2 GHG emissions from some aspects of livestock production. Solid manure, generally referred to as farmyard manure (FYM), differs from manure handled as liquid slurry by the inclusion of litter, usually cereal straw. The addition of litter to livestock excreta enables air to interact with the carbon (C) and nitrogen (N) in the urea and other low molecular weight compounds in urine, or as more complex organic compounds in faeces, bedding and spilt animal feed. This decomposition is brought about by microbial degradation and releases CH_4 and N_2O. Consequently, FYM is potentially a greater source of N_2O from buildings and stores than liquid slurry (IPCC, 2006). Relatively few studies have attempted to quantify GHG emissions from FYM and the first paper is a review of GHG emissions from FYM and the factors contributing to those emissions. Emission factors (EF) for GHG emissions from FYM are proposed.

There are concerns that rapid incorporation of FYM into soil, in order to decrease NH_3 emissions, will increase the pool of mineral N in soil and lead to increased emissions of N_2O (Bouwman, 1996). Few papers have been published which report the impact of solid manure application using NH_3 abatement techniques on emissions of N_2O. This thesis includes a review of field studies which measured emissions of both NH_3 and N_2O following application of slurry and solid manures to land using reduced-NH_3 techniques. The thesis also includes the results of four replicated field experiments to measure the impacts of immediate incorporation of four solid manures: cattle FYM; pig FYM; layer manure and broiler manure by mouldboard plough, disc or tine on emissions of NH_3 and N_2O.

Much work has been carried out to develop techniques to mitigate non-CO_2 GHG emissions from agriculture, in particular from the livestock sector. However, as well as developing abatement techniques to abate emissions from specific sources, it is also necessary to understand how inherent differences among modes of production and management systems might be used to decrease overall GHG emissions. This section summarizes a study to model how the UK livestock industry may be reconfigured to make the best use of those existing production systems which have been shown to produce smaller GHG emissions than other production systems currently in use.

Initiatives to abate emissions of GHG from agriculture began later than those to abate loss of NO_3^- to ground and surface waters (EC, 1991) or emissions of NH_3 (UNECE, 2000). Decreasing NO_3^- leaching will lessen indirect losses on N_2O, but may increase or decrease direct emissions depending on the approach used to abate NO_3^- leaching. Abating emissions of NH_3, by increasing the amount of manure-N that enters soil, may increase direct losses of N_2O (although indirect emissions of N_2O will be decreased). The impacts of the implementation of the EU Nitrates Directive on GHG emissions from agriculture have also been studied, both with respect to reductions in direct emissions and also by encouraging the more efficient uptake of N in livestock manures, thereby reducing the need for N fertilizer and the GHG emissions arising from N fertilizer manufacture and use.

There has been much debate about the merits of 'local sourcing' of foodstuffs in order to reduce total GHG emissions from food production primarily by reducing the GHG emissions arising from the long-distance transport of food. The thesis reports work to quantify all the GHG emissions arising from food production including those that are accounted for in other sectors (e.g. energy, transport…). These estimates are used to determine whether some foods may be produced in other parts of the world with smaller total GHG emissions than the same foods produced in the UK.

Finally, two records of soil temperature from 1976-2010 at Wolverhampton (UK) and Vienna (Austria) are analysed and discussed to assess if there have been any trends in temperature at either site and the findings compared with global data on air temperature trends over that period.

The overall aims of the work presented in this thesis are as follows:

- To quantify GHG emissions from litter-based farmyard manures (FYM).
- To identify and evaluate means by which agricultural production may be modified to abate GHG emissions.
- To assess synergies and conflicts between techniques to abate emissions of other N pollutants on emissions of N_2O.
- To analyse, report and discuss two records of soil temperature from 1976-2010 at Wolverhampton (UK) and Vienna (Austria) to assess if there have been any trends in temperature at either site and if these are consistent with the global records of temperature changes reported for that period.

The findings reported are relevant to both policy-makers and farmers. This thesis provides data that can be used for policy formulation (e.g. work on identifying current farming practices and sources of food products that minimize total GHG emissions). Guidance is also given on how farmers can better utilize livestock manure to increase crop uptake of manure-N and abate both direct and indirect GHG emissions. The thesis also provides data on soil temperature trends to complement global datasets of air and ocean temperatures.

Summary of the published works

Section 1

Estimating non-CO_2 greenhouse gas emissions from solid livestock manures

Agriculture is responsible for ~7% of UK GHG emissions (Anon., 2016), mainly as CH_4 from enteric fermentation and N_2O following the application of N fertilizers and livestock manure management. The thesis begins with an account of work carried out to better quantify estimates of GHG emissions from manure management.

*1. **Webb, J**., Sommer, S. G., Kupper, T., Groenestein, K., Hutchings, N. J., Eurich-Menden, B., Rodhe, L., Misselbrook, T. H. & Amon, B. (2012) Gaseous emissions during the management of solid manures. A review. Sustainable Agriculture Reviews. 8, 67-107.*

We reviewed papers published in peer-reviewed journals and also examined datasets generated by members of the 'European Agricultural Gaseous Emissions Inventory Researchers Network' (EAGER) as project reports, conference proceedings and other 'grey' literature. Where possible, datasets were amalgamated so that they could be subject to statistical analysis. Using this approach, we expected to be able to use more data and draw more robust conclusions on NH_3, N_2O and CH_4 emissions from systems producing solid manure. The data in the 'grey' literature were frequently reported in good detail and often, due to the absence of a word or page limit for these reports, more information was provided than in peer-reviewed papers. Details of how the data were screened prior to analysis and review are given in the full paper.

Our aims were to:

1. Describe the major processes driving emissions.

2. Assess whether the empirical data were sufficient to support a recommendation for an emission factor (EF).

3. Where the answer to 2 is no, explain why this is so.

4. Where the answer to 2 is yes, to propose an EF.

The review found that, due to the smaller emitting surface area in a tied stall, cattle housing systems with deep litter emit more N_2O and NH_3 than tied stalls. Buildings housing laying hens emit more NH_3 than buildings housing broilers. This is likely to be due to the smaller average weight of broilers and less annual N excretion. Decreased-emission housing systems for poultry, including the aviary system, can decrease NH_3 emissions by between 50-80%. The greatest N_2O-N emissions from buildings housing livestock were also from deep litter systems, but the amount of N_2O-N was smaller than that of NH_3-N by a factor of 15. Air exchange and temperature increase induced by aerobic decomposition during manure storage may greatly increase NH_3 emission.

Emissions of 0.25-0.30 of total-N have been recorded from pig and cattle manure heaps undergoing aerobic decomposition. Increased density of manure during storage significantly decreases temperatures in manure heaps. Storing solid manures at high density also lessens air exchange, which with the low temperature, limits the formation and transfer of NH_3 to the surface layers of the heap, thereby decreasing emissions. Most N_2O emission estimates from cattle and pig manure have been between 0.001-0.009 of total-N. Emission of N_2O from poultry manure tends to be small.

Mean unabated NH_3 emissions following application of manure to land were 0.79, 0.63 and 0.40 of total ammoniacal-N (TAN) from cattle, pig and poultry manure, respectively. The smaller emission from poultry manure is because the labile N in poultry excreta is in the form of uric acid and hydrolysis of uric acid to urea may take many months and is often incomplete even after application, hence limiting the potential for NH_3 emission. Manure incorporation within 4 h after application decreased NH_3 emission by a mean of 32, 92 and 85% for cattle, pig and poultry manure, respectively. Abatement following incorporation within ≥24 h after application was 20, 56 and 50% for cattle, pigs and poultry, respectively. Incorporation by disc or harrow decreased NH_3 emissions less than incorporation by plough. Emissions of N_2O following the application of cattle manure were 0.12 of TAN without incorporation after application and 0.073 TAN with incorporation after application. Conversely, emissions following application of pig and poultry manures were 0.003 and 0.001 TAN, respectively, without and 0.035 and 0.089 TAN, respectively, with incorporation after application. Emission factors for N_2O, NH_3 and CH_4 are proposed in Table 1.

2. ***Webb, J****., Thorman, R. E., Fernanda-Aller, M. & Jackson, D. R. (2014) Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types. Atmospheric Environment. 82, 280-287.*

This paper reports the impact on N_2O emissions of incorporating solid livestock manures to land immediately after application, in order to abate NH_3 emissions.

Rapid incorporation of solid manures into tillage land abates NH_3 emission by 40-90%, with the greatest abatement coming from ploughing (Mulder and Huijsmans, 1994; Webb *et al*., 2010). However, rapid incorporation of manure into soil will increase the pool of mineral N in the soil and could lead to increased N_2O emissions (Bouwman, 1996). Prior to this paper, few papers had been published reporting the impact of solid manure application using NH_3 abatement techniques on emissions of N_2O. In addition, some of those were incubation studies and hence extrapolation of their results to field-scale application needs caution. In a review of field studies which measured emissions of both NH_3 and N_2O following rapid incorporation of manures, Webb *et al*. (2010) reported that incorporation of solid manures may abate emissions of NH_3 while not increasing, or even decreasing, those of N_2O.

This paper reports the results of four replicated field experiments to measure the impacts of immediate incorporation of solid manures on emissions of NH_3 and N_2O. Four manures: cattle farmyard manure (FYM); pig FYM; layer manure and broiler manure were applied to the soil surface or immediately incorporated by mouldboard plough, disc or tine. Two experiments were conducted on a clay soil and two on a sandy soil to find out whether soil type interacted with incorporation technique to influence emissions of NH_3 or N_2O. Ammonia emissions were measured for 1 or 2 weeks, while N_2O emissions were measured for 60 days in one experiment and for a complete year in the other three experiments.

Cross-site analysis indicated no effect of incorporation by disc or tine on emissions of N_2O-N after 60 days, but incorporation by plough significantly increased direct emissions of N_2O-N compared with surface application of manure ($P < 0.001$). Direct emissions of N_2O-N, at ~0.67% of total N applied, were substantially greater at the coarse-textured site than at the heavy clay site (0.04% of total N applied; $P < 0.001$). The impact of incorporation on total annual direct emissions of N_2O-N differed in the three experiments where emissions were measured for a full year. There was no effect of incorporation on N_2O-N emissions in the first experiment on the clay soil, and in the second experiment at this site incorporation by plough or disc, but not tine, decreased direct emissions of N_2O ($P = 0.006$). However, on the sandy soil direct emissions of N_2O-N were increased when manures were incorporated by plough ($P = 0.002$), but not when incorporated by disc or tine.

These results indicate that immediate incorporation of solid manures to abate NH_3 emission does not necessarily increase emissions of N_2O. However, the impacts of immediate incorporation on emissions of N_2O appear to be related to soil type, with a greater possibility of emission increases on coarse sandy soils.

Direct annual N_2O-N emissions from all manures that were not immediately incorporated were always <1.0% of total N applied from the two experiments conducted on a clay soil (range 0.30-0.78%). At the sandy site, only annual direct N_2O-N emissions from cattle manure were <1.0% of total N applied with emissions from laying hen (layer) manure of 2.4% of the total N applied. Pelster *et al*. (2012) reported direct annual N_2O-N emissions of 1.8% of total N applied from the application of poultry manure and attributed this to the large C concentration of the manure. The results reported here suggest that inventories of N_2O emissions following manure application should discriminate according to manure type. Charles *et al*. (2017) suggested an N_2O-N EF of 0.35% for solid manures.

Significance of findings

There are very few published estimates of the effects of manure incorporation on emissions of N_2O or NH_3. These results provide four additional datasets of NH_3 and three of total annual N_2O-N emissions from four types of solid manure applied to the surface and incorporated by three implements. Annual direct N_2O-N emissions following manure application to the soil surface were a mean of 0.6 and 0.3% of total N applied on the clay and sandy soils, respectively.

Section 2

Approaches to abate greenhouse gas emissions from livestock production and other agricultural sectors

Quantifying agricultural GHG emissions enables the largest sources and hence priorities for abatement to be identified. As well as developing abatement techniques to abate emissions from specific sources, it is also necessary to understand how inherent differences among modes of production and management systems might be used to decrease overall GHG emissions. Initiatives to abate emissions of GHG from agriculture began later than those to abate emissions of NH_3 (UNECE, 2000). Since emissions of NH_3, together with those of N_2O, are part of the N cycle, decreasing NH_3 losses may have consequences for N_2O emissions. Abating emissions of NH_3, by increasing the amount of manure-N that enters soil, may increase direct losses of N_2O (although indirect emissions of N_2O will be decreased).

This section begins with work carried out using the Cranfield University Life Cycle Assessment (LCA) Model to identify how the UK livestock industry might be configured in order to minimize GHG and NH_3 emissions by concentrating production in those current management systems that emit the least per tonne of product. The section continues with a paper reporting the impacts on direct N_2O emissions of measures to abate NH_3 emissions following the application of livestock slurry to land.

3. ***Webb, J****., Audsley, E., Williams, A., Pearn, K. & Chatterton, J. (2014) Can the UK livestock industry be configured to maintain production while meeting targets to abate emissions of greenhouse gases and ammonia? Journal of Cleaner Production. 83, 204-211*.

The cost-effectiveness and practicality of techniques to abate GHG emissions from UK agriculture were summarized by Anon. (2007), while Webb *et al*. (2005, 2006b) summarized UK approaches to abate emissions of NH_3. However, the adoption of specific abatement techniques is not the only option to lessen emissions. There are inherent differences in emissions among existing livestock production systems, e.g. between:

- Manure managed as liquid slurry or litter-based FYM.
- Pigs raised outdoors or within buildings.
- Upland and lowland beef and sheep.

Since these systems are currently in commercial use, identifying and adopting those that produce the least emissions might be an effective means of abatement, while maintaining production.

In this study we quantified systematic differences in gaseous emissions among production systems in use at the time, in order to assess the extent to which UK livestock production could be maintained, while decreasing GHG and NH_3 emissions, by switching to those existing production methods that emit less GHG or NH_3. We then assessed the impact of adopting cost-effective abatement techniques on production.

The output from this exercise was an estimate of the greatest productivity, in terms of physical output and financial value of production, for each livestock sub-sector (Dairy, Beef, Pigmeat, Poultry meat, Eggs and Sheep) that can be achieved for the UK livestock sector as a whole, whilst decreasing both GHG and NH_3 emissions from the livestock sector by 20%. We used the Cranfield LCA Model (Williams *et al*., 2006) to calculate emissions to air among existing livestock production systems and to optimize the UK livestock sector in order to abate GHG and NH_3 emissions, while maintaining production at current levels. Output, defined as financial value, was optimized across all sub-sectors. The Cranfield LCA model took account of off-farm impacts e.g. imported soya replacing on-farm forage (if poultry replaces lamb).

Using current management systems the greatest livestock output that could be maintained, while meeting emission abatement targets, was 84% of current. Adopting the most appropriate manure management practises and improved feed conversion ratios enable a further increase in outputs to 86% of current. To optimize production, while abating emissions by 20%, the biggest reduction in output (54%) would take place within the beef sub-sector. This is because, per t of product, GHG emissions per t of beef tend to be greater than per t of other livestock products. However, GHG emissions from UK beef production are less than from some other regions (Webb *et al*., 2013b). Hence, from the perspective of global emissions, it is reasonable to identify means by which UK beef production may be maintained while emissions are lessened. UK beef production could be maintained at 100% of the baseline if beef calves were sourced from the dairy industry, but to do so would require major changes in UK dairy production.

The current focus on increasing annual milk yield per cow, which Vellinga *et al*. (2011) considered an effective GHG mitigation option, has reduced the longevity of dairy cows and increased the proportion of replacement animals. The average productive lifespan of dairy cows had decreased in the past 30 years from a mean of

4.8 lactations per cow to a mean of 3.8 in 2006 (Hanks and Kossaibati, 2013). In 2009 cows lived, on average, for 6.8 years producing milk for 4.3 years (Pritchard *et al.*, 2013). Yet dairy cows can expect to live 8 years and give 6 lactations before their health deteriorates. The first two years of a cow's life are spent growing and developing, so the heifer is producing CH_4 and consuming feed without producing milk. Hence, increasing the longevity of dairy cows could lessen GHG emissions by reducing the proportion of replacement animals (followers), providing total lifetime milk production is increased. Increasing the cows' productive lives can improve the margins for the herd. However, reducing the replacement rate demands very good management skills.

Further intensification of dairy production runs counter to our finding that, by sourcing calves from the dairy industry, emissions from beef production can be greatly decreased, while maintaining current production. This would require breeding dual-purpose cattle for the dairy herd producing less milk. While there are no breeds that currently match the productivity of pure Holsteins (Hanks and Kossaibati, 2013) which, with related Frisians, comprise ~90% of UK dairy cows, high-yielding animals produce large quantities of milk due, in part, to high-energy diets (McDonald *et al.*, 2011). Fuller (2001) argued that when crossed with native breeds, Freisians were long-lived and highly fertile and did well on low-cost feeding regimes, producing well-conformed beef offspring. Crossbred cows have more than a year's advantage in longevity and 30% greater lifetime productivity compared with purebred animals (Hocking *et al.*, 1988).

Ammonia emissions can be abated to the targets set without reducing production, albeit while imposing costs on the industry, but GHG emissions from livestock farming cannot be decreased by 20% without reducing output. This is because, while means to abate NH_3 emissions are conceptually simple and lend themselves to straightforward abatement practises that need not decrease production, the identification of such techniques to enable large decreases of GHG emissions has proved difficult. Large decreases in GHG emission either require decreased N fertilizer inputs or fewer livestock.

These findings imply that, ultimately, the only means of substantially lessening GHG from livestock production in the UK, without simply exporting production and emissions to other countries, may be to reduce consumer demand for livestock products.

Significance of findings

Worthwhile decreases in GHG emissions may be obtained by dairy production systems that increase the longevity of dairy cows, thereby reducing the proportion of the dairy herd that is comprised of unproductive replacement animals. Emissions of GHGs from beef production can be lessened by sourcing a greater proportion of calves from the dairy herd.

*4. **Webb, J**., Pain, B., Bittman, S. & Morgan, J. (2010) The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response - A review. Agriculture Ecosystems and Environment. 137, 39-46.*

Approaches to abate NH_3 emissions prioritize application of manures to land (e.g. Webb *et al*., 2005). There are three reasons for this. Firstly, emissions following the application of manures to land are a major source, accounting for ~40% of NH_3 emissions from UK agriculture (Webb and Misselbrook, 2004). Secondly, in contrast to abating NH_3 emissions at earlier stages of manure management, such as livestock housing or storage, abating emissions following land spreading will not pass the conserved NH_3 to another stage of manure management, where the NH_3 may subsequently be lost. Thirdly, techniques to abate NH_3 emissions following manure application are among the most cost-effective measures available (Cowell and ApSimon, 1998; Webb *et al*., 2006a,b).

We reviewed the abatement efficiency of the most widely used techniques for abating NH_3 emissions following manure spreading, estimated their impacts on emissions of N_2O and assessed their agronomic benefits.

A literature review collated measurements of NH_3 emissions following manure application by spreading techniques that abate NH_3 emission in comparison with emission following broadcast application to land by splashplate machines. We also reviewed the impacts of NH_3 abatement spreading techniques on emissions of N_2O, subsequent crop N uptake, silage quality and grazing palatability. Mean NH_3 abatement efficiency was estimated as simple means and weighted means taking account of the number of experiments reported in each paper.

Based on simple means of the reported NH_3 abatement efficiencies, abatement is greater from the use of trailing shoe (TS) (65%) and open-slot injection (OSI) (70-80%) machines than from the trailing hose (TH) (35%). There is considerable variation in the efficiencies reported, especially for the TH (0-75%) but also OSI (23-99%). Variation in emissions following the use of the TS was somewhat less (38-74%), although this may be due to there being fewer studies reported of the TS. When slurries or solid manures are applied to arable land, immediate incorporation by plough is the most effective abatement technique, decreasing emissions by ≥90%. These NH_3 abatement application techniques will also increase crop uptake of manure-N, increasing the value of manures and reducing the net cost of NH_3 abatement application techniques.

While it is likely that the use of these methods will, by increasing the amount of manure-N that enters the soil, increase direct emissions of N_2O, indirect emissions of N_2O, arising following the deposition of NH_3 to land, will be less. The current IPCC methodology (IPCC, 2006) estimates direct emissions of N_2O-N as 1% of N applied to land in organic manures. After deposition to land, 1% of the NH_3-N emitted will be re-emitted as N_2O. Hence, if we consider a scenario in which slurry is applied to land by surface application, at a rate which applies 100 kg ha^{-1} of TAN, and 50% of that TAN is lost as NH_3-N, then indirect emissions of N_2O-N will be 0.5 kg ha^{-1}. If the slurry is applied by TS or OSI, NH_3-N will be abated by 60-70%, and indirect emissions of N_2O-N will be only ~0.15 kg ha^{-1}. In order for total emissions of N_2O-N to be increased by abated NH_3 application, then direct emissions of N_2O-N would need to increase from 1% of N applied to 1.35%, a 35% increase. Such an increase has not generally been observed following application of slurry by NH_3 abatement application. While for solid manures NH_3 abatement application methods have been shown to have no effect on emissions of N_2O or to decrease them. Hence, while there are circumstances under which NH_3 abatement application techniques may increase emissions of N_2O, such increases are not inevitable.

We therefore concluded that concern over such emission trade-offs need not compromise advice on NH_3 abatement. The rapid incorporation of solid manures may abate emissions of $NH_{3,}$ while not increasing, or even decreasing, those of N_2O. The risk of increasing direct N_2O emissions may be lessened by injecting slurry to depths which increase the diffusion path to the soil surface sufficiently to lead to most denitrified N being emitted as N_2. Hence, it is possible to formulate approaches to abate NH_3 emissions, without axiomatically causing large increases in N_2O emissions. Smith *et al*. (2008) also concluded that under conditions that did not otherwise enhance N_2O emissions, there is no trade-off between NH_3 and N_2O production and more attention should be placed on controlling and abating odour and NH_3 emissions.

Significance of findings

Methods of manure application developed to abate NH_3 emissions do not axiomatically increase emissions of N_2O.

Section 3

Impacts of policy on greenhouse gas emissions from agriculture: consequences of the EU Nitrates Directive

Leaching and runoff of NO_3^- to ground and surface waters was the first N pollutant to be the subject of an emission reduction policy (EC, 1991). Abating NO_3^- leaching will lessen indirect losses of N_2O, but may increase or decrease direct emissions depending on the approach used to abate NO_3^- leaching.

Using the N in organic manures more effectively decreases losses to the environment. Abating N pollution will conserve more manure-N in the soil, making it potentially available for crop uptake. Losses of N, such as those of NH_3, are highly variable and abating those losses will make the manure-N content both greater and easier to predict. Initiatives to increase the proportion of manure-N taken up by crops will leave smaller residues of that manure-N after harvest which might otherwise subsequently be lost as NO_3^- or N_2O. This introduces a virtuous cycle in which confidence in the N fertilizer value of manure is increased, thus incentivizing a commensurate decrease in the use of mineral-N fertilizer and consequent emissions. Finally, as the perception of manure as a valuable source of N gains credit, more attention may then be given to reducing the risks of manure-N being lost to the environment.

These two papers report the impacts on direct N_2O emissions of measures to abate NO_3^- emissions following the adoption of the EU Nitrates Directive.

5. Velthof, G. L., Lesschen, J. P., ***Webb, J.****, Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J. & Oenema, O. (2014) The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000-2008. Science of the Total Environment. 48-49, 1225-1233.*

The Nitrates Directive (ND) (EC, 1991) was devised in order to abate NO_3^- leaching from agricultural land. This study was carried out to quantify the effects of the ND on the leaching and runoff of NO_3^- to ground and surface waters, and on emissions of NH_3, N_2O, nitrogen oxides (NOx) and N_2 to the atmosphere. We formulated scenarios with and without implementation of the ND. The MITERRA-Europe Model was used to calculate N emissions on a regional level in the EU-27 for the period 2000-2008.

The calculated total N loss from agriculture in the EU-27 was 13 M tonnes N in 2008, with 53% as N_2, 22% as NO_3^-, 21% as NH_3, 3% as N_2O, and 1% as NOx. Implementation of the ND was calculated to have decreased emissions of NH_3 (3%), N_2O (6%), NOx (9%), and N leaching and runoff (16%) between 2000-2008 compared with the scenario without the ND. However, there were large regional differences. The decreases of emissions from the application of the ND were mainly due to lesser inputs of N fertilizers and better distribution of livestock manures.

*6. **Webb, J**., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P. & Reid, J. (2013a) An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure N efficiency, In: Donald, S. (ed.), Advances in Agronomy. Academic Press, pp. 371-442.*

We evaluated the various approaches used by each member state (MS) of the European Union (EU) to estimate the efficiency of manure-N recovery by crops in order to determine the need for subsequent inputs of fertilizer-N. Crop utilization over more than one season was taken into account.

The aims were to identify the most effective measures and practices to improve manure-N efficiency with reference to how these methods might be utilized or adjusted with respect to differences in:

- Manure type: solid versus liquid manures; different types of livestock.
- Type of rotation/crop to which manure is applied: permanent versus annual.
- autumn- versus spring-sown.
- Time of application.
- Soil type.
- Climate.
- Method of application.
- Manure treatment prior to application.

We also provided recommendations for the most effective and practical means of increasing manure-N efficiency throughout the EU.

The review comprises three sections:

1. In Section 1, different approaches to the definition of manure-N efficiency among EU MS were reported and discussed. This includes a summary of the extent to which differences in these factors lead to significant differences in the availability of manure-N for both crop uptake and NO_3^- leaching among the MS and regions of the EU, together with an explanation of the reasons behind any differences reported.
2. Section 2 was a systematic review of recent literature to identify the most effective measures and practises to improve manure-N efficiency.
3. Section 3 briefly discussed our findings and conclusions and recommendations for increasing the efficiency with which manure-N may be used by crops.

Recommendations

Techniques, such as covering manure stores and land application of slurry by injection beneath the soil surface and rapid incorporation of both slurries and solid manures into uncropped soil, abate NH_3 emissions. Compared with application methods which mix the slurry with soil, injection of cattle slurry lessens N immobilization and increases manure-N efficiency by ~10-15%. In growing cereals, NH_3 emissions can be abated by band spreading within the canopy. Anaerobic digestion of slurry may also increase manure-N availability in the season of application by 10-20%, compared with undigested slurry. Slurry acidification may increase manure-N efficiency by 35-65% by abating total NH_3 losses by 70% compared with unacidified slurry stored without cover and not incorporated after spreading. Therefore, when deciding on N fertilizer application rates to crops, a requirement to take into account the N conserved by NH_3 emission abatement techniques would increase manure-N efficiency by ≤15%.

To fully utilize the fertilizer value of manure-N, uptake over more than 1 year needs to be accounted for. This is particularly important for solid manures, which provide less-available N in the season after application than slurries, but release more N to crops in subsequent years. Using manure-N as a sole N source may limit overall manure-N efficiency. Applying manures at smaller rates over a larger crop area, using N fertilizer at times when crop recovery of manure-N may be limited, may give the greatest overall manure-N efficiency.

Section 4

Life Cycle Assessment of total greenhouse gas emissions from a range of foods in the UK and elsewhere

*7. **Webb, J.**, Williams, A. G., Hope, E., Evans, D. & Moorhouse, E. (2013b) Do foods imported into the UK leave a greater environmental footprint than the same foods produced within the UK? International Journal of Life Cycle Assessment. 18, 1325-1343.*

This study of seven foods assessed whether there are modes or locations of production that require significantly fewer inputs, and hence cause less pollution, than others. For example, would increasing imports of field-grown tomatoes from the Mediterranean decrease GHG emissions by reducing the need for production in heated greenhouses in the UK, despite the additional transport emissions? We carried out a life-cycle inventory for each commodity, which quantified flows relating to LCA impact categories: primary energy use (PEU), acidification, eutrophication, abiotic resource use, pesticide use, land occupation and ozone depletion. The impacts of potential land use changed are not included in the model. The system boundary included all production inputs up to arrival at the retail distribution centre (RDC). The allocation of production burdens for meat products was on the basis of economic value. We evaluated indicator foods from which it is possible to draw parallels for foods whose production follows a similar chain:

- Tomatoes (greenhouse crops in the UK, field grown in Spain).
- Strawberries (protected cropping in the UK, field-grown in Spain).
- Apples (grown in the UK and stored for year-round supply or imported from New Zealand during spring and summer).
- Potatoes (early season imports from Israel or long-stored UK produce).
- Poultry and beef (UK production or imported from Brazil).
- Lamb (imported from New Zealand to balance domestic spring to autumn supply).

Total pre-farm gate global warming potentials (GWP) of potatoes and beef were less for UK production than for production in the alternative country. Up to delivery to the RDC, total GWP was less for UK potatoes, beef and apples than for production elsewhere. Production and transport to the RDC of tomatoes and strawberries from Spain, poultry from Brazil and lamb from New Zealand produced less GWP than in the UK, despite emissions that took place during transport. For foods produced with only small burdens of GWP, such as apples and strawberries, the burden from transport may be a large proportion of the total. For foods with inherently large GWP per tonne, such as meat products, burdens arising from transport may only be a small proportion of the total.

We concluded that when considering the GWP of food production, imports from countries where productivity is greater and/or where refrigerated storage requirement is less will lead to less total GWP than axiomatic preference for local produce. However, prioritizing GWP may lead to increases in other environmental burdens, in particular leading to both greater demands on and decreasing quality of water resources.

Significance of findings

Despite the additional emissions arising from long-distance transport due to greater productivity of some food products or the need for less energy to produce foodstuffs in some parts of the world, imports from distant regions may lead to less GHG emission than local produce.

Section 5

Accounting for the nitrogen in solid manures incorporated immediately after application

8. ***Webb. J.****, Fernanda-Aller, M., Jackson, D. R. & Thorman, R. (2016) Accounting for the nitrogen in solid manures incorporated immediately after application in order to abate emissions of ammonia. Nutrient Cycling in Agroecosystems. 106, 131-141.*

Following on from Webb *et al*. (2014), which reported four replicated field experiments to measure the impacts of immediate incorporation of solid manures on NH_3 and direct N_2O emissions, this paper reports the impacts of immediate incorporation of solid manures on apparent nitrogen recovery (ANR) and modelled NO_3^- leaching. Four manures (cattle FYM; pig FYM; layer manure and broiler manure) were applied to the soil surface or immediately incorporated by mouldboard plough, disc or tine. Two of the experiments were carried out on a clay soil and two on a sandy soil. Measured emissions of NH_3 and direct N_2O, modelled losses of N as

NO_3^- and ANR were totalled in order to estimate the amounts of manure-N applied that could be accounted for.

There was no overall significant effect of manure application technique on ANR, but there were significant increases in ANR following immediate incorporation in three experiments. Those three experiments were the two carried out on a clay soil and one on sandy soil in which manures were applied in spring. In these experiments loss of manure-N by NO_3^- leaching was small. In contrast, NO_3^- leaching removed much of the manure-N conserved by immediate incorporation when applied to the sandy soil in autumn.

Recovery of manure-N by the succeeding crop was ~8% for cattle FYM, ~13% for pig FYM and ~20% for poultry manures. Only ~30% of applied N could be accounted for from measurements of NH_3, N_2O and ANR and modelling of NO_3^-. While immediate incorporation by plough increased direct N_2O emissions from the sandy soil and all methods of immediate incorporation in autumn increased modelled estimates of NO_3^- leaching, these increases were only a small proportion of the NH_3-N conserved which was probably either recovered by the crop or remained in the soil. Therefore, concerns over so-called ‘pollution swapping’ should not be a barrier to the immediate incorporation of solid livestock manures in order to abate NH_3 emissions and increase crop recovery of manure-N.

One emission pathway that was neither measured nor modelled was emission as dinitrogen (N_2) gas. Some balance studies have suggested large proportions of manure-N may be lost as N_2. For example, Oenema *et al*. (2007) estimated that ~7% of manure-N was lost to the environment as N_2. Even if N_2 emissions were as much as 7% of the manure-N applied, this would only reduce the proportion of manure-N not accounted for in this study to ~66%.

We concluded that most of the manure-N that could not be accounted for is likely to have remained in SOM, where it may become available in subsequent years. Schröder *et al*. (2007) reported that while the N fertilizer replacement value (NFRV) of injected cattle slurry increases from ~50% when slurry is applied for the first time, to ~70% after 7-10 yearly applications, it would take two to four decades of yearly applications for the NFRV of surface-applied FYM to reach ~70% from an initial value of ~30%. It therefore seems likely that the N in solid manures conserved by NH_3 abatement may remain is soil to be recovered by crops over subsequent decades. Repeated immediate incorporation of solid manures to abate NH_3 emissions is likely to lead to a gradual increase in soil-available N that, over time, will further lessen the need for N fertilizers.

Significance of findings

Trade-offs between decreases in emissions of one pollutant as a result of adopting abatement techniques and consequent emissions of other pollutants can be resolved by calculating net changes in the overall costs of pollution arising from introduction of the abatement technique.

Section 6

Monitoring and analysis of trends in soil temperature 1976-2010

9. ***Webb, J.****, Amon, B., Subedi, M. & Fullen, M. A. (2017) Temporal changes in soil temperature at Wolverhampton, UK and Hohe Warte, Vienna, Austria 1976 to 2010. Weather. In press.*

Soil temperatures from 1976 to 2010 were measured at two sites: Compton (UK) and Hohe Warte (Austria). Measurements were taken at Compton at different soil depths under short grass cover as part of long-term meteorological monitoring to support field studies. Mercury glass thermometers (precision ±0.2˚C) were installed at 5, 10, 20, 30 and 60 cm depths. Readings were taken daily (0900 GMT), other than at weekends and national holidays, from August 1975 until December 2010. The data recorded from 1 January 1976-31 December 2010 were collated and analysed in this study. The soil belongs to the Salwick series, which are deep reddish fine loamy soils with slowly permeable subsoils developed over reddish till and glaciofluvial drift (Ragg *et al*., 1984). A typical texture is sand (2000±60 µm) 41.4%, silt (60±2 µm) 51.3% and clay (<2 µm) 7.3%; and soil organic matter (SOM) content is 2.7% by weight) (Brandsma *et al*., 1999). These results were compared with soil temperature trends over the same period from a site in Austria, Hohe Warte, near Vienna. Soil temperatures and snow cover in Austria were measured at the Zentralanstalt für Meteorologie und Geodynamik (ZAMG: http://www.zamg.ac.at; accessed 28/07/16) (Central Institute for Meteorology and Geodynamics), 1190 Vienna, Austria, co-ordinates: 48.249185N, 16.355085E, altitude: 203 m. The soil type was carbonate-free brown soil with relict brown soils.

Soil temperature at Compton, significantly increased between 1976-2010 by +0.04 to +0.08˚C year^{-1}, depending on depth. Temperature increases were greater in winter. Mean annual temperature at Hohe Warte increased by ~0.03˚C year^{-1} from 1976-2010. Significant temperature increases were recorded at Hohe Warte in summer, but not in winter. These differences were attributed to greater snow cover at Hohe Warte insulating the soil in winter, and to the drier summers at Hohe Warte enabling more rapid soil warming.

Since the Compton site is within an urban area, soil temperatures might be expected to be greater than at nearby rural sites. However, mean annual soil temperatures at Compton were similar to those measured at Hilton, a nearby rural site in Shropshire, ranging from 9.4˚C (10 cm depth) to 10.5˚C, compared with the range of 9.5˚C (20 cm depth) to 10.7˚C (10.7 cm depth) reported for Hilton (Subedi and Fullen, 2009).

Brazel *et al*. (2000) compared air temperature measurements between urban and nearby rural sites and measured maximum differences in Tmin of 4-5˚C and 1.7˚C in Tmax. Brazel *et al*. (2000) confirmed earlier work which correlated increasing differences between urban and rural temperatures with increasing urban populations, noting that as the population of Baltimore stabilized and then decreased there were no further increases in temperature differences with nearby rural areas. The decadal census of 1971-2011 inclusive indicates there was little change in the population of Wolverhampton over the measurement period, which decreased from 269,166 in 1971 to 236,573 in 2001 and increased to 249,470 in 2011. In addition, the Compton location is at the urban fringe, and not therefore subject to the greatest heat island effect. Hence, soil warming at Compton between 1976-2010 is unlikely to be due to the urban heat island effect.

Discussion

Quantify GHG emissions from litter-based farmyard manures.

Nitrous oxide emissions following the application of FYM to land remain uncertain. Webb et al. (2012) found that N_2O emissions from cattle manure (0.12 of TAN) were much greater than following the application of pig and poultry manures (0.003 and 0.001 TAN, respectively). Rapid (<4 h) incorporation of cattle FYM decreased N_2O emissions to 0.07 TAN, but rapid incorporation of pig and poultry manure increased N_2O emissions to 0.035 and 0.089 TAN, respectively. In contrast the field experiment (Webb *et al*., 2014a) measured smaller N_2O emissions (<0.001 N) following the surface application of cattle FYM than from other manures (0.006-0.013 N) on a sandy soil. In 2003 and 2005 emissions of N_2O following manure application to a clay soil were also greater from poultry manure (0.0076 and 0.0050, N respectively) than from cattle (0.0043 N) or pig FYM (0.0059 N) (Webb *et al*., 2014).

Immediate incorporation increased N_2O emissions from cattle and pig manure but decreased them following the application of poultry manures on a sandy soil (Webb *et al*.,2014). However, there was no effect of incorporation on N_2O emissions from any of the manures on a clay soil in 2003. In contrast, in 2005 total emissions of N_2O-N were decreased by all forms of incorporation.

Ammonia abatement conserves N thus increasing soil N potentially available to N_2O-producing micro-organisms. Furthermore, following ploughing, the complete burial of manure and the reduced oxygen concentration from its decomposition was likely to have resulted in the formation of anaerobic micro-sites within the soil matrix suitable for denitrification and subsequent generation of N_2O. It would therefore be expected that greater N_2O emissions would be measured following incorporation by ploughing than from by discing or using tines, and in turn than from when manure was left on the soil surface. Total annual N_2O emissions were much better related to N_2O emissions calculated over 60 days at GL (R^2 82%) than at DT (R^2 15%), although the relationship was highly significant at both sites ($P <0.001$). This perhaps suggests that a greater proportion of total annual emissions at GL were derived from nitrification of the NH_4^+ applied than at DT. Formation of N_2O via nitrification occurs at lesser moisture contents (40-60% water-filled pore space, WFPS) than via denitrification (60-80% WFPS). Hence the likelihood of reduction of N_2O to N_2 would be much greater on the clay than on the sandy soil and this may be the reason for incorporation decreasing N_2O emissions on the clay soil.

Evaluation of means by which GHG emissions from agricultural production may be abated.

In our study of optimizing UK livestock production to abate GHG and NH_3 emissions by 20% while maintaining output (Webb *et al*. 2014b), we found that 20% abatement of GHG emissions can only be obtained by reducing UK livestock production by ~14%. In contrast, the adoption of NH_3 abatement techniques by some sub-sectors (dairy, pigs and poultry) would enable maintenance of production closer to the baseline, while achieving or exceeding the necessary NH_3 abatement. The reason for this difference lies in the nature of agricultural GHG emissions, which are dominated by CH_4 and N_2O. In contrast to NH_3 emissions, GHG emissions are not dominated by emissions from a single episode, occur throughout the year, and comprise only a small proportion of input N and C. Given the demand for livestock produce it is likely that any shortfall in UK production would be met by increased imports and increases in production and emissions elsewhere. In addition, increases in production may take place using production systems with inherently greater emissions than those currently used in the UK.

Identifying the appropriate region or means of production

A key driver for the import of foods to the UK is consumer demand. Mila i Canals (2006) reported that >70% of consumers in UK urban areas consider that they should have the choice of purchasing any food product at any time of the year. Until the latter part of the 20th Century, the UK diet in winter included less fresh fruit and vegetables, but more dried, bottled, canned and frozen produce, than is now common. Increased consumption of fresh, or fresher, produce is potentially associated with health improvements through improved diet. Hence, if there is a demand for all-year availability of produce, and it is deemed that this demand should be met, then the most resource-efficient means of meeting such a demand may be to import recently harvested produce rather than store UK produce for long periods. This may remain so even when that produce must travel very long distances.

In general, our findings were that for foods, GHG emissions are not usually directly related to PEU, but to emissions of N_2O from N fertilizer and manure applications and CH_4 from enteric fermentation in the case of beef production. Nitrous oxide and CH_4 have a GWP considerably greater than that of CO_2 by *296 and *25, respectively (IPCC, 2006). For locations where yields are substantially less than the alternative, but overall inputs are comparable, emissions per tonne of produce will be greater (e.g. apples and strawberries in the UK, beef in Brazil). Therefore, sourcing from productive areas rather than trying to boost domestic yields with large energy inputs, whether directly in the case of heated greenhouse production, or indirectly through greater inputs of N fertilizer, is a potential means of lessening emissions per tonne of produce. This appears to be the case even when the foodstuffs are transported over a greater distance, as transport emissions are generally a small proportion of the total, albeit our estimates of PEU and GWP from shipping were greater than in some previous studies. However, in cases where there are similar emissions per tonne of produce (e.g. apples), then longer distance transport will be a more important component of the relative environmental burdens between sources.

For some sources (e.g. primary production and cold storage), our findings agree with the findings of other authors, but differences appear in shipping. Another crucial factor is the need for refrigeration. This appears less significant for meat products which are usually available throughout the year and which are always likely to need cooling during transport wherever produced. Refrigeration is a greater factor for those fruits and vegetables, which can only be harvested over a limited period and will therefore need storage, under conditions which inhibit deterioration, if they are to supply consumers for much or all of the year. Hence, it may be more effective to import seasonal produce that can be sold without prolonged storage than to keep the UK produce for 6-8 months. The exact balance depends very much on production burdens and losses during storage. It also needs to be remembered that long shelf-life products, such as frozen products, can be transported slower, and therefore, in a more efficient manner.

A recent study of crops grown in both the USA and Mexico concluded that trade in those foodstuffs between the two countries gave an overall decrease in adverse environmental impacts in both countries including a ~12% reduction in GHG emissions (Martinez-Melendez and Bennett, 2016).

Another aim of the work of Webb *et al*. (2013a) was to assess whether the production of food outside the UK, albeit with decreased GHG emissions, might export other environmental problems to those countries. Our results suggest this may be the case for some food products. The lesser consumption of PEU and smaller GWP from producing tomatoes and strawberries in Spain has to be balanced against the greater adverse impacts on water use and quality in that country. The increase in agricultural production in parts of Spain has led to aquifers becoming polluted by nitrates and other salts, to a lowering of the water table, and increasing energy use in water supply (Causapé *et al*., 2004; Schofield *et al*., 2001).

Assessment of synergies and conflicts between the abatement of other N pollutants on emissions of nitrous oxide.

Optimizing approaches to abatement of N emissions in terms of total mass of N released to the environment prioritizes abating emissions of those compounds emitted in the greatest amounts, with no account taken of differences in the severity of the impact of different N compounds on the environment: e.g. priority may be given to decreasing NH_3 or NO_3^- over N_2O when decreasing emissions of N. An estimate of the total costs to society of the various forms of N pollution from manures and fertilizers may indicate different priorities.

Pretty *et al*. (2000) estimated external costs of £1190 per t N_2O-N emitted against costs to the environment of £215 per t NH_3-N and £73 per t NO_3-N. In 2008, the estimated environmental costs of NH_3 were significantly increased to £1515 t^{-1} NH_3-N by Anon. (2008), to take account of the damage done to human health by ammonium-based particulate matter. In 2010 the UK Department for Energy and Climate Change (DECC, 2010) advised a cost of £10,061 t^{-1} N_2O-N. Since NO_3-N data were not given in Anon. (2008), a cost of £161 t^{-1} NO_3-N, provided by Anon. (2009) may be used to assess the net environmental cost of NH_3 abatement by immediate incorporation by ploughing. If the costs proposed by DECC (2010) and Anon (2008) for N_2O-N and NH_3-N are applied to an abatement technique such as slurry injection, which abates emissions of NH_3 by 70% but which is sometimes reported to increase emissions of N_2O (e.g. Wulf *et al*., 2002) then, in mass terms, abatement of NH_3-N would need to be at least 6.6 times greater than any increase in N_2O-N emissions for there to be a net decrease in the cost of the damage done to the environment. In the work reported by Webb *et al*. (2016) the abatement of NH_3-N was ~32 times greater than the increase in N_2O-N and hence an overall reduction in the cost of environmental damage can be obtained from immediate incorporation of solid manures. Moreover, these simple estimates only consider direct N_2O emissions. Since abatement of NH_3 will also abate indirect emissions of N_2O, the net benefit from immediate incorporation is likely to be greater.

These findings suggest that concerns over so-called 'pollution swapping' should not be a barrier to the immediate incorporation of solid livestock manures in order to decrease emissions of NH_3.

Comparison of measured trends in soil temperature with global datasets of air and ocean temperature changes between 1970 and 2010

Soil temperature at 5 cm depth significantly increased between 1976-2010 by +0.370˚C decade^{-1}, at Compton and by ~ 0.325˚C decade^{-1}, at 10 cm depth at Hohe Warte from 1976-2010. These rates of temperature increase were double those reported by Trenburth and Fusullo (2013) of ~0.165˚C decade^{-1} using the National Oceanic and Atmospheric Administration, National Climatic Data Centre, Goddard Institute for Space Studies, the Hadley Centre HADCRU3 dataset, and European Centre for Medium-Range Weather Forecasts ERA-I time series (Figure 1). While the apparently greater increase in soil temperature reported in this thesis is much greater than the reported increase in surface temperature, this author does not claim any significance in this difference as the soil temperature measurements were made from only two sites. Nevertheless, the trend reported here is similar to that reported by Subedi and Fullen (2009). It would be interesting to evaluate other data on soil temperature trends to determine if they are consistently different to reported trends in surface temperatures. During the preparation of Webb *et al.* (2017) the authors were unable to identify any other published datasets of soil temperature.

Increased soil temperatures may lead to positive or negative feedbacks in terms of N_2O and other GHG emissions. This subject is outside the scope of this thesis, which deals with emissions and their abatement and not the impacts of climate change and adaptation to those changes. However, insofar as soil moisture allows, a warmer soil is likely to increase microbial activity and mineralization of organic matter increasing emissions of N_2O and CO_2. However, any impacts of increased soil temperature may be offset by decreased soil moisture during the plant growing period which would reduce microbial activity. The net effects of warmer soil will be governed by the relationship between soil moisture and soil temperature, possibly increasing net GHG emissions in winter when soil will be moist but warmer than in previous years. Emissions of GHGs may decrease in summer as increased evapotranspiration leads to soils being drier for longer.

Conclusions

1. Methods of manure application developed to abate NH_3 emissions of do not axiomatically increase emissions of N_2O.
2. Optimizing UK livestock production to abate GHG emissions, while maintaining total output, indicates that a worthwhile decrease in GHG emissions may be obtained by dairy production systems that increase the longevity of dairy cows, thereby reducing the proportion of the dairy herd that is comprised of unproductive replacement animals.
3. Emissions of GHGs from beef production can be lessened by sourcing a greater proportion of calves from the dairy herd.
4. Implementation of the EU Nitrates Directive has decreased both N leaching losses to ground and surface waters, and gaseous emissions to the atmosphere.
5. The widespread introduction of methods to abate NH_3 emissions following application of manures to land can increase the proportion of manure-N recovered by crops, thereby reducing the need for N fertilizer and hence decreasing GHG emissions arising from both the manufacture and application of N fertilizers to land.
6. The distance that food travels by sea and land from the area of production to that of consumption may have relatively little impact on total GHG emissions per tonne of food product. Due to greater productivity of some food products or the need for less energy to produce foodstuffs in some parts of the world, imports from distant regions may lead to less GHG emission than local produce, despite the additional emissions arising from long-distance transport.
7. Nevertheless, the smaller consumption of PEU and GWP from producing tomatoes and strawberries in Spain has to be balanced against the greater

adverse impacts on water use and quality in that country. The increase in agricultural production in parts of Spain has led to aquifers becoming polluted by nitrates and other salts, to a lowering of the water table, increasing energy use in water supply, with potential adverse impacts on biodiversity.

8. Agricultural emissions of GHG are not as readily abated by 'end of pipe' technologies, as are some other pollutants such as NH_3. Some approaches to abate agricultural GHG emissions require drastic changes in the production and consumption of food that could have considerable and unwelcome impacts on both consumers and producers. However, identifying and prioritizing both modes and locations of production, together with utilizing inputs such as N fertilizer and livestock feeds more efficiently, can reduce GHG emissions while maintaining outputs.
9. Trade-offs between decreases in emissions of one pollutant as a result of adopting abatement techniques and consequent emissions of other pollutants can be resolved by calculating net changes in the overall costs of pollution arising from introduction of the abatement technique.
10. The soil temperature data collected at Compton (UK) and Hohe Warte (Austria) are consistent with the warming trend reported over the last 40 years.

Table

Table 1. Proposed emission factors for N_2O, NH_3 and CH_4

	Livestock type		N_2O	NH_3	CH_4
			g d^{-1} N animal place $(ap)^{-1}$		g d^{-1} ap^{-1}
Buildings	Dairy cattle	Deep litter	2.0	32	1250
	Dairy cattle	Tied stalls	0.7	12	200
	Dry sows	Litter	NA	12	NA
	Finishers	Litter	2.7	9	7
			Proportion of total N		
Manure storage	Cattle	FYM	0.15	0.009	NA
		Deep litter	0.08	0.002	NA
		Tied stall	0.04	0.005	NA
	Pig	FYM	0.31	NA	NA
		Deep litter	0.05	0.046	NA
	Poultry	Belt removed	0.02	NA	NA
		Litter	0.08	<0.001	NA
			Proportion of TAN		
Manure application	Cattle	FYM	0.79	0.12	NA
	Pig	FYM	0.63	0.003	NA
	Poultry	solid	0.40	0.001	NA

Figure

Figure 1.

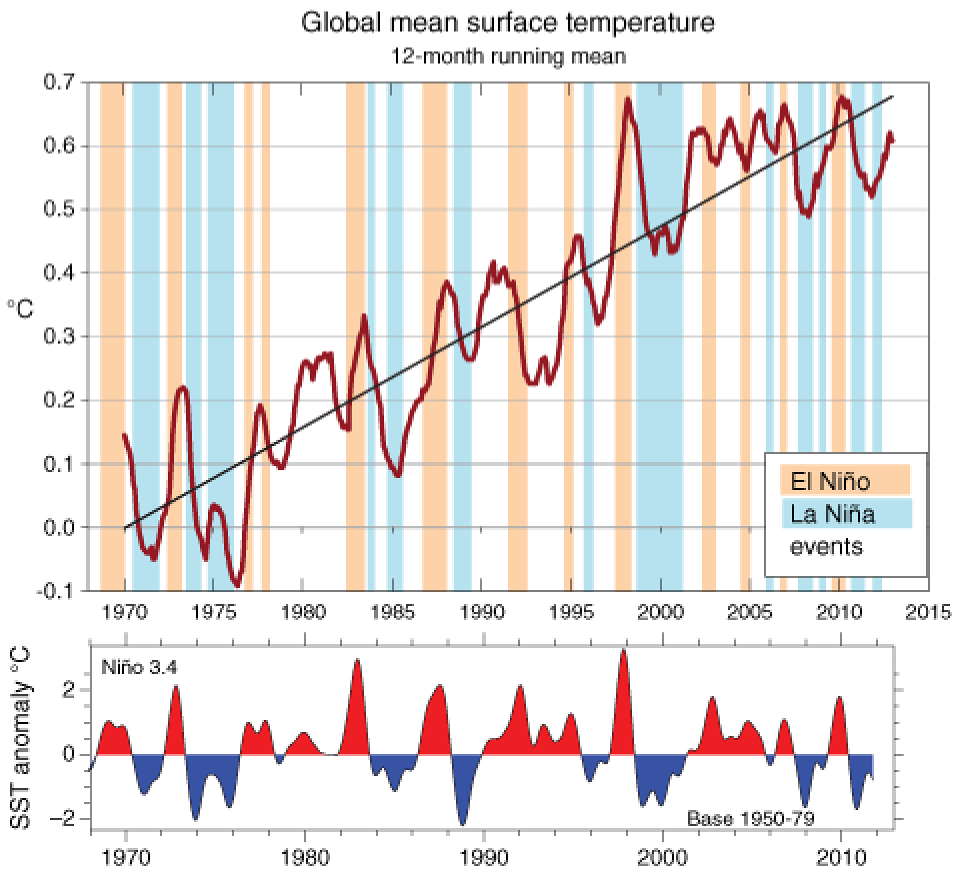

Figure 1. Global mean surface temperature 1969-2011 from Trenburth *et al.* (2013). The above figure has been reproduced by kind permission of Kevin B. Trenburth of the National Center for Atmospheric Research, Boulder, Colorado, USA.

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J Webb contribution to published works

Table of roles and attribution

Paper	Role	Proportion of paper written
1. **Webb, J**., Sommer, S. G., Kupper, T., Groenestein, K., Hutchings, N. J., Eurich-Menden, B., Rodhe, L., Misselbrook, T. H. & Amon, B. (2012) **Gaseous emissions during the management of solid manures. A review**. *Sustainable Agriculture Reviews*. 8, 67-107.	Lead author	25%
2. **Webb, J**., Thorman, R. E., Fernanda-Aller, M. & Jackson, D.R. (2014a) **Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types**. *Atmospheric Environment*. 82, 280-287.	Lead author	80%
3. **Webb, J**., Audsley, E., Williams, A., Pearn, K. & Chatterton, J. (2014b) **Can UK livestock production be configured to maintain production while meeting targets to reduce emissions of greenhouse gases and ammonia**? *Journal of Cleaner Production*. 83, 204-211.	Lead author	40%
4. **Webb, J**., Pain, B., Bittman, S. & Morgan, J. (2010) **The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response - A review**. *Agriculture Ecosystems and Environment*. 137, 39-46.	Lead author	70%
5. Velthof, G. L., Lesschen, J.P., **Webb, J**., Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J. & Oenema, O. 2014. **The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000-2008**. *Science of the Total Environment*. 48-49, 1225-1233.	Co author	10%
6. **Webb, J**., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P. & Reid, J. (2013a) **An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure N efficiency**, In: Donald, S. (ed.), *Advances in Agronomy*. Academic Press, 371-442.	Lead author	60%
7. **Webb, J.**, Williams, A. G., Hope, E., Evans, D. & Moorhouse, E. (2013b) **Do foods imported into the UK leave a greater environmental footprint than the same foods produced within the UK?** *International Journal of Life Cycle Assessment*. 18, 1325-1343.	Lead author	40%
8. **Webb. J.**, Fernanda-Aller, M., Jackson, D. R. & Thorman, R. (2016) **Accounting for the nitrogen in solid manures incorporated immediately after**		

application in order to abate emissions of ammonia. *Nutrient Cycling in Agroecosystems*. 106, 131-141.		
9. **Webb, J**., Amon, B., Subedi, M. & Fullen, M. A. (2017) **Temporal changes in soil temperature at Wolverhampton, UK and Hohe Warte, Vienna, Austria 1976 to 2010**. *Weather*. In press.	Lead author	60%

Co-authors' agreements to contribution

Paper	Role	Proportion of paper written	Co-author
1. **Webb, J**., Sommer, S. G., Kupper, T., Groenestein, K., Hutchings, N. J., Eurich-Menden, B., Rodhe, L., Misselbrook, T. H., Amon, B. (2012) **Gaseous emissions during the management of solid manures. A review**. *Sustainable Agriculture Reviews*. 8, 67-107.	Lead author	25%	Karin Groenestein

Dear J,

I would put your contribution to the 'Solid-manure-paper' as cited below at 25%

Webb J, Sommer SG, Kupper T, Groenestein K, Hutchings NJ, Eurich-Menden B, Rodhe L, Misselbrook TH, Amon B. (2012). Gaseous emissions during the management of solid manures. A review. *Sustainable Agriculture Reviews*. 8, 67-107.

Best wishes,

Karin

2. **Webb, J**., Thorman, R. E., Fernanda-Aller, M. & Jackson, D. R. (2014) **Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types**. *Atmospheric Environment*. 82, 280-7.	Lead author	80%	Fernanda Aller

As a co-author of the paper
Webb, J., Thorman, R. E., Fernanda-Aller, M., Jackson, D. R. (2014). Emission factors for ammonia and nitrous oxide emissions following immediate manure incorporation on two contrasting soil types. *Atmospheric Environment*. 82, 280-7.
I estimate that the proportion of paper written by Mr J. Webb was 80%

Dr Maria Fernanda Aller
Innovation and Solutions Environment
http://isenvironment.com/
[e-mail address redacted]

3. **Webb, J**., Audsley, E., Williams, A., Pearn, K. & Chatterton J. (2014) **Can the UK livestock industry be configured to maintain production while meeting targets to reduce emissions of greenhouse gases and ammonia?** *Journal of Cleaner*	Lead author	40%	Adrian Williams

Production. 83, 204-211.

Happy New Year, J!
I agree with the paper allocations.

Best wishes
Adrian

4. **Webb, J**., Pain, B., Bittman, S. & Morgan, J. (2010) **The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response - A review.** *Agriculture Ecosystems and Environment*. 137, 39-46. Lead author 70% Shabtai Bittman

Dear Mr. Webb,

I believe that your role in the manuscript listed below was at least 70%.

Webb J, Pain B, Bittman S, Morgan J. (2010). The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response - A review. Agriculture Ecosystems and Environment 137, 39-46.

Good luck with you future endeavors and all the best for the New Year.

Shabtai Bittman.

5. Velthof G. L., Lesschen J. P., **Webb, J**., Pietrzak, S., Miatkowski, Z., Pinto, M., Kros, J. & Oenema, O. (2014) **The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000-2008**. *Science of the Total Environment*. 48-49, 1225-1233. Co author 10% Gerard Velthof

Dear Jim

First I like to wish you a happy 2017.

I hereby state that the proportion of authorship to the following paper was 10%:

Velthof G.L., Lesschen J.P., Webb J, Pietrzak S, Miatkowski Z, Pinto M, Kros J, Oenema O, 2014. The impact of the Nitrates Directive on nitrogen emissions from agriculture in the EU-27 during 2000-2008. Science of the Total Environment 468-469, 1225-1233.

Kind regards

Gerard Velthof

6. **Webb, J**., Sørensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P. & Reid. J. (2013) **An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure N efficiency**, In: Donald, S. (ed.), *Advances in Agronomy*, Academic Press, 371-442. Lead author 60% Peter Sorensen

Greetings

I hereby confirm that J Webb wrote at least 60% of the Paper:
Webb J, Sørensen P, Velthof G, Amon B, Pinto M, Rodhe L, Salomon E, Hutchings N, Burczyk P, Reid J. (2013). An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase manure N efficiency, in: Donald, S. (Ed.), Advances in Agronomy, Academic Press, 371-442.

I was co-author on the paper.

Kind regards

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7. **Webb, J**., Williams, A. G., Hope, E., Evans, D. & Moorhouse, E. (2013) **Do foods imported into the UK leave a greater environmental footprint than the same foods produced within the UK?** *International Journal of Life Cycle Assessment*. 18, 1325-1343.	Lead author	40%	Adrian Williams

Happy New Year, J!
I agree with the paper allocations.

Best wishes
Adrian

8. **Webb, J**., Fernanda-Aller, M., Jackson, D. R. & Thorman, R. 2016 **Accounting for the nitrogen in solid manures incorporated immediately after application in order to reduce emissions of ammonia**. *Nutrient Cycling in Agroecosystems*. 106, 131-141.	Lead author	80%	Fernanda Aller

As a co-author of the paper
Webb, J., Fernanda-Aller, M., Jackson, D.R. and Thorman, R. (2016). Accounting for the nitrogen in solid manures incorporated immediately after application in order to reduce emissions of ammonia. Nutrient Cycling in Agroecosystems, 1-11. http://dx.doi.org/10.1007/s10705-016-9794-x

I estimate that the proportion of paper written by Mr J. Webb was 80%

9. **Webb, J**., Amon, B., Subedi, M. & Fullen, M. A. (2017) **Temporal changes in soil temperature at Wolverhampton, UK and Hohe Warte, Vienna, Austria 1976 to 2010**. Weather. In press.	Lead author	70%	Mike Fullen

'Dear J

I hope you are well. Thank you for your message and co-author file. In fact, I would put your contribution to the 'Weather' paper at 70%.'

Additional references. References in italics are those cited in other papers

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