Inventory of Ammonia Emissions from UK Agriculture

2020

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Inventory Submission Report
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T H Misselbrook, S L Gilhespy
Rothamsted Research, North Wyke, Okehampton, Devon EX20 2SB

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Glossary of abbreviations

AFBI	Agri-Food and Biosciences Institute
AHDB	Agriculture and Horticulture Development Board
BSFP	British Survey of Fertiliser Practice
CAFRE	College of Agriculture, Food and Rural Enterprise
CI	Confidence interval
DA	Devolved Administration
DAERA	Department of Agriculture, Environment and Rural Affairs (Northern Ireland)
DEFRA	Department for Environment, Food and Rural Affairs (UK)
EF	Emission factor
FYM	Farmyard manure
GHG	Greenhouse Gas
N	Nitrogen
n	Number of observations
NARSES	National Ammonia Reduction Strategy Evaluation System
NH_3	Ammonia
NIGTA	Northern Ireland Grain Trade Association
SE	Standard error
TAN	Total ammoniacal nitrogen
UAN	Urea ammonium nitrate
UNECE	United Nations Economic Commission for Europe

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Summary

The combined UK Agriculture GHG and Ammonia emission model was used to compile the 1990-2020 ammonia emission inventory for UK agriculture, ensuring consistency of approach in terms of nitrogen flows and transformations for both the ammonia and GHG emission estimates. Year-specific livestock numbers and crop areas were included for 2020, together with information on fertiliser N use for 2020 and any changes in farm management practices where data were available. The estimate of ammonia emissions from UK agriculture for 2020 was 225.9 kt NH_3, representing a substantial decrease of 12.9 kt from the previously reported estimate (2021 submission) for 2019. Revisions to emission factors, N excretion parameters and some historical activity data resulted in a decrease of 4.2 kt in the total estimate for 2019 between the two reporting years. Changes in activity data between 2019 and 2020 resulted in a decrease in emission of 8.7 kt between the two years. Ammonia emissions from agriculture have decreased by 21% over the time period 1990-2020 and by 3.3% since 2005.

Table 1. Estimate of ammonia emission from UK agriculture for 2020 with livestock emissions reported either by livestock category (a) or manure management category (b) together with other non-livestock sources (c)

Source	kt NH_3*	% of total
a. Livestock category		
Cattle	115.3	51
Dairy cows	*58.1*	*26*
Other cattle	*57.2*	*25*
Sheep	11.8	5
Pigs	15.9	7
Poultry	29.6	13
Minor livestock†	1.3	1
b. Management category		
Grazing/outdoors	19.3	9
Housing	58.5	26
Hard standings	16.3	7
Manure storage	19.8	9
Manure application	57.5	25
c. Other sources		
Fertiliser application	34.6	15
Sewage sludge application	4.7	2
Digestate application	15.3	7
Non-manure digestate	*12.8*	*6*
Manure digestate	*2.5*	*1*
TOTAL	**225.9**	**100**

† Horses on agricultural holdings, goats and deer

* Totals may differ from sum of components due to rounding

Estimate of ammonia emission from UK agriculture for 2020

The 1990 – 2020 inventory estimates were as made in previous submissions, using the combined GHG and ammonia emission model for UK agriculture. This model uses the same underlying approach as in the previously used national-scale NARSES model (Webb and Misselbrook, 2004), but incorporates a much higher level of spatial (10 km grid cells), temporal (monthly) and sectoral (greater disaggregation of dairy, beef, sheep, grassland and cropping sectors) resolution for the bottom-up calculations. As part of the model development and improvement, revisions were made to some parameters in the N-flow calculations compared with the NARSES model to ensure consistency between the estimates of ammonia and greenhouse gas emissions. Further details of the model and parameterisation are given in the UK Informative Inventory Report and National Inventory Report for the 2022 submission.

Key areas of revision in the 2020 inventory were:

- Inclusion of 2020 livestock numbers, crop areas and fertiliser N use;
- Revision to ammonia emission factors for pig housing systems based on a recent AHDB-funded study
- Revision to nitrogen excretion estimates for pig and poultry across the time series based on the Defra WT1568 report
- Revision to some Northern Ireland dairy sector data (herd management structure, standard diets, diet composition), based on review by Ferris (2021)

Derivations of emission factors and reduction efficiencies assumed for mitigation practices are detailed in Appendices 1 and 2.

The estimate of emission from UK agriculture for 2020 was 225.9 kt NH_3. Cattle represent the largest livestock source and housing and land spreading the major sources in terms of manure management (Table 1). A breakdown of the estimate is given in Table 3, together with a comparison with the previously submitted 2019 inventory estimate.

Major changes between 2019 and 2020

1. *2020 livestock numbers*

Headline changes from 2019 were:
Cattle – a decrease in cattle numbers, by 1.2% for dairy cows and by 1.6% for other cattle
Pigs – a 0.2% decrease in pig numbers
Sheep – a 2.5% decrease in sheep numbers
Poultry – a 2.2% decrease in total poultry numbers, 2.4% decrease in layers and 1.2% decrease in broilers

2. *Fertiliser N use*

Total fertiliser N use declined by 10.1% between 2019 and 2020, predominantly because of a wet autumn period resulting in a significant move from winter-sown to spring-sown crops which are associated with lower N application rates. The amount of fertiliser N applied as urea decreased by 30.6%, and of urea ammonium nitrate by 19.5%, with those fertiliser types representing 10 and 11%, respectively, of total fertiliser N use in 2020. In addition to these changes in fertiliser N use, some revisions were made to the implementation of the method of analysis of BSFP data for the Arable sector, to be consistent with that used for the Grass sector. Also, a correction to the implementation of urease inhibitor within the arable sector from being applied to all N fertiliser types to only to urea and UAN was made. These corrections resulted in some small increases in the emission estimate across the time series.

3. *Revision to ammonia emission factors for pig housing*

Data reported in the AHDB study 'New Ammonia Emissions Factors for the English Pork Industry' (Dimmock and Stoddart, March 2021), based on measurements undertaken by Charman Ag., have been included in the database for pig housing ammonia emission factors. Measurements were made to derive average annual ammonia emission factors for straw-bedded and slatted-floor housing systems for dry sows, farrowing sows, weaners and finishing pigs. Emissions were reported as kg NH_3/place/year and were converted to a %TAN basis based on standard N excretion values for the different pig categories as derived from Defra-funded project WT1568. This study provided the first measurements for farrowing sows on straw (previously estimated from dry sows on straw) and weaners on straw (previously estimated from weaners on slats). Expressed on a %TAN basis, there was no evidence of a trend in time in the emission factors when included with the existing database. However, expressed per animal place, emission factors have decreased over time because of decreasing N excretion rates associated with improved pig feed formulation and utilisation. Including these reported results in the emission factor database, and reviewing existing values, resulted in revised emission factors with a small increase in the value for dry sows and weaners on slatted floor systems, a decrease in the value for dry sows, farrowing sows and finishing pigs on straw, and for farrowing sows on straw, and almost no change for the values for finishing pigs on slatted-floor systems and weaners on straw (Table 2).

4. *Revision to pig and poultry N excretion rates*

Pig and poultry N excretion rates were revised based on values from Defra study WT1568 and the existing values used up to 2010 based on WT0715NVZ. The WT1568 showed that N excretion rates had largely continued to decrease (although not for all categories) since 2010, where previously rates had been kept constant at 2010 values. WT1568 is taken to be representative of 2016 values, and values post-2016 have been kept constant at 2016 values until further evidence of a continued trend becomes available. N excretion rates per pig or poultry category are interpolated between the 1990 and 2004 estimates (WT0715NVZ data) and between 2004 and 2016.

Table 2. Effect of inclusion of AHDB study values and review of existing values on ammonia emission factors (as % of TAN deposited in the house, together with standard error, SE, and number of observations, n) for pig housing

Housing system	Previous values			Updated values		
	EF	SE	n	EF	SE	n
Dry sows on slats	22.9	14.9	2	27.5	6.91	3
Dry sows on straw	43.9	9.62	12	30.8	9.80	9
Farrowing sows on slats	30.8	2.96	7	28.6	3.02	9
Farrowing sows on straw	= dry sows on straw			33.5		1
Boars on straw	= dry sows on straw			= dry sows on straw		
Finishing pigs on slats	29.4	2.27	17	29.2	2.73	18
Finishing pigs on straw	26.6	5.11	15	19.6	5.13	13
Weaners on slats	7.9	2.01	2	12.9	4.29	4
Weaners on straw	7.2			7.4		1

5. Revision to Northern Ireland dairy sector activity data

Conrad Ferris (AFBI, Northern Ireland) conducted a review of the allocation of dairy cattle in Northern Ireland to different management systems and dairy cow and young stock diets to improve the representativeness of the ammonia and GHG inventory for the Northern Ireland dairy sector, many parameters for which are currently based on survey data for England. Sources of information included DAERA, AFBI, CAFRE and NIGTA. Data were collated for 1990, 2005 and ‘present’. One of the more significant revisions was to the number of dairy cows managed as ‘all year housing’, being considered greater in Northern Ireland than the current estimate for England, with consequent knock-on effects for the quantity of manure generated at housing and managed through storage and spreading.

Table 3. Estimate of ammonia emissions (kt NH_3) from UK agriculture, 2020*

Source	2019 as per 2021 submission	**2019 as per 2022 submission**	**Reasons for change between submissions**	**2020**	**Reasons for change from 2019**
Cattle					
Grazing	8.5	**8.4**	Some revisions to the management and diets in the dairy sector for Northern Ireland	**8.3**	Decrease in cattle numbers offset to some extent by an increase in dairy cow milk yield and N excretion; increase in manure going to anaerobic digestion
Landspreading	35.4	**36.7**		**36.4**	
Housing	41.0	**41.2**		**41.0**	
Hard standings	16.3	**16.4**		**16.3**	
Storage	13.3	**13.3**		**13.2**	
Total Cattle	113.3	**116.1**		**115.3**	
Sheep					
Grazing	8.7	**8.7**		**8.4**	Decrease in sheep numbers
Landspreading	1.3	**1.3**		**1.2**	
Housing	1.3	**1.3**		**1.3**	
Storage	0.9	**0.9**		**0.9**	
Total Sheep	12.1	**12.1**		**11.8**	
Minor livestock†	1.4	**1.3**		**1.3**	
Pigs					
Outdoor	1.0	**1.1**	Revision to N excretion rates for all pig categories; revision to housing EF	**1.1**	Decrease in pig numbers; increase in manure going to anaerobic digestion
Landspreading	4.3	**4.0**		**3.9**	
Housing	10.3	**8.0**		**7.8**	
Storage	3.2	**3.2**		**3.1**	
Total Pigs	18.5	**16.3**		**15.9**	
Poultry					
Outdoor	1.0	**1.1**	Revision to N excretion rates for all poultry categories	**1.0**	Decrease in poultry numbers; increase in manure going to anaerobic digestion
Landspreading	21.9	**18.5**		**18.2**	
Housing	9.0	**8.3**		**8.0**	
Storage	2.8	**2.5**		**2.4**	
Total Poultry	33.7	**30.3**		**29.6**	
Fertiliser	40.8	**41.3**	Revision to method implementation for arable crops	**34.6**	Large decrease in total fertiliser N use
Sewage sludge	4.7	**4.7**		**4.7**	
Non-manure digestate	11.3	**12.5**	Revision to 2019 estimate of digestate quantity	**12.8**	Increase in the quantity of digestate
TOTAL	**238.8**	**234.6**		**225.9**	

*Totals may differ from sum of components due to rounding
†Including horses on agricultural holdings, goats and deer

Emission Trends: 1990 - 2020

Retrospective calculations based on the most recent inventory methodology were made for the years 1990 to 2020 (Table 4). There has been a steady decline in emissions from UK agriculture over the period 1990 – 2010, largely due to declining livestock numbers (Fig. 1) and fertiliser N use (Fig. 2), but also from increases in production efficiency, but this decline has levelled off in recent years. Emissions have declined by 22% since 1990, and by 4.7% since 2005, due to a combination of the trend in livestock numbers, fertiliser N use and some uptake of ammonia abatement techniques. It is anticipated that fertiliser N use will increase again from the sharp reduction seen between 2019 and 2020 that was due to poor autumn weather resulting in a move from winter- to spring-cropping associated with lower average N application rates.

Table 4. Estimates of ammonia emission from UK agriculture 1990 – 2020

Source	1990	2000	2005	2010	2015	2020
Total	**288.8**	**251.1**	**237.1**	**222.6**	**231.2**	**225.9**
Cattle	113.9	113.8	117.7	115.2	116.6	115.3
Sheep	14.8	14.8	12.5	10.6	11.8	11.8
Pigs	39.9	29.7	21.3	17.6	16.1	15.9
Poultry	51.5	50.3	42.7	32.8	28.2	29.6
Minor livestock	1.1	1.5	1.8	1.6	1.5	1.3
Fertiliser	59.4	39.2	37.1	39.4	43.5	34.6
Sewage sludge	1.5	1.8	3.7	3.9	4.3	4.7
Digestate	0.0	0.0	0.5	1.6	9.2	12.8
Field burning	6.6	0.0	0.0	0.0	0.0	0.0

Figure 1. Trends in livestock numbers 1990 – 2020. Changes are relative to a reference value of 100 in 1990.

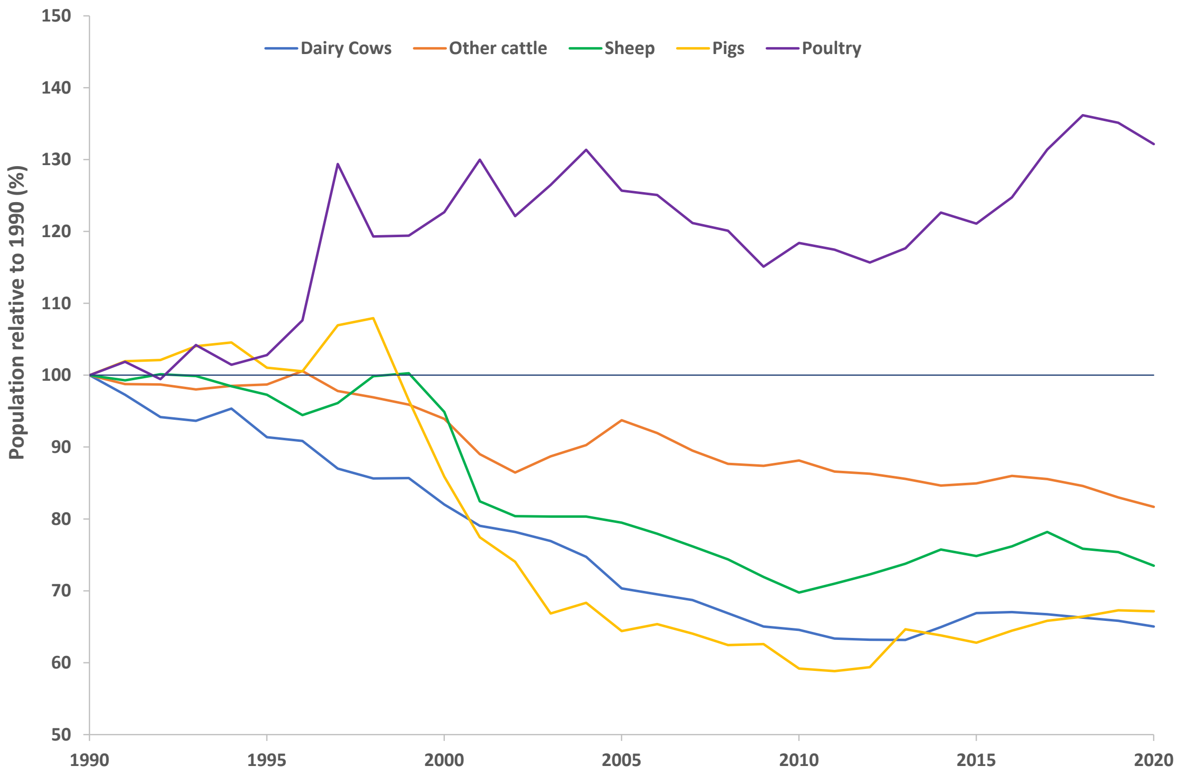
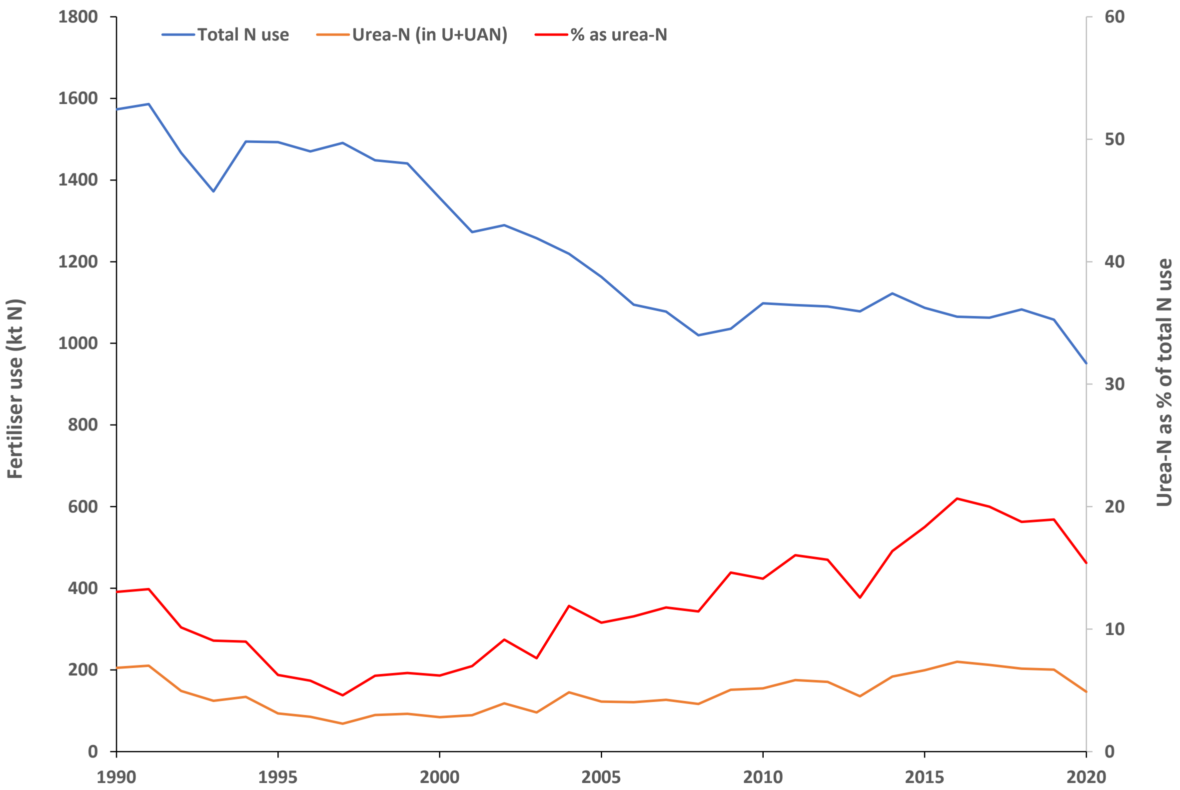


Figure 2. Changes in fertiliser N use 1990 – 2020.



Uncertainties

An estimate of the uncertainties in the emission inventory estimate was conducted using Monte Carlo simulation, in which a probability distribution function was provided for each of the model inputs (activity or emission factor data), based on the distribution of raw data or, where no or only single estimates exist, on expert assumptions. The 95% confidence interval for the total inventory estimate was estimated to be approximately ±15% (i.e. ±33.9 kt NH_3 for the 2020 estimate).

NB: uncertainties related to emissions from minor livestock, sewage sludge and digestate applications to land are not currently included in this overall estimate.

Appendix 1: Ammonia Emission Factors for UK Agriculture

Introduction

This report described the emission factors (EFs) and where appropriate standard errors (SE) for ammonia (NH_3) emissions from agricultural sources that are to be used in the improved greenhouse gas (GHG) emission inventory for UK agriculture being developed under the UK government-funded Defra project AC0114. The improved GHG inventory for UK agriculture uses a nitrogen (N) mass flow approach in calculating emissions from livestock manure management with the initial N input as excretion by livestock and subsequent losses and transformations (between organic and total ammoniacal N, TAN) being modelled at each management stage i.e. livestock housing, manure storage/treatment and manure application to land. Ammonia EFs are expressed as a percentage of the TAN content of the manure N pool at each management stage. In addition, EF are described for emissions from grazing returns (expressed as a percentage of TAN, which is generally equated with the urine fraction of the excreta) and for N fertiliser applications (with the EF expressed as a percentage of the total fertiliser N). Country- and practice-specific EFs have been derived for the major emission sources across the different agricultural sectors as described below.

1. Livestock housing

1.1. Cattle

Emission factors for two types of cattle housing are currently defined; slurry systems (solid-floor, cubicle housing with scraped passage) and deep litter straw-bedded housing generating farmyard manure (FYM). There is no differentiation between dairy and beef cattle, but a different EF was derived for calves on deep litter based on limited measurement data and the assumption that the straw bedding to excreta ratio is much greater for calves than for older cattle (Table 1). The underlying studies from which these EFs are derived are given in Annex 1 (Table A1).

It is recognised that slatted-floor slurry systems also exist for dairy and beef systems, particularly in Northern Ireland and Scotland, and that the current slurry housing system EF may not be representative of these systems.

Table 1. Cattle housing EFs (as % of TAN deposited in the house)

Housing system	EF	SE	n
Slurry, all cattle	27.7	3.85	14
Deep litter (FYM), all cattle except calves	16.8	1.97	10
Deep litter (FYM), calves	4.2	1.62	2

Seasonal differentiation in the EF is not included in the inventory. The EF for housing might be expected to be greater in summer, because of higher temperatures. However, work by Phillips *et al*. (1998) showed that summer emissions from dairy cattle housing, where the cattle come in for part of the day for milking, were of a similar magnitude to winter emissions.

1.2. Pigs

As for cattle, housing EFs for pigs have been derived for two management systems, slurry-based and FYM-based, but for a larger number of animal categories (Table 2). A review conducted as part of Defra project AC0123 in 2012 concluded that pig housing has not changed considerably over the inventory reporting period and that the EF reported here are relevant for current housing systems. This was largely confirmed (for EF expressed as %TAN) by a more recent housing emissions measurement study funded by AHDB (Dimmock and Stoddart, 2021). Most measurements have been made for finishing pigs on either slatted floor or straw-bedded systems, with fewer or no measurements for the other pig categories (Table A2).

Table 2. Pig housing EFs (as % of TAN deposited in the house)

Housing system	EF	SE	n
Dry sows on slats	27.5	6.91	3
Dry sows on straw	30.8	9.80	9
Farrowing sows on slats	28.6	3.02	9
Farrowing sows on straw	33.5		1
Boars on straw	30.8	dry sows value used	
Finishing pigs on slats	29.2	2.73	18
Finishing pigs on straw	19.6	5.13	13
Weaners on slats	12.9	4.29	4
Weaners on straw	7.4		1

1.3. Poultry

Measurements have been made from poultry housing for the poultry categories laying hens, broilers and turkeys (Table A3). For pullets, breeding hens and other classes of poultry not categorised in the table above, a weighted average of the broiler and turkey data were used to derive an emission factor of 14.1%. Laying hen systems are further categorised as cages (old-style, small battery cages, not permitted after 2012) without belt-cleaning, perchery, free-range and cages (old-style) with belt cleaning, and more modern housing systems as free-range single or multi-tier and colony cages and colony cages with belt-cleaning (based on data from Defra AC0123).

Table 3. Poultry housing EFs (as % of TAN deposited in the house)

Housing system	EF	SE	n
Layers, deep pit (‘old’ cages, perchery, free-range)	35.6	8.14	7
Layers, ‘old’ cages with belt-cleaning	14.5	4.79	5
Layers free-range single tier	20.1	5.85	3
Layers free-range multi-tier	10.7	3.37	3
Layers colony cages belt-cleaned	8.9	3.15	3
Broilers	9.9	0.93	15
Turkeys	36.2	30.53	3
Pullets, breeding hens and all other poultry	14.1	Based on broilers and turkeys	

1.4. Sheep

No specific measurements have been conducted for sheep housing, so the same value is used as for straw-bedded cattle housing i.e. 16.8% of the TAN deposited in the house.

1.5. Horses

Horses kept on agricultural holdings have an assumed N excretion of 50 kg per animal per year and are assumed to spend 25% of the year housed. Emission factors (expressed as %TAN) are assumed to be the same as for cattle on FYM.

2. Hard standings (unroofed outdoor concrete yards)

2.1. Cattle

From Misselbrook et al. (2006), an EF of 75% of the TAN left after scraping is assumed, based on mean measured values of 0.47 and 0.98 g NH_3-N animal^{-1} h^{-1} for dairy and beef cattle, respectively, with respective standard errors of 0.09 (n=28) and 0.39 (n=30) g NH_3-N animal^{-1} h^{-1}.

2.2. Sheep

An EF of 75% of the TAN left after scraping is also assumed for sheep, based on Misselbrook et al. (2006) and measured mean value of 0.13 g NH_3-N animal^{-1} h^{-1} and a standard error of 0.09 (n=7) g NH_3-N animal^{-1} h^{-1}.

3. Manure storage

3.1. Slurry

Derived EF for cattle and pig slurry storage are given in Table 4. Measurements from slurry lagoons and above-ground tanks are generally reported as emission per unit area, with only few studies containing sufficient information from which to derive an EF expressed as a percentage of the TAN present in the store (Tables A4 and A5). The EF for lagoons, in particular, are high and substantiated by very little underlying evidence (with no differentiation between pig and cattle slurries) so further measurements are warranted for this source. Emissions from below-slat slurry storage inside animal housing are assumed to be included in the animal housing EF, so below-slat storage does not appear as a separate storage category. As only few measurement data are available for EF derivation, and some categories of storage 'read across' from others, a default uncertainty estimate of ±30% for the 95% confidence interval is suggested for all slurry storage categories.

Table 4. Slurry storage EF (as % of TAN present in the store)

Storage system	EF	Uncertainty (95% CI)
Cattle slurry above-ground store (no crust)	10†	3.0
Cattle slurry weeping wall	5	1.5
Cattle slurry lagoon (no crust)	52	15.6
Cattle slurry below-ground tank	5‡	1.5
Pig slurry above-ground store	13	3.9
Pig slurry lagoon	52	15.6
Pig slurry below-ground tank	7*	2.1

†assumed to be double that of crusted slurry (for which measurements were made); ‡assumed to be the same as for above-ground slurry store with crust; *assumed to be half the value of above-ground slurry store

3.2. Solid manure

Derived EF for cattle, pig and sheep FYM and poultry manure storage are given in Table 5. There is large variability in the EF for cattle and pig FYM, with weather conditions in particular influencing emissions, and a combined EF of 28.2% (SE 6.28) is probably justified. Details of the underlying data are given in Tables A4, A5 and A6. The EF for horse FYM is assumed to be the same as that for cattle FYM.

Table 5. FYM and poultry manure storage EF (as % of TAN present in the store)

Storage system	EF	SE	n
Cattle FYM	26.3	8.28	10
Pig FYM	31.5	10.33	6
Sheep FYM	26.3	Cattle FYM EF used	
Layer manure	14.2	2.99	8
Broiler litter	9.6	2.69	11
Other poultry litter (excluding ducks)	9.6	Broiler litter EF used	
Duck manure	26.3	Cattle FYM EF used	

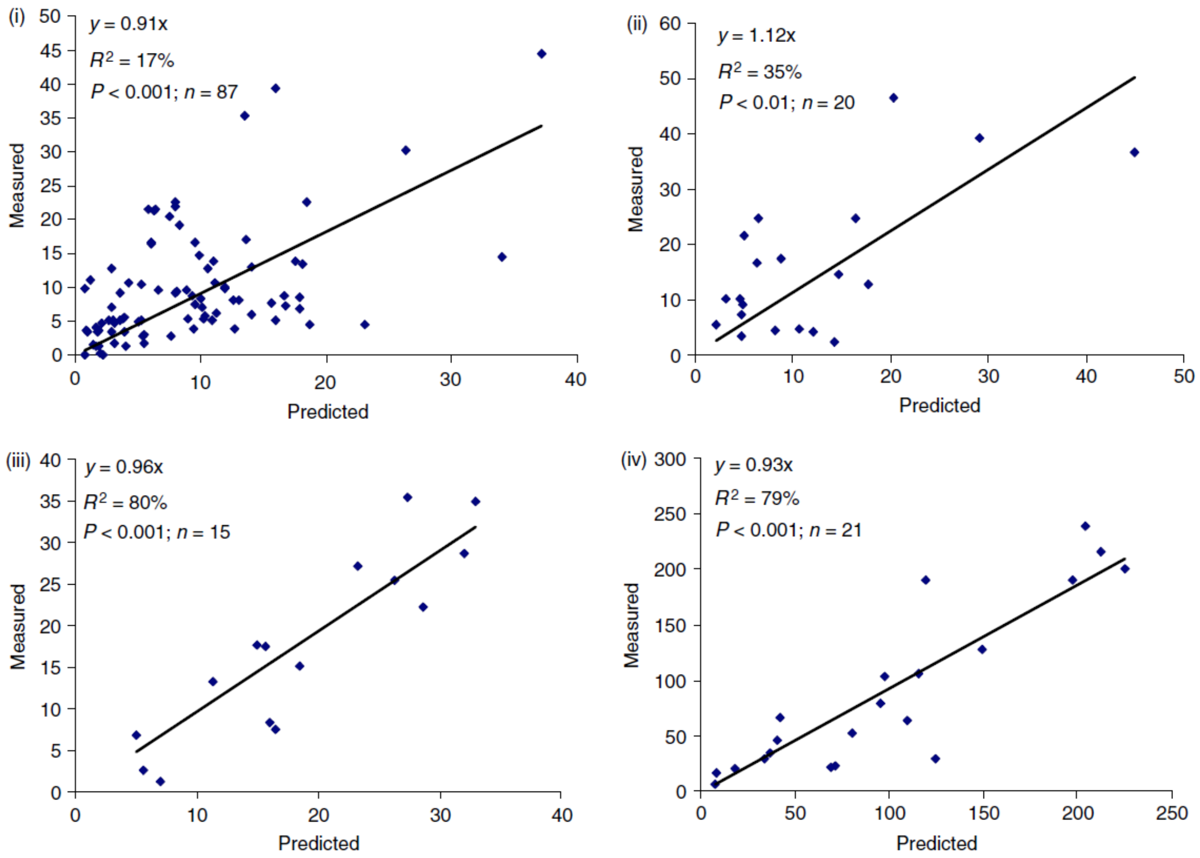
4. Manure application

Emission factors following manure applications to land are derived using the MANNER_NPK model (Nicholson et al., 2013), which established standard emission functions using a Michaelis-Menten curve fitting approach for different manure types and applied modifiers according to soil moisture, land use and slurry dry matter content (Table 6). Other modifiers included in the model according to wind speed and rainfall within 6 hours of application were not included in the national scale derivation of EF. Modifiers according to application method (splashplate assumed as baseline) and timing of soil incorporation are included as mitigation methods associated with an emission reduction efficiency and are detailed in the separate report on NH_3 emission mitigation techniques. Table 7 shows the resulting EF as used in the national inventory. Uncertainties for the weighted average EF in Table 7 were derived from the error terms in the modelled vs. observed plots using the MANNER_NPK model against UK-specific available data for cattle slurry, pig slurry, FYM (cattle and pig) and poultry manure (Fig. 1).

Table 6. Ammonia EF and modifiers according to the MANNER_NPK model

Manure type	Standard EF (as % of TAN applied)	Soil moisture modifier	Land use modifier	Slurry DM modifier	
				Slope	Intercept
Cattle slurry	32.4	x1.3 for dry soil (summer, May-July); x0.7 for moist soil	x0.85 for arable; x1.15 for grassland	8.3	50.2
Pig slurry	25.5	-	-	12.3	50.8
FYM (incl. duck)	68.3	-	-	-	-
Poultry manure	52.3	-	-	-	-

Figure 1. MANNER_NPK model performance against UK data sets for ammonia emissions following land spreading (Nicholson et al., 2013). Cattle slurry (I), pig slurry (II), FYM (III) and poultry manure (IV).



Standard errors for the derived slope values were 0.073, 0.148, 0.061 and 0.063 for I, II, III and IV, respectively.

Table 7. Manure application EF (as % of TAN applied to land)

Manure type	Land use	Season	Slurry DM	EF, %TAN	95% CI, %TAN
Cattle slurry	Grassland	Summer	<4%	32.4	
			4-8%	48.4	
			>8%	64.5	
			Weighted average	52.5	8.4
Cattle slurry	Grassland	Rest of year	<4%	17.4	
			4-8%	26.1	
			>8%	34.7	
			Weighted average	28.2	4.5
Cattle slurry	Arable	Summer	<4%	23.9	
			4-8%	35.8	
			>8%	47.7	
			Weighted average	38.8	6.2
Cattle slurry	Arable	Rest of year	<4%	12.9	
			4-8%	19.3	
			>8%	25.7	
			Weighted average	20.9	3.4
Pig slurry	-	-	<4%	19.2	
			4-8%	31.8	
			>8%	44.3	
			Weighted average	24.2	6.4
FYM (all)	-	-	-	68.3	8.7
Poultry manure (all)	-	-	-	52.3	7.1

5. Grazing and outdoor livestock

5.1. Cattle and sheep

The average EF for cattle and sheep (there was no evidence to warrant differentiation) was derived from a number of grazing studies (Table A7) with a range of fertiliser N inputs to the grazed pasture. Emissions due to the fertiliser applied to the grazed pasture were discounted using a mean EF for ammonium nitrate applications to grassland (1.4% of N applied). The remaining emission was expressed as a percentage of the estimated urine N (equated here with the TAN in excreta) returned to the pasture by the grazing cattle or sheep. A mean EF of 6% of excreted TAN, with a standard error of 0.7 (n=20) was derived. This value is also assumed for grazing deer and goats.

5.2. Outdoor pigs

Only two studies have made measurements of NH_3 emissions from outdoor pigs (Table A8), and sufficient data were provided from only one of these to derive a rounded EF of 25% of TAN excreted, with an assumed 95% confidence interval of ± 7.5 % of TAN excreted.

5.3. Outdoor poultry

No studies of emissions from outdoor poultry have been reported. An EF of 35 % of excreted TAN has been assumed, as it is likely that emissions from freshly dropped excreta will be substantially lower than from applications of stored manure in which hydrolysis of the uric acid will have occurred to a greater extent. The 95% confidence interval for this EF is assumed to be ± 15 % of TAN excreted. 20% of poultry droppings are estimated to be voided outside the house (Pers. comm. Elson, ADAS); this is an increase on the previous estimate of 12% and represents a real change in that newer systems are designed such that birds do spend longer outside.

6. Nitrogen fertiliser applications

A model based on Misselbrook et al. (2004) but modified according to data from the Defra-funded NT26 project is used to estimate EF for different fertiliser types. Each fertiliser type is associated with an EF_{max} value, which is then modified according to soil, weather and management factors (Table 8). EF are calculated and applied at a 10 km grid resolution, so averaged implied EF at DA or UK level may vary from year to year. The use of urease inhibitors with urea-based fertilisers and soil placement of N fertiliser are considered as abatement measures and are detailed in the separate report on NH_3 emission mitigation techniques.

Table 8. Nitrogen fertiliser application EF

Fertiliser type	EF_{max} (as % of N applied)	Modifiers†
Ammonium nitrate	1.8	None
Ammonium sulphate and diammonium phosphate	45	Soil pH
Urea	45	Application rate, rainfall, temperature
Urea ammonium nitrate	23	Application rate, rainfall, temperature
Other N compounds	1.8	None

†Modifiers:

Soil pH – if calcareous soil, assume EF as for urea; if non-calcareous, assume EF as for ammonium nitrate

Application rate

- if <=30 kg N ha^{-1}, apply a modifier of 0.62 to EF_{max}
- if >=150 kg N ha^{-1}, apply a modifier of 1 to EF_{max}
- if between 30 and 150 kg N ha^{-1}, apply a modifier of ((0.0032xrate)+0.5238)

Rainfall – a modifier is applied based on the probability of significant rainfall (>5mm within a 24h period) within 1, 2, 3, 4 or 5 days following application, with respective modifiers of 0.3, 0.5, 0.7, 0.8 and 0.9 applied to EF_{max}.

Temperature – apply a modifier, with the maximum value constrained to 1, of

$$RF_{temp} = e^{\left(0.1386 \times \left(T_{month} - T_{UKannual}\right)\right)/2}$$

where $T_{UKannual}$ is the mean annual air temperature for the UK

An uncertainty bound to the EF_{max} values of ±0.3 x EF_{max} is suggested based on the measurements reported under the NT26 project.

7. Digestate applications to land

7.1. Food and crop-based digestates

Tomlinson et al. (2019) derived an NH_3 EF for surface broadcast digestate (across all types) of 34.7% of the applied N (range 15.4 – 54). Assuming 80% of total N to be in the TAN form, a revised EF of 43% of TAN applied (range 19 – 68) is derived for use in the agricultural inventory model.

7.2. Livestock manure based digestate

Literature evidence on the effect of anaerobic digestion on NH_3 emissions at land spreading is mixed, with differing effects of a lower dry matter content (potentially reducing emissions) but higher pH and TAN content (potentially increasing emissions). The assumption applied in the UK inventory is that, expressed as a percentage of the TAN applied, the NH_3 EF for slurry-digestates are the same as for the corresponding slurry; for cattle and pig FYM-digestates, cattle and pig slurry EF are applied, and for poultry manure digestates the value for pig slurry is applied (based on their having similar characteristics).

7.3. Activity data

Material inputs to anaerobic digestion facilities are derived from the National Non-Food Crops Centre (most recently NNFCC, 2020), with estimated capacity and type of feedstock. Total N content of digestates is based on literature review (Tomlinson et al., 2019) giving mean values of 5.00, 3.97 and 3.35 kg t^{-1} for food-waste, energy crop and other organic residue based digestates, respectively, and it is assumed there is no trend across the time series. The TAN content of all digestate types is assumed as 80% of the total N content (RB209).

Annex 1: Sources of underlying data for the UK ammonia emission factors

Table A1. Studies delivering cattle housing EF

Study	Emission g NH_3-N lu^{-1} d^{-1}	No. studies	Emission Factor % TAN	Notes on derivation of EF as %TAN
Slurry-based systems				
Demmers et al., 1997	38.6	1	31.1	Dairy cows 1995, assume N excretion of 100 kg N per year
WA0653	21.2	6	19.2	Dairy cows 1998/99, assume N excretion of 105 kg N per year
Dore et al., 2004	72.5	1	53.1	Dairy cows 1998/99, assume N excretion of 105 kg N per year
WAO632/AM110	50.8	3	39.4	Using actual N balance data
Hill, 2000	29.4	1	22.8	Dairy cows 1997, assume N excretion of 104 kg N per year
AM0102	30.5	2	23.7	Dairy cows 2003, assume N excretion of 113 kg N per year
Mean	40.5		31.6	
Weighted mean	34.3		**27.7**	
Straw-bedded systems				
WA0618 (PT)	20.6	1	18.3	Growing beef, assume N excretion of 56 kg N per year
WAO632/AM110 (PT)	35.0	3	21.6	Using actual N balance data
WA0722	33.2	1	22.9	Dairy cows, 6,500 kg milk per year, therefore assume N excretion of 112 kg N per year
AM0103 (PT)	13.9	1	11.7	Growing beef, values directly from report
AM0103 (Comm farm)	16.7	1	13.4	Dairy cows, assuming 125 g TAN excretion per day (AM0103 report)
AC0102	14.0	3	12.5	Growing beef, assume N excretion of 56 kg N per year
Mean	22.2		16.7	
Weighted mean	23.1		**16.8**	
Calves				
Demmers et al. 1997	13.0	1	5.8	Assume calf weight 140 and N excretion 38 kg N per year
Koerkamp et al. 1998	6.2	1	2.6	Assume calf weight 140 and N excretion 38 kg N per year
Mean	9.6		**4.2**	

Table A2. Studies delivering pig housing EF

Study	n	Emission factor expressed as:			Av. Live weight	N excretion, kg/place/y
		kg NH_3/place/y	% TAN	% N		
Dry sows on slats						
Peirson, 1995	2	3.01	22.9	16.0	200	15.5
AHDB, 2021	1	3.65	36.7	25.7	200	11.7
Weighted mean			**27.5**	**19.2**		
Dry sows on straw						
Peirson, 1995	2	1.67	12.6	8.9	200	15.5
Koerkamp et al., 1998	1	2.61	19.8	13.9	200	15.5
OC9523	4	4.64	35.3	24.7	200	15.5
AM0102	1[†]	8.97	68.1	47.7	200	15.5
AHDB, 2021	1	2.29	23.0	16.1	200	11.7
Weighted mean			**30.8**	**21.6**		
Farrowing sows on slats						
Peirson, 1995	3	6.46	33.8	23.7	225	22.5
Koerkamp et al., 1998	1	4.41	23.1	16.1	240	22.5
AM0102	3	5.38	30.4	21.3	225	20.8
AHDB, 2021	2	3.76	21.0	14.7	225	21.1
Weighted mean			**28.6**	**20.0**		
Farrowing sows on straw						
AHDB, 2021	1	6.01	33.5	23.5	225	21.1
Weaners on slats						
Peirson, 1995	1	0.84	22.5	15.7	12	4.4
Koerkamp et al., 1988	1	0.22	5.9	4.1	12	4.4
AHDB, 2021	2	0.35	10.3	7.2	18	4.0
Weighted mean			**12.2**	**8.6**		
Weaners on straw						
AHDB, 2021	1	0.25	7.4	5.1	18	4.0

Finishers on slats						
Peirson, 1995	3	3.18	26.9	18.8	50	13.9
Demmers, 1999	1	2.41	25.3	17.7	25.7	11.2
Koerkamp et al., 1998	1	1.59	16.7	11.7	35	11.2
WA0632	1	3.66	40.4	28.3	60	10.7
WA0720 (fan vent, comm farm)	1	4.59	41.5	29.1	50	13.0
WA0720 (acnv, comm farm)	3	3.42	31.0	21.7	50	13.0
WA0720 (part slat, comm farm)	2	2.28	20.7	14.5	50	13.0
WA0720 (fan vent, Terrington)	1	2.85	21.6	15.2	67.5	15.5
WA0720 (part slat, Terrington)	1	2.31	17.6	12.3	67.5	15.5
AHDB, 2021	1	2.60	26.8	18.8	70	11.4
Weighted mean			**29.2**	**20.4**		
Finishers on straw						
Peirson, 1995	2	2.40	20.3	14.2	50	13.9
Koerkamp et al., 1998	1	0.88	9.2	6.4	35	11.2
WA0632	1[†]	5.65	53.7	37.6	60	12.4
AM0102	1	1.06	9.6	6.7	50	13.0
AM0103 Terrington	2	2.72	23.6	16.7	75	13.4
AM0103 Commercial	1	1.21	10.9	7.7	40	13.0
AC0102	4	1.68	16.6	11.6	45	11.9
AHDB, 2021	1	1.66	17.1	12.0	70	11.4
Weighted mean			**19.6**	**13.7**		

[†]Weighting value reduced to 1 from 4 or 5 as values seem to be high outliers

Table A3. Studies delivering poultry housing EF

Study	Emission g N $lu^{-1}d^{-1}$	No. studies	Emission Factor % TAN	Notes
Layers – deep-pit (cages, perchery, free-range)				
Peirson, 1995	79.0	3	22.1	Assume N excretion 0.82 kg (1995)
G Koerkamp, 1998	184.1	1	49.2	Assume N excretion 0.82 kg (1995)
G Koerkamp, 1998	146.1	1	39.0	Assume N excretion 0.82 kg (1995)
WA0368	139.2	1	36.8	Assume N excretion 0.79 kg (1998)
WA0651	196.8	1	57.9	Assume N excretion 0.78 kg (2000)
Mean	149.0		41.0	
Weighted mean	107.0		**35.6**	
Layers – deep litter: assume same EF as for perchery				
Layers – belt-cleaned (cages)				
Peirson, 1995	36.0	3	10.1	Assume N excretion 0.82 kg (1995)
WA0651 Gleadthorpe	79.2	1	23.3	Assume N excretion 0.78 kg (2000)
WA0651 comm. farm	64.8	1	19.1	Assume N excretion 0.78 kg (2000)
Mean	60.0		17.5	
Weighted mean	50.4		**14.5**	
Layers – Free-range single tier				
AC0123		3	20.1	Refer to AC0123 for details
Layers – Free-range multi-tier				
AC0123		3	10.7	Refer to AC0123 for details
Layers – colony cages with belt cleaning				
AC0123		3	8.9	Refer to AC0123 for details
Broilers				
Demmers et al. 1999	42.0	1	7.0	Assume N excretion 0.56 kg (1995)
Robertson et al 2002	44.0	4	8.3	Assume N excretion 0.55 kg (2000)
Frost et al 2002	54.0	4	9.2	Assume N excretion 0.55 kg (2000)
WA0651 winter	36.0	4	9.5	Derived N excretion from N balance
WA0651 summer	67.2	4	15.6	Derived N excretion from N balance
WA0651 drinkers	52.8	2	10.9	Derived N excretion from N balance
Mean	49.3	19	10.1	
Weighted mean	50.1		**10.5**	
Turkeys				
Peirson et al, 1995	93.0	3	**36.6**	

A measurement from Groot Koerkamp *et al*. (1998) for broiler housing (164 g N lu^{-1} d^{-1}) has been excluded from the inventory. This measurement was from a very old housing system, not representative of broiler housing, and was also based on a single measurement in time rather than an integrated measurement over the duration of the crop.

Table A4. Studies delivering cattle manure storage EF

Mean EF g N m^{-2}d^{-1}	Values g N m^{-2}d^{-1}	n	Emission as % TAN	Source
Slurry stores and lagoons without crusts				
3.42				Assumed to be double that for crusted stores (WA0641, WA0714)
Slurry stores and lagoons with crusts, weeping wall stores				
1.71	0.6		**2.3	(Phillips *et al*., in press)
	1.27, 3.65, 5.7		NA	WA0625
	0.44	2	*6.0	WA0632*
	1.8		NA	WA0641
	1.7		NA	Hill (2000)
	0.48	2	NA	WA0714
	0.5,0.72,0.42,0.7		51.5 (lagoons)	WA0717
	3		5.3 (w.wall)	AM0102
	4.2		NA	
Below ground slurry tanks				Assume same as for crusted above-ground tank
FYM heaps	**g N t^{-1} initial heap mass**			
265	421, 101, 106		NA	WA0618
		2	49	WA0519
		2	29	WA0632
		3	11	Chadwick, 2005
		2	31	WA0716
		1	11	Moral et al., 2012

** Emissions expressed per day. This value assumes 90 d storage.
Slurry stores are assumed to develop a crust unless they are stirred frequently.
Values derived from measurements made using Ferm tubes have been corrected to account for incomplete recovery of ammonia by Ferm tubes (Phillips *et al*., 1998). (*IGER values have been corrected using a factor of **0.7**).

Table A5. Studies delivering pig manure storage EF

Mean EF g N m^{-2} d^{-1}	Values g N m^{-2} d^{-1}	n	Emission as %TAN	Source
Slurry stores and lagoons				
3.16	1.34	4	13.0	WA0632
	2.47, 6.2		NA	WA0625
	2.4		NA	Phillips *et al*. (1997)
	1.56		NA	WA0708
	5.0		NA	Phillips *et al*. (1997)
Below ground slurry tanks				Assume 50% of EF for above-ground tank
FYM heaps	**g N t^{-1} initial heap mass**			
1224	539	4	20	WA0632
	1015	2	54	WA0716

Values derived from measurements made using Ferm tubes have been corrected to account for incomplete recovery of ammonia by Ferm tubes (Phillips *et al*., 1998).

Table A6. Studies delivering poultry manure storage EF

Mean EF	Values	n	Emission as %TAN	Source
g N t^{-1} initial heap mass				
Layer manure				
1956	318	2	3.5	WA0712
	3172	4	14.3	WA0651 (belt scraped)
	3141	1	29.5	WA0651 (deep pit)
	1193	1	20.0	WA0651 (belt scraped)
Litter				
1435	478	1	2.2	WA0712
	1949	4	19.9	WA0651 (winter)
	158	4	1.8	WA0651 (summer)
	639	2	8.4	WA0651 (drinkers)
	3949		NA	WA0716

Table A7: Studies delivering cattle and sheep grazing EF

	N input	Urine N	NH_3 emission	Due to fertiliser	Due to urine	Emission Factor
			Kg N ha^{-1}			%TAN
CATTLE						
Bussink	*Fert Res 33 257-265*					
1987	550	425	42.2	7.7	34.5	8
1988	550	428	39.2	7.7	31.5	7
1988	250	203	8.1	3.5	4.6	2
Bussink	*Fert Res 38 111-121*					
1989	250	64.2	3.8	3.5	0.3	0
1989	400	76.2	12.0	5.6	6.4	8
1989	550	94.3	14.7	7.7	7	7
1990	250	217.4	9.1	3.5	5.6	3
1990	400	339	27.0	5.6	21.4	6
1990	550	407.1	32.8	7.7	25.1	6
Lockyer	*J Sci Food Agric 35, 837-848*					
1	26	0.6455				2
2	26	0.7025				3
Jarvis et al	*J Ag Sci 112, 205-216*					
1986/87	0	69	6.7	0	6.7	10
1986/87	210	81	9.6	2.94	6.66	8
1986/87	420	207	25.1	5.88	19.22	9
AC0102						
Beef, North Wyke	0			0		10
Beef, Cambridge	0			0		7
SHEEP						
Jarvis et al	*J Ag Sci 117, 101-109*					
GC	0	169	1.1	0	1.1	1
HN	420	321	8.0	5.88	2.08	1
AC0102						
Boxworth	0					4
North Wyke	0					10

Table A8. Studies delivering EF for outdoor pigs

	Emission g N $lu^{-1}d^{-1}$	EF %TAN	Source
Outdoor sows/piglets	25	26.1	Williams et al. (2000)
	66*	NA	Welch (2003)

*This value is probably an overestimate as emission rates were below the detection limit on a number of occasions (and those data were not included).

The EF was derived from the Williams et al (2000) study, assuming the standard N excretion value for sows and a body weight of 200kg, giving a mean EF of 25 %TAN (assumed to be the same across all animal sub-categories).

References

Baines, S., Svoboda, I. F. and Sym, G. (1997*) Estimates of slurry, manure storage and housings in use in Scotland and Northern Ireland*. Report to MAFF (WA0620), SAC Ayr.

Bussink, D.W. (1994). Relationship between ammonia volatilization and nitrogen fertilizer application rate, intake and excretion of herbage nitrogen by cattle on grazed swards. *Fertilizer Research* **38**, 111-121

CAMAR: Groot Koerkamp, P. W. G., Metz, J. H. M., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schröder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O. and Wathes, C. M., 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *Journal of Agricultural Engineering Research* **70**, 79-95.

Chalmers, A. G., et al. (2001). *Fertiliser use on farm crops for crop year 2000*. British Survey of Fertiliser Practice, Edinburgh: The Stationery Office.

Chadwick, D.R. (2005). Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. *Atmospheric Environment* **39**, 787-799.

Chambers, B.J., Smith, K.A. and van der Weerden, T.J. (1997). Ammonia emissions following the land spreading of solid manures. In *Gaseous Nitrogen Emissions from Grasslands*. Eds S.C. Jarvis and B.F. Pain, CAB International, Oxford, pp. 275-280.

Chambers, B. J., Lord, E. I., Nicholson, F. A. and Smith, K. A. (1999). Predicting nitrogen availability and losses following application of organic manures to arable land: MANNER. Soil Use and Management 15, 137-143.

Cumby T., Sandars D., Nigro E., Sneath R. and Johnson G. (2005) Physical assessment of the environmental impacts of centralised anaerobic digestion. Report by Silsoe Research Institute. 112pp.

DANI (1998). Statistical Review of Northern Ireland Agriculture, 1997. Department of Agriculture for Northern Ireland, Economics and Statistics Division, Belfast, Northern Ireland, UK.

Defra (2001) http://www.defra.gov.uk/esg/work_htm/publications/cs/fps/fpsfinalreport.PDF

Demmers, T.G.M., Phillips, V.R., Short, J.L., Burgess, L.R., Hoxer, R.P. and Wathes, C.M (1997). Validation of ventilation rate measurement methods and the ammonia emission from a naturally-ventilated UK dairy and beef unit. In*: Ammonia and Odour Emissions from Animal Production Facilities*. Eds J.A.M. Voermans and G.J. Monteney, Proceedings of an international symposium held at Vinkeloord, Netherlands, 6-10 October 1997. Published by NTVL, Rosmalen, NL pp. 219-230.

Demmers, T.G.M., Burgess, L.R., Short, J.L., Phillips, V.R., Clark, J.A. and Wathes, C.M. (1999). Ammonia emissions from two mechanically ventilated UK livestock buildings. *Atmospheric Environment* **33**, 217-227.

Dimmock, J., Stoddart, H. (2021). New Ammonia Emission Factors for the English Pork Industry. AHDB Report, March 2021.

Dore, C. J., Jones, B. M. R., Scholtens, R., Burgess, L. R., Huis in't Veld, J. W. H., Phillips, V. R. (2004). Robust methods for measuring ammonia emission rates from livestock buildings and manure stores. Part 1 Comparative demonstrations of three methods on the farm. *Atmospheric Environment* **38**, 3017-3024.

Dragosits U., Jones S.K., Vogt E. and Sutton M.S. (2006) 2005 Update on Ammonia emissions from non-agricultural sources for the NAEI. CEH Report AS06/20. Centre for Ecology & Hydrology Edinburgh, Bush Estate, Penicuik. 14pp.

Hill, R.A. (2000). Emission, dispersion and local deposition of ammonia volatilised from farm buildings and following the application of cattle slurry to grassland. PhD Thesis, University of Plymouth.

Hodge, I. and Renwick, A. (2006). Business as usual projections of agricultural activities for the water framework directive: Phase 2. Final Report. Rural Business Unit, Environmental Economy and Policy Research Group, Department of Land Economy, 19 Silver Street, Cambridge CB3 9EP.

Jarvis, S.C; Hatch, D. J; Orr, R.J. and Reynolds, S.E. (1991). Micrometeorological studies of ammonia emissions from sheep grazed swards. *Journal of Agricultural Science Camb*ridge, **117**, 101-109

Jarvis, S. C. and Bussink, D. W. (1990). Nitrogen losses from grazed swards by ammonia volatilization. Proceedings of the 13th General Meeting of the European Grassland Federation, June 25-29, 1990, Banska Bystrica, Czechoslovakia, p.13-17.

Kirchmann, H., and Witter, E. (1989). Ammonia volatilization during aerobic and anaerobic manure decomposition. *Plant and Soil* **115**, 35-41.

Koerkamp, P., Metz, J. H. M., Uenk, G. H., Phillips, V. R., Holden, M. R., Sneath, R. W., Short, J. L., White, R. P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K. H., Pedersen, S., Takai, H., Johnsen, J. O. and Wathes, C. M. (1998). Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *Journal of Agricultural Engineering Research* **70**, 79-95.

Ledgard, S. F. (1996). Nitrogen inputs and losses from New Zealand dairy farmlets, as affected by nitrogen fertilizer applications: year one. *Plant and Soil* **181**, 65-69.

MAFF (2000). *Fertilizer Recommendations for Agricultural and Horticultural Crops (RB209), 7th Edition.* Her Majest's Stationery Office, London, UK.

Mercer, D. R. (1993*) Estimates of the number and types of poultry housing in use in England and Wales.* Report to MAFF, ADAS Nottingham.

Misselbrook, T.H., Webb, J. and Gilhespy, S.L. (2006). Ammonia emissions from outdoor concrete yards used by livestock – quantification and mitigation. *Atmospheric Environment* **40**, 6752-6763.

Misselbrook, T.H., Sutton, M.A. and Scholefield, D. (2004). A simple process-based model for estimating ammonia emissions from agricultural land after fertilizer applications. *Soil Use and Management* **20**, 365-372.

Misselbrook, T. H., Smith, K. A., Johnson, R. A. and Pain, B. F. (2002). Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. *Biosystems Engineering* **81**, 313-321.

Misselbrook, T. H., Webb, J., Chadwick, D. R., Ellis, S. and Pain, B. F. (2001). Gaseous emissions from outdoor concrete yards used by livestock. *Atmospheric Environment* **35**, 5331-5338.

Misselbrook, T. H., Pain, B. F. and Headon, D. M. (1998). Estimates of ammonia emission from dairy cow collecting yards. *Journal of Agricultural Engineering Research* **71**, 127-135.

Moral, R., Bustamante, M.A., Chadwick, D.R., Camp, V., Misselbrook, T.H., 2012. N and C transformations in stored cattle farmyard manure, including direct estimates of N-2 emission. *Resources Conservation and Recycling* **63**, 35-42.

NNFCC (2020) Anaerobic Digestion Deployment in the United Kingdom (http://www.nnfcc.co.uk/publications/report-anaerobic-digestion-deployment-in-the-uk). (Accessed August 2020).

Nicholson, F.A., Bhogal, A., Chadwick, D., Gill, E., Gooday, R.D., Lord, E., Misselbrook, T., Rollett, A.J., Sagoo, E., Smith, K.A., Thorman, R.E., Williams, J.R., Chambers, B.J. (2013). An enhanced software tool to support better use of manure nutrients: MANNER-NPK. *Soil Use and Management* **29**, 473-484.

Nicholson F., Bhogal A., Cardenas L., Chadwick D., Misselbrook T., Rollett A., Taylor M., Thorman R., and Williams J. (2017) Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. *Environmental Pollution* **228**, 504-516.

Nicholson, F. A., Chambers, B. J. and Smith, K. A. (1996) Nutrient composition of poultry manures in England and Wales. *Bioresource Technology* **58**, 279-284.

Nicholson, R. J. and Brewer, A. J. (1994) *Estimates of the numbers and types of slurry and manure stores in use in England and Wales related to livestock species*. Report to DEFRA (WA0611), ADAS Cambridge.

Pain, B. F., Rees, Y. J. and Lockyer, D. R. (1988). Odour and ammonia emission following the application of pig or cattle slurry to land. In*: Volatile emissions from livestock farming and sewage operations*, eds V C Neilsen, J H Voorburg and P L'Hermite. Elsevier Applied Science, London, pp. 2 - 11.

Pain, B. F., Phillips, V. R., Clarkson, C. R. and Klarenbeek, J. V. (1989). Loss of nitrogen through ammonia volatilisation following the application of pig or cattle slurry to grassland. *Journal of the Science of Food and Agriculture* **47**, 1-12.

Peirson, S. (1995). Measurement of odour and ammonia emissions from livestock buildings, Phase 1 - Final Report to MAFF. Project no. WAO601, ADAS Beverley.

Phillips, V.R., Sneath, R.W., Williams, A.G., Welch, S.K., Burgess, L.R., Demmers, T.G.M. and Short, J.L. (1997). Measuring emission rates of ammonia, methane and nitrous oxide from full-sized slurry and manure stores. In*: Ammonia and Odour Emissions from Animal*

Production Facilities. Eds J.A.M. Voermans and G.J. Monteney, Proceedings of an international symposium held at Vinkeloord, Netherlands, 6-10 October 1997. Published by NTVL, Rosmalen, NL pp. 197-208.

Phillips, V. R., Bishop, S. J., Price, J. S. and You, S. (1998). Summer emissions of ammonia from a slurry-based, UK, dairy cow house. *Bioresource Technology* **65**, 213-219.

Robertson, A. P., Hoxey, R. P., Demmers, T. G. M., Welch, AS. K., Sneath, R. W., Stacey, K. F., Fothergill, A., Filmer, D. and Fisher, C. (2002). Commercial-scale studies of the effect of broiler-protein intake on aerial pollutant emissions. *Biosystems Engineering* **82**, 217-225.

Sheppard, A. (1998) The Structure of Pig Production in England and Wales. Results of the National Survey of Pig Production Systems. *Special Studies in Agricultural Economics Report No. 40*, University of Exeter.

Smith, K. A. and Chambers, B. J. (1995). Muck from waste to resource - utilization: the impacts and implications. *Agricultural Engineer*, **50**, 33-38.

Smith, K. A. and Frost, J. P. (2000). Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 1: cattle and sheep. *Bioresource Technology* **71**, 173-181.

Smith, K. A., Charles, D. R. and Moorhouse, D. (2000a). Nitrogen excretion by farm livestock with respect to land spreading requirements and controlling nitrogen losses to ground and surface waters. Part 2: pigs and poultry. *Bioresource Technology* **71**, 183-194.

Smith, K. A., Jackson, D. R., Misselbrook, T. H., Pain, B. F. and Johnson, R. A. (2000b). Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural Engineering Research* **77**, 277-287.

Smith, K. A., Brewer, A. J., Dauven, A. and Wilson, D. W. (2000c). A survey of the production and use of animal manures in England and Wales. I. Pig manure. Soil Use and Management 16, 124-132.

Smith, K. A., Brewer, A. J., Crabb, J. and Dauven, A. (2001a). A survey of the production and use of animal manures in England and Wales. II. Poultry manure. Soil Use and Management 17, 48-56.

Smith, K. A., Brewer, A. J., Crabb, J. and Dauven, A. (2001b). A survey of the production and use of animal manures in England and Wales. III. Cattle manures. Soil Use and Management 17, 77-87.

Sommer, S.G., Christensen, B.T., Nielsen, N.E., and Schjrrring, J.K. (1993). Ammonia volatilization during storage of cattle and pig slurry: effect of surface cover. *Journal of Agricultural Science, Cambridge*, **121**, 63-71.

Sutton, M. A., Dragosits, U., Tang, Y. S. and Fowler, D. (2000). Ammonia emissions from non-agricultural sources in the UK. *Atmospheric Environment* **34**, 855-869.

Thompson, R. B., Pain, B. F. and Lockyer, D. R. (1990a). Ammonia volatilization from cattle slurry following surface application to grassland. I. Influence of mechanical separation, changes in chemical composition during volatilization and the presence of the grass sward, *Plant and Soil* **125**, 109-117.

Thompson, R. B., Pain, B. F. and Rees, Y. J. (1990b). Ammonia volatilization from cattle slurry following surface application to grassland. II. Influence of application rate, windspeed and applying slurry in narrow bands. *Plant and Soil* **125**, 119-128.

Tomlinson S.J., Thomas I.N., Carnell E.J., and Dragosits U. (2019). Reviewing estimates of UK ammonia emissions from landfill, composting & anaerobic digestion: Improvement Plan 2018. Report for Defra (AQ_IP_2018_20). April 2019. 63pp.

van der Weerden, T. J. and Jarvis, S. C. (1997). Ammonia emission factors for N fertilisers applied to two contrasting grassland soils. *Environmental Pollution* **95**, 205-211.

Wathes, C. M., Holden, M. R., Sneath, R. W., White, R. P. and Phillips, V. R. (1997). Concentrations and emission rates of ammonia, nitrous oxide, methane, carbon dioxide, dust and endotoxin in UK broiler and layer houses. *British Poultry Science* **38**, 14-28.

Webb, J., (2001). Estimating the potential for ammonia emissions from livestock excreta and manures. *Environmental Pollution* **111**, 395-406.

Webb, J., and Misselbrook, T. H. (2004). A mass-flow model of ammonia emissions from UK livestock production. *Atmospheric Environment* **38**, 2163-2176.

Webb, J., Misselbrook, T., Pain, B. F., Crabb, J. and Ellis, S. (2001). An estimate of the contribution of outdoor concrete yards used by livestock to the UK inventories of ammonia, nitrous oxide and methane. *Atmospheric Environment* **35**, 6447-6451.

Welch, D.C. (2003) A methodology for the measurement of distributed agricultural sources of ammonia outdoors. PhD thesis, University of Nottingham.

Williams, J. R., Chambers, B. J., Hartley, A. R., Ellis, S. and Guise, H. J. (2000). Nitrogen losses from outdoor pig farming systems. *Soil Use and Management* **16**, 237-243.

WRAP 2014. A survey of the UK Anaerobic Digestion industry in 2013. Waste and Resources Action Programme. http://www.wrap.org.uk/content/survey-uk-anaerobic-digestion-industry-2013. (Accessed September 2016).

WRAP 2016a. Field Experiments for Quality Digestate and Compost in Agriculture. Waste and Resources Action Programme. http://www.wrap.org.uk/content/digestate-and-compost-agriculture-dc-agri-reports. (Accessed September 2016).

DEFRA Projects

Final reports from the following projects are available from Defra:

AC0114	GHG Platform – data management
AC0123	Developing new ammonia emission factors for modern livestock housing (Phase 2)
AM0101	National ammonia reduction strategy evaluation system (NARSES)
AM0102	Modelling and measurement of ammonia emissions from ammonia mitigation pilot farms
AM0103	Evaluation of targeted or additional straw use as a means of reducing ammonia emissions from buildings for housing pigs and cattle
AM0110	Additional housing measurements for solid vs. liquid manure management systems
AM0111	Measurement and abatement of ammonia emissions from hard standings used by livestock
AM0115	Investigation of how ammonia emissions from buildings housing cattle vary with the time cattle spend inside them
DO108	Food and Agriculture Policy Research Institute – UK Project
ES0116	Field work to validate the manure incorporation volatilization system (MAVIS)

KT0105	Manure Nutrient Evaluation Routine (MANNER-NPK)
LK0643	UK Poultry Industry IPPC Compliance (UPIC)
NT2001	Integration of animal manures in crop and livestock farming systems: nutrient demonstration farms
NT2402	Impact of nutrition and management on N and P excretions by dairy cows
NT2605	The behaviour of some different fertiliser-N materials - Main experiments
OC9117	Ammonia emission and deposition from livestock production systems
WA0519	Enhancing the effective utilisation of animal manures on-farm through effective compost technology
WA0618	Emissions from farm yard manure based systems for cattle
WA0625	The effects of covering slurry stores on emissions of ammonia, methane and nitrous oxide
WA0632	Ammonia fluxes within solid and liquid manure management systems
WA0633	Predicting ammonia loss following the application of organic manures to land
WA0638	Low cost, aerobic stabilisation of poultry layer manure
WA0641	Low-cost covers to abate gaseous emissions from slurry stores
WA0651	Ammonia fluxes within broiler litter and layer manure management systems
WA0652	Field ammonia losses in sustainable livestock LINK Project LK0613
WA0653	Quantifying the contribution of ammonia loss from housed dairy cows to total N losses from dairy systems (MIDaS2)
WA0707	Effect of storage conditions on FYM composition, gaseous emissions and nutrient leaching during storage
WA0708	Covering a farm scale lagoon of pig slurry
WA0712	Management techniques to minimise ammonia emissions during storage and land spreading of poultry manures
WA0714	Natural crusting of slurry storage as an abatement measure for ammonia emission on dairy farms
WA0716	Management techniques to reduce ammonia emissions from solid manures
WA0717	Ammonia emissions and nutrient balance in weeping-wall stores and earth banked lagoons for cattle slurry storage
WA0720	Demonstrating opportunities of reducing ammonia emissions from pig housing
WA0722	Ammonia emission from housed dairy cows in relation to housing system and level of production
WT0715NVZ	Nitrogen and phosphorus output standards for farm livestock

Appendix 2: Reduction efficiencies for ammonia mitigation methods applicable to the UK ammonia emission inventory

Introduction

Agriculture is the major source of ammonia (NH_3) emissions to the atmosphere in the UK, accounting for >80% of anthropogenic emissions. Most of these emissions derive from urea excreted by farmed livestock (or uric acid in the case of poultry) and emissions will therefore arise wherever livestock excreta are deposited or managed i.e. at grazing, in livestock housing and during manure storage and application to land. Emissions also arise from inorganic nitrogen fertilisers applied to land. The emission factors used to quantify these emissions in the national inventory are reported separately. A growing number of potential mitigation methods applicable to one or more of the emission sources have been described in the literature. This report lists those that are currently included in the inventory of NH_3 emissions from UK agriculture together with the mean NH_3 emission reduction efficiency associated with each method. In addition, the current state of knowledge regarding the impact of the implementation of each method on emissions of nitrous oxide and methane is given so that these mitigation methods can be fully included in the revised combined agricultural GHG and NH_3 emission inventory.

Emission reduction methods

Only explicit mitigation methods are included here – i.e. those that are associated with a reduction in the emission factor for a particular source. Implicit mitigation methods, generally associated with efficiency improvements (e.g. a reduction in fertiliser use through better accounting for manure nitrogen use; a reduction in livestock numbers associated with productivity improvements), will be reflected in the inventory through changes in the activity data and are not described here. One exception in the current NH_3 emission inventory is the inclusion of a dietary measure, namely low crude protein diets for dairy cows, which is associated with a 20% reduction in the ammoniacal nitrogen content of dairy cow excreta over the housed winter period. In the revised emission inventories, N excretion will be derived using a balance approach according to diet and production characteristics and will therefore reflect any changes in the crude protein content of the diet.

Mitigation methods are categorised according to the emission source i.e. livestock housing, hard standings, manure storage, manure spreading and fertiliser application. Data sources are given, but the reported emission reduction efficiencies are not necessarily the arithmetic mean of reported studies but are more aligned with the expert judgement approaches used in the

Defra 'Mitigation Methods - User Guide' (Newell Price et al., 2011) and the UNECE Task Force for Reactive Nitrogen 'Options for Ammonia Mitigation Guidance Document' (Bittman et al., 2014). These documents and other cited literature should be consulted for more detailed information on the mitigation methods included in Table 1.

Uncertainties are not well defined for these emission reduction estimates, so following 2006 IPCC Guidelines for Tier 2 approach to estimating emissions from manure management, uncertainty bound of ±20% of the reported value are applied with constraining limits of 0 and 100% also implemented.

Table 1. Reduction efficiencies for ammonia emission mitigation methods and an indication of their impact on nitrous oxide and methane emissions

Emission source	Mitigation method	Ammonia emission reduction efficiency (%)	Nitrous oxide[†]	Methane[†]	Data source
Cattle housing	Increased scraping frequency in cubicle house (from 2 to 4x per day)	15	-	-	Webb et al. (2006); Braam et al. (1997)
	Grooved flooring system for rapid urine draining	35	-	-	Swiestra et al. (2001); Bittman et al. (2014)
Pig housing	Partly slatted floor with reduced pit area	30	-	-	Bittman et al. (2014)
	Acid air scrubbing techniques	80	-	-	Bittman et al. (2014)
	Frequent slurry removal with vacuum system	25	-	-	Bittman et al. (2014)
	Floating balls on below-slat slurry surface	25	-	-	Bittman et al. (2014)
Poultry housing	Air drying of manure on laying hen manure belt systems	30	?	?	Bittman et al. (2014)
	Acid air scrubbing techniques	80	-	-	Bittman et al. (2014)
	Poultry litter drying (e.g. heat exchangers)	60	?	?	Defra WA0638; Defra AC0123
Dairy cow collecting yards	Wash down with water twice per day	70	-	-	Misselbrook et al. (2006)
Slurry storage	Crusting of cattle slurry	50	↑ EF from 0 to 0.005 (IPCC 2006)	↓ Methane Conversion Factor from 17 to 10% (IPCC 2006)	Misselbrook et al. (2005)
	Floating cover (e.g. expanded clay granules)	60	-	-	Bittman et al. (2014); Defra AC0115

	Tight lid, roof or tent structure	80	-	-	Bittman et al. (2014)
FYM/poultry manure storage	Sheeting cover	60	↓ by 30%	-	Chadwick (2005)
Slurry application	Trailing hose	30	-	-	Smith et al. (2000); Misselbrook et al. (2002); Bittman et al. (2014)
	Trailing shoe	60	-	-	Smith et al. (2000); Misselbrook et al. (2002); Bittman et al. (2014)
	Shallow injection	70	-	-	Smith et al. (2000); Misselbrook et al. (2002); Bittman et al. (2014)
Cattle slurry to arable	Incorporation within 4h by plough	59	-	-	Defra ES0116
	Incorporation within 4h by disc	52	-	-	Defra ES0116
	Incorporation within 4h by tine	46	-	-	Defra ES0116
	Incorporation within 24h by plough	21	-	-	Defra ES0116
	Incorporation within 24h by disc	19	-	-	Defra ES0116
	Incorporation within 24h by tine	17	-	-	Defra ES0116
Pig slurry to arable	Incorporation within 4h by plough	67	-	-	Defra ES0116
	Incorporation within 4h by disc	59	-	-	Defra ES0116
	Incorporation within 4h by tine	52	-	-	Defra ES0116
	Incorporation within 24h by plough	29	-	-	Defra ES0116
	Incorporation within 24h by disc	26	-	-	Defra ES0116
	Incorporation within 24h by tine	23	-	-	Defra ES0116
Cattle, pig and duck FYM	Incorporation within 4h by plough	71	-	-	Defra ES0116
	Incorporation within 4h by disc	47	-	-	Defra ES0116
	Incorporation within 4h by tine	39	-	-	Defra ES0116
	Incorporation within 24h by plough	34	-	-	Defra ES0116
	Incorporation within 24h by disc	23	-	-	Defra ES0116
	Incorporation within 24h by tine	19	-	-	Defra ES0116

Poultry manure	Incorporation within 4h by plough	82	-	-	Defra ES0116
	Incorporation within 4h by disc	64	-	-	Defra ES0116
	Incorporation within 4h by tine	45	-	-	Defra ES0116
	Incorporation within 24h by plough	56	-	-	Defra ES0116
	Incorporation within 24h by disc	44	-	-	Defra ES0116
	Incorporation within 24h by tine	31	-	-	Defra ES0116
Urea fertiliser	Urease inhibitor	70	↓ (Smith et al. 2012)	-	Defra NT26
UAN fertiliser	Urease inhibitor	40	?	-	Defra NT26

† ↑ increase in emission; ↓ decrease in emission; - no effect; ? uncertain of effect

References

Bittman, S., Dedina, M., Howard, C.M., Oenema, O., Sutton, M.A., (eds), 2014. *Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen*, Centre for Ecology and Hydrology, Edinburgh, UK

Newell Price et al 2011 User Guide

Braam, C.R., Ketelaars, J., Smits, M.C.J., 1997. Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. Netherlands Journal of Agricultural Science 45, 49-64.

Defra AC0115 Improvements to the national inventory: Methane

Defra AC0123 Developing new ammonia emission factors for modern livestock housing (Phase 2)

Defra ES0116 Field work to validate the manure incorporation volatilization system (MAVIS)

Defra WA0638 Lost cost, aerobic stabilisation of poultry layer manure

Misselbrook, T.H., Brookman, S.K.E., Smith, K.A., Cumby, T.R., Williams, A.G., McCrory, D.F., 2005. Crusting of stored dairy slurry to abate ammonia emissions: pilot-scale studies. Journal of Environmental Quality 34, 411-419.

Misselbrook, T.H., Smith, K.A., Johnson, R.A., Pain, B.F., 2002. Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. Biosystems Engineering 81, 313-321.

Misselbrook, T.H., Webb, J., Gilhespy, S.L., 2006. Ammonia emissions from outdoor concrete yards used by livestock - quantification and mitigation. Atmospheric Environment 40, 6752-6763.

Smith, K.A., Dobbie, K.E., Thorman, R., Watson, C.J., Chadwick, D.R., Yamulki, S., Ball, B.C., 2012. The effect of N fertilizer forms on nitrous oxide emissions from UK arable land and grassland. Nutrient Cycling in Agroecosystems 93, 127-149.

Smith, K.A., Jackson, D.R., Misselbrook, T.H., Pain, B.F., Johnson, R.A., 2000. Reduction of ammonia emission by slurry application techniques. Journal of Agricultural Engineering Research 77, 277-287.

Swierstra, D., Braam, C.R., Smits, M.C., 2001. Grooved floor system for cattle housing: Ammonia emission reduction and good slip resistance. Applied Engineering in Agriculture 17, 85-90.

Webb, J., Ryan, M., Anthony, S.G., Brewer, A., Laws, J., Aller, M.F., Misselbrook, T.H., 2006. Cost-effective means of reducing ammonia emissions from UK agriculture using the NARSES model. Atmospheric Environment 40, 7222-7233.