UK Centre for Ecology & Hydrology

Analysis of the impact to ammonia emissions of covers on slurry/digestate stores near nitrogen-sensitive protected habitats in England

Carnell E.J., Misselbrook T., Tomlinson S.J., Dragosits U.

Issue Number 1

Date 03/12/2021

Title Analysis of the impact to ammonia emissions of covers on slurry/digestate stores near nitrogen-sensitive protected habitats in England

Client Defra

UKCEH contact details Ed Carnell, Ulli Dragosits
UKCEH Edinburgh Research Station, EH26 0QB

t: 0131 445 4343 (reception)
e: edcarn@ceh.ac.uk, ud@ceh.ac.uk

Authors Carnell E.J., Misselbrook T., Tomlinson S.J., Dragosits U.

Date 03/12/2021

Contents

1 Introduction

1.1 Background and policy context

Slurry and digestate stores can be substantial local ammonia emission sources and can impact on nearby nitrogen-sensitive habitats and designated nature conservation sites, both through the resulting elevated ammonia concentrations and their contribution to atmospheric nitrogen deposition. To mitigate these impacts, a key measure for slurry stores and liquid digestates is to cover the emitting surfaces and therefore reduce volatilisation, through slurry store covers. These covers can be of a rigid or floating type.

The key policies for mitigation of ammonia emissions relevant to slurry store covers include the following:

1) The National Emissions Ceilings Regulations (NECR)[1], where the UK Government committed to reducing ammonia emissions by 8% and 16% by 2020 and 2030, respectively (from 2005 levels).
2) The Clean Air Strategy (CAS)[2], with the following relevant commitments
    a. to cover slurry and digestate stores by 2027;
    b. to reduce nitrogen deposition on protected, priority, sensitive habitats in England by 17% by 2030
3) The 25 Year Environment Plan[3], with a commitment to restore 75% of protected sites to favourable condition by 2042.

1.2 Aims and objectives

The main aim of this study was to investigate the impact of installing impermeable and permeable covers on slurry and digestate stores to reduce ammonia emissions, and thereby the resulting atmospheric nitrogen (N) input to nitrogen-sensitive protected sites in England (SSSIs and SACs). The outputs from this study will help inform the implementation of targets and commitments under the NECR, CAS and 25 Year Environment Plan.

1.3 Project outline

The work presented here is the first part of a two-part study:

- Part 1 - a rapid analysis of existing datasets and assumptions used in the UK agricultural emission inventory to characterise slurry and digestate stores in England at a holding/site level, respectively, and model their likely emissions and potential emission savings through mitigation by store covers; and for the

[1] https://www.legislation.gov.uk/uksi/2018/129/contents/made
[2] https://www.gov.uk/government/publications/clean-air-strategy-2019
[3] https://www.gov.uk/government/publications/25-year-environment-plan

emission data to be related to sensitive designated sites (SSSIs, SACs) in terms of proximity and likelihood of environmental impact (zones of 1 km, 2 km, 5 km, 10 km).

- Part 2 – further analysis with additional data provided, i.e. Ordnance Survey slurry store locations, provided by Defra. This analysis will be carried out following completion of Part 1 of the study, to test the assumptions used in the agricultural emission inventory on the location of stores and type(s) of manure management systems (i.e. slurry or farmyard manure) present at farms of different types and sizes. These data may enable an improvement of the assumptions made on the manure management systems present at farms in England. The analysis carried out under Part 1 (i.e. this report) of the study will then be reassessed, and recommendations made on how the outcomes may be able to inform potential improvements to the agricultural emission inventory.

Part 1 of the study was structured as follows, with a number of research questions posed and answered for each of the three stages:

- Profiling of slurry and digestate stores in England
- Profiling of nitrogen-sensitive sites in England
- Impact of slurry and digestate store covers on emission reductions in England

2 Profile of slurry and digestate stores in England

2.1 Research questions

- How many agricultural holdings and anaerobic digestion plants in England are likely to have slurry/digestate stores?
- What type of stores are they (e.g. lagoons, tanks etc.)?
- What type of manure (i.e. beef, dairy, pig, or mixed) or digestate is likely to be stored in each of these stores?
- What is the estimated capacity/volume of slurry stored in England (by livestock sector)?
- Where are the majority of these slurry/digestate stores geospatially located?

2.2 Methods

Slurry store profiles

Dairy, beef and pig production generate volumes of manure which can be managed as a liquid slurry or as farm yard manure (FYM). Slurry separation into liquid and semi-solid components is also a possibility, but currently little practiced on farms in England and ignored for the purposes of this study. The choice of manure management practice for a specific farm will depend on several factors including farm size, ability to invest, land management and personal preference. For this study, farm size was used to associate the probability of manure management system (slurry or farm yard manure) and slurry store type.

June Agricultural Survey (JAS) and Cattle Tracing System (CTS) data at the individual holding level data for England for 2019, as used in the UK agricultural emission inventory, were used together with farm size threshold criteria to allocate each holding to a specific farm size category. An initial allocation was made for holdings with dairy cows, with ‘bin’ sizes of 0-50, >50-150, >150-250 and >250 dairy cows. For farms without dairy cows, allocation was then made according to total cattle numbers (dairy followers and beef cattle), with the same ‘bin’ sizes as for dairy cows. Subsequently, holdings without cattle but with pigs were categorised firstly according to number of sows (‘bin’ sizes 0-25, >25-100, >100-750, >750), and then (for remaining farms without sows but with pigs, predominantly finishing pigs) to total number of pigs ('bin’ sizes 0-300, >300-1000, >1000-2000, >2000).

Livestock types associated with each farm size categorisation were subsequently associated with a probability of being managed on a slurry-based system. Underlying activity data for the 2019 agricultural emission inventory for England (as derived from the Defra AC0114 manure management practices report) give proportions of each livestock type being managed as slurry (rather than FYM, or ‘outdoor’ for pigs) as 80, 20, 20, 35 and 34% for dairy cows, other dairy cattle, beef cattle, sows and other pigs, respectively. This national breakdown was adjusted according to the farm size thresholds, such that the proportion of animals associated with a slurry-based system increased as holding size increased (Table 1). Weighted averages across the livestock type/farm size categories agreed with the national breakdown.

Table 1. Proportion of manure managed as slurry for each livestock type on given farm size categories, England, 2019

Farm categorisation	% of manure managed as slurry				
	Dairy cows	Other dairy cattle	Beef cattle	Sows	Other pigs
Dairy cows					
0-50	0	0	0	0	0
>50-150	35	10	10	0	0
>150-250	100	10	10	10	0
>250	100	35	35	10	0
Total cattle					
0-50	-	0	0	0	0
>50-150	-	10	10	0	0
>150-250	-	20	20	10	0
>250	-	50	50	10	0
Sows					
0-25	-	-	-	0	0
>25-100	-	-	-	0	0
>100-750	-	-	-	20	20
>750	-	-	-	65	65
Total pigs					
0-300	-	-	-	-	0
>300-1000	-	-	-	-	0
>1000-2000	-	-	-	-	20
>2000	-	-	-	-	65

The agricultural emission inventory model provides a national breakdown of slurry storage by store type (based primarily on Farm Practices Survey data) with seven potential categories for cattle slurry and six for pig slurry, of which only five have been used in this study. One of these categories, ‘slurry direct spread (no storage)’ has been omitted for this study and it is assumed that all slurry produced on a holding is stored in some way; the proportion of slurry assumed in the inventory model as ‘direct spread’ has therefore been reallocated to the other available storage categories on a pro-rata basis. Slurry bags have also been omitted as the current inventory reflects zero uptake of this storage type. For cattle slurry, weeping wall stores are assumed to be predominantly associated with smaller holdings, and for cattle and pig slurry, anaerobic digestion is assumed to be associated with larger holdings. Other store types were assumed to be distributed evenly across farm size categories. Assumed breakdown of storage category by farm size/livestock type category is given in Table 2 and a comparison against the national breakdown is given in Table 3.

The inventory model treats manure from each livestock type independently whereas specific holdings may have multiple livestock types, the slurry from which is then assumed to all be stored in a single store for a given holding. This makes it difficult to provide an exact match for the proportional storage breakdown between this study and the inventory model, but a very close approximation has been achieved (Table 3).

Table 2. Proportional breakdown of slurry storage method by livestock type and farm size category, England, 2019

Farm categorisation	**% of slurry managed by store type**				
	Above ground tank	**Below ground tank**	**Lagoon**	**Weeping wall**	**Anaerobic digestion**
Dairy cows					
0-50	-	-	-	-	-
>50-150	20	13	17	50	0
>150-250	28	19	23	30	0
>250	38	25	32	0	5
Total cattle					
0-50	-	-	-	-	-
>50-150	12	8	10	70	0
>150-250	24	16	20	40	0
>250	38	26	32	0	4
Sows					
0-25	-	-	-	-	-
>25-100	-	-	-	-	-
>100-750	22	48	30	-	0
>750	20	44	27	-	9
Total pigs					
0-300	-	-	-	-	-
>300-1000	22	48	30	-	0
>1000-2000	21	47	29	-	3
>2000	20	44	27	-	8

Table 3. Comparison of weighted average slurry storage breakdown (%) by farm size and livestock type with the breakdown used in the national inventory, England, 2019

Store type	Inventory 2019	Reprofiled inventory data†	This project	
CATTLE			**Dairy cows**	**Other cattle**
Above ground tank	29.3	32.5	32.6	32.6
Below ground tank	19.5	21.7	21.7	21.7
Lagoon	24.4	27.1	27.2	27.2
Slurry bag	0.0	0.0	-	-
Weeping wall	14.7	16.3	15.7	15.7
Anaerobic digestion	2.3	2.5	2.8	2.8
Direct spread	9.8	-	-	-
PIGS			**Sows**	**Other pigs**
Above ground tank	17.8	20.3	20.3	20.3
Below ground tank	39.5	44.9	44.9	45.0
Lagoon	24.4	27.8	27.8	27.8
Slurry bag	0.0	0.0	-	-
Anaerobic digestion	6.1	6.9	7.1	6.9
Direct spread	12.2	-	-	-

†Assuming no 'Direct spread' category

Within each defined farm size bin for a given livestock type, the probability of a given holding being managed as a slurry system was combined with the probability of the slurry being stored in a given store type to derive a probability for slurry storage within a given store type for that holding.

The total potential slurry volume for the holding was calculated from the number of different livestock within the different categories and volume output per livestock type. Slurry volumes (Table 4) are as estimated as per the UK inventory, derived as described in the Scenario Modelling Tool report (Defra ECM 55618: Greenhouse gas and air quality scenario modelling tool; Agricultural Desk SMT Version 1.0 Report, Appendix C). Excretal volumes are based on feed intake and digestibility; slurry storage volumes include a dilution factor of 1.6 for cattle and pigs to account for wash water, rainfall and yard run-off. Total ammoniacal N (TAN) in slurry arriving at storage was derived from the inventory model output for each livestock type on a slurry-based system; the quantity of TAN includes half of the mineralisation that is assumed to occur during storage as that is assumed (in the inventory model) to contribute towards ammonia emissions from stored slurry.

Table 4. Slurry volumes (m^3) and quantity of total ammoniacal N (TAN, kg) produced per animal category per year for those livestock reared on a slurry-based system

Sector	Animal type	Annual slurry volume (m^3 per animal)	TAN at storage (kg N per animal)
Dairy	Calf	0.28	0.30
Dairy	Cow	30.69	36.62
Dairy	Heifer	7.51	9.47
Dairy	Replacement	7.68	9.78
Beef	Breeding Bull	16.33	16.81
Beef	Calf	1.00	0.87
Beef	Cow	17.80	15.94
Beef	Female for Slaughter	11.50	12.05
Beef	Heifer	13.50	13.79
Beef	Male for Slaughter	12.97	13.58
Beef	Replacement	13.21	13.29
Pig	Boar	0.00	0.00
Pig	Fattening 20-80kg	1.22	4.98
Pig	Fattening <20kg	0.36	2.37
Pig	Fattening >80kg	2.11	8.06
Pig	Gilt	1.83	8.64
Pig	Sow	2.76	9.14

An assumption (simplification) in this study was that any manure arising from the use of hard standings on FYM-based holdings would remain as FYM, whereas in the inventory model this is treated as slurry. This resulted in an overestimation of the quantity of slurry of ~7.8% (and TAN of ~4.9%) entering storage and, hence, the estimate of emissions from storage. Results were therefore scaled back in line with published agricultural emission inventory totals.

Emission factors associated with each store type are given in Table 5 and are as used in the UK inventory model.

Table 5. Emission factors (as %TAN) by slurry storage type

Store type	EF (NH_3-N emission as a % of TAN in store)	
	Cattle	Pig
Above-ground tank	10	13
Below-ground tank	5	7
Lagoon	52	52
Weeping wall	5	5
Anaerobic digestion†	2	2.6

†EF for anaerobic digestion assumes these stores are already covered

FARG data provided by Natural England (as supplied by Defra, March 2021) were ultimately not used for verification purposes regarding proportional breakdown of store type, incidence of crusting or store dimensions. As farms were self-selecting in terms of applying to the FARG scheme, and indeed the scheme conditions may have favoured farms with certain store types, the proportional store type breakdown would not necessarily be representative of farms across England as a whole. The response regarding incidence of crusting, which showed much lower than 80% of stores associated with crust formation, was subjective, based on farmer opinion, and a thin 'skin' may not have been considered as a crust, whereas experimental evidence has shown that this can be very effective at reducing ammonia emissions. Therefore we have retained the UK inventory estimate of 80% cattle slurry stores as being crusted in the calculations for this project. The information on store capacity was variable in nature (given sometimes as volume (often without specific units), sometimes as multiple volumes, sometimes in months, and sometimes not at all), with no information on store surface area, and was difficult to associate with a specific number and type of animal, so these data were not used within the project.

The assumptions were implemented at an individual holding level, using probabilities for the likely systems for each sector and farm size bin, on average, as described above. Results are only shown in this report at a non-disclosive level , i.e. no data point refers to fewer than five holdings, and therefore the report can be freely shared, as required by Defra.

AD store profiles

Anaerobic digestion (AD) is the process in which organic materials are broken down in anaerobic conditions to produce biogas and also fertilisers referred to as digestates.

There are around 370 facilities in England in the AD industry (NNFCC[4]), processing a wide range of feedstock materials, including animal manures/slurries, food wastes and food processing wastes, oils, vegetable matter and more. In 2018, ca. 10 Mt of feedstocks were used for AD in England. There is a wide range of practices and processes associated with AD plants, such as the type of digester (e.g. thermophilic) and whether the resulting digestate is separated into liquid and solid fractions or retained 'whole' (i.e. non-separated). Furthermore, some AD plants operate under the PAS110 scheme with the intent of producing digestate that is no longer classified as waste.

In most cases, in a similar manner to regular slurries, the digestate needs to be stored following the digestion process. In the current UK Inventory[5], some assumptions are made on which emissions from the storage of these digestates are estimated (from expert consultation and literature). These assumptions include:

I. Broad UK-wide percentages for the production of whole, liquid and solid digestates (70%, +/- 10%; 22%, +/- 10%; 8%, +/- 8%, respectively).
II. All sites that are known to adhere to the PAS110 scheme will have covered stores for whole, liquid and solid digestates.
III. 70% of all remaining sites will have covered storage for whole & liquid digestate and 0% of sites will cover solid fibrous heaps.

[4] https://www.nnfcc.co.uk/publications/report-anaerobic-digestion-deployment-in-the-uk

[5] Tomlinson S.J., Williams .M, Carnell E.J., Tang Y.S., Sutton M.A. and Dragosits U. (2021) Ammonia emissions from UK non-agricultural sources in 2019: contribution to the National Atmospheric Emission Inventory. UKCEH Report. Centre for Ecology & Hydrology, Edinburgh Research Station, Bush Estate, Penicuik. 29pp.

Beyond very occasional site profiles in industry publications, there is no systematically surveyed information with regards to covers on stores at AD facilities. Therefore the above assumptions were applied across all sites, with the broad split being whether the site adheres to PAS110 licensing or not.

To attempt to further our knowledge in this area, experts at AquaEnviro, Anaerobic Digestion & Bioresources Association (ADBA) and Renewable Energy Association (REA) were contacted to establish whether any further detail was known with regards to storage of digestates and the presence of covers. The questions were;

- It is currently assumed (from the PAS110 accreditation standards) that any whole/liquid digestate produced at a PAS110 certified AD plant must be held in a store with a cover (until dispatched from the holding) - is this assumption correct and is this what is happening to stored digestate across the industry?
- With regards to the above, is there a requirement for the solid fraction of separated digestate to be covered? If yes, is it generally the case?
- Do you know of any data, surveys or general evidence as to the extent of coverings of digestate at those AD plants not on the PAS110 scheme?
- Could any of the known data/assumptions for PAS110 digestate covers be applied to these non-PAS110 AD sites? Or are the circumstances, such as exemptions and process types, too varied? Does the lack of stricter guidance/regulation reduce the % of covered stores?

Furthermore, a very small Google Earth survey was undertaken of a random sample of AD facilities to try to ascertain whether any information could be gained from publicly available photo imagery.

2.3 Results

The results presented below show non-disclosive summary data for England for 2019. Data relating to fewer than 5 holdings cannot be shown in this report, to conform with the data agreement associated with the holding level data for the agricultural emission inventory. However, all calculations were carried out at the full resolution of the original holding level data and subsequently aggregated to a non-disclosive level.

Farm size categorisation and association with specific slurry store types

Table 6 gives the distribution of the different livestock types across the holding size categories, showing that while a large proportion of holdings are in the smallest categories, these account for a relatively small proportion of total livestock numbers. Almost all dairy followers are included in the ‘dairy cows’ holdings together with approximately one quarter of beef cattle. The majority of sows are represented on the ‘sows’ holdings, while other pigs are distributed between ‘sows’ and ‘total pigs’ holdings, with some on ‘total cattle’ holdings, but very few on ‘dairy cows’ holdings. This means that manure types according to livestock category are broadly consistent, although there is some mixing of pig and cattle slurries at the holding level. Tables 7 and 8 show the probability for a given holding to be associated with a specific store type according to holding size category.

Table 6. Distribution of holdings and livestock numbers by farm size category

	No. holdings	% holdings in category	% of total Dairy cows	% of total Other dairy cattle	% of total Beef cattle	% of total Sows	% of total Other pigs
Dairy cows							
0-50	4,811	46	3	5	15	1	2
>50-150	2,943	28	26	24	5	0	0
>150-250	1,567	15	27	26	4	0	0
>250	1,228	12	44	42	4	0	1
Total	**10,549**	**100**	**100**	**97**	**28**	**2**	**3**
Total cattle							
0-50	13,230	50	0	0	8	6	8
>50-150	8,615	32	0	1	23	3	5
>150-250	2,752	10	0	1	15	1	2
>250	2,004	8	0	1	25	2	3
Total	**26,601**	**100**	**0**	**3**	**72**	**12**	**17**
Sows							
0-25	1,491	70	0	0	0	2	5
>25-100	182	9	0	0	0	3	3
>100-750	356	17	0	0	0	38	24
>750	104	5	0	0	0	42	13
Total	**2,133**		**0**	**0**	**0**	**86**	**45**
Total pigs							
0-300	1,389	69	0	0	0	0	1
>300-1000	162	8	0	0	0	0	3
>1000-2000	257	13	0	0	0	0	11
>2000	201	10	0	0	0	0	20
Total	**2,009**		**0**	**0**	**0**	**0**	**35**

Table 7. Probability for a given holding being associated with a specific slurry store type for cattle

1. Dairy cows					
Dairy cows on holding	**Above-ground tank**	**Below-ground tank**	**Lagoon**	**Weeping wall**	**Anaerobic digestion**
0-50	0%	0%	0%	0%	0%
>50-150	7%	5%	6%	18%	0%
>150-250	28%	19%	23%	30%	0%
>250	38%	25%	32%	0%	5%
2. Other cattle					
Total cattle on holding	**Above-ground tank**	**Below-ground tank**	**Lagoon**	**Weeping wall**	**Anaerobic digestion**
0-50	0%	0%	0%	0%	0%
>50-150	1%	1%	1%	7%	0%
>150-250	5%	3%	4%	8%	0%
>250	19%	13%	16%	0%	2%

Table 8. Probability for a given holding being associated with a specific slurry store type for pigs?

3. Sows				
Total sows on holding	**Above-ground tank**	**Below-ground tank**	**Lagoon**	**Anaerobic digestion**
0-25	0%	0%	0%	0%
>25-100	0%	0%	0%	0%
>100-750	4%	10%	6%	0%
>750	13%	29%	18%	6%
4. Other pigs				
Total pigs on holding	Above-ground tank	Below-ground tank	Lagoon	Anaerobic digestion
0-300	0%	0%	0%	0%
>300-1000	2%	5%	3%	0%
>1000-2000	8%	19%	12%	1%
>2000	16%	36%	22%	6%

The estimated number of slurry stores in England by store type, for 2019, is summarised in Table 9, with Table 10 showing estimated slurry volumes and TAN content, adjusted to match the emission inventory totals.

Table 9. Estimated number of slurry stores in England by store type (2019)

Store type	Count
Above Ground	1,818
Below Ground	1,346
Lagoon	1,562
Weeping Wall	1,808
Anaerobic digestion	124

Table 10. Estimated slurry volume and TAN content (for England by livestock sector) - adjusted to 2019 inventory.

Sector	**Store Type**	**Slurry volume (m^3)**	**Slurry TAN content (kg N)**
Beef	Above Ground	2,217,313	2,255,416
Beef	Below Ground	1,478,209	1,503,610
Beef	Lagoon	1,847,761	1,879,513
Beef	Weeping Wall	1,221,311	1,231,898
Beef	Anaerobic digestion	179,777	183,079
Beef total	**All types**	**6,944,370**	**7,053,517**
Dairy	Above Ground	9,282,595	11,237,436
Dairy	Below Ground	6,188,397	7,491,624
Dairy	Lagoon	7,735,496	9,364,530
Dairy	Weeping Wall	4,490,021	5,436,885
Dairy	Anaerobic digestion	784,272	949,311
Dairy total	**All types**	**28,480,780**	**34,479,786**
Pig	Above Ground	345,591	1,559,897
Pig	Below Ground	698,173	3,149,065
Pig	Lagoon	450,120	2,030,921
Pig	Weeping Wall	24,671	112,756
Pig	Anaerobic digestion	100,630	451,975
Pig total	**All types**	**1,619,185**	**7,304,614**
All sectors total	**All types**	**37,044,335**	**48,837,917**

The map in Figure 1 shows the estimated probable location of holdings containing slurry stores in England in 2019, taking into account the assumptions described above about the distribution of slurry by livestock sector and farm size. The areas with the highest densities are predominantly associated with dairy and pig farming. Figure 2 shows the estimated location by livestock sector – N.B. the estimated number of stores should not be confused with the emissions associated with stores, with the latter taking into account volumes, types of slurry present, surface areas, etc. Emissions are quantified and illustrated with maps in Section 4 of this report.

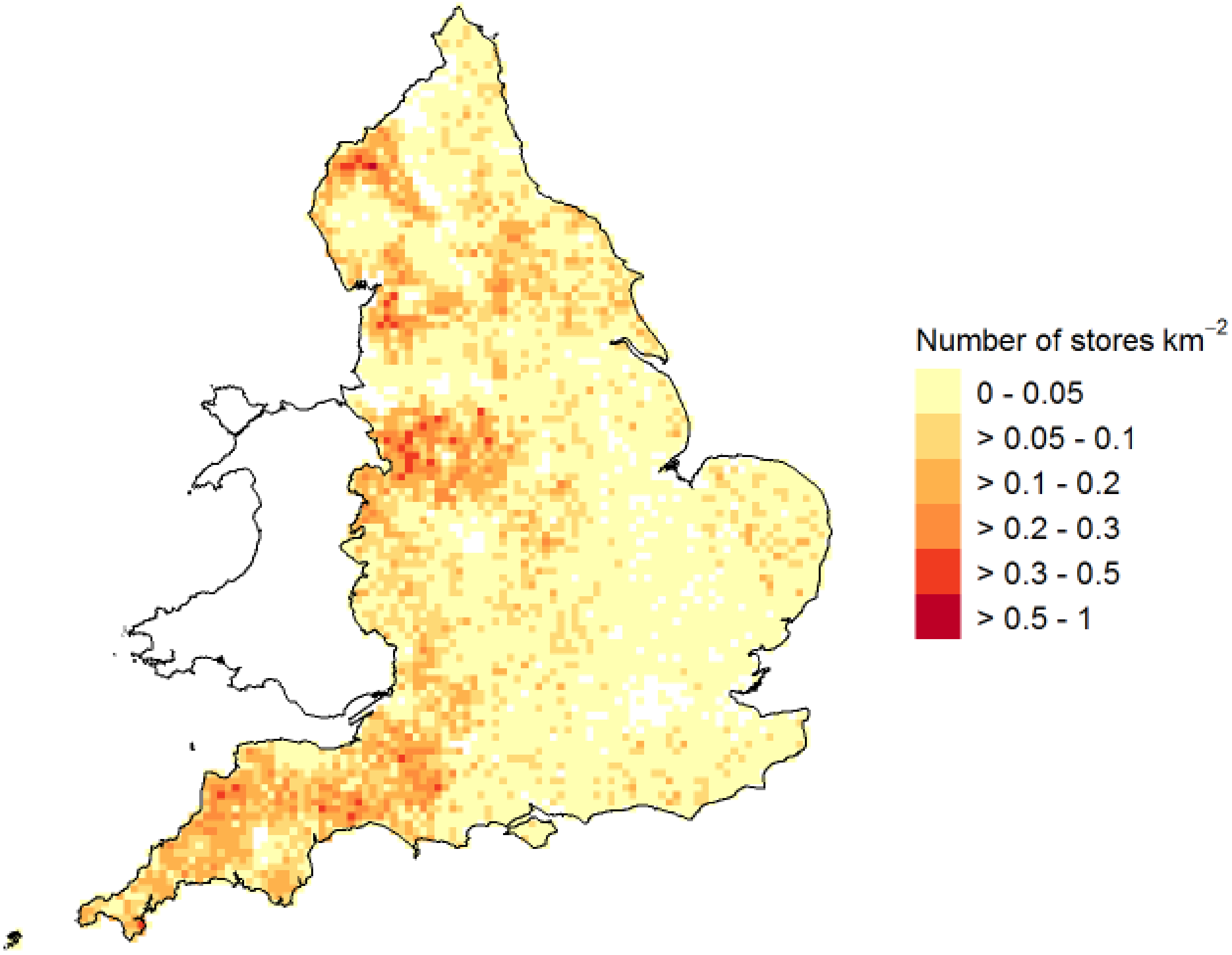

Figure 1. Spatial distribution of holdings containing slurry stores in England (2019), at a 5 km by 5 km grid resolution, expressed as a probability of stores present, according to the assumptions made.

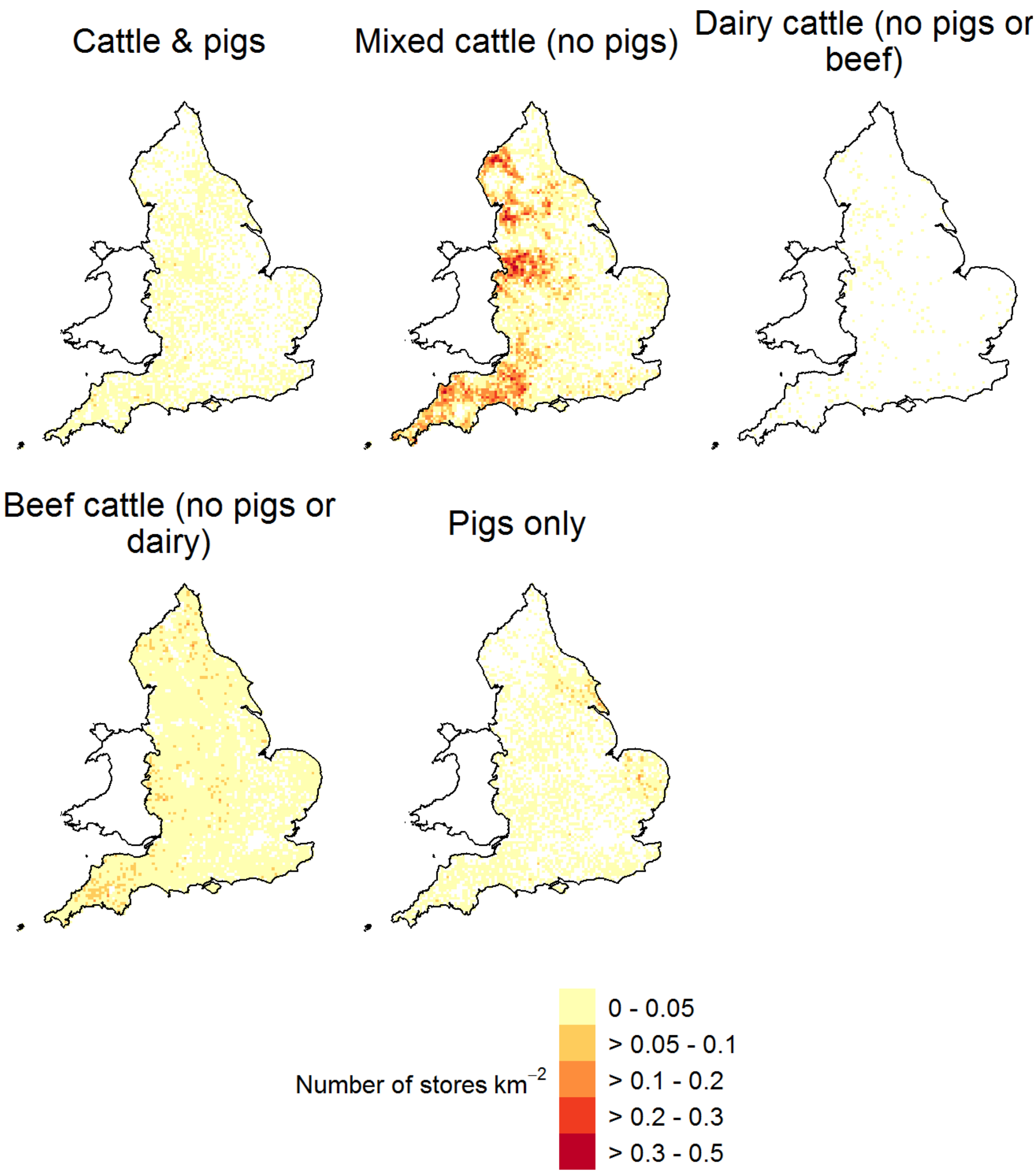

Figure 2. Spatial distribution of holdings containing slurry stores in England (2019), by livestock sector, at a 5 km by 5 km grid resolution, expressed as a probability of stores present (according to the assumptions made).

Anaerobic Digestion

In the 2018 UK National Atmospheric Emission inventory (NAEI, submitted 2020), ~370 sites were reported for England. These sites processed 10Mt of feedstock materials, which is broken down into 4.1 Mt of food wastes and organic materials, 3.6 Mt of crop wastes or bioenergy crops, 1.6 Mt of animal slurries and manures and 0.7 Mt of miscellaneous materials (sewage, oils etc.). 74 sites (1.8 Mt) processed crop material exclusively, 35 sites (0.3 Mt) animal manures and slurries exclusively, 62 (3.2 Mt) solely organic/food wastes and the remaining ~200 processed mixed feedstocks. Following engagement with experts at AquaEnviro, ADBA and REA (Section 2), no new quantitative data was obtained. In fact, the assumption that all PAS110 sites have covers for their digestate materials is not completely correct (it is a recommendation, not a requirement) and therefore it is likely emissions from digestate stores are slightly underestimated in the inventory (from this perspective). However, no adjustment has been made within this project to the emissions totals, compared with the inventory.

No survey or quantitative data are known with regards store covers by any of the contacted parties. There was a recommendation from two consultations to engage the Environment Agency to establish whether there are any covering conditions imposed under the Environmental Permitting Regulations, and also to be aware of the forthcoming guidance on ‘Appropriate measures for biowaste treatment’.

A Google Earth survey of a random sample of sites (10%) revealed complications of this method due to the difficulty of identifying which tank was specifically used for digestate from a given facility, especially when the facility was located on an industrial estate, or if the facility had other such stores for regular slurries or other composted materials etc. Furthermore the registered address of the facility is not always exactly at the location of the facility.

Overall the information suggests that while the evidence is quite scarce re store covers, the current assumptions are reasonable.

2.4 Summary and conclusions

Individual slurry stores in England were profiled, based on information from the 2019 UK agricultural emission inventory on the probability of systems used by livestock type and farm size. The methodology uses the best information available at a holding level, as data on systems used is only collected by national surveys in the UK, rather than a dedicated database that covers all holdings. There is very limited data available on slurry storage systems, incidence of natural crust formation, dimensions and implemented mitigation measures (i.e. slurry covers installed) from the Farming Ammonia Reduction Grant (FARG) Scheme[6], for a small number of farms in England. However, the self-selecting nature and relatively small number of farms within the scheme mean that such data cannot be considered as a representative sample for England.

From a perspective of giving credit for the implementation of mitigation in the inventory, it is important that such information is recorded and applied in the emission inventory, ideally not as an average proportion of slurry or AD stores that have been covered, but linked with the farm location. Any future schemes that support the installation of slurry or AD covers should both record and make available data for inclusion in the annual emission inventory compilation.

[6] https://www.gov.uk/government/publications/farming-ammonia-reduction-grant-scheme-claim-form-and-offer-terms/guide-to-farming-ammonia-reduction-grant-scheme

3 Profile of nitrogen-sensitive sites in England

3.1 Research questions

- Which English nitrogen-sensitive protected habitats (SSSIs and European sites, i.e. SACs) are most impacted by ammonia emissions from slurry stores?
- Where are these protected habitats geospatially located?

3.2 Methodology

Spatial analysis was carried out linking the estimated geographical location of all slurry stores (using the farm location from the June Agricultural Survey) with site boundary data for all designated SSSIs, SACs in England. By building distance relationships between the two datasets, the following analyses were possible:

- Number of slurry stores present within concentric zones around each site. Zones of 1 km, 2 km, 5 km and 10 km were investigated.
- Emission estimates from slurry stores within each concentric zone (using holding level information on livestock types and numbers present at each farm, and the assumptions on systems most likely present)
- Potential for emission savings from covering all slurry stores within each concentric zone.

3.3 Results

The sites estimated to be most affected by emissions from slurry stores (both in terms of numbers of stores and emissions) and potential savings from store covers are summarised and discussed in Section 4 (Impact of slurry covers on emission reduction).

Large tables of all SSSIs and SACs with the number of slurry stores estimated to be present (probability-based) and related emission, for each of the concentric zones, are provided as spreadsheet annexes.

4 Impact of slurry covers on emission reduction

4.1 Research questions

- Which slurry stores are likely to have a natural crust?
- What is the likelihood of covers being present on slurry stores (i.e. probabilities for slurry and digestate stores), i.e. current implementation?
- How many slurry stores are estimated to fall within the zones of 1km, 2km, 5km and 10km from these protected habitats?
- What is the estimated volume of manure/digestate contained in these slurry/digestate stores which fall within the distances outlined above?
- What is the estimated reduction in ammonia emissions (and nitrous oxide and methane emissions if possible) from installing covers of different types on slurry/digestate stores for the four zones (1 km, 2 km, 5 km, 10 km)?

4.2 Slurry storage mitigation options and current implementation

Mitigation options for slurry storage include natural crusting (for cattle slurry) and the installation of a fixed or floating cover. Reduction efficiencies and costs for these options are given in Table 11 and the current implementation rate for each option (2019) for England, which needs to be taken into account when assessing the impact of further implementation, is given in Table 12. These implementation rates are relatively uncertain; the proportion of cattle stores developing a crust is based on a single survey of frequency of slurry agitation (an effective crust is assumed to develop where slurry stores are not frequently agitated). Implementation of store covers for cattle slurry stores is assumed to be zero in the inventory methodology, based on past Farm Practice Surveys. However, in reality there is a very small number of known covered cattle slurry stores e.g. from the Farming Ammonia Reduction Grant (FARG) scheme. For pig slurry storage the assumption is that farms above the IED threshold (accounting for approximately 24% of pigs in England) have a store cover as part of their best practice implementation. For digestate stores, there are no current survey data available, but best practice is assumed and is generally required by large AD plant operators. Further survey data would greatly help in reducing these uncertainties. Further details underlying the costs estimates are given in the Scenario Modelling Tool project report (Defra ECM55618). A reduction in slurry spreading costs is assumed with the implementation of a fixed cover due to exclusion of rainfall. A floating cover is assumed to be LECA (light expanded clay aggregates).

Impacts on methane and nitrous oxide emissions from slurry storage through the implementation of different covers are effectively zero based on the current inventory methodology and underlying emission factors. Methane is generated through microbial processes within the stored slurry and the rate of generation and release to the atmosphere (through cover vents specifically designed to avoid dangerous methane concentrations building up in the store headspace, or through cracks/gaps in crusts and floating material covers) is assumed to be the same. The presence of a cover may increase the stored slurry temperature, thereby increasing the methane generation/emission rate, but this is not reflected in our current methodology. Methane oxidation through a natural crust, as included in IPCC Guidelines, is also not included in the UK inventory as literature data suggest that this doesn't occur to any great extent, as generated methane predominantly escapes at crust edges and through cracks/gaps from specific ebullition events. Similarly, the generation of nitrous oxide within slurry crusts is not currently reflected in the UK inventory methodology. Retaining N in the stored slurry through the use of covers and reduction in ammonia emissions will result in a higher quantity of N been applied to land and therefore an associated increase in direct and indirect nitrous oxide emissions associated with that land spreading.

Table 11. Ammonia emission reduction efficiency and annualised costs associated with slurry storage cover options

	Natural crust	**Fixed cover**	**Floating cover**
Emission reduction (%)	50	80	60
Cost – above-ground tank (£ m^{-3} slurry)	0.00	1.48	0.70
Cost – lagoon (£ m^{-3} slurry)	0.00	N/A	1.31

Table 12. Implementation rates for slurry store covers (% of slurry associated with a cover), England, 2019.

Sector	**Store type**	**Crust**	**Fixed cover**	**Floating cover**
Dairy/Beef	Above-ground tank	80	0	0
Dairy/Beef	Below-ground tank	N/A	N/A	N/A
Dairy/Beef	Lagoon		N/A	
Dairy/Beef	Weeping wall	N/A	N/A	N/A
Dairy/Beef	Anaerobic digestion	0	100	0
Pig	Above-ground tank	N/A	24	0
Pig	Below-ground tank	N/A	N/A	N/A
Pig	Lagoon	N/A	N/A	24
Pig	Anaerobic digestion	N/A	100	0

4.3 Results

Emissions from slurry stores in England, by livestock sector and store type are summarised in Table 13. The dairy sector is by far the largest contributor to slurry store emission, followed by the pig sector, with beef systems the smallest. In terms of store types, emissions from dairy lagoon are the single largest source, owing to the much larger surface areas that promote more ammonia volatilisation than from stores with a higher volume to surface area ratio (such as above ground tanks).

Emission savings were calculated by livestock sector and store type, with all stores covered with the most effective applicable cover type (Table 11). Above-ground stores were covered with fixed covers and slurry lagoons with floating covers (Table 14). Below ground and weeping wall stores were not covered, and anaerobic digestate stores were assumed to be already covered (Table 11).

The largest overall emission savings were estimated for the dairy sector at ca. 1.5 kt NH_3, with ca. 0.6 kt for the pig sector and ca. 0.3 kt for the beef sector, adding up to 2.5 kt NH_3. Of this total, 1 kt NH_3 is associated with slurry lagoons on dairy farms. Of an estimated 6.9 kt emissions from slurry stores, the total potential emission reduction is 36%.

Table 13. Estimated ammonia emission from slurry tanks in England in 2019 (per sector and store type).

Sector	Store Type	TAN content (kg N)	% with crust / cover	Crust/cover emission reduction (%)	NH_3 emission (kg NH_3 yr^{-1})
Beef	Above Ground	2,255,416	80	50	145,419
Beef	Below Ground	1,503,610	0	0	80,788
Beef	Lagoon	1,879,513	80	50	630,148
Beef	Weeping Wall	1,231,898	0	0	66,189
Beef	Anaerobic digestion	183,079	0	0	3,935
Dairy	Above Ground	11,237,436	80	50	731,007
Dairy	Below Ground	7,491,624	0	0	406,115
Dairy	Lagoon	9,364,530	80	50	3,167,696
Dairy	Weeping Wall	5,436,885	0	0	294,729
Dairy	Anaerobic digestion	949,311	0	0	20,585
Pig	Above Ground	1,559,897	24	80	174,529
Pig	Below Ground	3,149,065	0	0	234,799
Pig	Lagoon	2,030,921	24	60	962,911
Pig	Weeping Wall	112,756	0	0	6,005
Pig	Anaerobic digestion	451,975	0	0	12,517

Table 14. Potential emission reductions by livestock sector and store type: emission reductions assume all stores are covered with most effective cover type.

Sector	Store Type	NH_3 emission (kg NH_3 yr^{-1})	Potential NH_3 emission (kg NH_3 yr^{-1})	Difference (kg NH_3 yr^{-1})	Difference (%)
Beef	Above Ground	145,419	48,473	-96,946	-67
Beef	Below Ground	80,788	80,788	0	0
Beef	Lagoon	630,148	420,099	-210,049	-33
Beef	Weeping Wall	66,189	66,189	0	0
Beef	Anaerobic digestion	3,935	3,935	0	0
Dairy	Above Ground	731,007	243,669	-487,338	-67
Dairy	Below Ground	406,115	406,115	0	0
Dairy	Lagoon	3,167,696	2,111,797	-1,055,899	-33
Dairy	Weeping Wall	294,729	294,729	0	0
Dairy	Anaerobic digestion	20,585	20,585	0	0
Pig	Above Ground	174,529	43,200	-131,328	-75
Pig	Below Ground	234,799	234,799	0	0
Pig	Lagoon	962,911	449,958	-512,953	-53
Pig	Weeping Wall	6,005	6,005	0	0
Pig	Anaerobic digestion	12,517	12,517	0	0
Total		**6,937,372**	**4,442,858**	**-2,494,513**	**-36%**

The closer a slurry store (or any ammonia emission source) is to a designated site, the larger the benefit from mitigation measures. This is due to ammonia being a highly reactive gas with atmospheric concentrations and dry deposition decreasing relatively rapidly along a gradient away from sources. However, the larger the overall reduction in emissions in wider areas around a site, the lower the background concentrations and any dry and wet deposition that arrives from further afield.

The buffer zones surrounding the SSSI/SAC designated sites in England are presented in Figure 3. The figure clearly shows that the majority of England is within 10 km of a SSSI site, while SACs are less widespread.

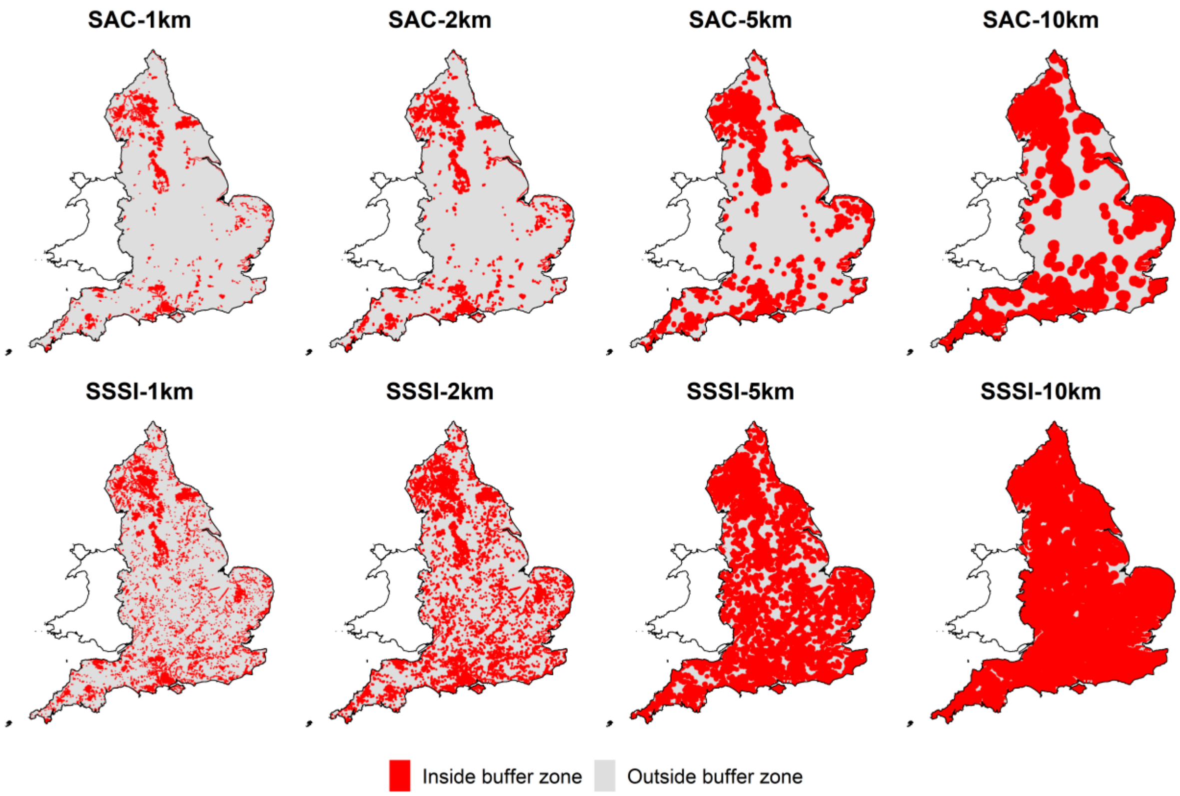

Figure 3. Buffer zones surrounding SAC and SSSI sites in England

Table 15 provides an estimate of the number of holdings containing slurry stores by designated site type and buffer zone. The table further demonstrates that SSSIs are more widespread than SACs (see Figure 3), and therefore a larger number of slurry stores are targeted in zones surrounding SSSIs (as the land area is greater). Similarly Table 16 presents the estimated amount of slurry produced by buffer zone and associated current emission estimates.

Table 15. Number of holdings estimated to contain slurry stores by designated site type and buffer zone

Buffer	SAC		SSSI	
	Number of holdings	% nationally	Number of holdings	% nationally
1 km	561	8%	1,247	19%
2 km	1,061	16%	2,537	38%
5 km	2,346	35%	5,304	80%
10 km	4,085	61%	6,552	98%
England	6,658	100%	6,658	100%

Table 16. Estimated amount of slurry produced by slurry stores near designated sites by site type and buffer zone

Designation	Buffer	Slurry produced		Emission estimates	
		Volume of slurry (000 m_3)	% nationally	Emissions from slurry (t NH_3 yr^{-1})	% nationally
SAC	1 km	2,898	8%	518	7%
SAC	2 km	5,754	16%	1,033	15%
SAC	5 km	12,770	34%	2,368	34%
SAC	10 km	23,103	62%	4,293	62%
SSSI	1 km	6,404	17%	1,171	17%
SSSI	2 km	13,481	36%	2,476	36%
SSSI	5 km	29,273	79%	5,492	79%
SSSI	10 km	36,471	98%	6,816	98%
England		**37,044**	**100%**	**6,937**	**100%**

Table 17 provides a summary of potential absolute emission reductions across all SACs and SSSIs by livestock sector and concentric zone. Table 18 shows % contributions by livestock sector across all sites by type and zone. Tables 19 and 20 show the same information as emission densities, i.e. in kg NH_3 ha^{-1} $year^{-1}$ from slurry stores (absolute and relative, by livestock sector and concentric zone). Data for all individual designated sites relating to Tables 17-20 are provided in the form of spreadsheets as an annex. Figures 5 and 6 illustrate the effect of increasing buffer zones surrounding SSSIs and SACs, in terms of area, number of holdings (with slurry stores estimates), slurry produced and ammonia emissions relative to national totals.

Table 17. Estimated emission reduction by designated site type, buffer zone and livestock sector (kt NH_3 yr^{-1})

Designation	Buffer	Dairy	Beef	Pig	Total
SAC	1km	0.115	0.029	0.039	0.183
SAC	2km	0.236	0.051	0.079	0.366
SAC	5km	0.525	0.106	0.216	0.847
SAC	10km	0.975	0.179	0.383	1.537
SSSI	1km	0.248	0.067	0.104	0.418
SSSI	2km	0.539	0.127	0.219	0.884
SSSI	5km	1.210	0.248	0.519	1.977
SSSI	10km	1.520	0.302	0.626	2.449

Table 18. Estimated emission reduction by designated site type and buffer zone (kt NH_3 yr^{-1}) inc. proportion (%) by livestock sector

SITETYPE	BUFFER	Total reduction (kt NH_3)	Dairy	Beef	Pig
SAC	1km	0.18	62.89	15.63	21.48
SAC	2km	0.37	64.44	14.04	21.52
SAC	5km	0.85	61.98	12.54	25.48
SAC	10km	1.54	63.43	11.67	24.90
SSSI	1km	0.42	59.19	16.02	24.78
SSSI	2km	0.88	60.94	14.31	24.75
SSSI	5km	1.98	61.21	12.55	26.23
SSSI	10km	2.45	62.08	12.34	25.58

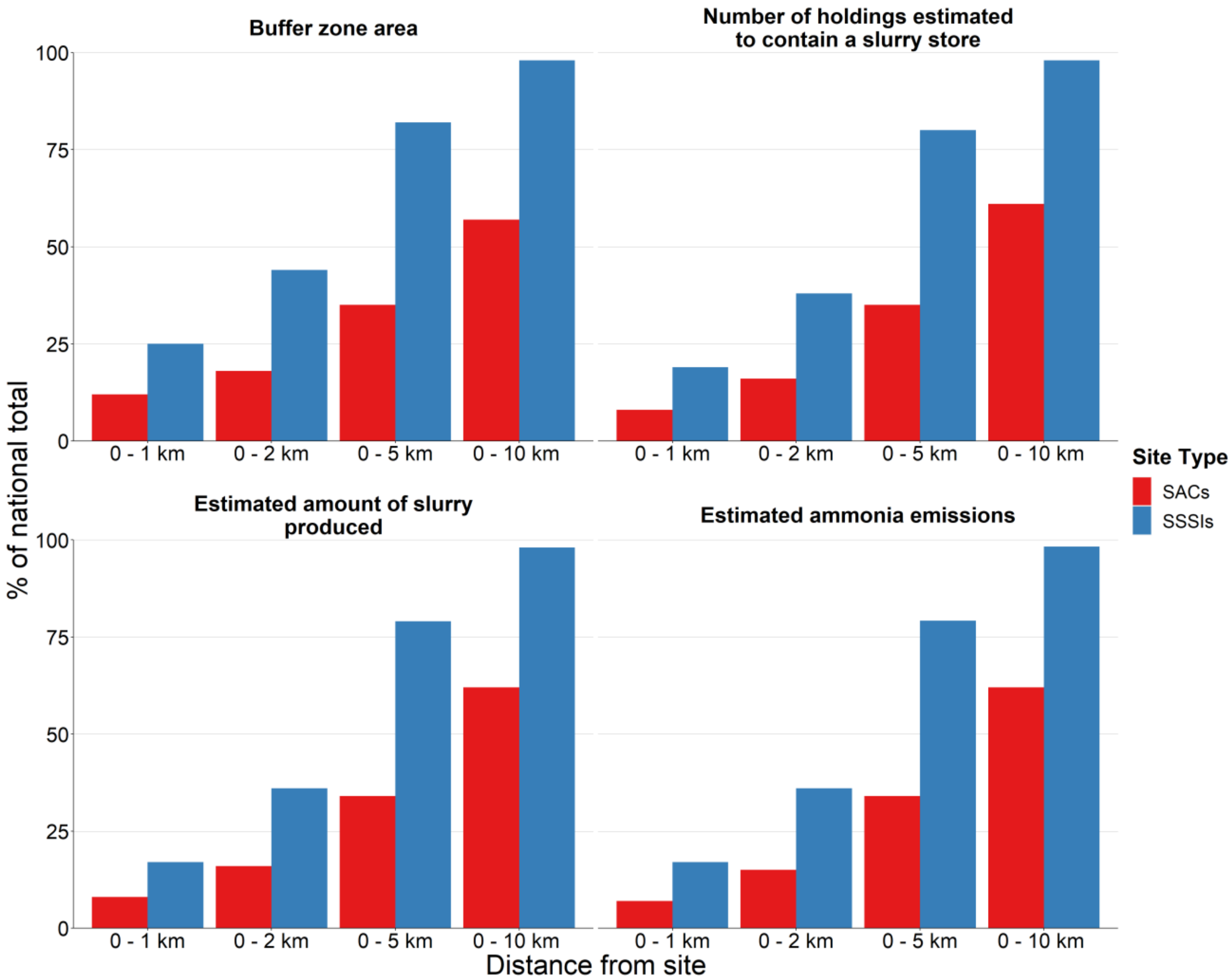

Figure 4. The effect of increasing buffer zones surrounding SSSIs and SACs, in terms of area, number of holdings (with slurry stores estimates), slurry produced and ammonia emissions relative to national totals.

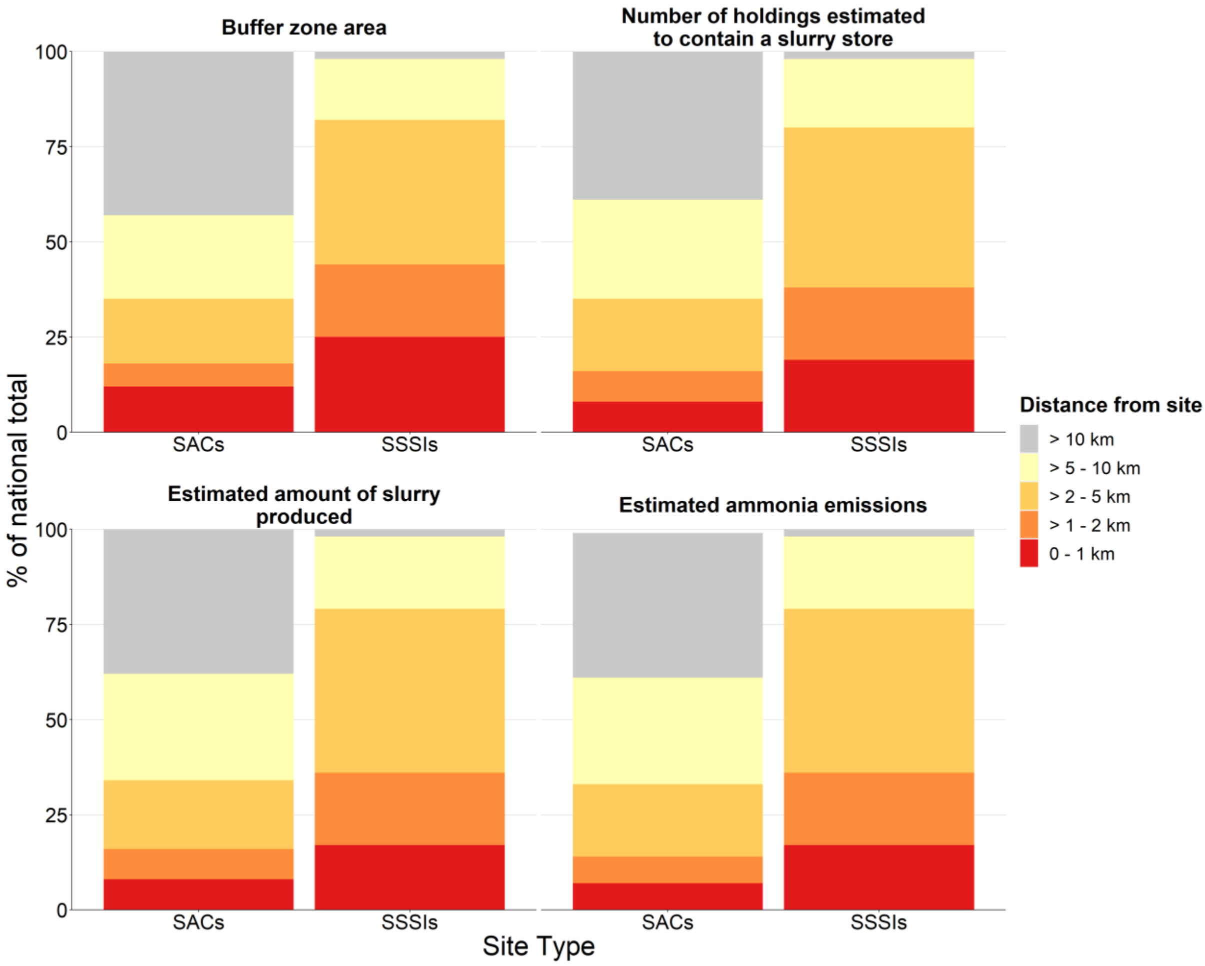

Figure 5. The effect of concentric buffer zones surrounding SSSIs and SACs, in terms of area, number of holdings (with slurry stores estimates), slurry produced and ammonia emissions relative to national totals.

Table 19. Average reduction in emission density for all sites in England by buffer zone size, designated site type and livestock sector (kg NH_3 ha^{-1} yr^{-1})

SITETYPE	BUFFER	Dairy	Beef	Pig	Total
SAC	1km	0.181	0.024	0.127	0.333
SAC	2km	0.151	0.020	0.077	0.248
SAC	5km	0.118	0.020	0.046	0.185
SAC	10km	0.124	0.020	0.040	0.185
SSSI	1km	0.321	0.041	0.266	0.628
SSSI	2km	0.223	0.027	0.121	0.371
SSSI	5km	0.133	0.022	0.058	0.213
SSSI	10km	0.112	0.021	0.045	0.176

Table 20. Average reduction in emission density by buffer zone and designated site type (kg NH_3 ha^{-1} yr^{-1}) inc. proportion (%) by sector

SITETYPE	BUFFER	Total reduction (kt NH_3)	Dairy	Beef	Pig
SAC	1km	0.33	54.51	7.19	38.31
SAC	2km	0.25	60.89	8.13	30.98
SAC	5km	0.18	63.92	11.02	25.06
SAC	10km	0.18	67.35	10.89	21.76
SSSI	1km	0.63	51.15	6.59	42.26
SSSI	2km	0.37	59.96	7.37	32.66
SSSI	5km	0.21	62.62	10.28	27.10
SSSI	10km	0.18	63.13	11.76	25.11

The spatial distribution of emissions from slurry stores in England, by livestock type, is illustrated in Figure 6, separately for the dairy, beef and pig sectors. This shows that any measures applied at dairy farms would be mostly providing immediate local benefits at designated sites located in the western half of England, whereas measures on beef farms would be more spread out, whereas the most intensive pig farming is based in the east of England. However, for all three livestock sectors, the key determinant for bringing local mitigation benefits to a designated site is the close proximity of nearby slurry stores at the individual site level, rather than the larger spatial patterns across England.

Figure 7 illustrates potential emission reductions by livestock sector across England. These follow the same spatial patterns as the emissions overall.

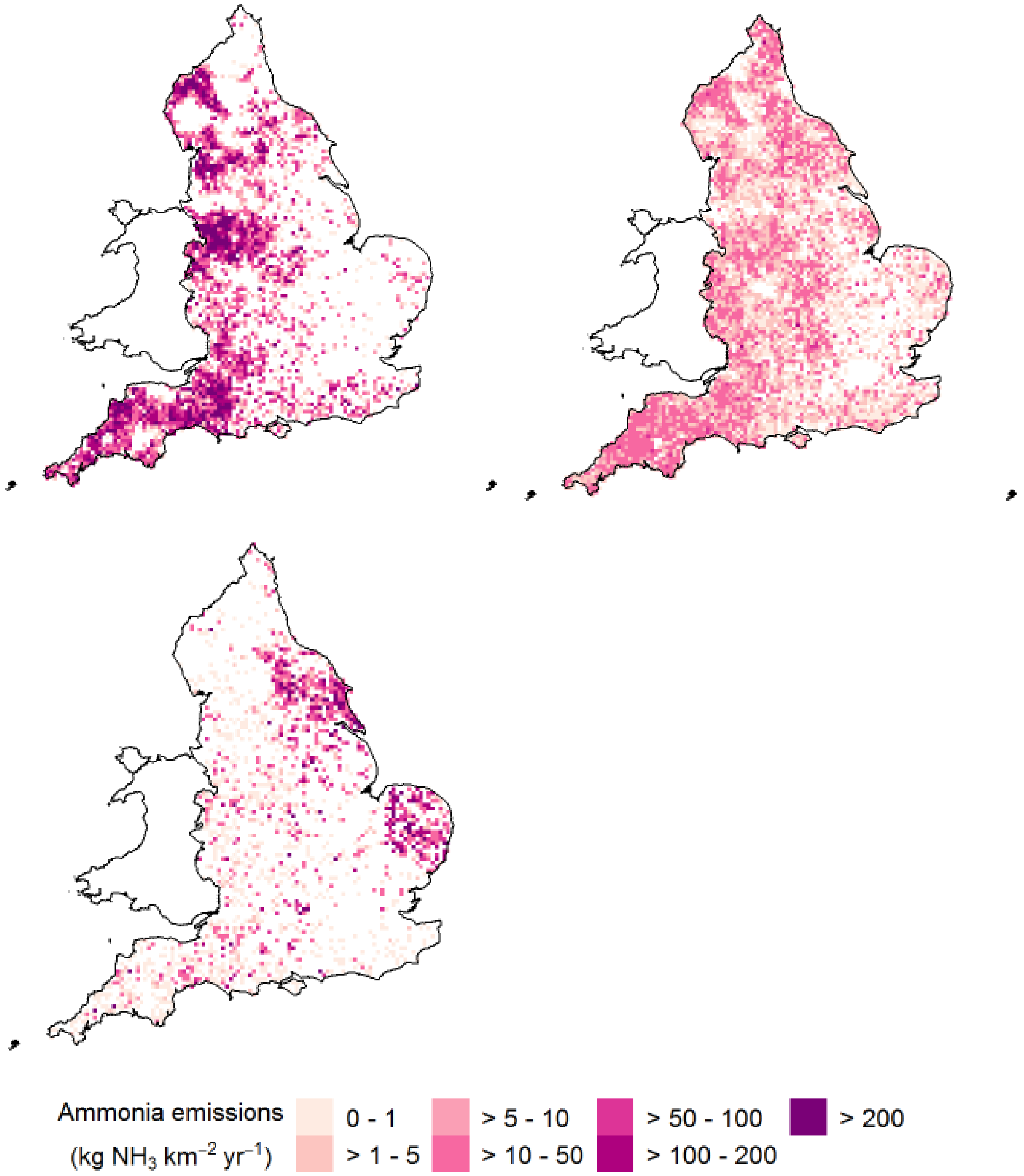

Figure 6. Spatial Distribution of NH_3 emissions associated with slurry storage (5 km by 5 km grid resolution). Dairy (top left), beef (top right), pig (bottom)

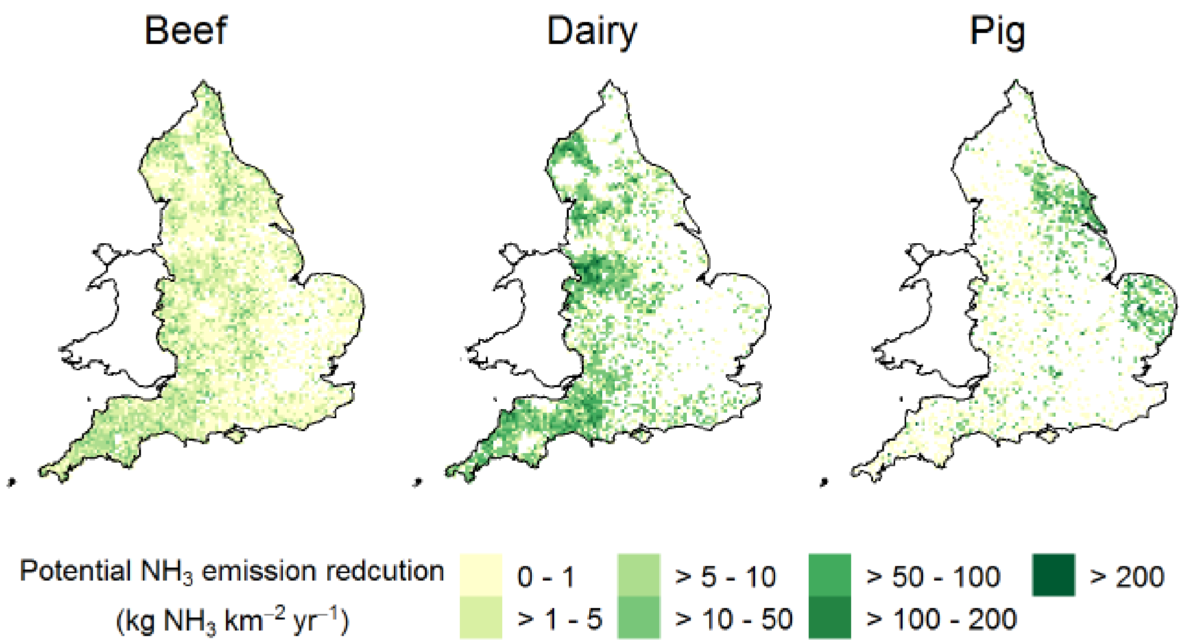

Figure 7. Potential NH_3 emission reductions from covering slurry stores, by livestock sector, on a per-area basis, i.e. reduction in emission density (5 km by 5 km grid resolution)

Anaerobic Digestion

In the current NAEI for 2018 it is estimated that 0.73 kt of NH_3 are emitted from AD facility digestate stores in England (this does not include digestates from any manures or slurries, 1.6 Mt, to avoid double counting with other parts of the emissions inventory and this study). However, as noted in Section 2.3, this may be an underestimate due to over-estimating the prevalence of covers. The scope to reduce these emissions is therefore quite limited at a national level, however, any sensitive habitats and designated sites located close to any uncovered digestate store would benefit from covers being installed.

Table 21 below shows the potential effect, with current inventory assumptions, that having no covers or 100% covers may have on the current NAEI emissions estimate.

Table 21. Emissions from anaerobic digestion stores (excluding slurries and manures)

	Current Inventory (NAEI)	**No stores covered**	**All stores covered**
Emissions from storage (kt NH_3)	0.74	2.82	0.05

Furthermore, with relation to AD facility locations and their proximity to SACs and SSSIs, Figure 8 shows the total number of sites and their estimated emissions from stores within 1km, 2km, 5km and 10km zones.

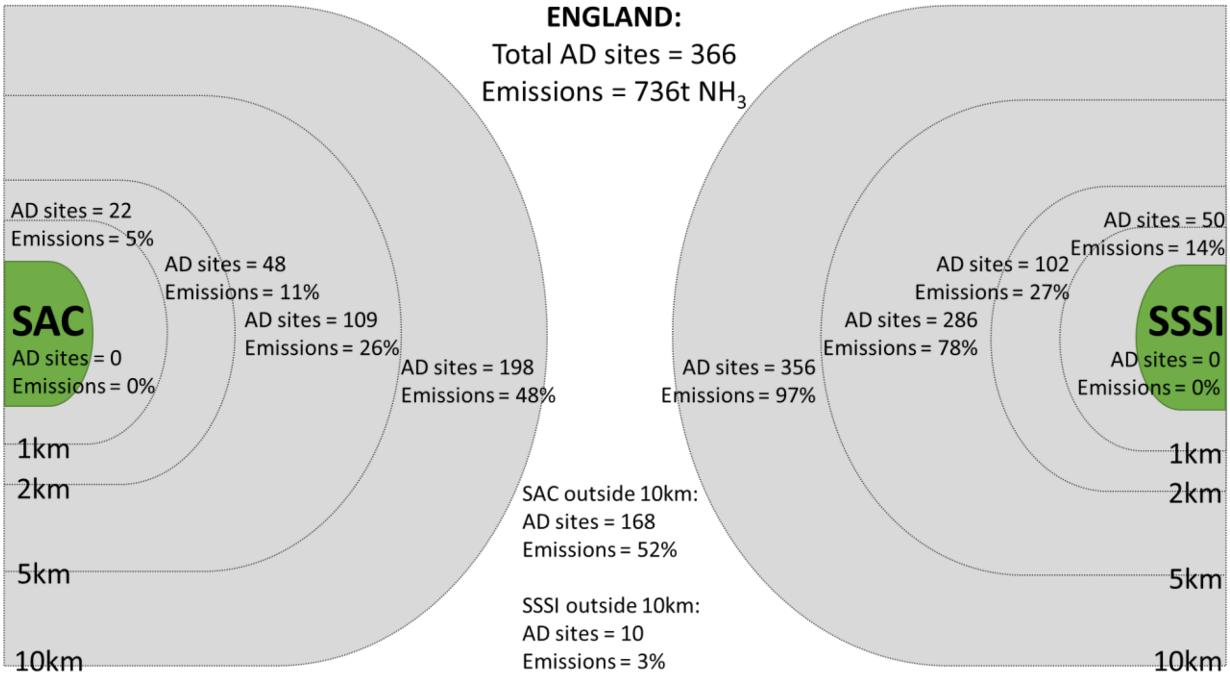

Figure 8. Presence of digestate stores within concentric zones around SACs and SSSIs in England (1 km, 2 km, 5 km, 10 km) and associated proportion of total NH_3 emissions from digestate store. Feedstocks exclude slurries and manures, to avoid double-counting with the slurry store covers analysed separately in this study.

5 Summary, discussion & conclusions

This study investigated the potential impact of installing covers on slurry and digestate stores on ammonia emissions in England, both at a country scale and spatially targeting this measure near nitrogen-sensitive designated sites (SACs, SSSIs).

The analysis was carried out in three steps:

1) Profiling each holding with cattle and/or pigs present to determine the probability of slurry storage, including store type, on the farm, using assumptions based on average practice by livestock sector (dairy, beef, pig) and herd size.
2) Quantifying emissions from slurry storage for each nitrogen-sensitive designated site, using the holding level probabilities from Step 1, for concentric zones of 1 km, 2 km, 5 km and 10 km.
3) Estimating the potential savings of emissions from covering all slurry stores for England as a whole and the spatial distribution of these potential benefits in relation to the location of sensitive designated sites.

Natural crusting of slurry stores reduces ammonia emission by an average of 50%, whereas floating covers can reduce emissions by ca. 60% and rigid covers by ca/ 80%. Installing the most effective covers on all on-farm slurry stores (i.e. impermeable covers on above-ground tanks and permeable covers on lagoons) was estimated to reduce emissions from slurry stores by ~2.5 kt NH_3. This would provide a saving of 36% in emissions associated with the storage of slurries in England overall (2019), from a current best estimate of 6.9 kt NH_3. The largest savings are associated with the dairy sector (1.5 kt NH_3, followed by 0.6 kt for pigs and 0.3 kt for beef cattle). Covering all suitable stores would therefore contribute towards achieving the targets of the NECR and objectives of the CAS and 25 Year Environment Plan, by reducing atmospheric emissions and their subsequent impacts on sensitive habitats and designated sites through elevated ammonia concentration and nitrogen deposition.

It has been demonstrated that spatial targeting of ammonia reduction measures near designated sites gives higher returns for investment in mitigation than an even spread of the same effort across the country (e.g. Defra Project AC0109[7], and JNCC/Defra project Nitrogen Futures[8]). The total predicted emission reductions from slurry covers within 1 km of all SACs and SSSIs are relatively small (compared to covering all slurry stores), at 183 t and 418 t NH_3, respectively, or 366 t and 884 t NH_3, for all suitable stores within 2 km of SACs and SSSIs, respectively. However, mitigation of intensive local “hot spot” point sources such as slurry stores by up to 80% (depending on the system in use) can reduce elevated atmospheric concentrations at nearby designated sites considerably. Therefore, if slurry covers were prioritised close to designated sites, i.e. using a spatially targeted approach, this could make a considerable difference to those sites.

[7] http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=14938
[8] https://jncc.gov.uk/our-work/nitrogen-futures/

It should be noted that emission reductions at the storage stage of manure management result in a higher proportion of valuable nitrogen fertiliser being retained for land spreading to arable crops and grassland. If the slurry is then spread with low-emission techniques such as injection or trailing hose/trailing shoe, using best practice, this can result in savings due to less additional mineral nitrogen fertiliser being needed to achieve the same overall nitrogen input. If slurry stored under covers is spread using splash-plate technology, there is the potential for more ammonia being volatilised. However, this does not offset all savings from the installation of covers.

If such measures were supported in, e.g., the Environmental Land Management Scheme under development, it would be important to clearly record the location of the measures (holding ID), the type of store and cover, and the volume and surface area of the store. By making such data available for use in the UK's agricultural emission inventory, this would then enable crediting measures explicitly and ensuring that progress in emission reductions can be reported accurately. This is not only important for NECR targets, but also for enabling more accurate assessments and reporting of local emissions for quantifying the environmental benefits.

BANGOR
UK Centre for Ecology & Hydrology
Environment Centre Wales
Deiniol Road
Bangor
Gwynedd
LL57 2UW
United Kingdom
T: +44 (0)1248 374500
F: +44 (0)1248 362133

LANCASTER
UK Centre for Ecology & Hydrology
Lancaster Environment Centre
Library Avenue
Bailrigg
Lancaster
LA1 4AP
United Kingdom
T: +44 (0)1524 595800
F: +44 (0)1524 61536

EDINBURGH
UK Centre for Ecology & Hydrology
Bush Estate
Penicuik
Midlothian
EH26 0QB
United Kingdom
T: +44 (0)131 4454343
F: +44 (0)131 4453943

WALLINGFORD (Headquarters)
UK Centre for Ecology & Hydrology
Maclean Building
Benson Lane
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
United Kingdom
T: +44 (0)1491 838800
F: +44 (0)1491 692424

enquiries@ceh.ac.uk

www.ceh.ac.uk