Scenario modelling - spatial targeting of ammonia mitigation measures in Northern Ireland

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Client Ref: DAERA E&I 17/4/02

Issue Number 1

Date 11/05/2020

Title	Scenario modelling - spatial targeting of ammonia mitigation measures in Northern Ireland
Client	DAERA
Client reference	E&I 17/4/02
UKCEH reference	NEC06547 / Issue number 1
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Date	11/05/2020

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1.1 Summary

This report describes the scenario modelling undertaken to test the potential impact of bundles of ammonia (NH_3) mitigation measures on atmospheric emissions, concentrations and deposition as well as effects on sensitive vegetation, and, in particular, on designated sites (SACs, ASSIs). The scenarios tested both Northern Ireland-wide and spatially targeted options near designated sites. Ammonia is very reactive and effects are known to occur locally, close to emission sources, and spatial targeting has previously been shown in UK studies to be more cost-effective per unit of emission reduction than country-wide measures where reductions are spread more thinly over a much larger area (i.e. same overall emission reduction).

The scenarios tested here included a large (25%) reduction in emissions across the agriculture sectors for the whole of Northern Ireland (M-NI), and additional enhanced mitigation measures in areas close to designated sites. The modelling carried out has clearly shown the substantial impact of the large bundle of NI-wide measures. Given the relatively high baseline emissions across agricultural landscapes with high levels of agricultural activities across much of Northern Ireland, this NI-wide mitigation effort has the potential to reduce emissions significantly, as already shown with a previous modelling exercise carried out in 2018. The suite of measures included in the M-NI scenario in this report has been refined over the past 12 months and is considered more suitable and realistic in terms of policy options. The M-NI scenario resulted in 2 SACs and 14 ASSIs brought out of exceedance of the 1 µg NH_3 m^{-3} critical level (based on maximum concentrations at sites). The additional spatially targeted measures (“enhanced mitigation scenario”, EM-NI), modelled for buffer zones surrounding the sites, increased overall emission reductions by a further 1-4% (SAC scenarios) and 1-5% (ASSI scenarios) compared to the baseline, depending on the width of the zones (1, 2 and 5 km tested). These scenarios resulted in several additional sites brought out of critical levels exceedance, 1 SAC (Lough Teal) and 5 ASSIs, for the 5 km zones. For N deposition, no additional sites are brought below critical loads, but there is a substantial reduction in excess nitrogen input to sites across NI (i.e. reduction in the maximum average accumulated exceedance per site). It should also be noted that local ammonia emission reduction mostly decreases dry deposition of ammonia-related nitrogen (NH_x), with a small effect on wet NH_x deposition, which is more associated with regional/long-range pollution. Ammonia mitigation also does not influence the N deposition component related to NOx emissions (mainly from combustion), which are not targeted in the scenarios.

While the spatially targeted scenarios have not decreased the number of sites in exceedance (critical levels) dramatically, substantial further reductions in NH_3 concentrations and deposition can be shown. It has been illustrated clearly that, per unit of emission saved, spatial targeting is much more effective in reducing NH_3 concentrations and N deposition at designated sites. For example, spatially targeted measures under EM-SAC1 (1 km zone of enhanced mitigation) are estimated to be, on average, ~5.8 times more effective in reducing average NH_3 concentrations at sites (per unit emission saved), compared with the wider EM-NI scenario. Spatially targeting a 1km zone surrounding ASSIs is shown to be ~ 4.6 times more effective than wider mitigation under EM-NI. In terms of deposition, spatial targeting local of NH_3 sources is more effective at reducing dry NH_x deposition than wet deposition. Applying enhanced measures in a 1 km zone surrounding SACs is on average ~4 times more effective at reducing dry NH_x deposition at sites compared with non-spatially targeted enhanced mitigation. There are large differences between sites in the effectiveness of

reducing concentrations and deposition through targeted mitigation, based on the make-up of the emission source sectors in the vicinity, and the ability to influence concentrations or deposition at sites through spatial targeting with the enhanced measures tested (mainly reducing cattle and pig emissions). Spatially targeting sources near sites in areas with high emission densities can be almost as effective as NI-wide mitigation in terms of dry NH_x deposition reduction (e.g. Turmennan), however this does not hold for all sites, with some sites much more suitable than others for spatial targeting.

In summary, the following approach for maximising the effectiveness of mitigation measures for the benefit of designated sites is proposed:

- Implementation of country-wide measures to decrease NH_3 concentrations and N deposition from a very high baseline - This will lead to improved conditions for sensitive habitats and species in both source areas (with high concentrations and deposition) as well as in more remote areas, where long-range deposition will be reduced.
- Spatial targeting locally – this has been shown to be more effective at “spot-reducing” high concentrations and dry deposition than the same amount of emission reduction spread more widely across the country
- Using a mix of well understood and effective measures more generically, as well as specific targeting, depending on local source types, management systems in place and opportunities for improvement, by engaging locally.

1.2 Updated emission baseline and mitigation scenarios considered

The first step in this this modelling study was to update the **ammonia baseline** (previously 2015/16) to 2017[1] and to re-examine and update the assumptions made for the **modelled NI-wide emission reductions** from the baseline across Northern Ireland. This was mainly to update the assumptions on which modelling during the summer of 2018 was based and which estimated a 24-26% reduction in total NI NH_3 emissions.

Following on from this earlier work, ongoing deliberations and reviews of Daera's Ammonia Project resulted in changes of what are considered the most suitable and realistic policy options. For example, major changes to the timing of slurry spreading during the year (spring/summer/autumn) or the widespread retrofitting of air scrubbers in livestock housing across Northern Ireland are no longer considered as the most appropriate measures, while a move towards acidification of slurry now appears to have some stakeholder interest. In addition, further information became available on potential ammonia reduction measures applicable for cattle housing. Table 1 below outlines the ammonia reduction scenario to be modelled across Northern Ireland (NI-wide ammonia mitigation, M-NI). The uptake rates proposed are based on an assessment of what is likely to be possible to achieve within a 5-10 year timeframe. The new NI-wide emission mitigation scenario achieves a very similar % reduction in emissions, but is considered much more realistic and achievable.

Given that the modelling exercise last year did not result in sufficient reductions in harmful atmospheric ammonia inputs to designated sites to bring sites below critical thresholds (due to very high baselines), further scenario modelling was proposed, to evaluate the impact of additional spatially targeted measures in the vicinity of designated sites. For these Nitrogen Reduction Zones (NRZ), two categories of measures were to be assessed:

- An exclusion zone where no slurry or manure is spread (1 km zone away from the boundary of a designated site), where the slurry and manure is instead spread further away, on land at least 2 km or 5 km (two scenarios) from any designated site and within Northern Ireland.
- Application of a bundle of Enhanced Mitigation measures (EM-NI), similar to measures applied NI-wide but with more ambitious uptake rates and tested over fixed concentric zones of 1/2/5 km away from the boundary of a designated site.

The enhanced mitigation measures are detailed in Table 2 below.

[1] N.B. The emission totals for non-agricultural ammonia in Northern Ireland are as reported for 2017 in the latest published National Atmospheric Emission Inventory (NAEI, naei.beis.gov.uk). However, the spatial distribution for 2016 had to be used (with scaling), as the 2017 maps were only be published and available in autumn 2019 (after the model runs were completed). For NO_x and SO_2 maps (used in the chemical transport modelling to derive NH_3 concentrations and N deposition), the latest available NAEI maps (2016) were scaled to the latest available totals (2017).

Table 1 – Bundle of ammonia measures to be tested as a NI-wide scenario.

	NH_3 reduction measure	Details of measure to be modelled	Implementation rate of measure uptake across NI
1.	**Longer grazing season**	An additional week's grazing at either end of the current average grazing season.	100% uptake
2.	**Stabilised urea fertiliser**	All urea fertiliser to be used in combination with a urease inhibitor – 70% reduction in emissions from urea fertiliser.	100% uptake
3.	**Low emission slurry spreading**	Move away from the use of splash plate for slurry spreading. Use of trailing shoe to grassland (60% emission reduction) and trailing hose to arable land (30% reduction). Current assumption in inventory is that only 10% of slurry is applied by trailing shoe.	100% uptake of Low Emission Slurry Spreading- 50% as Trailing Shoe and 50% as Trailing Hose / Dribble Bar
4.	**Slurry acidification**	Acidify cattle and pig slurry to reduce storage emission by 70% and emissions at spreading by 60%.	5% uptake of acidification in store; further 10% uptake of acidification at spreading stage
5.	**Structure of dairy cow collecting yards**	Collecting yards in the Dairy sector should be slatted or covered with scraping system connected to a tank.	15% uptake
6.	**Lower crude protein diet for livestock**	Reduce protein content of dairy cows during housed periods from 17-18% to 15-16%, to achieve a 20% reduction in N excretion.	75% uptake across all livestock types
		Reduce CP intake of beef diets from 14% CP as assumed in NAP to 13% CP.	
		Reduce Crude Protein intake of pig finishers from AFBI baseline of 17% CP to 15% CP.	
		Reduce the Crude Protein content of Broiler and Layer diets by 1% CP.	
7.	**Genetic improvement in livestock**	Achieve a 5% decrease in Nitrogen excretion rate for Pigs and Poultry.	75% uptake for Pigs and Poultry
		Achieve a 2.5% decrease in Nitrogen Excretion rate for beef and dairy.	50% uptake for Cattle
8.	**Covering above ground slurry stores**	Cover above ground tanks and lagoons with a solid cover.	30% of all above ground stores
9.	**Low emission cattle housing**	Achieve uptake of cattle housing reduction measures. The modelled measure will be the implementation of slat mats with scrapers to achieve a 40% ammonia reduction. Alternative measures may be considered by farmers, e.g. grooved flooring.	25% uptake of slat mats with scrapers in the beef sector and 35% uptake in the Dairy Sector
10.	**Low emission pig and poultry housing- install ammonia reduction measures in housing in the pig and poultry sectors.**	In the pig sector, there are a range of technologies which can potentially be applied. This modelling exercise will assume a 35% reduce in pig emissions through housing solutions.	25% uptake
		In the laying hen sector, regular (at least weekly) removal of litter through manure belts to achieve a 70% emission reduction.	60% uptake
		In the Broiler sector, alum acidification will achieve a 70% reduction in ammonia emissions.	15% uptake

Table 2 – Bundle of measures to be implemented for the Enhanced Mitigation scenario in zones around designated sites.

Enhanced NH_3 reduction measure	Details of measure to be modelled
1. Slurry acidification	10% of slurry is acidified within housing and spread by trailing shoe, 40% of slurry is acidified at field stage and spread by trailing shoe, 10% of slurry is spread by shallow injection without any acidification and 40% of slurry is spread by trailing shoe without acidification.
2. Installation of scrapers and slat mats cattle housing	Scrapers and Slat Mats retrofitted on 60% of Cattle Housing.
3. Installation of scrubbers to pig & poultry units	Scrubbers retrofitted on all existing enclosed pig and broiler units.
4. Poultry litter removal	Regular (at least weekly) removal of litter through manure belts in all laying hen housing.
5. Low crude protein diets	100% uptake of low crude protein diets across all livestock.
6. Slurry store covers	Covering 75% of above ground slurry stores.

The modelled emission scenarios provided by Tom Misselbrook (Rothamsted Research) were spatially distributed using the UKCEH AENEID[2] model to produce emission maps at a 1 km by 1 km grid resolution. These were processed by the FRAME model to create 1 km NH_3 concentration and N deposition maps, which in turn have been processed by the critical levels and critical loads modelling tools by UKCEH.

Table 3 presents a description of all NH_3 emission scenarios and their corresponding Scenario code, which is used throughout the remainder of the report to identify scenarios.

[2] Dragosits U., Sutton M.A., Place C.J. and Bayley A.A. (1998) Modelling the Spatial Distribution of Agricultural Ammonia Emissions in the UK. *Environmental Pollution* **102** (S1) p.195-203.;
Hellsten S., Dragosits U., Place C.J., Vieno M. and Sutton M.A. (2008) Modelling and assessing the spatial distribution of ammonia emissions in the UK. *Environmental Pollution* **154**, 370-379.
Hellsten S**,** Dragosits U., Place C.J., Dore A.J., Tang Y.S., Sutton M.A. (2018) Uncertainties and implications of applying aggregated data for spatial modelling of atmospheric ammonia emissions. *Environmental Pollution* **240**:412-421.

Table 3: Emission scenario descriptions

Scenario code	Description of mitigation	Mitigation area
BASELINE	Baseline emissions (2017)	-
M-NI	NI-wide mitigation (ca. -25% NH_3 overall)	NI
MSD-SAC1A/B	Manure/slurry spreading displacement	1km from SACs (a) displaced to 2-5 km distance, b) displaced to 5-10* km distance from site boundaries)
MSD-ASSI1A/B	Manure/slurry spreading displacement	1km from ASSIs
EM-NI	Enhanced mitigation	NI
EM-SAC1	Enhanced mitigation	1km from SACs
EM-SAC2	Enhanced mitigation	2km from SACs
EM-SAC5	Enhanced mitigation	5km from SACs
EM-ASSI1	Enhanced mitigation	1km from ASSIs
EM-ASSI2	Enhanced mitigation	2km from ASSIs
EM-ASSI5	Enhanced mitigation	5km from ASSIs

*The 10 km buffer zone was extended to 15 km for Moninea Bog SAC and Killard ASSI, as there were no suitable displacement zones within a 10 km zone that were at least 5 km away from other designated sites.

All scenarios were assessed in terms of:

- Emission reduction achieved
- Reduction in NH_3 concentration and deposition achieved
- Reduction of exceedance of critical levels (i.e. due to decreased NH_3 concentrations)
- Reduction of exceedance of critical loads (i.e. due to decreased N deposition) and average accumulated exceedance (AAE)

1.3 Description of enhanced mitigation scenarios

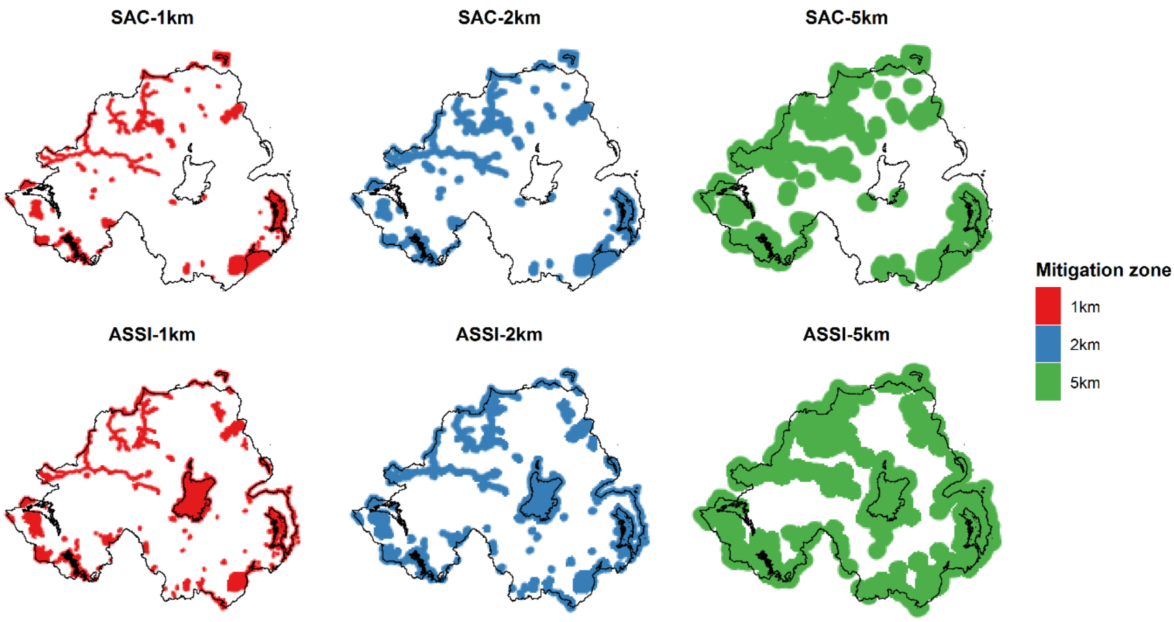

Figure 1: Areas of mitigation surrounding SACs and ASSIs in Northern Ireland under the enhanced mitigation scenarios.

The spatially targeted emission scenarios were based on different sizes of buffer zones (Nitrogen Reduction Zones, NRZ) around all nitrogen-sensitive SAC or ASSI sites, respectively, in Northern Ireland. Figure 1 shows the mitigation zones for the designated sites sensitive to atmospheric nitrogen input, which are recorded in the UK Air Pollution Information System (APIS). Buffer zone widths tested were 1, 2 and 5 km. Within these zones, enhanced mitigation measures (and their respective emission factors; EFs) were applied, in addition to the measures tested under the NI-wide mitigation scenario (M-NI). The emission scenario modelling is based on livestock numbers and crop/grassland areas as per the agricultural emission inventory. N.B. the emission factors were unchanged between the enhanced mitigation scenarios in the NRZ and the NI-wide mitigation scenario for the following emission source sectors: sheep, horses, goats, farmed deer, and mineral fertiliser application.

1.4 Emission totals of mitigation scenarios

The total NH_3 emissions for M-NI and the spatially targeted scenarios with enhanced mitigation (EM-XXX) or manure/slurry displacement (MSD-XXX) are shown in Figure 2. Table 4 presents the absolute and relative difference between emission scenarios compared with baseline and M-NI.

Table 4 - Scenario NH_3 totals in kilotonnes (kt NH_3-N), including absolute and relative differences to baseline (HGD refers to horses, goats and farmed deer).

Scenario	Cattle	Sheep	Pigs	Poultry	Horses, Goats & Deer	Fertiliser	Total	Comparison to baseline		Comparison to M-NI	
								kt N	%	kt N	%
Baseline	17.69	0.56	2.27	4.18	0.01	2.07	26.78	-	-	-	-
M-NI	12.55	0.56	1.66	3.83	0.01	1.42	20.03	-6.75	25%	-	-
MSD-SAC1A/B	12.55	0.56	1.66	3.83	0.01	1.42	20.03	-6.75	25%	0	0%
MSD-ASSI1A/B	12.55	0.56	1.66	3.83	0.01	1.42	20.03	-6.75	25%	0	0%
EM-SAC1	12.4	0.56	1.61	3.82	0.01	1.42	19.82	-6.96	26%	-0.21	1%
EM-SAC2	12.26	0.56	1.57	3.81	0.01	1.42	19.63	-7.15	27%	-0.4	2%
EM-SAC5	11.84	0.56	1.43	3.79	0.01	1.42	19.05	-7.73	29%	-0.98	5%
EM-ASSI1	12.34	0.56	1.52	3.82	0.01	1.42	19.67	-7.11	27%	-0.36	2%
EM-ASSI2	12.15	0.56	1.42	3.81	0.01	1.42	19.37	-7.41	28%	-0.66	3%
EM-ASSI5	11.62	0.56	1.25	3.76	0.01	1.42	18.62	-8.16	30%	-1.41	7%
EM-NI	10.76	0.56	0.99	3.65	0.01	1.42	17.39	-9.39	35%	-2.64	13%

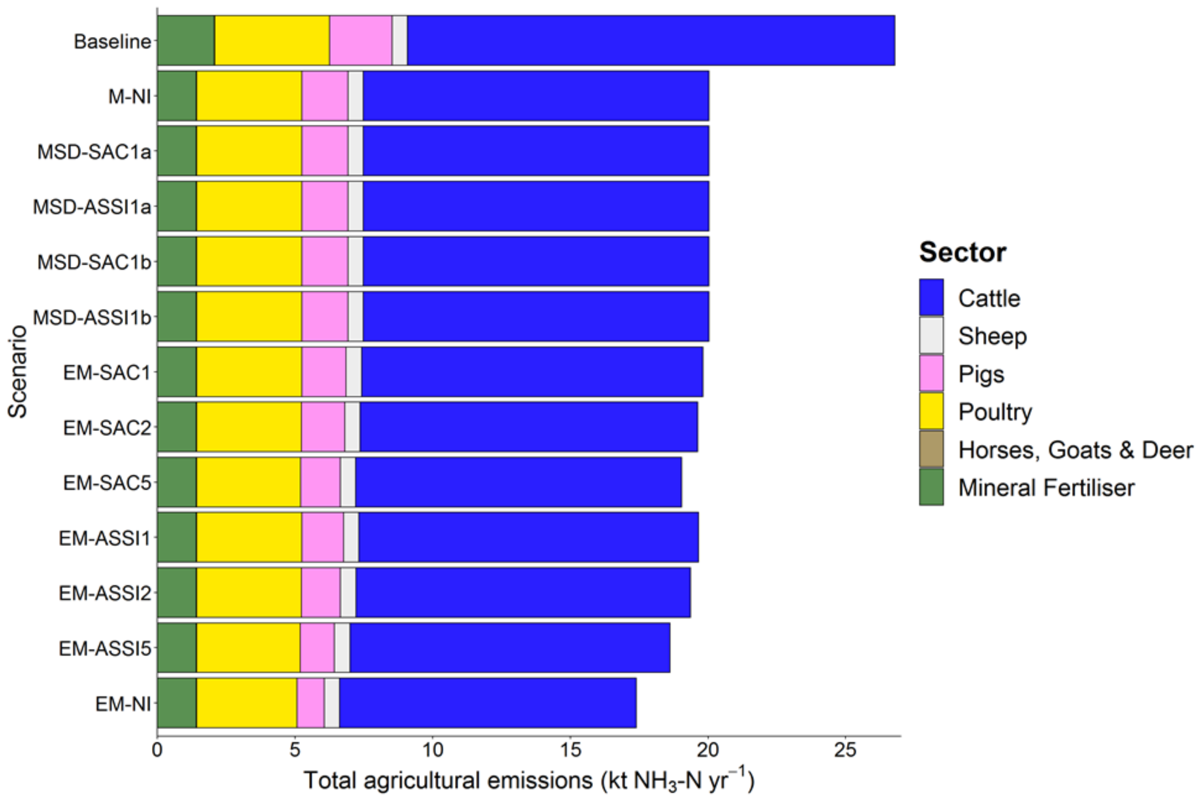

Figure 2: Total NH_3-N emissions by scenario and detailed by agricultural sector.

Figure 3 illustrates the spatial distribution of differences in emissions between the Baseline and NI-wide (M-NI) scenarios, with local emission reductions varying between 0 and ~50%, depending on the sectors and activities present in each model grid square and relevant mitigation measures.

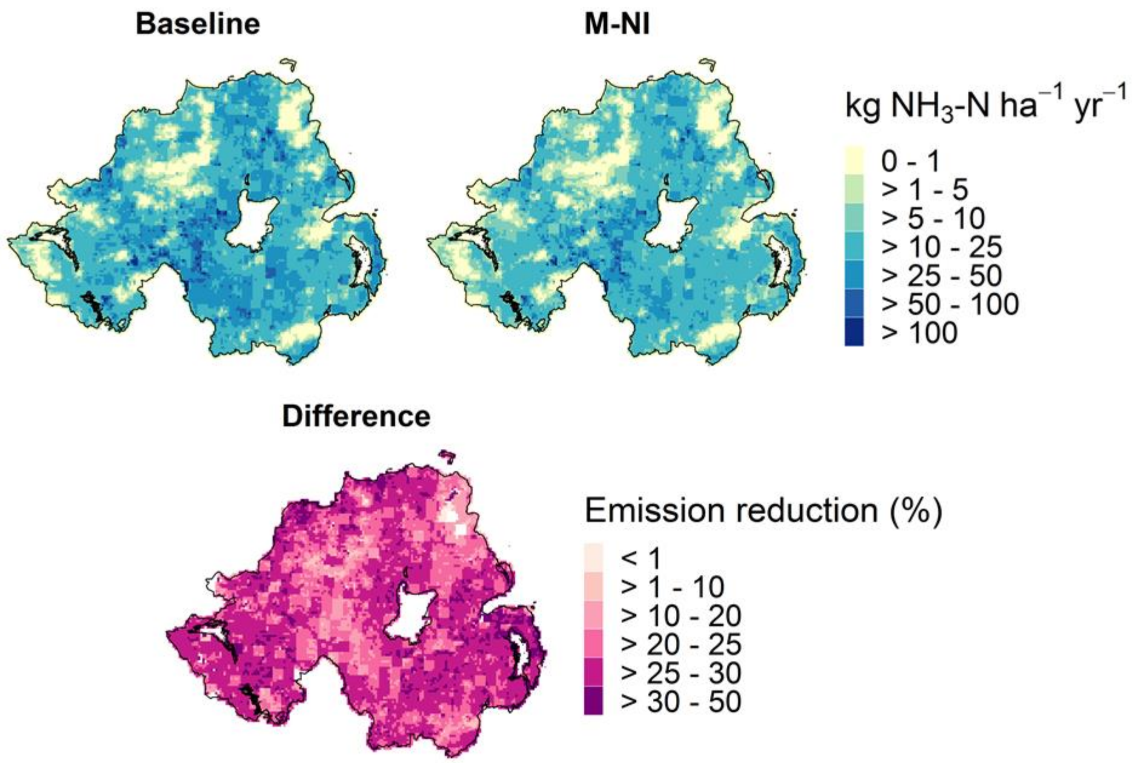

Figure 3: Total agricultural emissions under baseline and NI-wide (M-NI) scenarios, with relative emissions reductions under M-NI compared to baseline.

1.5 Agricultural emission density estimates

To assess the potential of (non-targeted and enhanced/targeted) mitigation at individual designated sites, agricultural emission densities were estimated, in a separate process, using the point location of individual farm holdings (from holding level data available for this project under license by Daera) that are within a 2 km buffer zone of each site. It is important to note that the method used for deriving these emission density estimates differs from the national gridded emissions modelling (used as input for modelling atmospheric concentrations and deposition). This is because sources in the national emission estimates are distributed across wider areas by weighting with land cover rather than being treated as individual point sources (as with the emission density calculations). However, the same set of emission factors (EFs) is used for each source type (livestock housing, manure storage and landspreading, grazing, mineral fertiliser application etc.), to provide consistency across both approaches. In this analysis, all emissions sources from a given farm are assumed to take place at a single point location (i.e. the farm's registered location, which is often based on a postcode, which is a simplification), rather than being dispersed by suitable land cover types as for the emission maps used as inputs to the FRAME model. The complementary emission density approach provides an indication of the potential reduction that could be achieved if mitigation measures were to be applied to individual farms surrounding SACs (see Carnell et al. 2017[3] for more information on the methodology used).

Figure 4 presents estimated agricultural emission densities in 2 km buffer zones surrounding all nitrogen sensitive SACs, with emissions estimated using EFs from the baseline, M-NI & EM-NI scenarios, respectively. Figure 4 clearly shows that the implementation of these mitigation scenarios would be expected to be more effective at some sites than at others. This is because the mitigation options selected under the "enhanced" scenarios (EM-xxx) are targeted at reducing emissions from some source sectors more than from others. Emissions from the cattle and pig sectors, in particular, are more reduced under both the non-targeted (M-NI) and enhanced (EM-xxx) scenarios. The two smallest emission sectors, sheep and horses/goats/farmed deer are not altered in any of the mitigation scenarios, whereas mineral fertiliser emissions are not targeted with the enhanced measures, and only relatively minor changes are investigated for the poultry sector, in terms of enhanced mitigation measures. This is due to the fact that the reduction measures applied for the poultry sector relate only to housing and storage emissions, and not landspreading. Therefore, sites with many cattle and pigs in the surrounding area are expected to benefit most from the additional measures being tested in the modelling.

[3] Carnell E.J., Misselbrook T.H., Dore A.J., Sutton M.A. and Dragosits U. (2017) A methodology to link national and local information for spatial targeting of ammonia mitigation measures. Atmospheric Environment, 163, pp 195-204. doi: 10.1016/j.atmosenv.2017.05.051

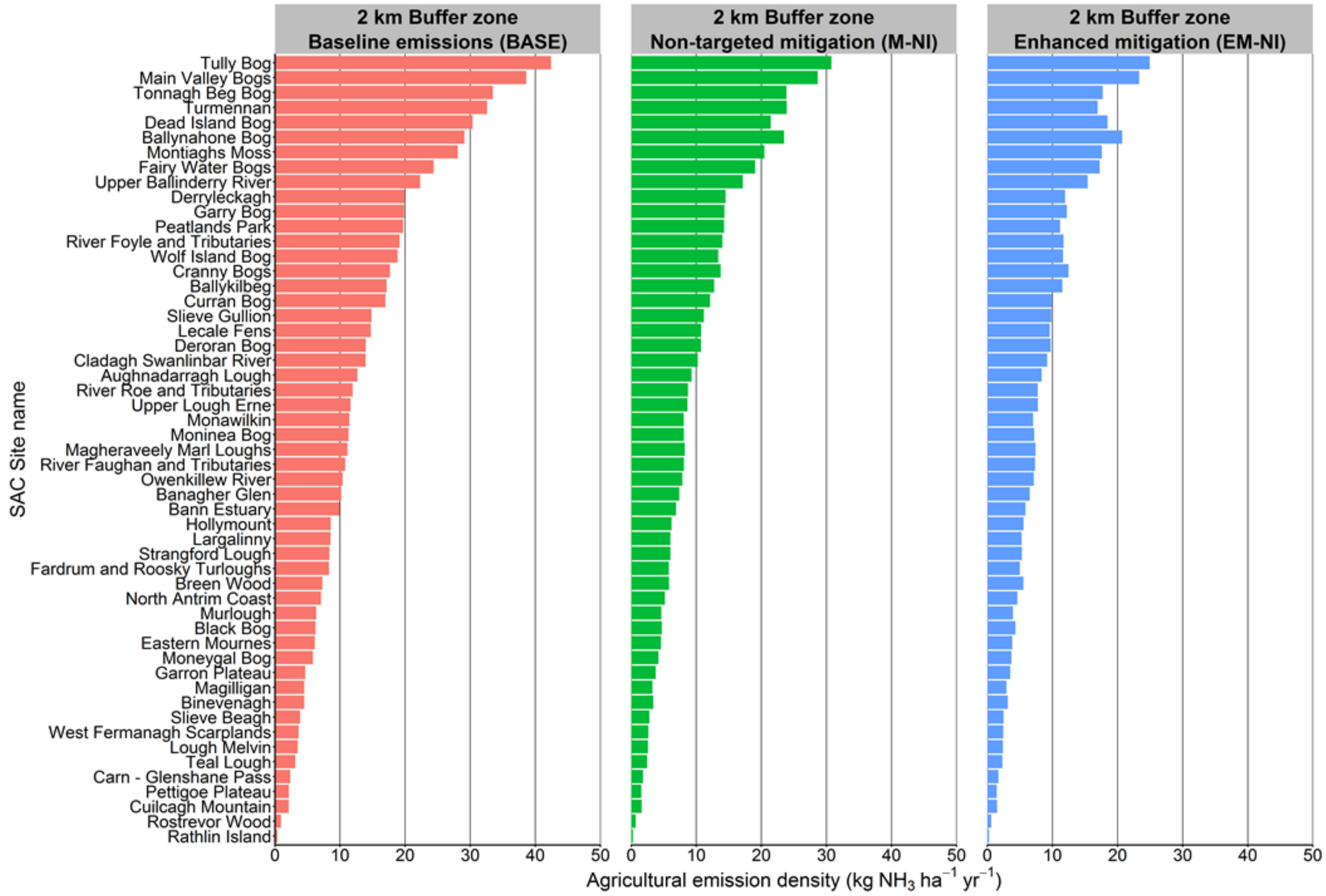

Figure 4: Estimated agricultural emission densities in 2 km buffer zones surrounding SACs, calculated using emission factors under the baseline, M-NI and EM-NI scenarios.

Relative reductions in agricultural emission densities in 2 km buffer zones surrounding SACs (compared to baseline) are presented in Figure 5. This figure clearly shows that, on average, the NI-wide non-targeted mitigation suite of measures lowers emissions by ~20 – ~30% compared to baseline (average NI-wide reduction 25%). Combining the NI-wide reduction measures with the enhanced mitigation options is estimated to reduce emissions by almost 50% at some sites, such as Turmennan SAC (from ~27% reduction under NI-wide measures to ~48% reduction with the additional enhanced measures, compared with the baseline). At other sites though, the additional emission reduction potential is much smaller, due to the mix of sources/sectors present in the surrounding area, e.g. at Cuilcagh Mountain, where the additional enhanced measures only further reduce emissions by ~5%. In summary, the potential for absolute emission reduction is highest where emission densities are highest and measures are targeting the mix of sectors present (i.e. are a good match for the sectors). For remote sites with smaller emission densities and less targeted sectors (such as upland sites with more extensive sheep and beef rearing), local emission reductions will be smaller, but the sites nevertheless still benefit from the regional/NI-wide reductions resulting in decreasing ammonia concentrations and N deposition across NI.

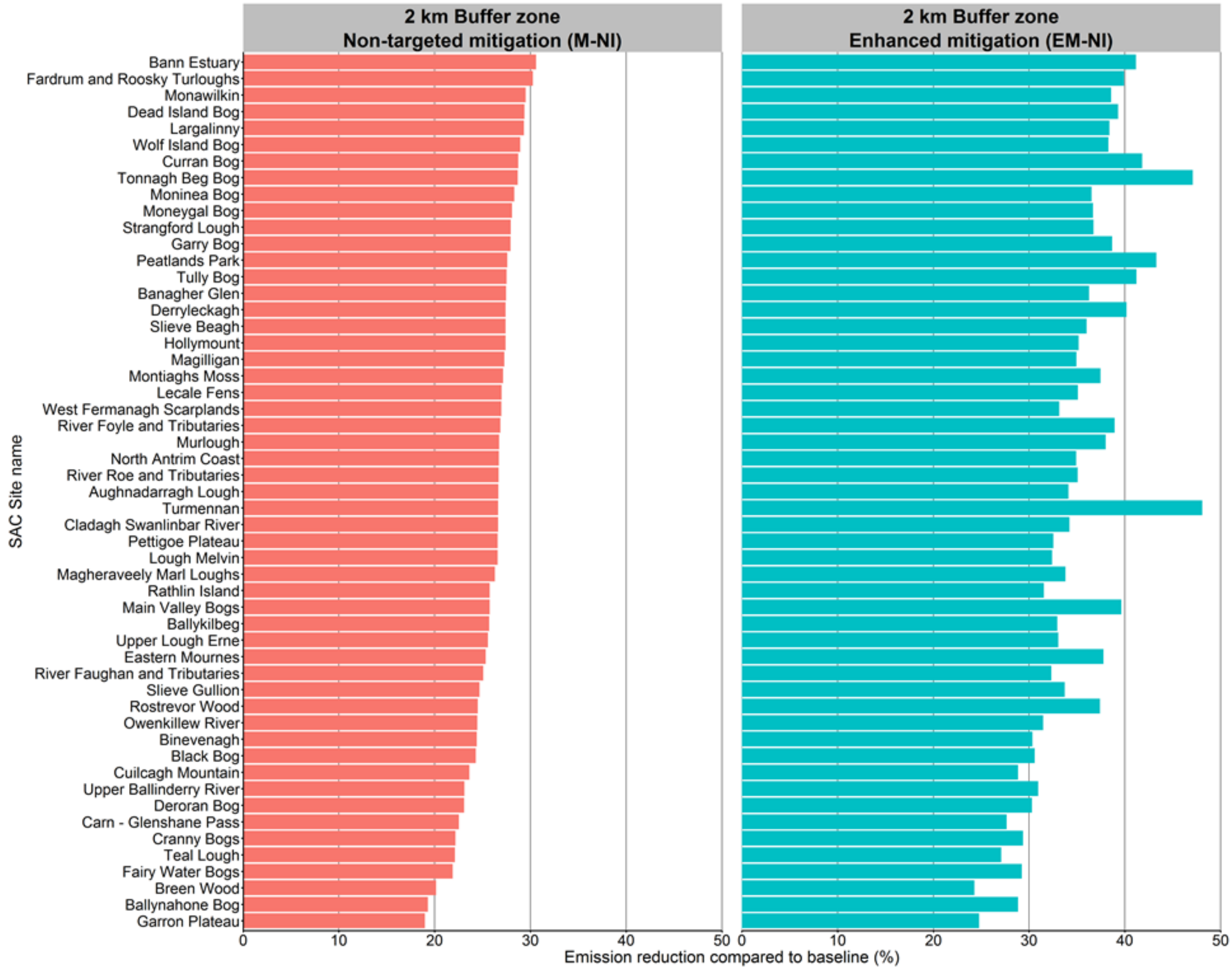

Figure 5- Relative reductions in estimated agricultural emission densities in 2 km buffer zones surrounding SACs (compared to baseline).

The data summarised in Figures 4 and 5 above can be further analysed at the emission source sector level (Figures 6, 7, below), with two example SACs shown. A large proportion of agricultural emissions estimated in buffer zones surrounding Turmennan SAC comes from sources associated with beef cattle and pigs (Figure 6). Consequently, as emissions from pigs and cattle are targeted in the enhanced measures, emissions are expected to be greatly reduced if enhanced measures were to be implemented at farms surrounding this site (negative bars show the amount of mitigation achieved, i.e. the difference between the baseline and the scenarios, by source sector). In contrast, implementing enhanced mitigation to farms surrounding Upper Ballinderry River SAC is not expected to achieve similarly substantial reductions when compared with the non-targeted mitigation (M-NI). This is because a large proportion of the estimated emissions are associated with poultry, a sector which is not as heavily targeted in the enhanced mitigation measures. These examples clearly illustrate that spatial targeting (or indeed any mitigation strategy) can only achieve its objective subject to local presence/absence of sources (e.g. Figure 4, sites with largest vs smallest emission reduction).

N.B. In order to comply with the data license agreement for this study, results were aggregated to only show output data that refer to at least five agricultural holdings. For categories where this requirement was not met, emissions were aggregated into the category “Other sources”. For example, in buffer zones with fewer than 5 holdings containing pigs, the category "pigs" was aggregated with another category (or categories), as needed, so each category contains at least 5 holdings.

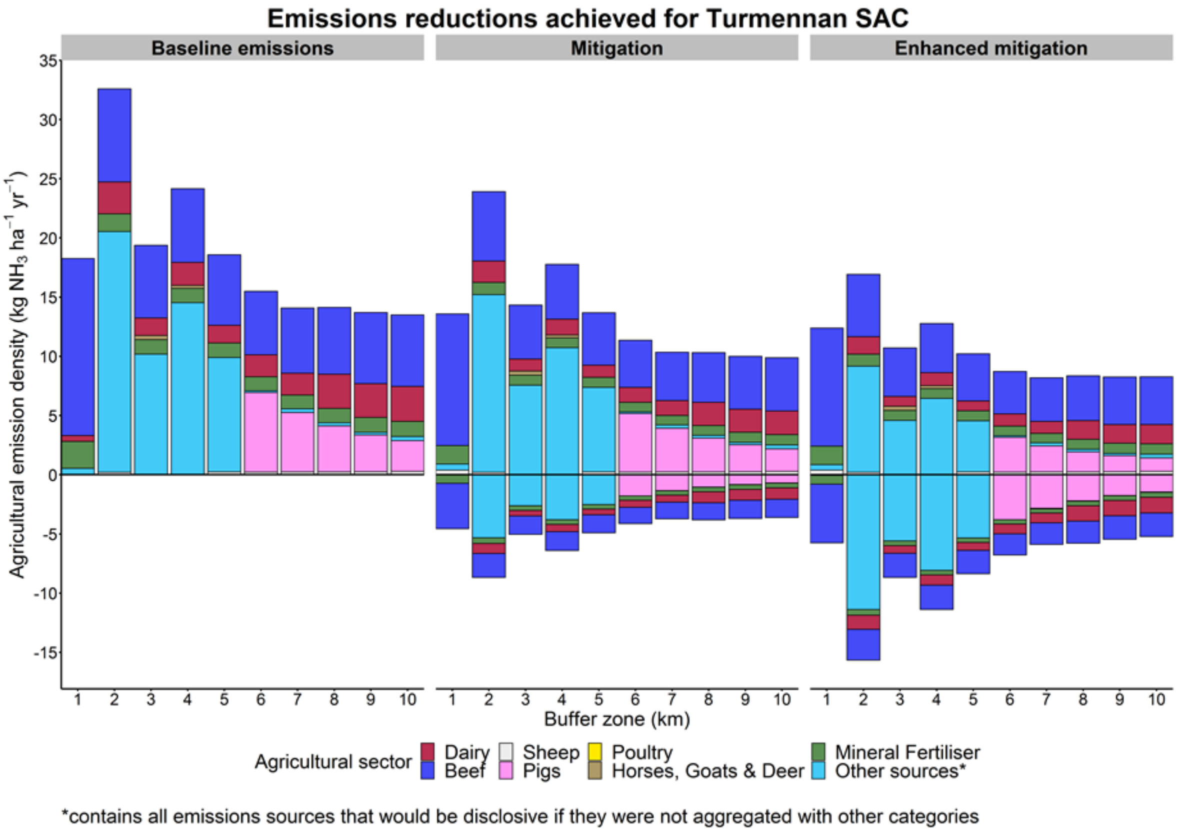

Figure 6: Estimated agricultural emission densities in concentric buffer zones surrounding Turmennan SAC.

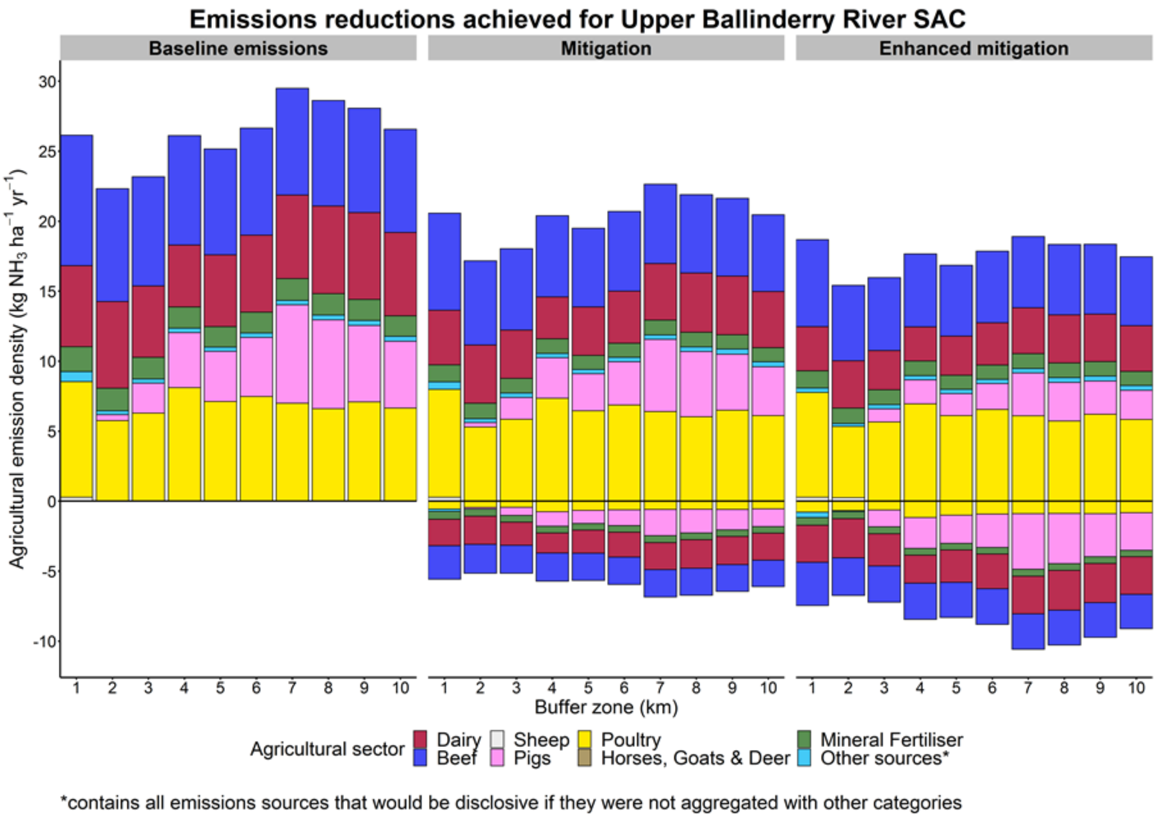

Figure 7: Estimated agricultural emission densities in concentric buffer zones surrounding Upper Ballinderry River SAC.

1.6 Emission reductions achieved through enhanced mitigation

Figure 8 presents emission reductions achieved through enhanced mitigation around SACs, compared with the wider NI-wide (M-NI) mitigation scenario. Emissions are shown by agricultural sector and emission activity. The figure illustrates that substantial housing and manure/slurry spreading emission reductions are achieved in the cattle and pig sectors through enhanced measures around designated sites. For the pig sector, these housing/spreading emission reductions are partially offset by increased storage emissions (i.e. lower emissions at the housing stage leading to higher N content in the stored slurry/manure, thereby increasing storage emissions (negative numbers in Figure 7), but then resulting in further reductions due to low-emission spreading techniques being applied). For the poultry sector, the enhanced measures (scrubbers, belt-systems for manure removal) mainly affect the housing component.

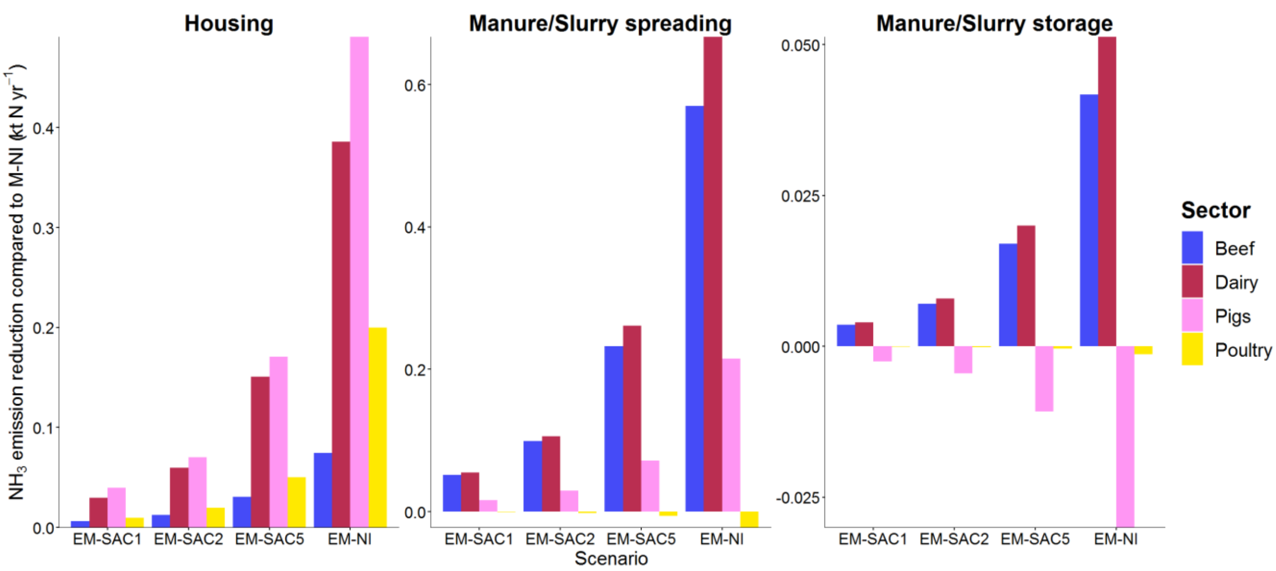

Figure 8: Emission reductions achieved through enhanced mitigation around SACs, compared with the M-NI emission scenario.

1.7 Quantification of displaced manure and slurry emissions

Figure 9 shows the results of scenarios where manure/slurry spreading emissions displaced from a 1 km zone around SACs under scenario MSD-SAC1a/b (i.e. not emission reductions as such, compared with M-NI). These land spreading emissions are redistributed to areas of 2 – 5 km away from SAC boundaries under MSD-SAC1a and between 5 – 10+ km under MSD-SAC1b. The redistribution zone had to be extended to 5 – 15 km at Moninea Bog SAC, as there were no remaining available areas > 5 km from this and other nearby SACs in the initial 5 – 10 km zone. The areas of displacement necessarily vary with the size of the SAC, with the most spatially distributed/largest SACs (River Foyle and Tributaries; Upper Lough Erne) being associated with the largest amounts of manures/slurries being displaced.

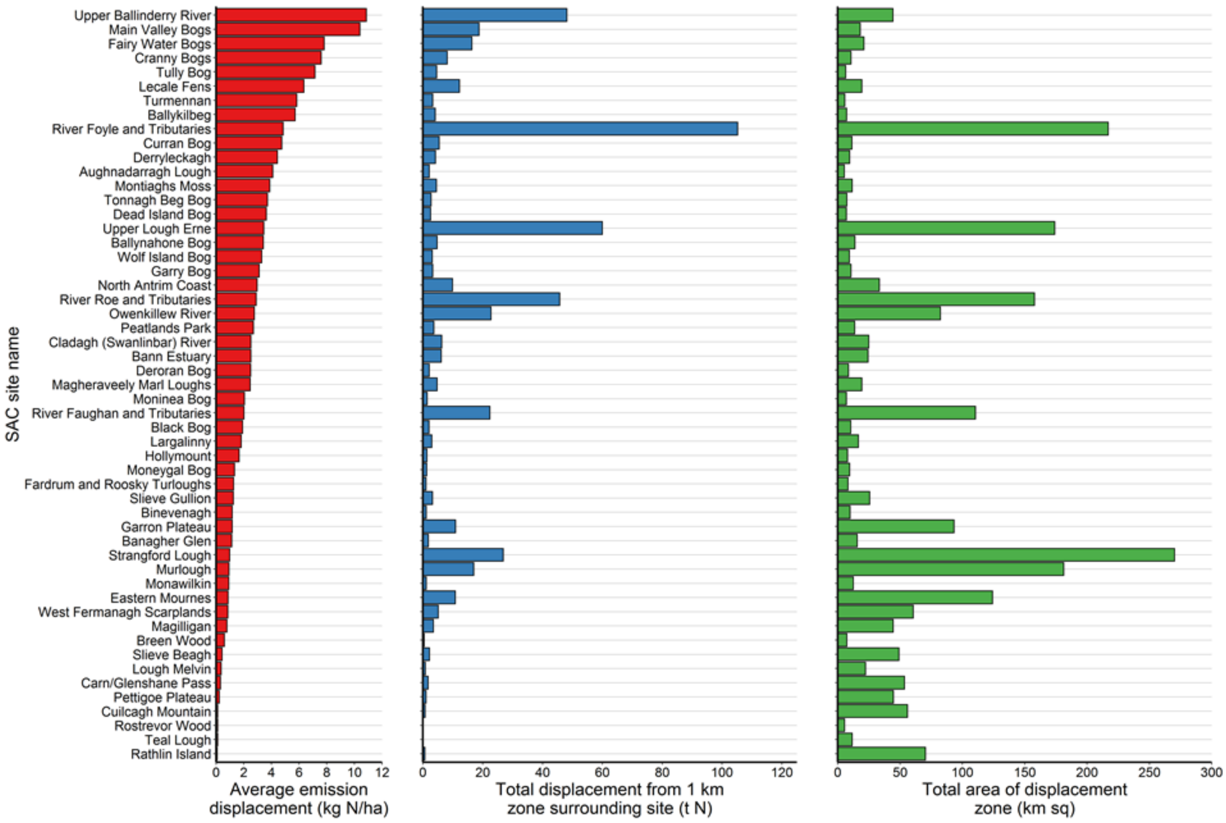

Figure 9: Average displacement of landspreading ammonia emissions from a 1km buffer zone surrounding SACs in Northern Ireland (expressed as NH_3-N ha^{-1} $year^{-1}$) left, total displacement (expressed as NH_3-N $year^{-1}$) middle and area of displacement zone (km^2) right

The spatial distribution of the displaced emissions associated with landspreading of slurry and manures under Scenarios MSD-SAC1a and MSD-SAC1b is presented in Figures 10 and 11. For some sites, the larger and further removed redistribution zone of 5 - 10km (for scenario MSD-SAC1b and MSD-ASSI1b) from the SAC led to new emission hotspots as there was limited space available in the redistribution zone, due to the presence of other SACs nearby. The increased emissions associated with slurry/manure spreading in some areas may potentially lead to increased exceedance of Critical Loads/Critical Levels (CL/CLe) at some sites (and to exceedances of maximum application rates under NVZ rules). N.B. this has not been taken into account here and would need to be investigated separately, if such a measure were to be tested further for practicalities). The relative impact of the displaced manure/slurry emissions is assessed later in Figures 14 and 18. The total displacement of manure/slurry spreading and the associated ammonia emissions from a 1 km zone surrounding all SACs is equal to 0.48 kt NH_3-N.

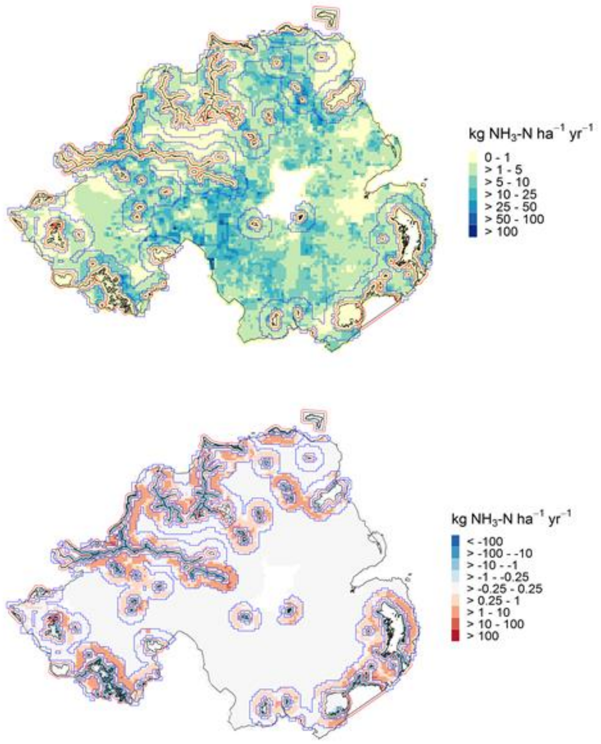

Figure 10: Emission estimates **from manure and slurry spreading activities only** (kg NH_3-N ha^{-1} yr^{-1}) for MSD-SAC1a (left) and emission displacement compared to M-NI (right).

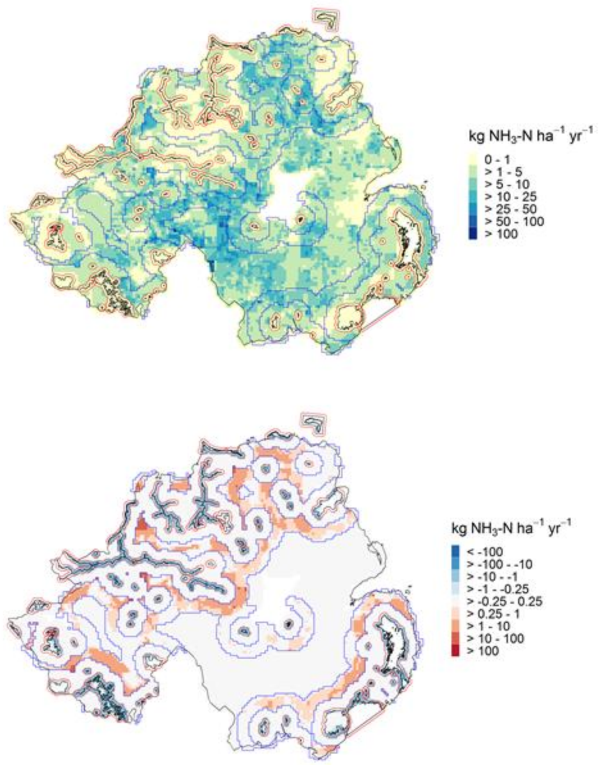

Figure 11: Emission estimates **from manure and slurry spreading activities only** (kg NH_3-N ha^{-1} yr^{-1}) for MSD-SAC1b (left) and emission displacement compared to M-NI (right).

1.8 Modelled Ammonia Concentrations

Atmospheric N deposition and NH_3 concentrations were estimated for each scenario using the FRAME model. The spatially distributed emission maps (for each scenario) were processed in FRAME, taking account of wider boundary conditions (i.e. atmospheric transport across the wider UK and European model domains). Estimated baseline concentrations were used to calibrate the model against concentration measurements from the UK National Ammonia Monitoring Network in Northern Ireland (sites at Hillsborough, Lough Navar, Coleraine). Mitigation scenario runs were adjusted accordingly (relative to baseline). Figure 12 shows the estimated NH_3 concentrations under each scenario associated with spatial targeting at SACs. There is a clear reduction in concentrations between the M-NI scenario and the baseline, with areas exceeding 4 NH_3 µg m^{-3} decreasing substantially and more generally overall concentration reductions (purple/red/amber areas in the maps). Further reductions are also estimated for spatial targeting, with EM-SAC 5km showing noticeably fewer areas exceeding 3 µg NH_3 m^{-3} than the NI-wide mitigation scenario (M-NI, 25% emission reduction compared to baseline). This is despite the EM-SAC5 scenario only reducing emissions in the buffer zones around the SACs (see Figure 1 for extent and spatial distribution of designated sites and buffer zones) by a further 4 % of baseline emissions in total.

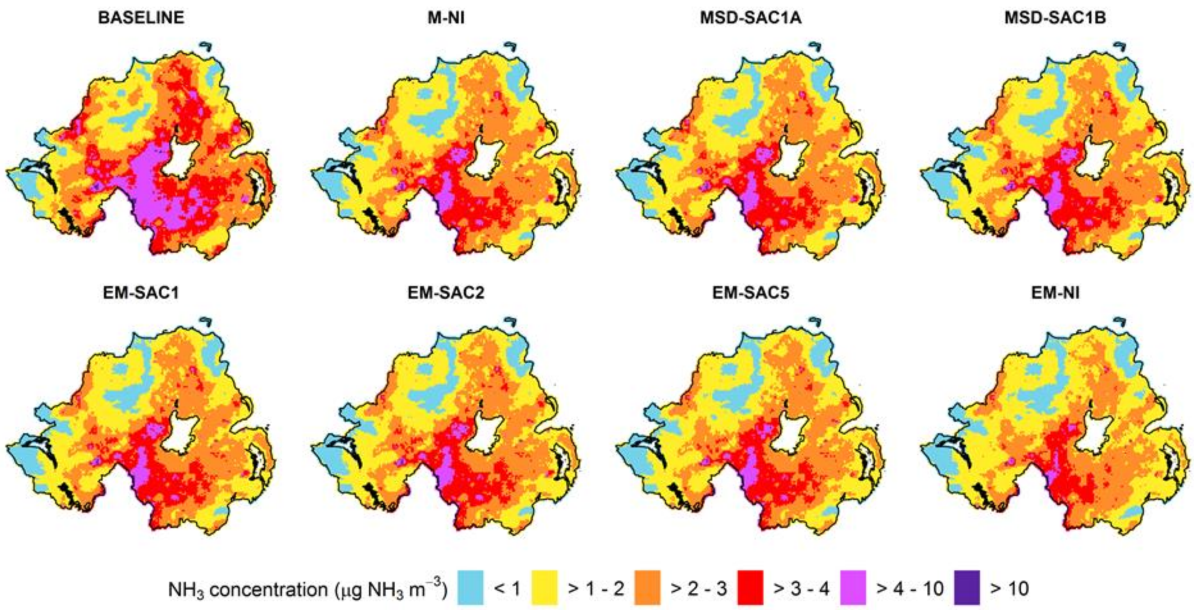

Figure 12: Model-estimated ammonia concentrations under each emission scenario associated with spatially targeting SACs (for ASSIs see appendix).

Figure 13 presents the reductions in concentration compared with baseline. This Figure shows the additional reductions through spatial targeting more clearly than the concentration plots (shown above in Figure 12). The manure displacement scenario MSD-SAC1A has some very small areas where concentrations are higher than the baseline (shown in red, near western border with RoI), this is due to slurry displacement leading to an estimated increase in emissions in areas away from designated sites (to counterbalance a decrease in emissions surrounding sites; N.B. modelling simplified).

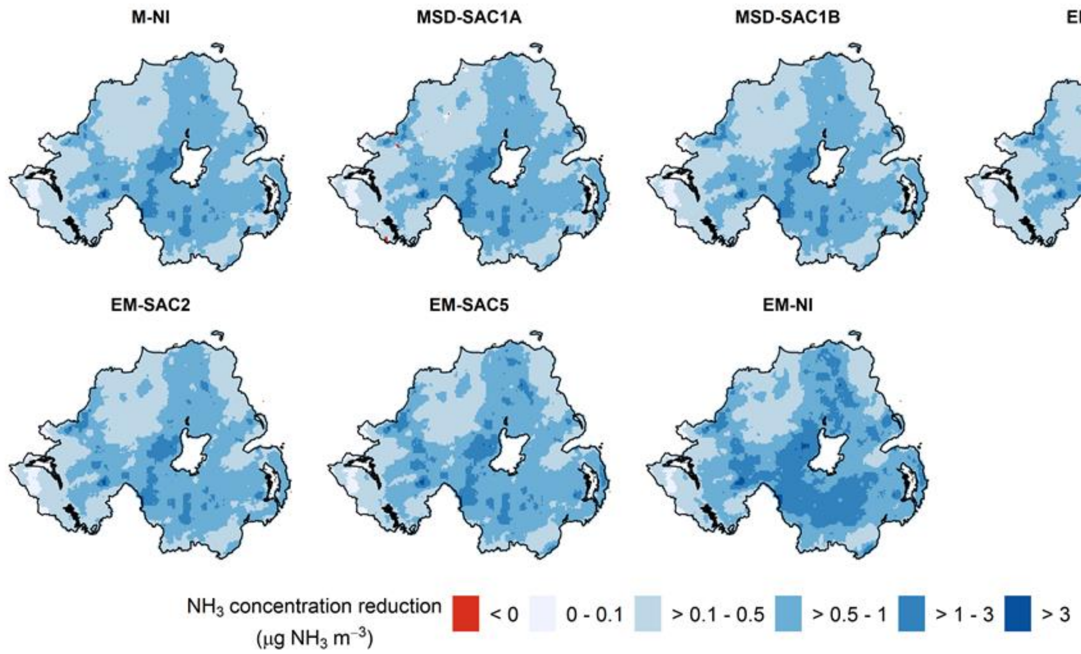

Figure 13: Model estimated reductions in ammonia concentrations compared to baseline for each emission scenario associated with spatially targeting SACs (for ASSIs see appendix).

Figure 14 compares the additional change in NH_3 concentration achieved through spatially targeted mitigation. Areas in red indicate areas of increased concentrations and blue indicates additional reductions compared to M-NI. This comparison shows that the spatial patterns of modelled concentrations under the manure displacement (MSD) scenarios have a very different spatial distribution to the M-NI scenario despite the total overall emission totals being the same.

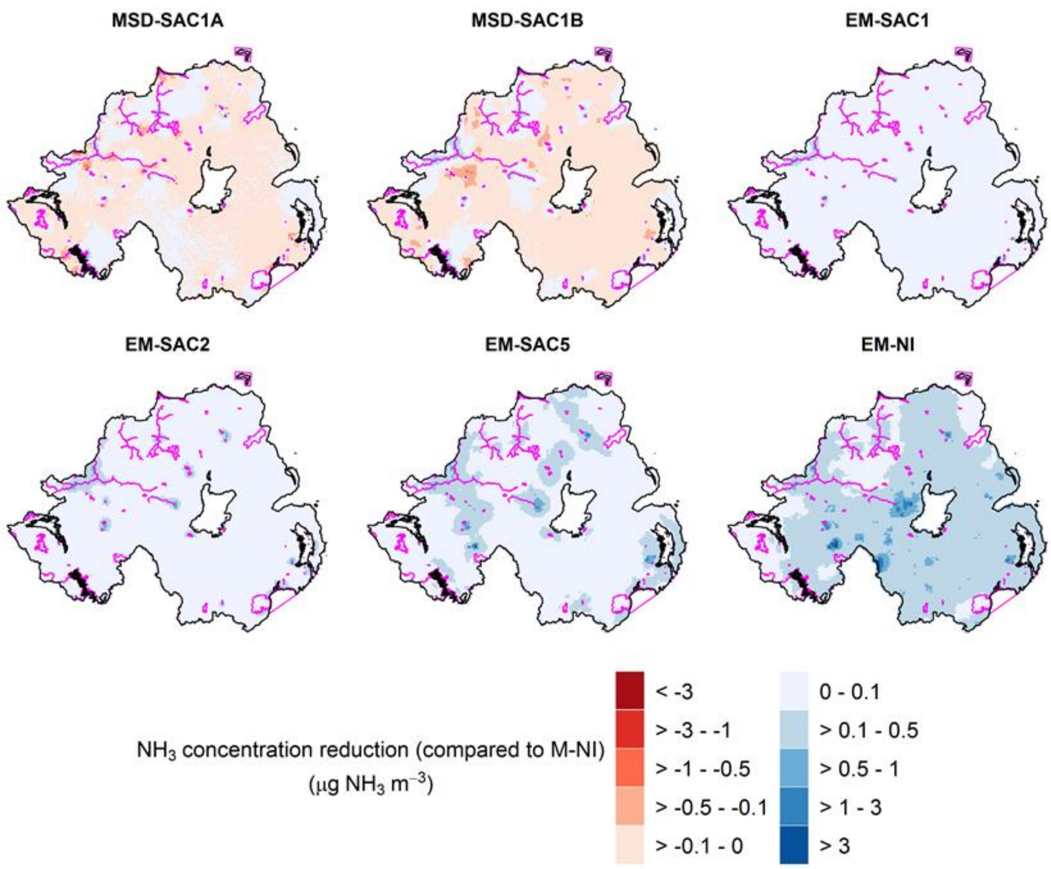

Figure 14: Model estimated reductions in ammonia concentrations compared to M-NI for each emission scenario associated with spatially targeting nitrogen sensitive SACs (shown in pink) for ASSIs see appendix.

The variation in estimated NH_3 concentrations at SACs in Northern Ireland is presented in Figure 15. At the majority of sites, there is a substantial reduction in NH_3 concentrations under the M-NI scenario compared to the baseline. Variations in concentrations in all relevant grid squares intersecting sites are shown in grey (minimum and maximum concentrations). The more spatially variable concentrations are across a site, the larger the grey region is, which shows the deviation from the area-weighted mean (e.g. see the large river SACs, Upper Ballinderry River, River Foyle and Tributaries). An area-weighted mean is used to reflect the most likely concentration at a given site. For example, if a large proportion of a site is situated in a grid-square with low concentrations but also has a small area intersecting a grid-square with a high concentration, the overall area-weighted mean concentration will more closely reflect the lower concentration as the most likely across the site.

The largest and most spatially expansive sites, such as SACs designated for river and lough features tend to have higher variability in concentrations, but this is also true for some smaller sites. An example of the latter is Moninea Bog, where the highest concentration is due to a large industrial combustion source close to the site (source: naei.beis.gov.uk). For expansive sites that span multiple 1 km grid squares (such as riverine and lough features), it may be more difficult to lower maximum concentrations at these sites through the national scale modelling approach employed here. However, this depends on the source sector(s) responsible for the estimated maximum concentration vs. the measures tested (i.e. the larger and more varied a site, the more likely it is that a hard-to-mitigate grid square is present). As illustrated above, the success of spatial targeting of measures depends on the presence/absence of suitable measures for any local source types/hotspots of elevated NH_3 in the scenario definitions. A national scale modelling exercise such as this study can provide indicative estimates of likely reductions possible, on average. However, implementing a spatially targeted approach at sites such as SACs would require an additional assessment of local sources, practices, mitigation measures already in place, etc., rather than assuming that the average practices modelled at the national scale apply equally across all holdings present. For example, some holdings may already have implemented measures that cannot be credited to individual farms in the national scale modelling, as relevant data are not currently available. Similarly, local holdings may use different management practices/systems than the national average assumed, and measures used in the modelling (on average) may not be applicable, e.g. slurry-based vs. farmyard manure (FYM) based systems, or different types of poultry houses. Taking account of actual systems in place locally and deriving a local action plan from a selection of possible measures that work for the site, in collaboration with local stakeholders, is how Natural England and Natural Resources Wales are exploring potential implementation of spatially targeted measures (e.g. Shared Nitrogen Action Plans (SNAPs); see also IPENS-49[4], IPENS-50 reports[5]).

1.9 Critical Level exceedance

Figure 16 presents the exceedance of the 1 µg NH_3 m^{-3} critical level at SACs in Northern Ireland and the variation in exceedance at each site. The figure illustrates that the majority of sites being brought out of exceedance occurs under all mitigation scenarios (with the exception of MSD-SAC1). This is not surprising though, given that the M-NI scenario achieves the highest level of emission reductions, and additional total reductions made under the enhanced mitigation scenarios are much smaller. Teal Lough however, is no longer exceeded under EM-SAC5 and many other sites are much closer to the 1 µg NH_3 m^{-3} with spatial targeting.

The enhanced mitigation measures do provide substantial reductions at sites situated in areas of intensive pig and cattle farming, such as Turmennan SAC (see e.g. Figure 6). The area-weighted mean NH_3 concentration at Turmennan SAC under EM-SAC5, for example (enhanced measures applied to farms within a 5km buffer zone of SAC sites), is estimated at 2.1 NH_3 µg m^{-3}, compared to 3.6 NH_3 µg m^{-3} under the baseline and 2.7 NH_3 µg m^{-3} under M-NI. This 1.5 NH_3 µg m^{-3} reduction brings the site much closer to the 1 NH_3 µg m^{-3} critical level relevant to the site. For some sites, simply removing slurry spreading from the vicinity of the site (i.e. not an emission reduction overall across NI, but displacement), also appears to be effective, for example at Turmennan or Cranny Bogs.

[4] Dragosits U., Carnell E.J., Misselbrook T.H. and Sutton M.A. (2014) Site categorisation for nitrogen measures. Final report to Natural England on project IPENS-049. October 2014. 20pp. + appendix.

[5] Misselbrook T.H., Dragosits U. and Williams J. (2014) Case Studies for delivering ammonia measures. Final report to natural England on IPENS project 50. 16pp.

Figure 15: Estimated area-weighted mean NH_3 concentrations (µg NH_3 m^{-3}) at SACs in Northern Ireland under each mitigation associated with spatially targeting SACs (for ASSIs see appendix). Including minimum and maximum concentration values. Critical levels are shown in light blue for lichens mosses and bryophytes (1 NH_3 µg m^{-3}) and higher plants in dark blue (3 NH_3 µg m^{-3}).

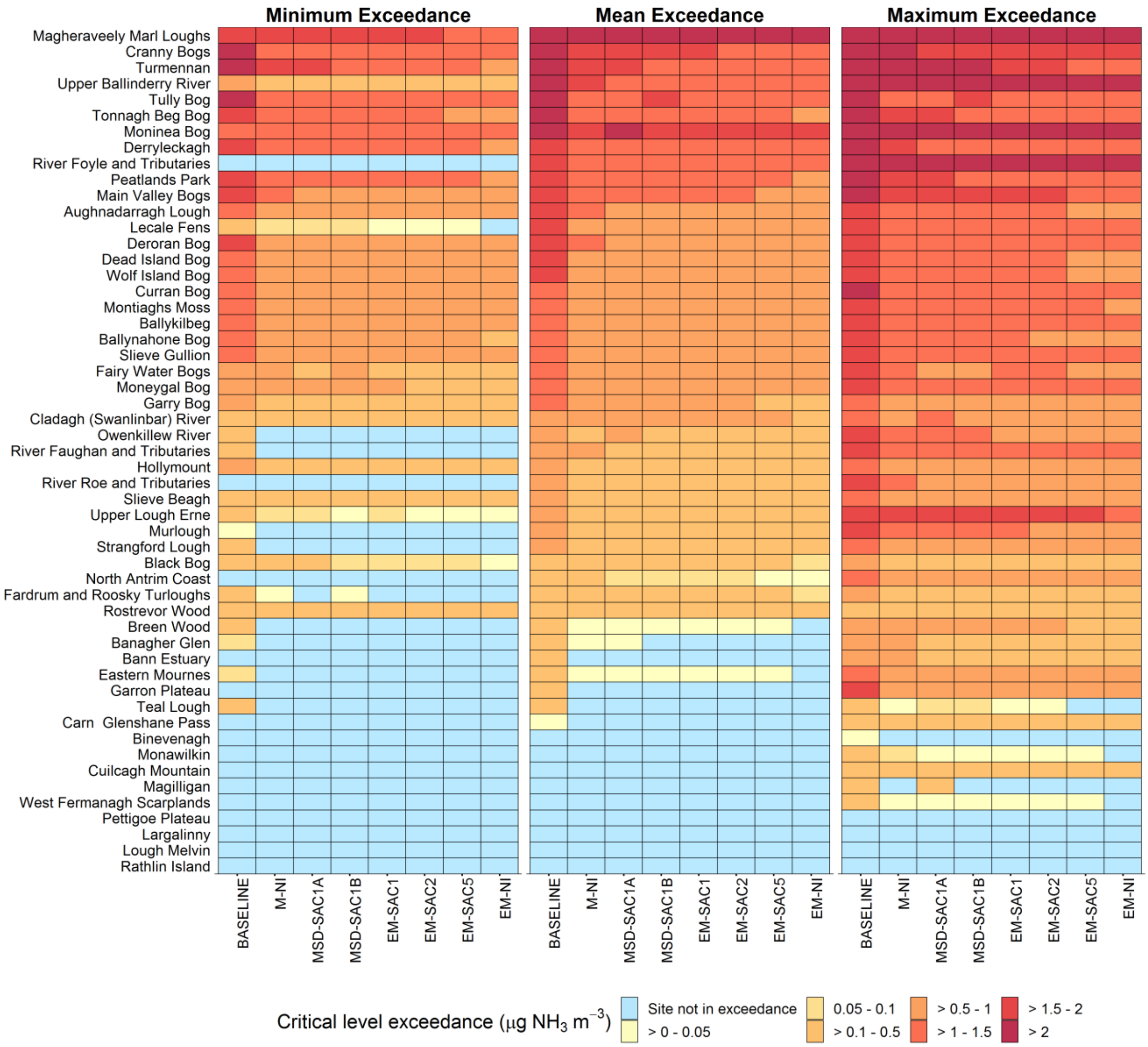

Figure 16: Estimated exceedance of 1 µg NH_3 m^{-3} critical level at SACs in Northern Ireland, comparing minimum, area-weighted mean and maximum exceedance values.

Although it may appear that the reductions in NH_3 concentrations achieved under the spatially targeted enhanced mitigation are minor, this is largely because all of the enhanced mitigation scenarios provide relatively small overall *emission* reductions, in addition to the M-NI scenario (see Table 4 above). Consequently, the M-NI scenario provides most of the total emission reduction (~25 % compared to baseline), with the targeted mitigation equating to an additional 1 – 4 % of reductions across NI (or 10 % if enhanced mitigation is applied everywhere in EM-NI). Although an additional 1 % to 4 % (for SACs) emission reduction compared to M-NI may appear marginal, this extra reduction, per unit of emissions reduced, is more efficient at reducing NH_3 concentrations at sites.

Figure 17 compares the effectiveness of spatially targeted enhanced mitigation in terms of reducing overall NH_3 concentrations at designated sites compared to non-spatially targeted NI-wide mitigation under M-NI. The Effectiveness Multiplier indicates how much more effective spatially targeted enhanced mitigation is, compared to M-NI. For example, a value of 2 indicates that, per unit emission reduction, spatially targeted mitigation is twice as effective (on average) at reducing overall NH_3 concentrations at designated sites across NI than M-NI. The additional benefit of enhanced measures on top of the 25% NI-wide emission reduction (M-NI) clearly shows that spatially targeted mitigation delivers the highest impact (per unit emission reduction). The figure shows that the added benefit of enhanced measures within a 1 km buffer zone of SACs is ~2.8 times higher. The overall NI-wide emission reduction associated with targeting a 0 – 1km buffer zone around nitrogen-sensitive SACs (under EM-SAC1) is minor (0.21 kt NH_3-N yr^{-1}) compared to the NI-wide emission reductions modelled under M-NI (6.75 kt NH_3-N). This relatively modest emission reduction (associated with EM-SAC1) achieves an average concentration (area-weighted) reduction of 0.02 µg NH_3 m^{-3} at (nitrogen-sensitive) SAC sites. In contrast, while average concentration reductions under M-NI are much higher (0.25 µg NH_3 m^{-3} at nitrogen-sensitive SAC sites), the overall *emission* reduction required to achieve this reduction in concentration is much higher and would require a higher level of resources to implement.

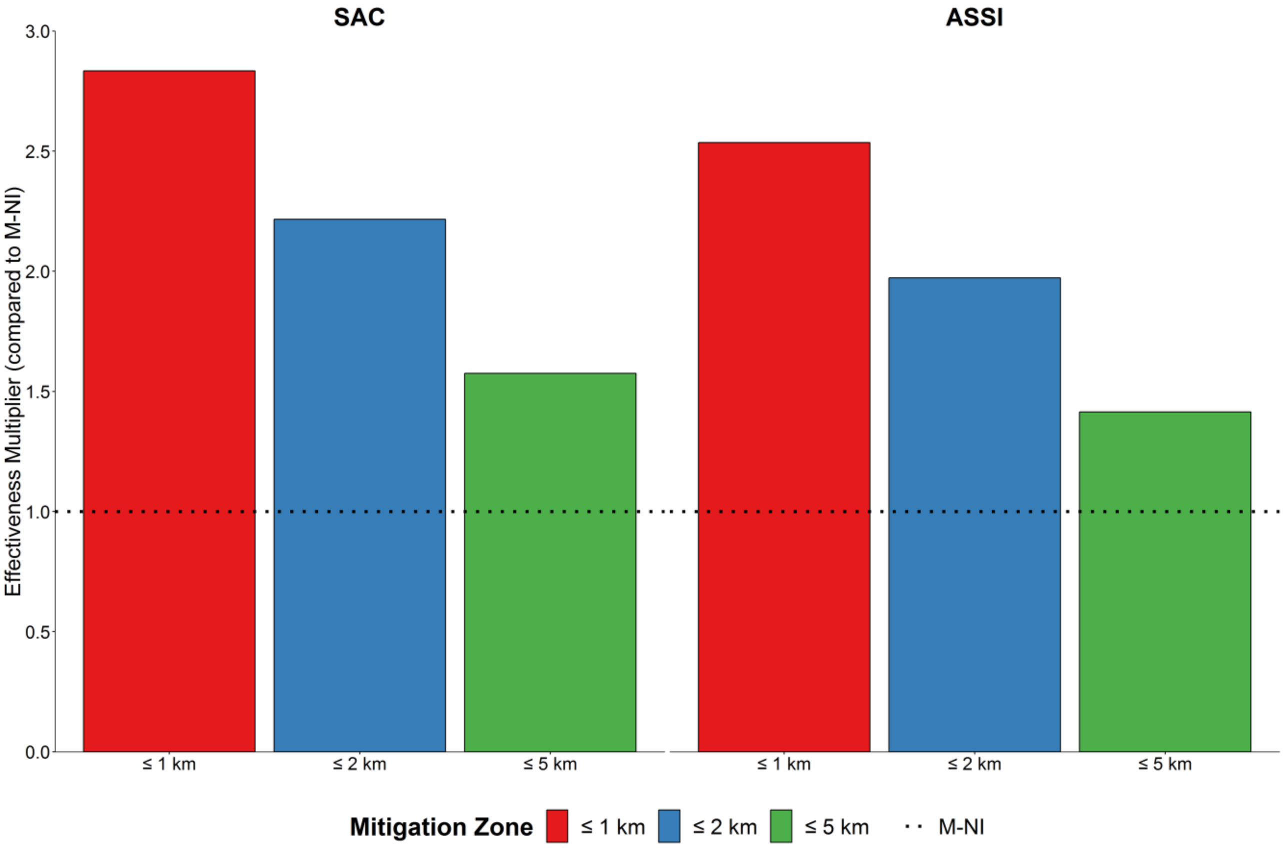

Figure 17: A comparison between overall effectiveness of the spatially targeted enhanced mitigation scenarios in terms of average area-weighted NH_3 concentration reductions at nitrogen sensitive sites (overall area) and compared to reductions achieved by the M-NI scenario (dotted line). The effectiveness multiplier indicates how many more times effective spatial targeting is at achieving NH_3 concentration reductions than M-NI per unit emission reduction.

Figure 18 compares the overall reduction in average (area-weighted) NH_3 concentrations at sensitive sites to total emission reductions. To assess the additional benefit (compared to M-NI) of spatially targeting enhanced measures at individual sites, modelled emission reductions were quantified individually for each mitigation zone surrounding each site and compared to concentration reductions achieved at each site. To compare to the non-spatially targeted scenario (EM-NI, i.e. enhanced measures NI-wide), site level emission reductions under the EM-NI were calculated by scaling site-level emission reductions under the EM-SAC5/EM-ASSI5 scenarios to the equivalent reduction achieved under EM-NI (based on overall total emission estimates). Mean site level emission reductions under EM-NI were compared to mean NH_3 concentration reductions at sites as a benchmark to compare the effectiveness of spatial targeting. Figure 18 shows the mean effectiveness of spatially targeting individual sites in reducing NH_3 concentrations, with all sites being included equally, regardless of size, i.e. a designation-weighted indicator (as opposed to an area-weighted indicator taking account of the overall area of all sensitive sites, as shown in Figure 17). Figure 18 suggests that spatially targeting SACs is typically more effective than targeting ASSI.

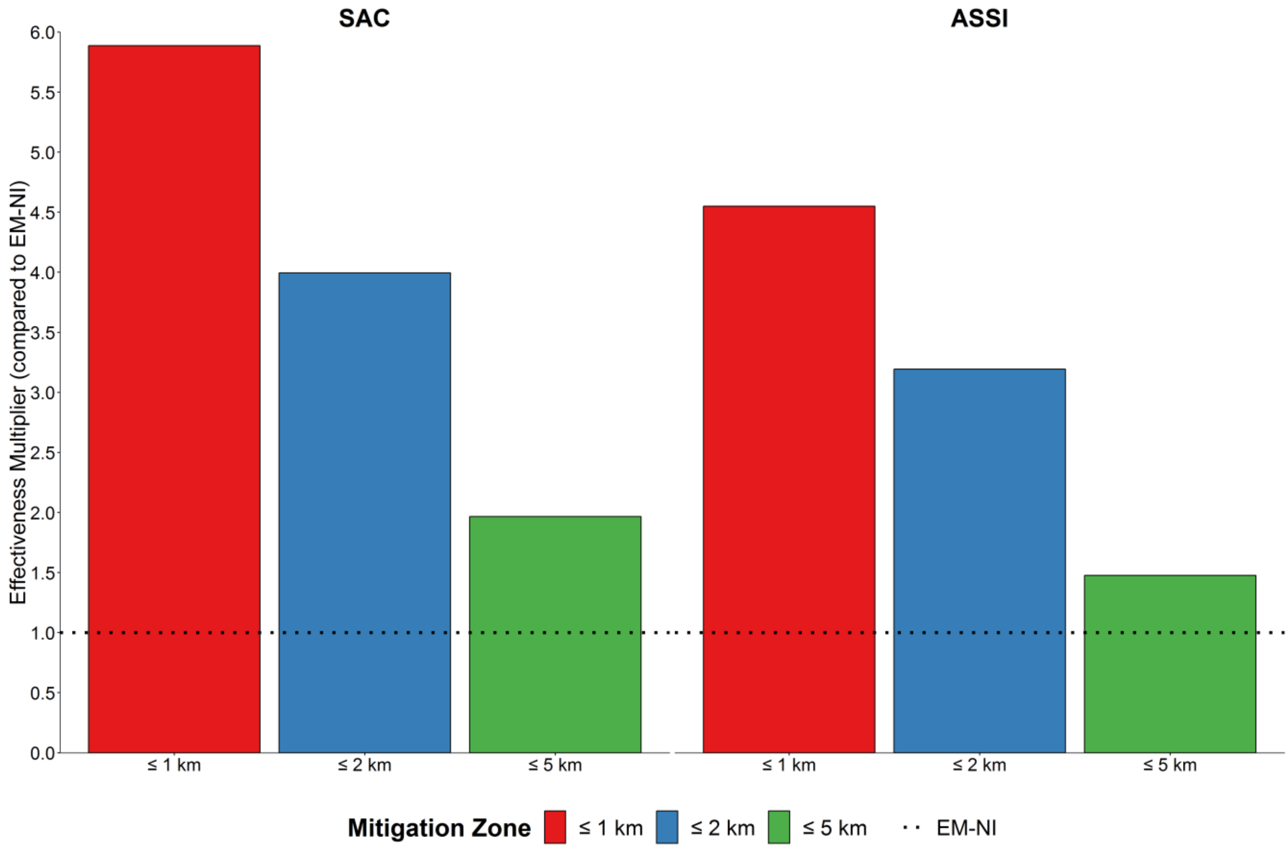

Figure 18: A comparison between average effectiveness of the spatially targeted enhanced mitigation scenarios in terms of average NH_3 concentration reductions at nitrogen sensitive sites (average area-weighted reduction at sites) and compared to reductions achieved under EM-NI scenario (dotted line). The effectiveness multiplier indicates how many times more effective spatial targeting is at achieving NH_3 concentration reductions than EM-NI per unit of emission reduction.

Spatially targeting SACs may be more effective than targeting ASSIs, for the following reasons:

- **Nitrogen sensitive SACs are, on average, ~ 1.5 times the size of nitrogen sensitive ASSI sites**. The larger site area of SAC sites is acting as a natural buffer zone for the central parts of the sites, thereby overall reducing average concentrations at sites further than for smaller sites.
- **Nitrogen sensitive ASSIs are less clustered across the wider area of NI than nitrogen sensitive SACs** (see Figure 1), and therefore less likely to co-benefit from emission reductions in zones surrounding nearby sites

Although SAC sites are typically larger than ASSIs, more (nitrogen sensitive) ASSIs (n = 107) were spatially targeted in this study than SAC sites (n = 53)**. The NI-wide emission reductions associated with the EM-ASSI1 are correspondingly higher**

(0.36 kt N yr^{-1}) than the equivalent SAC scenario EM-SAC1 (0.21 kt N yr^{-1}) therefore. In order to evaluate how effective spatially targeting is at reducing NH_3 concentrations at designated sites, Figure 19 compares the overall effectiveness of each concentric buffer zone at all nitrogen sensitive SACs and ASSIs.

Quantifying the emission and concentration reductions achieved by each mitigation zone allows an assessment of how effective increasing the width of the mitigation zone is. Figure 19 shows that spatial targeting of sources ≤ 1 km from sites is up to 14 times more effective at reducing concentrations than the average benefit of targeting sources > 5 km from sites. Figure 19 (in contrast to Figure 18) shows the additional benefit of extending the mitigation zone from 1 km - 2 km, and beyond, to 2 – 5km. It is clear from Figure 19 that the 1 and 2 km enhanced mitigation scenarios benefit from the inclusion of the 0 – 1 km buffer zone, and subsequent zones are increasingly less effective at reducing concentrations at sites. However, the contribution from the outer part of a 5 km zone (i.e. 2 - 5 km) is still twice as high for SACs as the implementation of M-NI only (despite the much smaller overall NI-wide reduction in emissions needed for implementing the enhanced measures in the buffer zones)

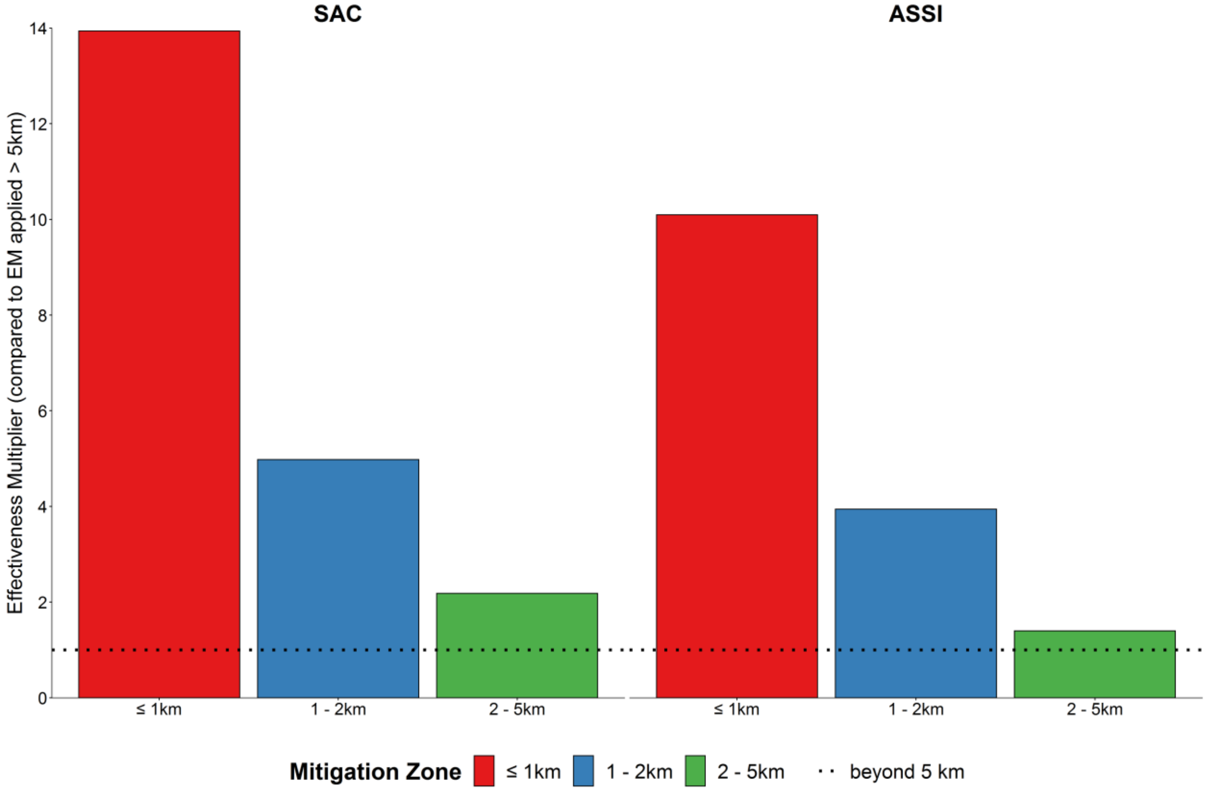

Figure 19: A comparison between average effectiveness of the spatially targeted enhanced mitigation zones in terms of NH_3 concentration reductions at nitrogen sensitive sites (by site) and compared to average reductions achieved by applying enhanced measures at distances > 5 km from sites (dotted line). The effectiveness multiplier indicates how many more times effective spatial targeting is at achieving NH_3 concentration reductions than the average effectiveness of applying measures at distances > 5km from sites. Emission and concentration reductions have been calculated for each concentric buffer zone rather than overall zone covered by each scenario.

In summary, the effectiveness of spatial targeting of measures on atmospheric NH_3 concentrations varies by site and depends on a number of factors:

- The **intensity of emission sources** that surround each site. Spatial targeting is more likely to benefit sites that are situated in intensive agricultural regions (with emission sources present that are targeted by the enhanced measures) compared to sites in extensive agricultural regions with low emission densities in the surrounding area. Sites with low baseline NH_3 concentrations may therefore be more difficult to target than sites with high baseline NH_3 concentrations.

- The **type of emission sources that surround** each site. The suite of measures that form the enhanced mitigation bundle are designed to target cattle, pig and poultry emissions sources in particular, therefore sites with high emission densities from these sectors are likely to benefit more than sites that are associated with high fertiliser emissions, for example. Similarly, sites with high non-agricultural NH_3 emissions are, by definition, less suitable for targeting with purely agricultural measures (unless agricultural emission densities are also high).
- The **proportion of the mitigation zone that is within NI**. The enhanced mitigation zones only target emission sources within NI, therefore sites near the border with the Republic of Ireland may receive little benefit from enhanced mitigation, as a large proportion of close-by sources may be outside the zone of influence of NI mitigation policy. To protect such sites, cross-border efforts would be beneficial.

Table 5 compares the effectiveness of spatial targeting between Turmennan SAC and Upper Ballinderry River SAC in terms of reducing ammonia concentrations at the two sites. On average, applying enhanced measures in zones > 5 km from SACs provides ~0.001 µg NH_3 m^{-3} concentration reduction per tonne N emission reduction (compared to M-NI), this indicator of overall effectiveness is what is used as a comparison in estimating the Effectiveness Multiplier below. Table 5 shows that spatially targeting a 0 - 1 km zone of Turmennan SAC achieves a 0.44 µg NH_3 m^{-3} reduction (compared to M-NI) in NH_3 concentration from an emission reduction of ~3.7 t N (compared to EM-NI), thus providing 0.117 µg NH_3 m^{-3} reduction in concentration per tonne N emission reduction. Targeting this 0 - 1 km area surrounding Turmennan is therefore on average 117 times more effective than the average saving achieved by targeting zones > 5 km around SACs. The agricultural emission density estimates for Turmennan (presented in Figure 6 above) clearly show that the enhanced measures provide substantial reductions to overall agricultural NH_3 emissions in the area surrounding Turmennan SAC. Applying enhanced measures surrounding Turmennan SAC seems to be very effective at lowering emissions associated with the pig sector in particular.

Due to the linear shape of Upper Ballinderry River SAC, the mitigation zone (where spatially targeted mitigation is applied) is much larger than the overall site area (where NH_3 concentration reductions are assessed). This means that Upper Ballinderry River SAC may be less suitable for spatial targeting, as measures would need to be applied over a very large area, to achieve reductions at a relatively small receptor (i.e. actual site area rather than envelope surrounding the site). The agricultural emission density estimates for Upper Ballinderry River SAC (Figure 6 above) also show that emissions associated with poultry farming are dominant in the areas surrounding the site. This sector is not as heavily targeted in the enhanced mitigation measures as some other sectors, and therefore emissions remain relatively unchanged.

Table 5 clearly demonstrates this, with modest NH_3 concentration reductions at Upper Ballinderry River SAC despite much higher emission reductions compared to Turmennan SAC. However, spatial targeting around Upper Ballinderry River SAC is still more effective in reducing concentrations at the site than mitigation at a distance of >5km from the site, e.g. >8 times more effective for a 1 km zone, but at a relatively low absolute level of concentration reduction.

Table 5: Comparison of concentration and emission reductions (in addition to reductions made under M-NI) achieved by spatial targeting at Turmennan SAC and Upper Ballinderry River SAC. The effectiveness multiplier indicates how many more times effective spatial targeting is at achieving NH3 concentration reductions than EM-NI per unit emission

Site	Buffer zone	Concentration reduction (µg NH_3 m^{-3})	Emission reduction (kg N)	Effectiveness multiplier of enhanced measures*
Turmennan SAC	0 - 1 km	0.44	3,783	117.30
	1 - 2km	0.07	4,688	14.16
	2 - 5km	0.11	23,438	4.54
	> 5 km	0.05	53,390	-
Upper Ballinderry River SAC	0 - 1 km	0.11	13,142	8.27
	1 - 2km	0.04	13,065	2.93
	2 - 5km	0.06	46,320	1.24
	> 5 km	0.09	121,357	-

** Compared to the mean concentration reduction per mean emission reduction of enhanced mitigation applied in zones > 5 km from sites. The effectiveness multiplier indicates how many more times effective spatial targeting is at achieving NH_3 concentration reductions than the overall effectiveness of EM-NI, per unit emission reduction. Emission and concentration reductions have been calculated for each concentric buffer zone rather than overall zone covered by each scenario.*

1.10 Total Nitrogen Deposition Estimates

N deposition rates to semi-natural vegetation (woodlands, bogs, heaths, fens, montane habitats etc.), fertilised grassland, arable land etc. vary depending on the type of vegetation and nitrogen saturation. For example, fertilised grassland that has a much higher N content in its tissues has a much slower uptake rate of dry deposition to leaf surfaces, compared with low-N vegetation such as bogs. For semi-natural vegetation types, dry deposition rates (also referred to as deposition velocities) can be roughly categorised into low-growing habitats vs woodland habitats, with the latter being characterised by much larger leaf surface area and therefore higher deposition velocities. Figure 20 shows the estimated N deposition to low-growing semi-natural vegetation (i.e. non-woodland habitats) under each scenario associated with spatial targeting at SACs. There is a clear decrease in deposition between the baseline and the M-NI scenario, with areas exceeding 30 kg N ha^{-1} yr^{-1} substantially reduced, and also in areas of lower-deposition. Further reductions are also estimated for spatial targeting, with EM-SAC5 showing a noticeably higher proportion of areas < 10 kg N ha^{-1} yr^{-1} compared to the NI-wide mitigation scenario (M-NI, 25% emission reduction compared to baseline).

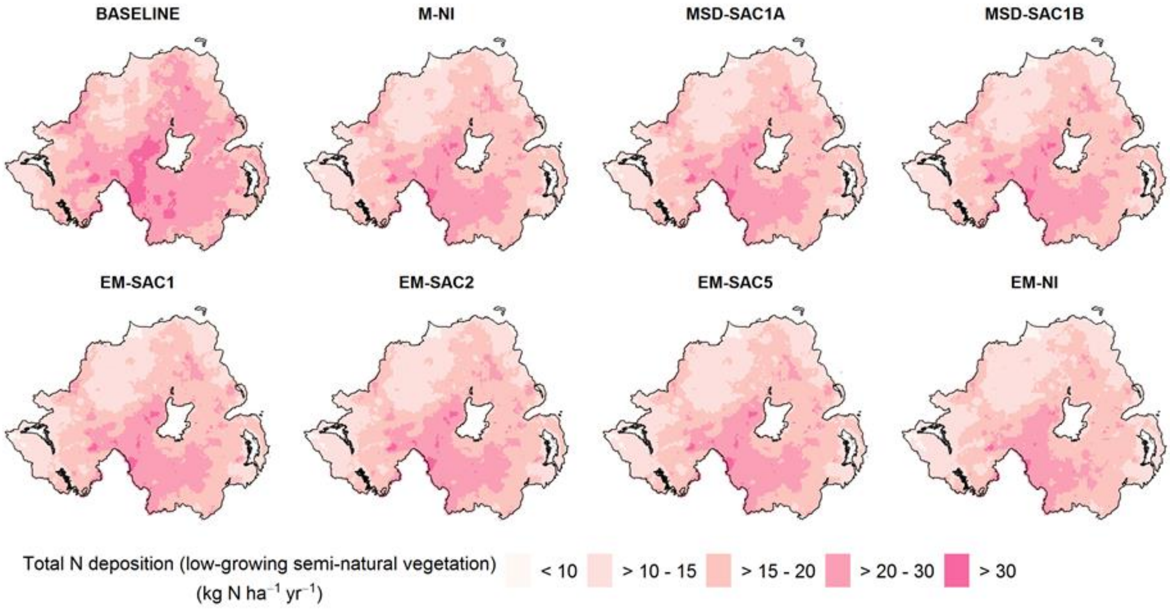

Figure 20: Estimated total N deposition to low-growing semi-natural vegetation (i.e. non-woodland habitats) in Northern Ireland, under each mitigation scenario associated with spatially targeting SACs (for ASSIs see appendix).

The absolute reduction in N deposition (to low-growing semi-natural vegetation) compared to baseline is presented in Figure 21. The figure illustrates a general reduction across Northern Ireland with the largest decreases around deposition hotspots in the baseline scenario (see Figure 20). Modelled N deposition estimates under the spatially targeted mitigation scenarios are compared to reductions M-NI in Figure 22. The additional changes in deposition (compared with M-NI) show that the areas associated with the greatest decreases correspond to areas surrounding the SACs (with N-sensitive features) and are also associated with areas of highest emission reductions. The manure/slurry displacement scenarios (MSD-SAC1a and MSD-SAC1b) clearly show deposition to be lower in areas surrounding sites and increased deposition in areas away from N-sensitive designated sites where the displaced emissions were relocated (similar to the modelled concentrations).

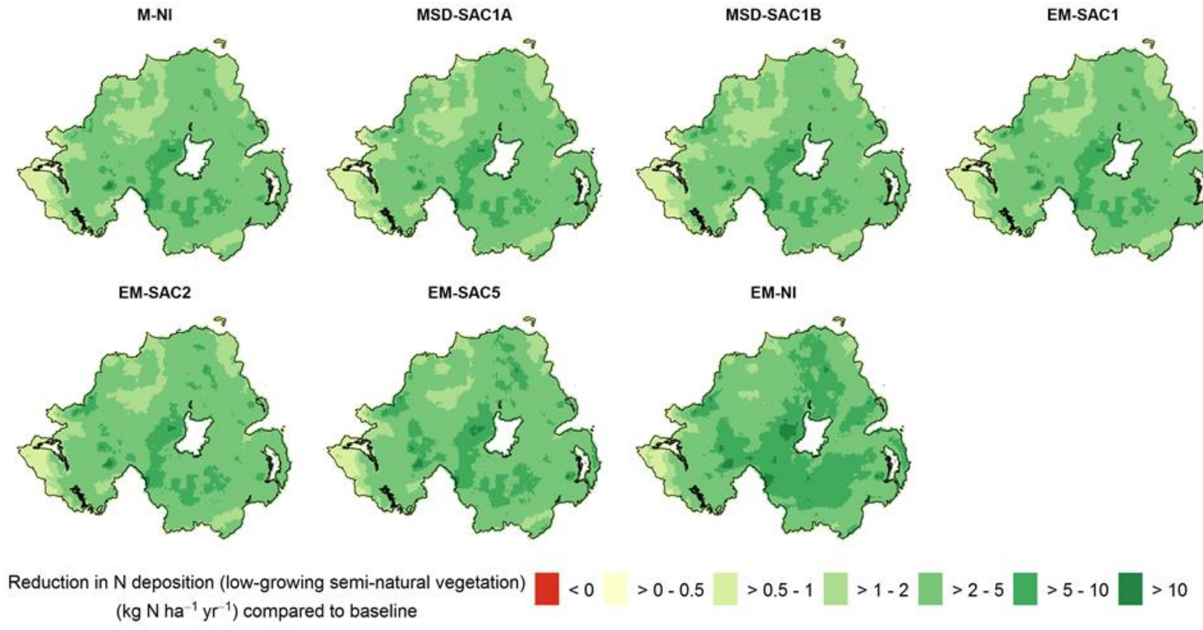

Figure 22: Estimated reduction in total N deposition to low-growing semi-natural vegetation compared to baseline in Northern Ireland for each mitigation scenario associated with spatially targeting N-sensitive SACs (for ASSIs see appendix).

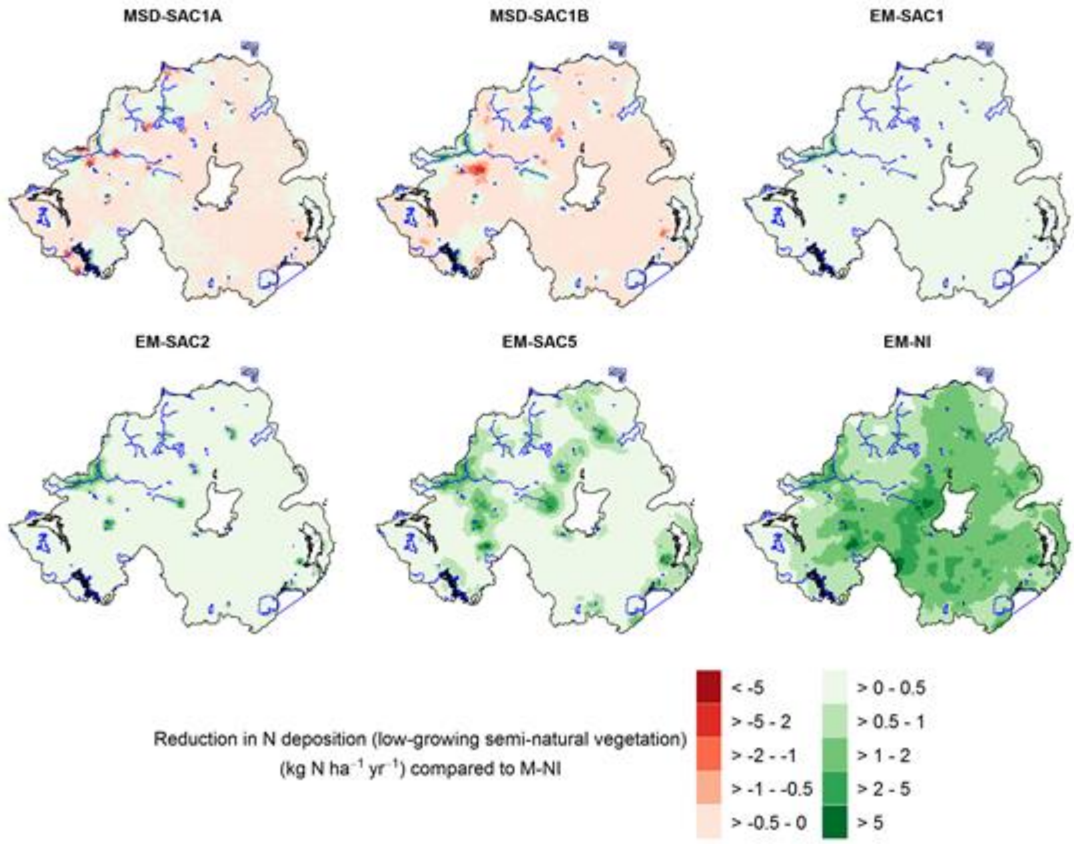

Figure 22: Estimated reduction in total N deposition to low-growing semi-natural vegetation compared to M-NI in Northern Ireland for each mitigation scenario associated with spatially targeting N-sensitive SACs (shown in blue) for ASSIs see appendix.

Figure 23 presents the variation in N deposition at nitrogen sensitive SACs in Northern Ireland. As with NH_3 concentrations, the figure shows that the largest reductions are made under M-NI, which is unsurprising given that the M-NI scenario achieves the highest level of emission reductions, and additional total reductions made under the enhanced mitigation scenarios are much smaller.

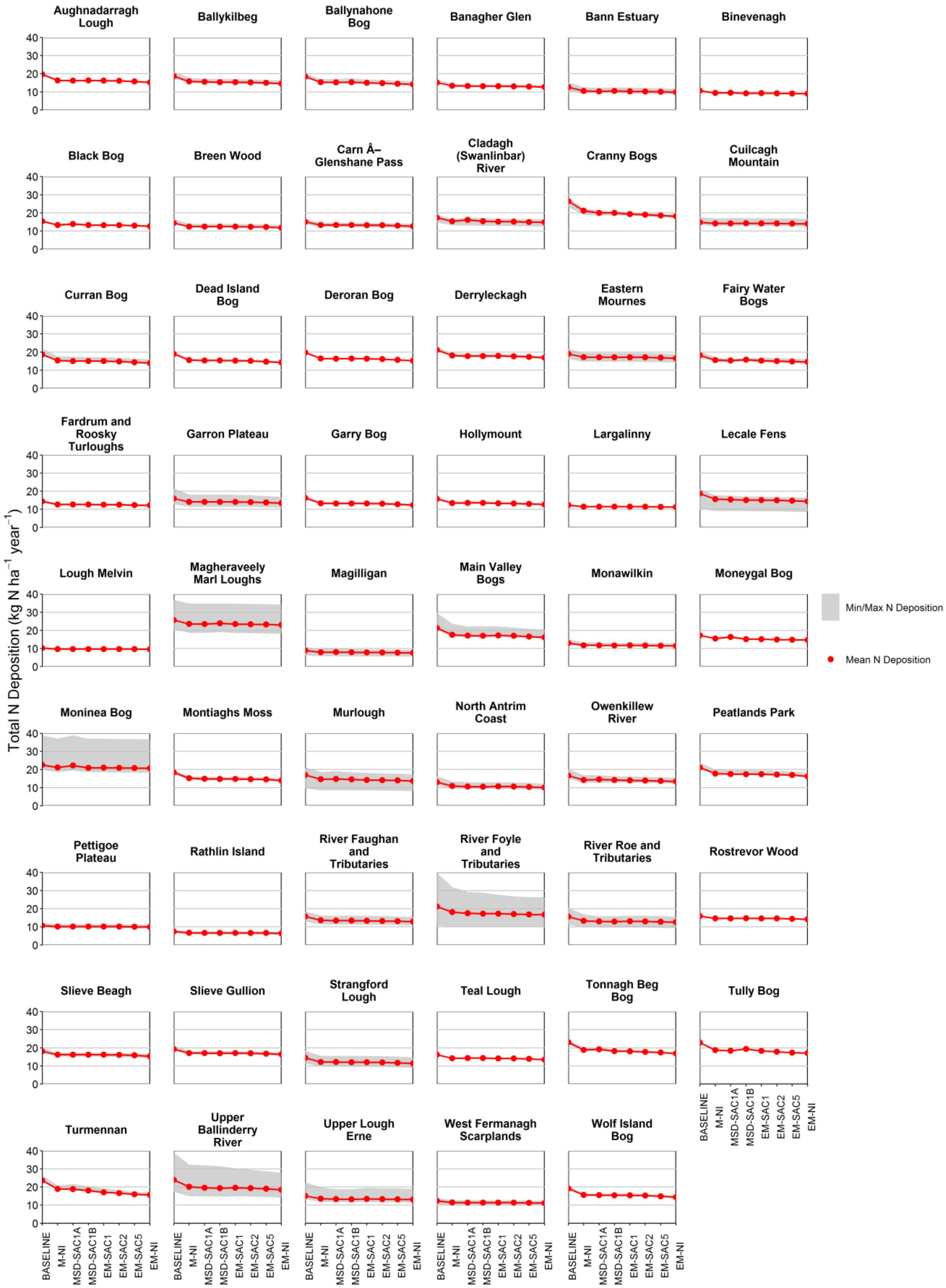

Figure 23: Mean total N deposition (kg N ha^{-1} yr^{-1}) at SACs in Northern Ireland under each mitigation associated with spatially targeting SACs (for ASSIs see appendix). Including minimum and maximum total N deposition values.

Figure 24 compares the effectiveness of spatially targeted enhanced mitigation in terms of reducing wet and dry deposition received by designated sites, compared to non-spatially targeted mitigation under M-NI. The Effectiveness Multiplier indicates how much more effective spatial targeting is, compared to M-NI. For example, a value of 2 indicates that, per unit of emission reduction, spatially targeted mitigation is twice as effective (on average) at reducing deposition received by designated sites (overall) than M-NI. The figure clearly shows that implementing mitigation near sites is more effective at reducing dry deposition than wet deposition, as dry deposition is typically due to more local sources. It is also clear from Figure 24 that the enhanced mitigation is more effective at reducing deposition than non-spatially targeted mitigation (M-NI) per unit emission reduction. The additional benefit of the spatial targeting scenarios is more pronounced for the SAC scenarios, which is probably due to the same reasons outlined above, regarding the effectiveness of NH_3 concentration reductions.

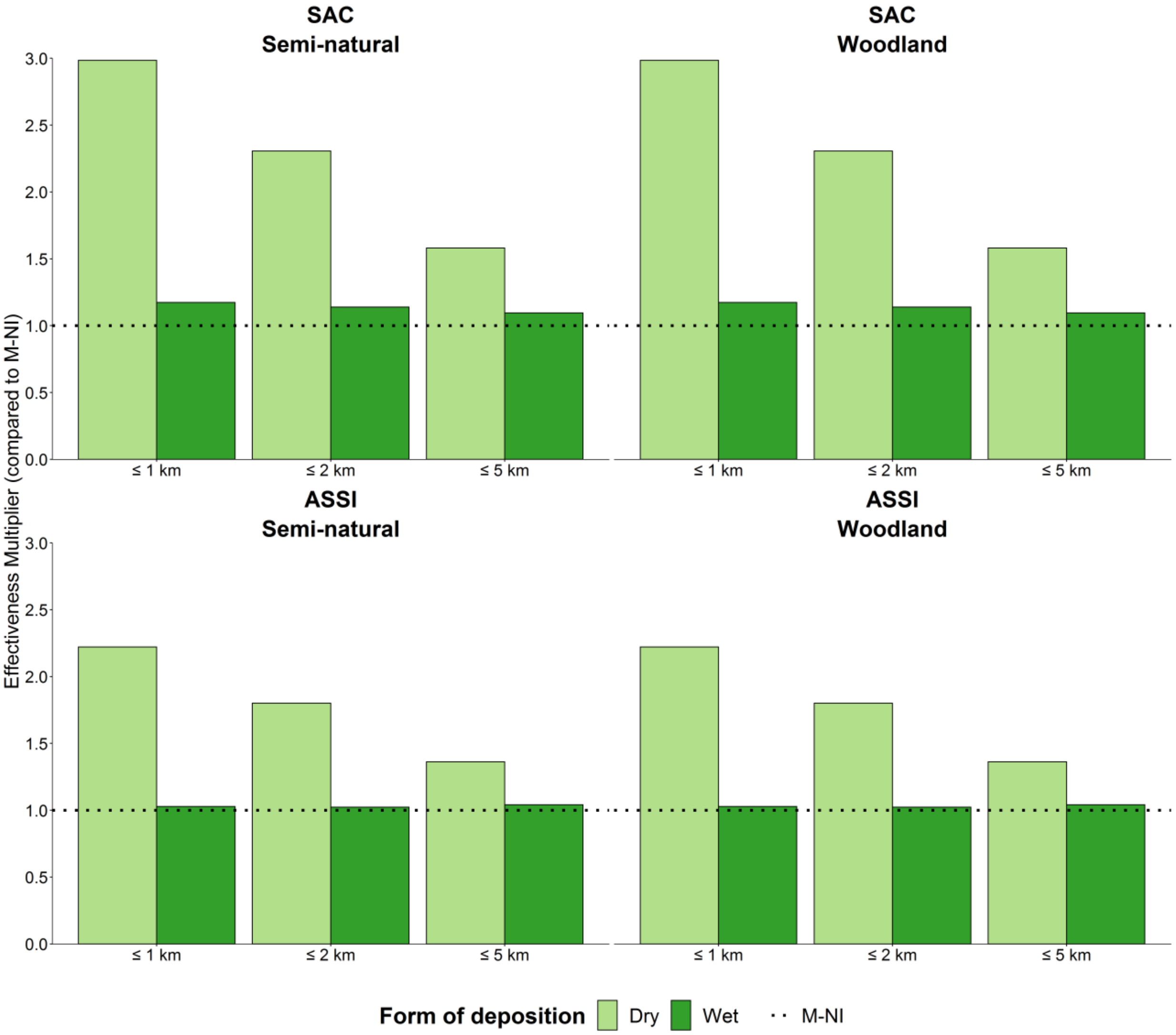

Figure 24: A comparison between overall effectiveness of the spatially targeted enhanced mitigation scenarios in terms of N deposition to low-growing semi-natural and woodland features at nitrogen sensitive sites (overall area) and compared to reductions achieved by the M-NI scenario (dotted line). The effectiveness multiplier indicates how many more times effective spatial targeting is at achieving deposition reductions than M-NI per unit emission reduction.

To assess the benefit of spatially targeting NH_3 emissions to reduce dry NH_x deposition at individual sites, modelled emission reductions were quantified for each mitigation zone surrounding each site and compared to modelled dry NH_x deposition reductions achieved at each site. Site level emission reductions under the EM-NI scenario were calculated by scaling site-level emission reductions under the SAC/ASSI zones to the equivalent reduction under EM-NI (based on overall total emission estimates). Mean site level emission reductions under EM-NI were compared to modelled dry NH_x deposition reductions at sites as a benchmark to compare the effectiveness of spatial targeting. Figure 25 shows the mean effectiveness of spatial targeting individual sites in reducing dry NHx deposition (as opposed to total wet/dry N deposition received by all SAC/ASSI sites shown in Figure 24). The figure suggests that spatially targeting a 1 km zone surrounding SACs is on average 4 times more effective at reducing dry NH_x deposition than applying enhanced measures NI-wide. However, the 5 km zones are still nearly twice as effective as NI-wide mitigation, on average, for SACs, and approx. 1.3 times more effective for ASSIs.

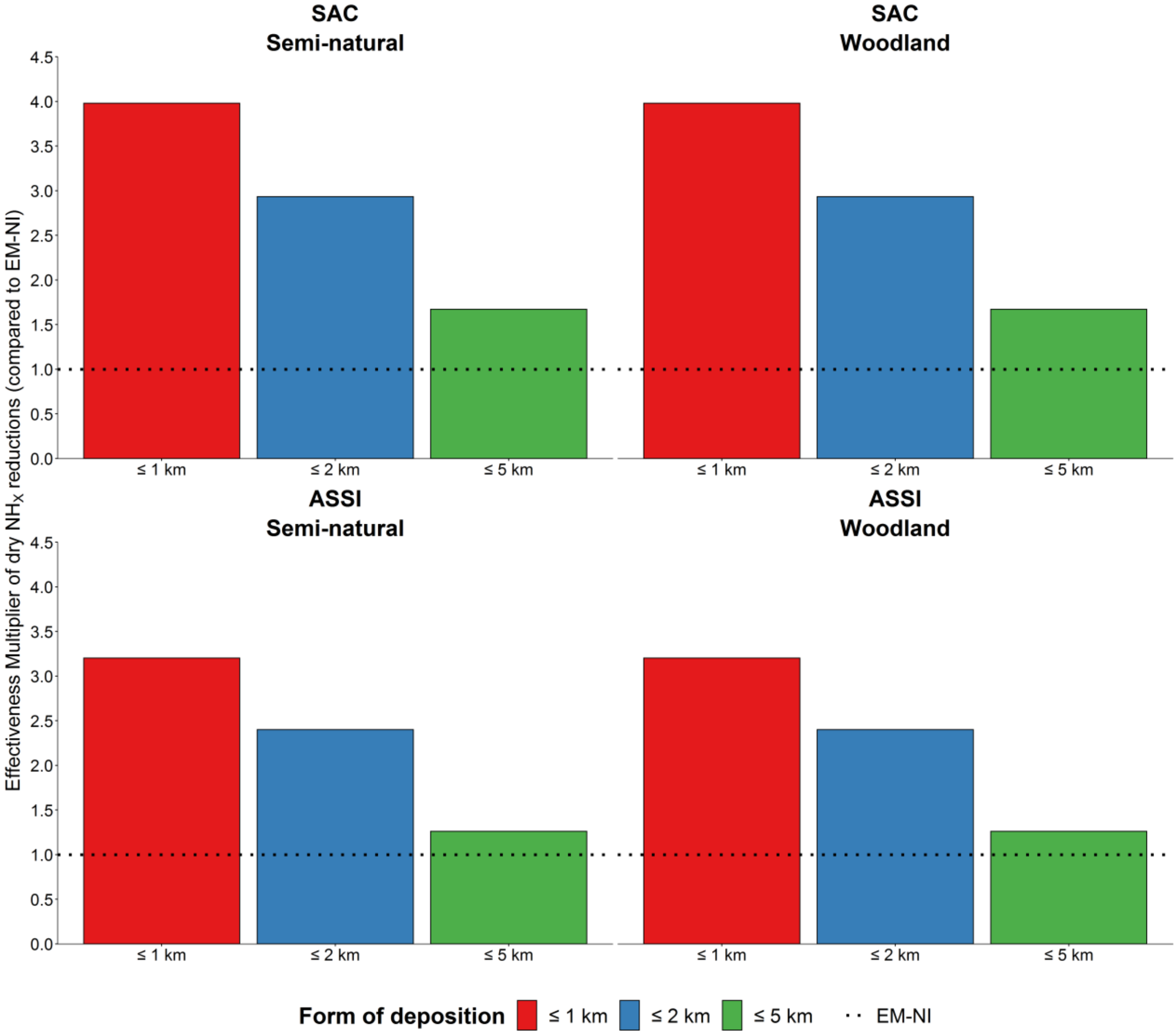

Figure 25: A comparison between overall effectiveness of the spatially targeted enhanced mitigation scenarios in terms of the reduction in dry NH_x deposition to semi-natural and woodland features at nitrogen sensitive sites (average area-weighted reduction at sites) and compared to reductions achieved under EM-NI scenario (dotted line). The effectiveness multiplier indicates how many more times effective spatial targeting is at achieving dry NH_x deposition reductions than EM-NI per unit emission reduction.

Table 6 compares the effectiveness of spatial targeting between Turmennan SAC and Upper Ballinderry River SAC, in terms of reducing dry NH_x deposition to low-growing semi-natural features at sites. Table 6 shows that spatially targeting a 0 - 1 km zone around Turmennan SAC achieves on average a 1.86 kg N ha^{-1} yr^{-1} reduction in dry NH_x deposition (compared to M-NI). This represents a 10 % reduction in total N deposition compared with M-NI. Most of the benefit in terms of dry NH_x deposition reduction (15%) is therefore achieved within the 5 km buffer zone for Turmennan, compared with the NI-wide implementation of enhanced measures (16%). The 2 km zone is expected to provide similarly substantial reductions (12%), and even the 1 km zone still provides a 10% reduction.

As with concentrations, the linear nature of Upper Ballinderry River SAC, means that higher emission reductions are needed to achieve more substantial deposition reductions and the site is therefore less suitable for spatial targeting. Applying enhanced measures in the 0 – 1 km zone of Upper Ballinderry River SAC yields a 2 % reduction in dry NH_x deposition, despite higher emission reductions than Turmennan SAC (see Table 6). Again, spatial targeting in a 5 km zone (5% reduction) is almost as effective as NI-wide enhanced measures (7% reduction). However, even with enhanced measures applied NI-wide, the average reduction in dry NHx deposition is only 1.4 kg N ha^{-1} yr^{-1}, indicating that high emission reductions are needed more widely to reduce N deposition substantially. This may indicate that a high proportion of deposition received at this site originates from more distant N emission sources.

Table 6: Comparison of dry NH_x deposition (to low-growing semi-natural features) and emission reductions (in addition to reductions made under M-NI) achieved by spatial targeting at Turmennan SAC and Upper Ballinderry River SAC. The effectiveness multiplier indicates how many more times effective spatial targeting is at dry NH_x deposition reductions than EM-NI per unit emission

Site	Site Area	Buffer width (km)	Total deposition under M-NI (kg N ha^{-1} yr^{-1})	Average reduction in dry NHx deposition (kg N ha^{-1} yr^{-1})	Reduction in dry NHx deposition (% of total N deposition under M-NI)
Turmennan	14.8	< 1	18.9	1.9	10%
		< 2		2.3	12%
		< 5		2.8	15%
		NI-wide		3.1	16%
Upper Ballinderry River	58.9	< 1	20.1	0.5	2%
		< 2		0.7	3%
		< 5		1.0	5%
		NI-wide		1.4	7%

1.11 Average Annual Exceedance/Excess Nitrogen indicator

The Average Annual Exceedance (AAE) indicator (also referred to as “excess nitrogen” more recently) has been estimated at all designated sites using the method below:

$$AAE\ (kg\ N\ ha^{-1}\,yr^{-1}) = \frac{exceedance\ (kg\ N\ ha^{-1}\,yr^{-1}) * habitat\ area\ (ha)}{total\ habitat\ area\ (ha)}$$

Estimating AAE provides an exceedance value averaged across the whole habitat area and provides a more intuitive value for comparing the exceedance results under each scenario, i.e. a measure of how much deposition has been reduced by, rather than the binary exceedance/non-exceedance indicator (magnitude of remaining exceedance). The AAE results are presented in Figure 26 and illustrate that AAE decreases at a number of sites with spatial targeting. For example, Lecale Fens SAC is estimated to have an average annual exceedance of 4 kg N ha^{-1} yr^{-1} under the baseline scenario, this reduces to 1.3 kg N ha^{-1} yr^{-1} under M-NI. The exceedance is further reduced under spatial targeting (e.g. to 0.8 kg N ha^{-1} yr^{-1} under EM-SAC5), and closer to being brought out of exceedance (i.e. an AAE of 0 kg N ha^{-1} yr^{-1}). The figure therefore shows that, although many remain in exceedance of critical loads under the spatially targeted mitigation scenarios, the extent of the exceedance continues to decrease.

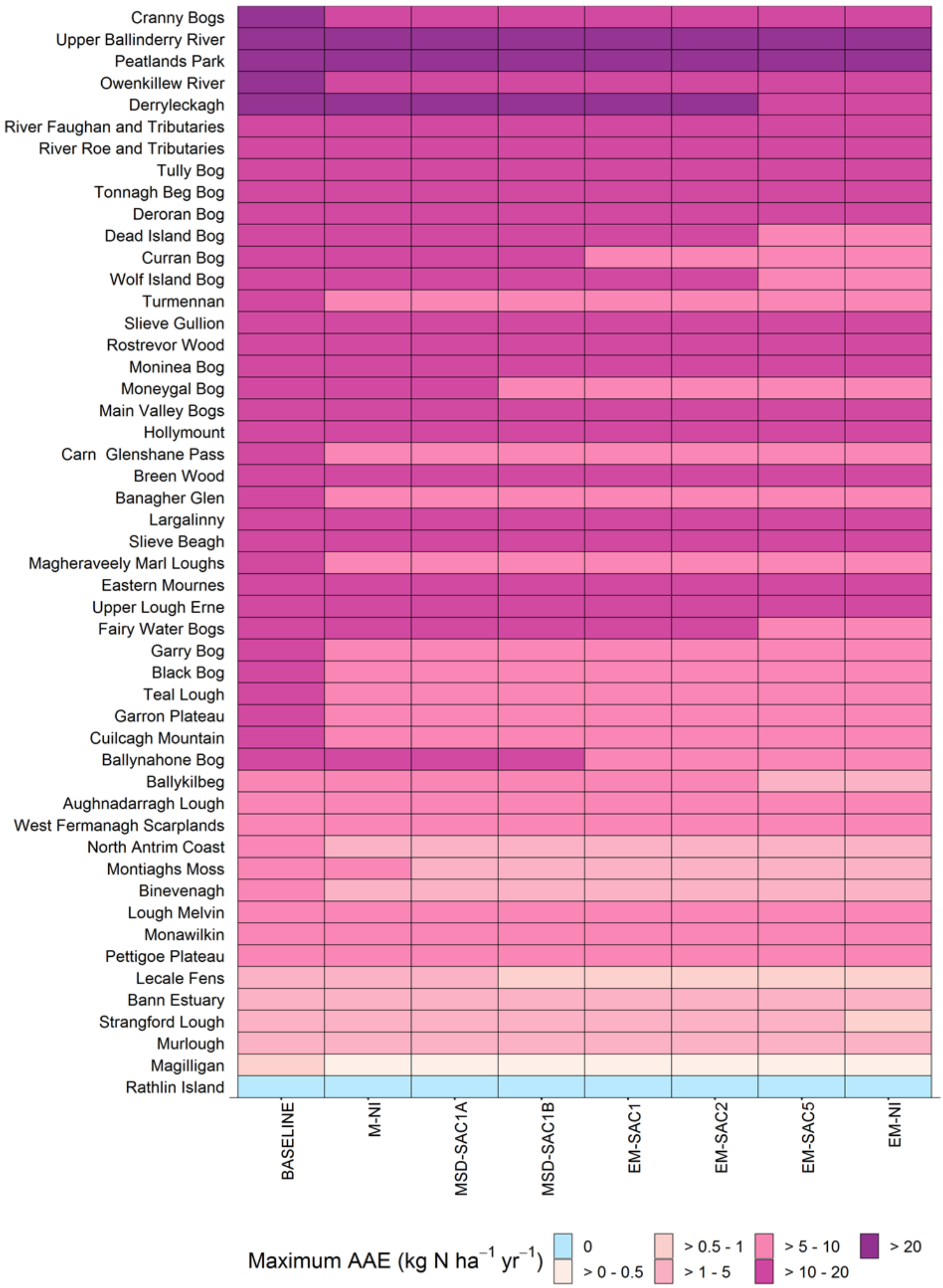

Figure 26: Maximum Average Accumulated Exceedance (AAE) at SACs in Northern Ireland.

1.12 Summary, discussion & conclusions

The scenario modelling carried out has clearly shown the substantial impact of the large bundle of NI-wide measures (M-NI) which achieves a 25% reduction in agricultural emissions across Northern Ireland. Given the relatively high baseline emissions across intensive agricultural landscapes, this effort reduces emissions significantly (compared to baseline), as already shown in last year's modelling study, but now repeated with what are considered more suitable and realistic policy options. This NI-wide scenario results in two SACs brought out of exceedance of the 1 µg NH_3 m^{-3} critical level (based on maximum concentrations at sites), and 14 ASSIs (based on maximum concentrations at sites). The additional spatially targeted measures ("enhanced mitigation scenario"), modelled for buffer zones surrounding the sites, increased overall emission reductions by a further 1-4% (SAC scenarios) and 1-5% (ASSI scenarios) compared to the baseline, depending on the width of the zones (1, 2 and 5 km tested). These scenarios resulted in additional sites brought out of exceedance, 1 SAC (Lough Teal) and 5 ASSIs.

In terms of estimated decreases in NH_3 concentrations and N deposition, the NI-wide measures achieve the bulk of the overall improved conditions at the SACs. However, it has been illustrated clearly that, per unit of emission saved, spatial targeting is much more effective in reducing NH_3 concentrations and N deposition at designated sites. For example, it is estimated that the spatially targeted measures under EM-SAC1 (1 km zone of enhanced mitigation) are, on average ~5.8 times more effective at reducing NH_3 concentrations at SAC sites per unit of emissions reduced. Spatial targeting of NH_3 emission reductions is also effective at targeting dry NH_x deposition at sites.

The effectiveness of spatial targeting varies between sites - this is due to the make-up and density of the emission source sectors near each site, and the ability to influence concentrations or deposition at sites through the bundle of enhanced measures tested (which overall mainly target cattle and pig emissions). The results also clearly illustrate that targeting a 0 – 1 km zone surrounding sites is the most efficient location for implementing measures to reduce NH_3 concentrations and dry NH_x deposition, per unit of emission reduction. However, it has also been shown that, at a site level, targeting measures within buffer zones can be almost as effective as applying measures NI-wide, in terms of reductions in dry NH_x deposition.

This study has shown clearly that spatial targeting of mitigation measures near protected nature conservation sites is several times more effective than applying the same amount of emission reductions NI-wide, both for reducing NH_3 concentrations and related N deposition at the sites. It is also important to contemplate the limitations of the 1 km grid modelling approach for assessing the effectiveness of spatial targeting of measures. This is for the following reasons:

- The underlying UK emission model at the 1 km grid resolution aggregates and smooths out the individual emission sources located across the fields and farms contained in each grid cell. This can be illustrated with an example from a study by Vogt et al. (2013; Figure 27). The study modelled and measured ammonia concentrations across an area of 6 km by 6 km, with a large number of poultry houses (layers) and extensive upland sheep and cattle farming. This example illustrates the potential for very high spatial variability of ammonia concentrations over a short distance, and how averaging emissions (and concentrations) over a 1 km grid cell can smooth out considerable local differences.

- The high-resolution agricultural emission model used in the UK (AENEID, 1 km grid) smooths out the emissions of each farm (i.e. housing, grazing, landspreading, manure storage, yards, mineral fertiliser application) over several grid cells, weighted by land use, and aggregated to meet disclosivity agreements for use of the holding-level farm census/survey data. Therefore, the actual location of livestock houses in the landscape and their relative location and distance to the boundary of designated sites becomes more diffuse.

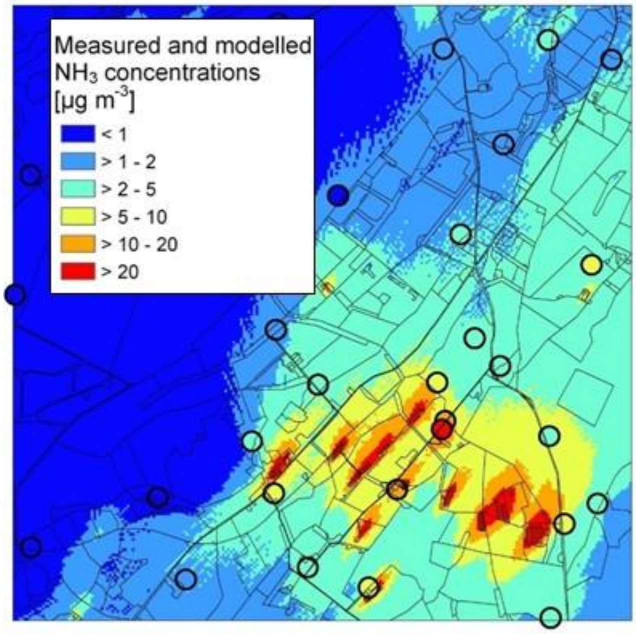

Figure 27 – Annual average modelled (grid) and measured (circles) ammonia concentrations in a landscape in southern Scotland (6 km by 6 km). After Vogt et al. 2013.

- The UK agricultural emission inventory model (Misselbrook et al.) can only apportion management practice (e.g. slurry vs solid manure systems, and open slurry lagoons vs covered circular tank etc.) and credit any existing mitigation measures "on average", i.e. across NI, due to level of detail available the underlying data. Therefore, for example, a layer or broiler across all farms in NI will have very similar emission factors as mapped across NI in the subsequent high-resolution AENEID modelling, averaged across all management systems, with local practice being smoothed out.

In reality (as shown in Figure 27), the distribution of ammonia concentrations and dry deposition will be more spatially variable and reflect individual emission sources across the wider landscape surrounding sensitive sites. It is the individual nature, size and location of each source, in relation to a nearby designated site (or sites), that will determine how effective spatial targeting can be.

The modelling carried out in the present study for Northern Ireland applied a set of carefully considered measures at specific implementation rates, to quantify the effectiveness of spatial targeting in addition to wider NI-wide measures. However, to assess the likely effectiveness of spatial targeting at a site level, the following points should be considered, instead of a blanket approach where the agricultural landscape is considered more homogeneously and diffusely, as laid out above. It is important to take account of

- the relative distance between the source(s) and site(s)
- prevailing wind direction,
- land use between the source and site boundary (e.g. woodland vs. heavily manured fields),
- farm management practice and systems,
- mitigation measures already in place/potential for mitigation (e.g. a farm may already operate using Best Available Techniques)

Further work is currently ongoing to cluster designated sites, based on characteristics such as N input pathways (e.g. local, national or transboundary), key sectors contributing to emissions locally (emission density) and to deposition (source attribution), level of threat through atmospheric N input, etc. This work is being carried out under a parallel project for Daera (contact: Aine O'Reilly).

In summary, the following approach for maximising the effectiveness of mitigation measures for the benefit of designated sites is proposed:

- Implementation of country-wide measures to decrease NH_3 concentrations and N deposition from a very high baseline - This will lead to improved conditions for sensitive habitats and species in both source areas (with high concentrations and deposition) as well as in more remote areas, where long-range deposition will be reduced.
- Spatial targeting locally – this has been shown to be more effective at "spot-reducing" high concentrations and dry deposition than the same amount of emission reduction spread more widely across the country
- Using a mix of well understood and effective measures more generically, as well as specific targeting, depending on local source types, systems in place and opportunities for improvement, by engaging locally.

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