UKCEH
Our planet. Decoded.

afbi AGRI-FOOD & BIOSCIENCES INSTITUTE

Atmospheric ammonia, acid gas and aerosol monitoring network in Northern Ireland: 2022

Report for 2022 calendar year

15/02/2026

Espina-Martin P., Tomlinson S., Pearson, C., Tigli M., Thacker, S., Salisbury, E., Hunt, A., Guyatt H., Smith, H., Graham, C., Chetiu N., Simmons I., Stephens A.C.M., Iwanicka A., Duarte F., Leaver D., Twigg M., Braban C.F., Hood C., Scheffler J., Vieno M., Tang Y.S., Keenan P.O., Pereira M.G., McIlroy J. and Dragosits U.

Issue Number 1



Title	Atmospheric ammonia, acid gas and aerosol monitoring network in Northern Ireland: 2022
Client	DAERA
Client reference	E&I project 17/4/02

UKCEH contact details

P. Espina-Martin, U. Dragosits
UKCEH, Bush Estate, Penicuik, Midlothian EH26 0QB

t: 0131 4458562 (P Espina-Martin)
t: 0131 4458519 (U Dragosits)
e: pabesp@ceh.ac.uk / ud@ceh.ac.uk

Author Espina-Martin P., Tomlinson S., Pearson, C., Tigli M., Thacker, S., Salisbury, E., Hunt, A., Guyatt H., Smith, H., Graham, C., Chetiu N., Simmons I., Stephens A.C.M., Iwanicka A., Duarte F., Leaver D., Twigg M., Braban C.F., Hood C., Scheffler J., Vieno M., Tang Y.S., Keenan P.O., Pereira M.G., McIlroy J. and Dragosits U.

Approved by	U Dragosits
Date	21/05/2026

Table of contents

1. Summary	4
2. NI ALPHA® and DELTA® network	6
2.1. Changes in the NI NH_3 Network	9
2.2. Data Quality Management	9
3. Results and Discussions	10
3.1 Meteorological conditions	10
3.2. Annual mean NH_3 concentrations	11
3.3. Spatial patterns	14
3.4. Seasonal variability	17
3.5. Monitored vs modelled NH3	22
3.6. DELTA measurements	26
4. Conclusions and next steps	39
5. References	40

1. Summary

A Northern Ireland-wide ammonia monitoring network was established in March 2019 across the country, with 25 ammonia (NH_3) monthly monitoring sites implementing the UKCEH ALPHA® method (Adapted Low-cost Passive High Absorption sampler®) and 4 reactive gas and aerosol monitoring sites implementing the UKCEH DELTA® method (DEnuder for Long Term Atmospheric sampling® system). From March 2022, all ALPHA® sites were added into the UK National Ammonia Monitoring Network (NAMN), while only one DELTA® site from the original NI network joined the UK Acid Gases and Aerosol Network (AGANet). This resulted in a total number of 26 sites for the Northern Ireland network from March 2022 onwards (excluding the sites already with NAMN in Northern Ireland).

The aim of these measurements is to provide sufficient data to (i) explore spatial and temporal patterns in NH_3 concentrations, (ii) compare results with atmospheric transport model output and for verification of UK NAEI emissions inventory and the atmospheric transport model, (iii) to enable longer-term trend analysis and potential for quantifying change over time due to change in activities and/or the implementation of policy measures, and (iv) monitor and assess relationship between NH_3 and interacting acid gases (HNO_3, SO_2) and inorganic particulate phase composition (ammonium: NH_4^+, nitrate: NO_3^-, sulphate: SO_4^{2-}, chloride: Cl^-, sodium: Na^+, calcium: Ca^{2+}, magnesium: Mg^{2+}).
Monthly measurements from March 2019 to December 2022 are presented in this report. Previous reports delivered updates on the measured concentrations for project years (from March to February), however from this report onwards reporting is based on calendar year data (January to December) for annual concentrations and statistics, for the 2022 year. Data from three existing UK NAMN and AGANet sites (Coleraine, Hillsborough, Lough Navar) are also included in the report, to augment the network data.

Spatial patterns and seasonal variability (January to December 2022)

- Annual mean NH_3 concentrations in NI in 2022 show high spatial variability, in line with 2021 data across the 25 sites. The lowest NH_3 annual mean concentrations occurred at rural background sites (e.g., 0.6 µg NH_3 m^{-3} for 2022 at Beaghs Burn (AFBI03-A), while the highest annual mean concentration occurred in an area dominated by emissions from dairy farming (9.14 µg NH_3 m^{-3} at Drumclamph 2 (AFBI29-A).
- 2022 had the highest maximum monthly concentration spike recorded since the start of the monitoring back in 2019 at Drumclamph 2 (AFBI29-A; 54.4 µg NH_3 m^{-3}) Caddy Rd. (dominating source: mixed cattle, AFBI20-A; 32.4 µg NH_3 m^{-3}) and Ratarnet Rd. (dominating source: dairy AFBI12-A; 26.25 µg NH_3 m^{-3}).
- All sites show seasonal variability in NH_3 concentrations, with key drivers related to agricultural activities and meteorological conditions. The highest monthly

concentrations are typically observed in spring and autumn when manure applications take place. It is important to note that a spring concentration peak (in all years) is also observed at background sites, suggesting the regional influence of agricultural emissions even at these more remote locations, in addition to smaller local emission sources and increased temperatures during the warmer part of the year. Smaller concentrations in the winter months across the network reflect a reduction in emissions in cold, wet conditions with little agricultural activity as well as an enhancement of the partitioning of NH_3 (g) into ammonium (NH_4^+) (p) aerosols. Warmer and drier conditions in the summer months, coupled to seasonal grazing of animals and the displacement of the NH_3 /NH_4^+ equilibrium towards the gas phase are likely to contribute to the elevated monthly concentrations

- Ammonia continues to be the largest component in the gas and aerosol measurements for the inorganic N species reported in the DELTA® network. NH_3 is the dominant contributor to atmospheric nitrogen input to sensitive receptors over many parts of Northern Ireland.
- Aerosol phase continues to be dominated by secondary inorganic aerosols (SIA) NH_4NO_3 and $(NH_4)_2SO_4$ and Na & Cl related to sea salt sources.

Comparison with model estimates

- Annual average measured NH_3 concentrations have been compared with outputs from the UK European Monitoring and Evaluation Programme model (EMEP4UK, Simpson et al., 2012; Vieno et al., 2016), a 3-D Eulerian chemical transport model widely utilized in scientific research and policy support at both global and regional scales. The annual average NH_3 concentrations across the network agree well with modelled predictions (R^2 = 0.64, FAC2 = 92%) in 2022.

2. NI ALPHA® and DELTA® network

A network of 25 ammonia (NH_3) monitoring sites was established in early March 2019 across Northern Ireland by UKCEH and AFBI, using the same methodology as implemented in the UK's National Ammonia Monitoring Network (NAMN) using UKCEH ALPHA® samplers (Adapted Low-cost Passive High Absorption sampler®). In addition, 4 sites were established to monitor reactive gases and inorganic aerosols, implementing the UKCEH DELTA® method (DEnuder for Long Term Atmospheric sampling® system) as used in the UKs Acid Gases and Aerosols Network (AGANet) and NAMN (Figure 1).

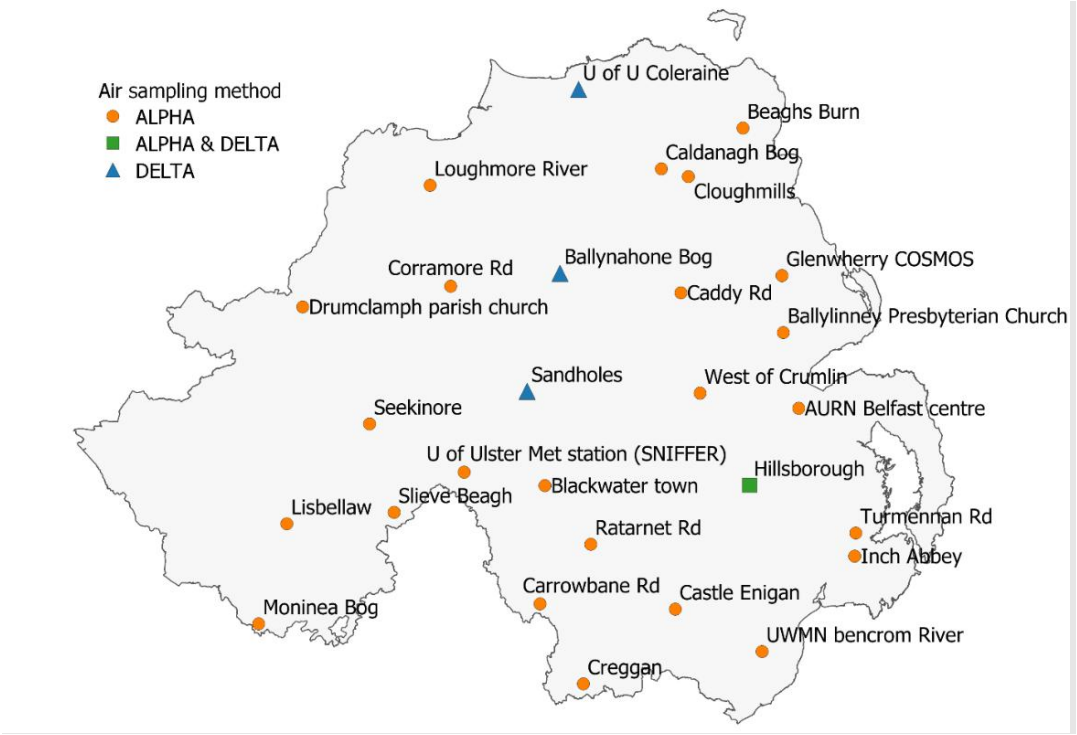


Figure 1. Map of Northern Ireland ALPHA® and DELTA® network (total = 28 sites) for 2022, established across Northern Ireland in March 2019. There were 25 ALPHA® sites monitoring NH_3 (ALPHA network) and 3 DELTA® sites monitoring NH_3, interacting gases and aerosols (DELTA® network) up to March 2022.

In March 2022, Hillsborough (AFBI25-D), U of U Coleraine (AFBI27-D) and Sandholes (AFBI28-D) were closed following review. The remaining sites (24 ALPHA sites (without Hillsborough, AFBI25-A, mainly established for co-location with high-resolution monitoring for a period) and the remaining DELTA site (Ballynahone Bog, AFBI26-D, retained in addition to pre-existing long-term UKEAP DELTA monitoring at Hillsborough and Lough Navar) joined the UK's National Ammonia Monitoring Network (NAMN[1]) and Acid Gases and Aerosol Network (AGANet) under the UK Eutrophying and Acidifying Pollutants (UKEAP[2]) contract.

[1] https://uk-air.defra.gov.uk/networks/network-info?view=nh3
[2] https://uk-air.defra.gov.uk/networks/network-info?view=ukeap

Table 1 shows the equivalent UKAIR codes for each one of the NI network sites that were incorporated into the UKEAP network. The pre-UKEAP site codes are used for this report, but from 2023 onwards the UKAIR codes will be used.

Table 1. Equivalence between the pre-UKEAP site codes and their correspondent UKAIR code from March 2022 onwards.

Site name	Code pre-UKEAP	UKAIR code
U of Ulster met station	AFBI01-A	UKA00938
Castle Enigan	AFBI02-A	UKA00939
Beaghs Burn	AFBI03-A	UKA00383
Slieve Beagh	AFBI04-A	UKA00940
Moninea Bog	AFBI05-A	UKA00941
Seekinore	AFBI07-A	UKA00942
Lisbellaw	AFBI08-A	UKA00943
Glenwherry COSMOS	AFBI09-A	UKA00944
UWMN Bencrom River	AFBI10-A	UKA00945
Blackwatertown	AFBI11-A	UKA00946
Ratarnet Rd	AFBI12-A	UKA00947
Inch Abbey	AFBI13-A	UKA00948
Belfast Centre	AFBI14-A	UKA00212
Ballylinney Church	AFBI15-A	UKA00949
West of Crumlin	AFBI16-A	UKA00950
Loughmore River	AFBI17-A	UKA00951
Caldanagh Bog	AFBI18-A	UKA00952
Cloughmills	AFBI19-A	UKA00953
Caddy Rd	AFBI20-A	UKA00954
Turmennan Rd	AFBI21-A	UKA00955
Carrowbane Rd	AFBI22-A	UKA00956
Creggan	AFBI23-A	UKA00957
Corramore Rd	AFBI24-A	UKA00958
Ballynahone Bog	AFBI26-D	UKA00959

The ALPHA® sites had been selected to provide representative coverage at the time of network design (2018) of (i) the range of modelled concentrations from FRAME (now replaced with EMEP4UK for model/measurement intercomparisons), (ii) each of seven major dominant emission source classifications: cattle (beef and dairy), pigs & poultry, sheep, mixed, non-agricultural, fertiliser and background (very low emission density, < 1 kg N ha^{-1} yr^{-1}), and (iii) spatial coverage across Northern Ireland.

The DELTA® sites provide monthly measurements of NH_3, as well as concurrent measurement of acid gases (nitric acid: HNO_3, sulphur dioxide: SO_2) and inorganic aerosols (ammonium: NH_4^+, nitrate: NO_3^-, sulphate: SO_4^{2-}, chloride: Cl^-, sodium: Na^+, Ca^{2+}, magnesium: Mg^{2+}). This evidence is useful for evaluating atmospheric transport models and for estimating a budget of reduced nitrogen (NH_3 and NH_4^+) vs. oxidised nitrogen (sum of HNO_3 and NO_3^-), and also of sulphur.

As of April 2022, only Ballynahone Bog (UKA00959) was retained with a DELTA® sampler under the current contract. Prior to the inclusion of the NI NH_3 network into the NAMN, NH_3 monitoring under the NAMN only included three sites in Northern Ireland: Hillsborough (different from AFBI25-A & D), Lough Navar and Coleraine (Figure 2, Table 2). Data from these three long-term sites, established in the 1990s, are also included in the report, to augment the network data.

Table 2: ALPHA® and DELTA® measurement sites under previously existing long-term UKEAP sites in Northern Ireland before the establishment of the NI NH_3 network and its subsequent incorporation into UKEAP.

Network / site name	AFBI code	Method/Air pollutants measured	UK-AIR ID	Number of sites
NAMN / Coleraine	S79	ALPHA® / Gas: NH_3	UKA00401	1 ALPHA
NAMN / AGANet: Hillsborough	S44	DELTA® / Gases: NH_3, HNO_3, SO_2; Aerosols: NH_4^+, NO_3^-, SO_4^{2}, Cl^-, Na^+, Ca^{2+}, Mg^{2+})	UKA00293	2 DELTA
NAMN / AGANet: Lough Navar	S45		UKA00166	

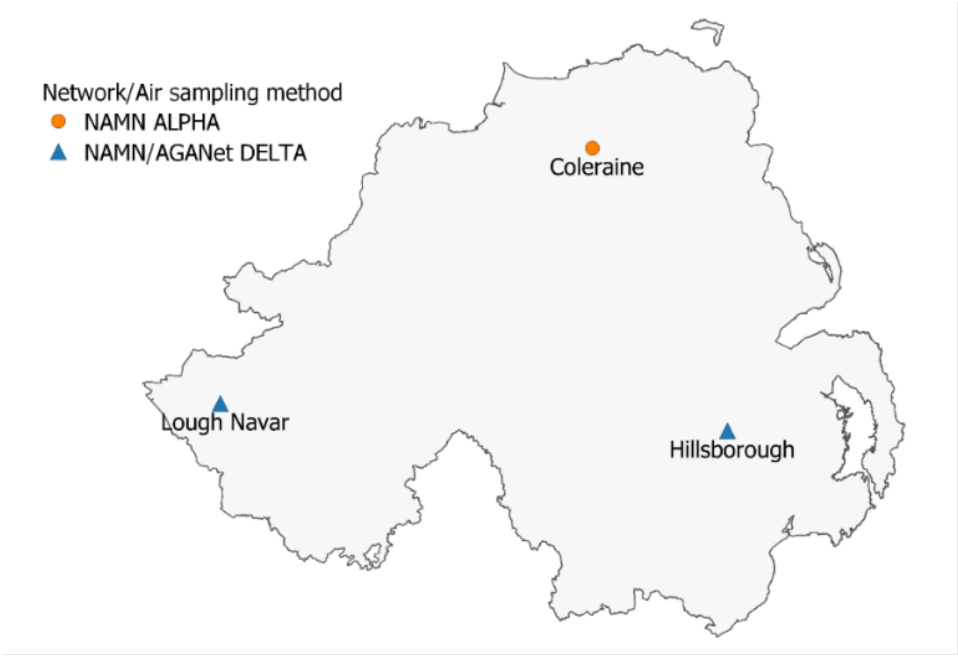


Figure 2. Long-term national network monitoring sites located in Northern Ireland under the UKEAP (UK Eutrophying and Acidifying Atmospheric Pollutants) network pre-2022: Coleraine (NAMN ALPHA: NH_3) and Hillsborough / Lough Navar (NAMN-AGANet[3] DELTA: NH_3, acid gases & aerosols).

[3] https://uk-air.defra.gov.uk/networks/network-info?view=ukeap

2.1. Changes in the NI NH_3 Network

Since the establishment of the network, some changes were made to keep the network as representative as possible:

- AFBI06 (Drumclamph: cattle dairy) was discontinued in August 2019 due to a large local source and was relocated to *AFBI29 Drumclamph 2 in September 2019.
- AFBI25 (Hillsborough: mixed cattle) is not representative for the surrounding area as it was deliberately set up close to a large emission source. This site had installed an ALPHA® sampler (AFBI25-A), a DELTA® sampler (AFBI25-D) and a Picarro Cavity Ring-Down Spectroscopy (CRDS) NH_3 gas analyser (Picarro model Q2103; https://www.picarro.com) with high time-resolution, continuous measurement of NH_3. An Automatic Weather Station (Campbell Scientific; www.campbellsci.eu) was also installed at the same time and these instruments are operated alongside the network measurements at Hillsborough, for local scale assessment rather than representativity within the NI NH_3 network. Results from the transect will be reported in a separate short document, as they are not relevant in the context of NI-wide monitoring.

Table 3: Operational air monitoring network in Northern Ireland during 2022 calendar year.

Site Type	Air pollutants measured	Number of sites
ALPHA®	Gas: NH_3	24
DELTA®	Gases: NH_3, HNO_3, SO_2 Aerosols: NH_4^+, NO_3^-, SO_4^{2}, Cl^-, Na^+, Ca^{2+}, Mg^{2+})	1
Total number of sites		**25**

2.2. Data Quality Management

The ALPHA® and DELTA® samplers are prepared and analysed at the UKAS-accredited UKCEH Lancaster laboratory, following standard protocols developed by UKCEH (Tang et al., 2001; Sutton et al., 2001) and implemented in the UK NAMN (Tang et al., 2018a) and UK Acid Gas and Aerosol Monitoring Network (Tang et al., 2018b). Detailed descriptions of the ALPHA® and DELTA® methods were provided in the Year 1 report (Tang et al., 2021). Starting from March 2022, the NI NH_3 network follows the UKEAP data ratification process explained in Twigg et al. (2023). This process includes:

1. Review and flagging of data based on field and laboratory comments.
2. Automated processes and flagging based on metadata and quality controls.
3. Expert scientist review including site specific reviews.

All data presented in this report has gone under QA/QC and is fully ratified.
The minimum number of valid monthly measurement data needed to calculate an annual mean is 9 (75 % data capture). This is to avoid bias in the estimated annual mean, particularly since NH_3 is known to exhibit large seasonal variability.

3. Results and Discussions

3.1 Meteorological conditions

The monthly averaged temperature and precipitation data for Northern Ireland from March 2019 to December 2022 are shown in Figure 3, alongside the longer-term average for the 2009-2018 period.

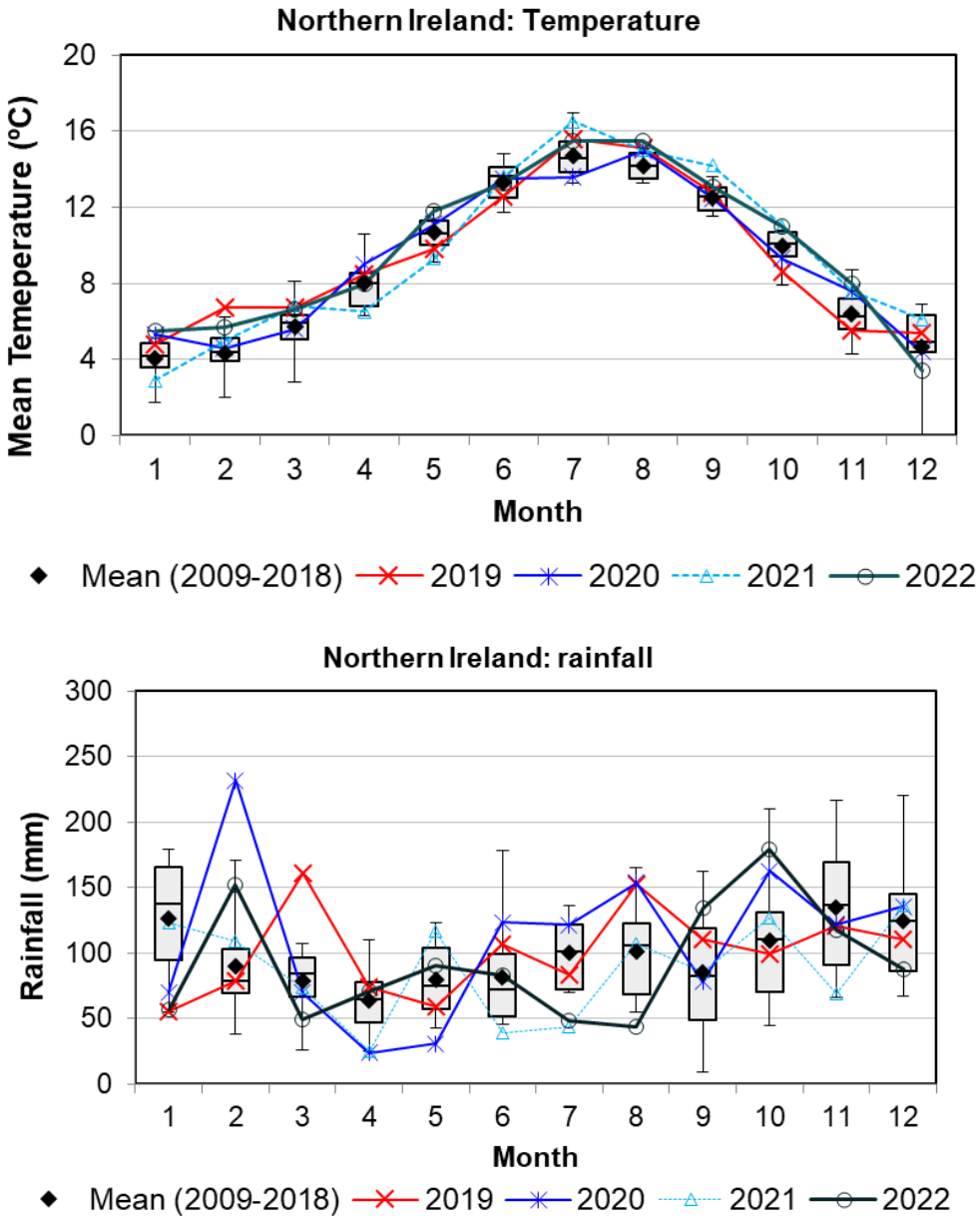


Figure 3: Comparison of 2019 to 2022 mean monthly temperature (top) and rainfall (bottom) data against the 10-year averaged monthly data (2009 to 2018) in NI. The diamonds in the boxplots show the mean, with the grey boxes indicating the median and interquartile range, and the error bars showing the ranges (minimum and maximum). Source: https://www.metoffice.gov.uk/pub/data/weather/uk/climate/datasets/, accessed 24/01/2025).

The 2022 annual average temperature ± standard deviation of 9.8°C ± 4.1 is the highest in Northern Ireland's records from 2009 (Annual means range 2009-2021: 7.95 – 9.58 ºC). Monthly mean temperatures in 2022 were frequently higher than the 10-year average (2009-2018), and only in December (3.4°C) was the temperature below the longer-term average (4.6°C). The summer months in 2022 were also associated with a notably dry period in July and August (48 and 44 mm of rain, respectively) compared to the 10-year average (2009-2018, 100 and 101 mm, respectively).

3.2. Annual mean NH_3 concentrations

Annual mean NH_3 concentrations for each monitoring site were calculated using the monthly data for the following periods, i.e. full calendar years with monitoring data from the NI NH_3 network since its establishment:

- 2020 calendar year
- 2021 calendar year
- 2022 calendar year

Annual mean concentrations were derived from the valid monthly values in each calendar year (maximum 12), giving each month equal weighting. Where an extended sample exposure period occurred (> 1 month), the time-integrated average concentrations were assigned to each of the relevant months over that period. Annual mean data for the three years are summarised in Table 4 and represented in Figure 4. The DELTA sites AFBI25-D, AFBI27-D and AFBI28-D had only two months of 2022 data each as these sites were discontinued, and they are only presented here for data completeness.

No conclusions should be drawn for these sites for the 2022 calendar year.

In 2022, all sites aside from Beaghs Burn (AFBI03-A, background, 0.6 µg NH_3 m^{-3}), Loughmore River (AFBI17-A, mixed cattle, 0.82 µg NH_3 m^{-3}) and Lough Navar (S45, background, 0.59 µg NH_3 m^{-3}) exceeded 1 µg NH_3 m^{-3}, the critical level for lichens and bryophytes. However, both Lough Navar and Loughmore River had less than 9 months of data in 2022 and thus not being fully representative of the annual conditions at these sites.

Most sites annual average concentrations did not change more than ± 1 µg NH_3 m^{-3} compared to 2021 values (when at least >9 months of data were available for 2021 and 2022). The exceptions were:

- Ratarnet Rd (AFBI12-A) decreased 1.5 µg NH_3 m^{-3} compared to 2021.
- Four sites increased their annual mean concentration more than 1 µg NH_3 m^{-3}: U of Ulster Met. Station (AFBI01-A; 1.72 µg NH_3 m^{-3}), Inch Abbey (AFBI13-A; 2.55 µg NH_3 m^{-3}), Drumclamph 2 (AFBI29-A; 2.26 µg NH_3 m^{-3}), and AFBI Hillsborough (AFBI25-A, 1.8 µg NH_3 m^{-3}) these sites are dominated by pigs and poultry, mixed cattle, dairy and mixed cattle dominant sources, respectively.

Table 4. Annual mean NH_3 concentrations measured at 29 sites in the AFBI ALPHA® and DELTA® networks for the calendar years 2020, 2021 and 2022. ID number includes description of sampling method annotated with an A for ALPHA sites and D for DELTA sites. Shaded in blue are the NAMN/AGANet sites prior to the unification of the NI NH_3 network into UKEAP in March 2022. Concentrations are expressed in µg NH_3 m^{-3}. Ammonia concentrations shown in light grey must not be used as they are not representative average annual concentrations and data are only shown for completeness.

		2020 Jan – Dec 20		2021 Jan – Dec 21		2022 Jan – Dec 22	
ID	Name	Mean	n	Mean	n	Mean	n
AFBI01-A	U of Ulster met station	**2.63**	*7	**3.31**	12	**5.03**	11
AFBI02-A	Castle Enigan	**3.60**	12	**3.03**	12	**3.18**	12
AFBI03-A	Beaghs Burn	**0.53**	12	**0.68**	10	**0.60**	12
AFBI04-A	Slieve Beagh	**1.15**	11	**1.11**	12	**1.68**	12
AFBI05-A	Moninea Bog	**2.10**	12	**2.27**	12	**2.20**	12
AFBI07-A	Seekinore	**2.77**	12	**3.98**	12	**3.51**	11
AFBI08-A	Lisbellaw	**3.88**	12	**4.37**	12	**5.02**	12
AFBI09-A	Glenwherry COSMOS	**1.67**	12	**2.10**	12	**2.23**	12
AFBI10-A	UWMN Bencrom River	**0.92**	12	1.14	*6	**1.09**	10
AFBI11-A	Blackwater town	3.82	*5	**5.71**	12	**5.33**	11
AFBI12-A	Ratarnet Rd	2.69	*5	**8.91**	10	**7.41**	12
AFBI13-A	Inch Abbey	**1.83**	12	**1.80**	12	**4.35**	12
AFBI14-A	AURN Belfast centre	**2.53**	12	**2.88**	12	3.01	*8
AFBI15-A	Ballylinney Church	**4.36**	11	**5.02**	12	**5.49**	12
AFBI16-A	West of Crumlin	**2.54**	12	**2.96**	12	**3.60**	12
AFBI17-A	Loughmore River	**1.03**	12	**1.12**	10	0.82	*8
AFBI18-A	Caldanagh Bog	**3.18**	12	**2.95**	12	**3.04**	12
AFBI19-A	Cloughmills	**3.68**	12	**3.53**	12	**3.44**	12
AFBI20-A	Caddy Rd	**4.55**	12	**7.45**	10	**9.12**	11
AFBI21-A	Turmennan Rd	**1.91**	12	**1.83**	10	**1.77**	12
AFBI22-A	Carrowbane Rd	3.34	*7	**4.59**	11	**4.93**	11
AFBI23-A	Creggan	**2.76**	12	**3.33**	12	**2.97**	12
AFBI24-A	Corramore Rd	**0.98**	12	**1.25**	12	**1.74**	12
AFBI29-A	Drumclamph 2	**5.77**	12	**6.88**	12	**9.14**	12
AFBI25-A	AFBI Hillsborough-A	**6.92**	12	**6.3**	12	**8.1**	10
AFBI25-D	AFBI Hillsborough-D	5.71	*7	4.50	*7	4.86	***2**
AFBI26-D	Ballynahone Bog	**2.90**	11	2.74	*7	3.24	*6
AFBI27-D	U of U Coleraine Met Station	2.20	*6	1.94	*7	1.09	***2**
AFBI28-D	Sandholes	**3.27**	11	**4.90**	9	5.18	***2**
S44-D	NAMN/AGANet-Hillsborough	**3.12**	9	**2.50**	9	**2.91**	9
S45-D	NAMN/AGANet-Lough Navar	**0.60**	9	0.53	*8	0.59	*7
S79-A	NAMN-Coleraine	2.18	*6	**3.50**	12	**3.28**	12

*n = no. of valid monthly measurement periods used in calculating annual mean. *Sites with n < 9 months of data are expected to be less representative of the average yearly concentrations and are highlighted in red. In red and bold are the sites that were discontinued after the first 2 months of 2022.*

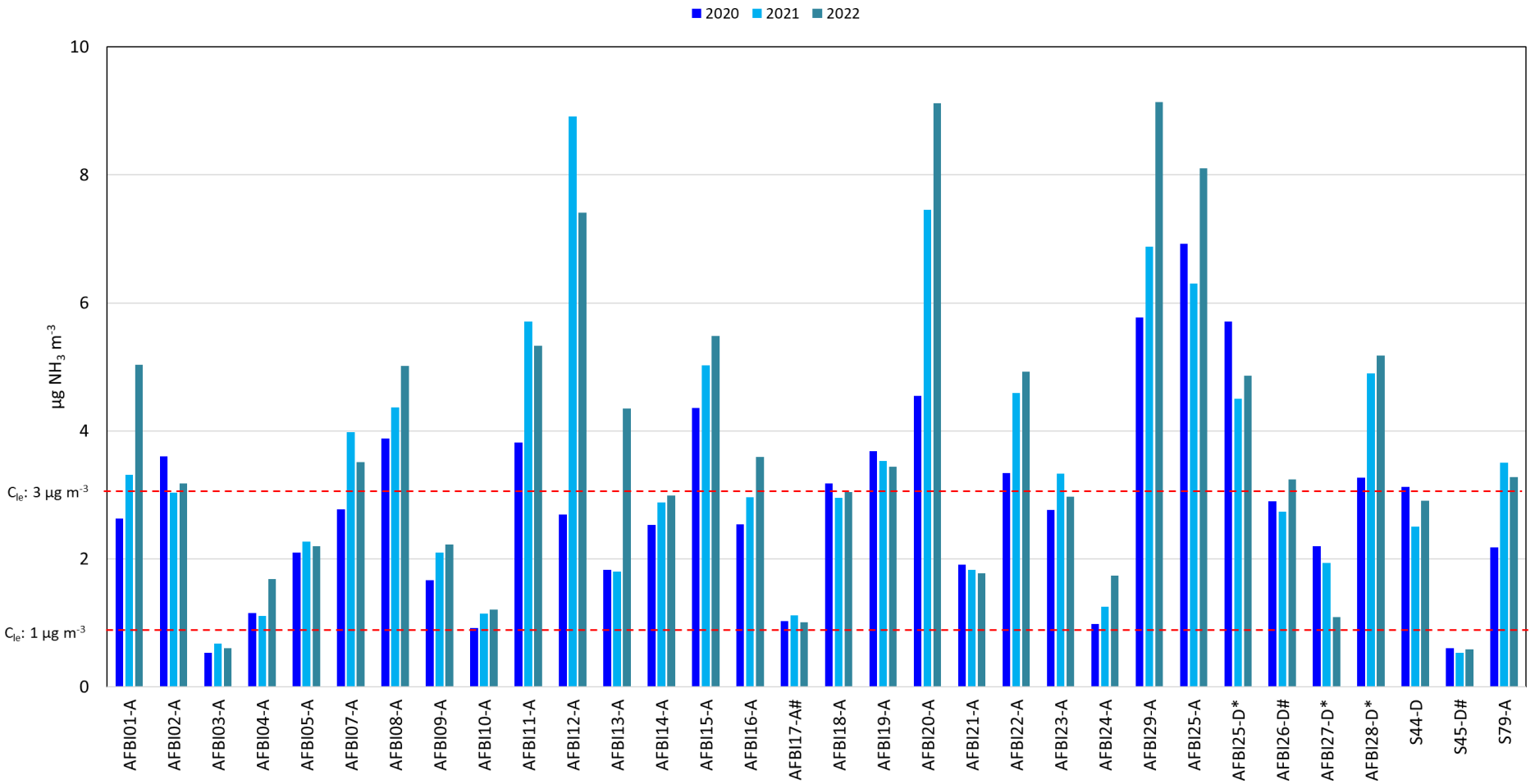


Figure 4. Annual NH_3 concentrations for 2020, 2021 and 2022 years at the NI NH_3 network. 2022 data for DELTA sites AFBI25-D, AFBI27-D and AFBI28-D are marked with * symbols to highlight they only contain two months in the calculated annual average and are presented for completeness only. Sites with # have more than 5 but fewer than 9 monthly data points and therefore have higher uncertainty regarding their representativeness. The red dashed lines represent the annual critical levels of 1 and 3 µg NH_3 m^{-3}.

3.3. Spatial patterns

Figure 5 shows the mean annual concentrations spatial distribution in NI NH_3 network, both for 2022 and for the 3-year period 2020-2022 for comparison purposes. The map shows no clear geographical trend in 2022 as NH_3 concentrations were highly variable over the monitored area; This variability is directly tied to the presence of agricultural emission sources near the monitoring sites.

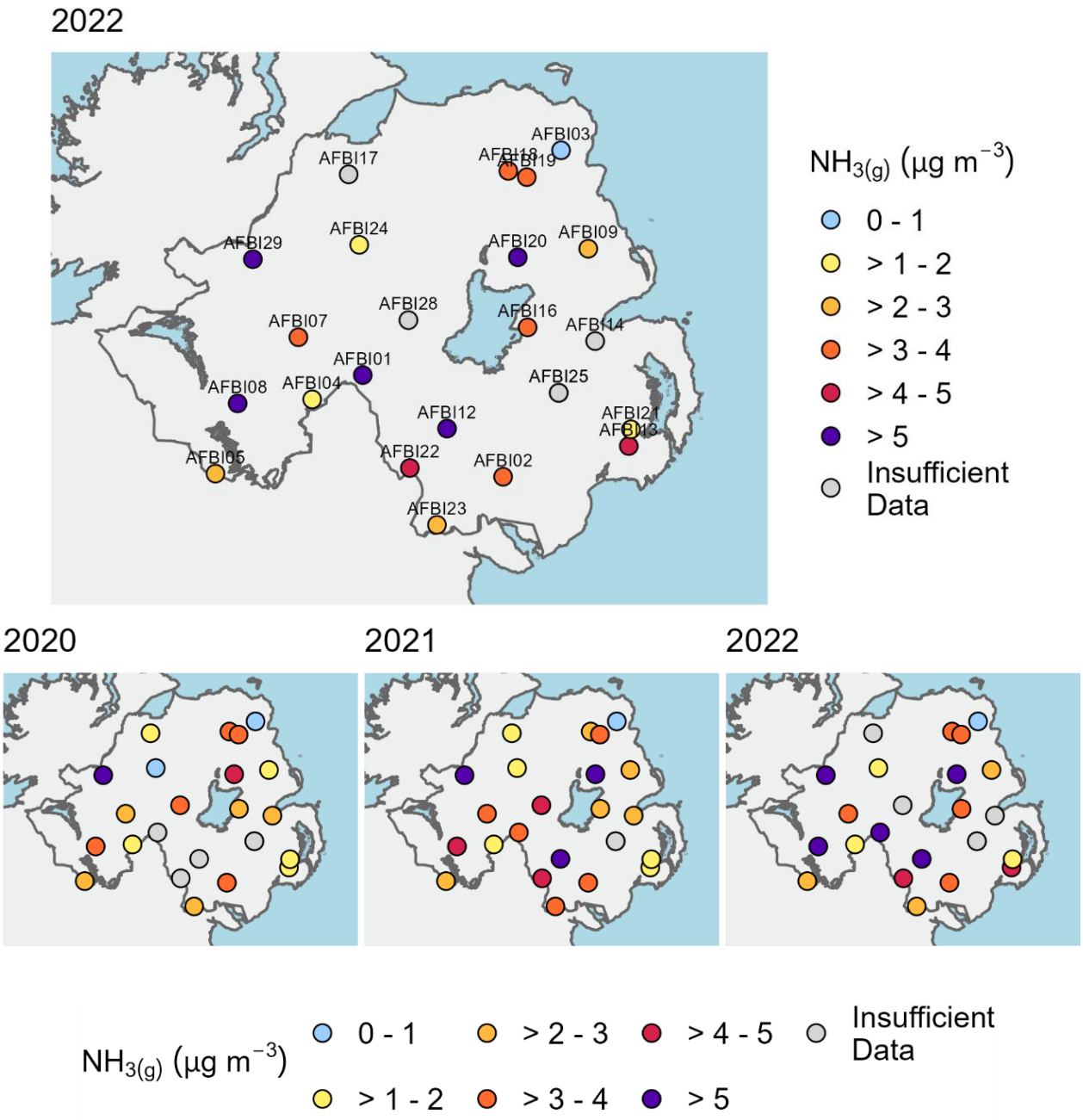


Figure 5: Annual 2022 mean NH_3 concentrations (top); Comparison of annual mean concentrations from 2020 to 2022 (bottom). Grey dots represent the sites with insufficent data to be annually representative (data capture less than 75%).

Figure 6 shows the mean NH_3 concentrations from 2020 to 2022 grouped by their dominant NH_3 emission source classifications, based on emission modelling output. This metric was assigned according to the dominant modelled NH_3 source for each 5 km grid cell, to aid interpretation of seasonal patterns in NH_3 concentrations. Since there are no 5 km grid squares in NI with emissions dominated by either sheep or the application of mineral fertilizers, these two categories have no representation.
The five dominant emission source sectors covered by the NI network sites are:

- Cattle (beef, dairy, mixed)
- Pigs & Poultry (combined for data disclosure reasons)
- Non-agricultural sources
- Mixed (where no single source sector dominates, i.e. represents at least 45% of the total emissions)
- Background (very low NH_3 emissions of <1 kg N ha^{-1} y^{-1}).

Considering only sites that have sufficient data for the year (at least 9 months), fifteen sites exceeded 3 µg NH_3 m^{-3} (the critical level for N-sensitive higher plants/semi-natural vegetation, which is not relevant for fields of agricultural crops and improved grassland). This predominantly occurred in areas dominated by livestock emissions in 2022, with mixed cattle sources having 8 sites (AFBI02-A, AFBI07-A, AFBI11-A, AFBI13-A, AFBI15-A, AFBI18-A, AFBI20-A and AFBI25-A), areas with predominantly dairy sources having 3 (AFBI08-A, AFBI12-A, AFBI29-A) and pig and poultry-influenced sites have one site (AFBI01-A) exceeding 3 µg NH_3 m^{-3}. The other three sites exceeding 3 µg NH_3 m^{-3} are dominated by non-agricultural sources (AFBI22-A) and mixed agricultural sources (AFBI16-A and AFBI19-A).
In 2022, several sites recorded their highest monthly concentrations since observations had begun (since 2020, refer to Figure 6). Drumclamph 2 (AFBI29-A) reported the highest overall monthly concentration in the network during 2022, at 54.4 µg NH_3 m^{-3}, while sites such as U of Ulster met. station (AFBI01-A), AFBI Hillsborough A (AFBI25-A) or Caddy Rd. (AFBI20-A) exceeded the maximum concentrations observed in 2021 by >10 µg NH_3 m^{-3} (Figure 6b). These spikes were likely caused by local agricultural activities, such as slurry spreading, very close to the monitoring sites, and/or weather conditions that favour high volatilisation rates during the relevant months.

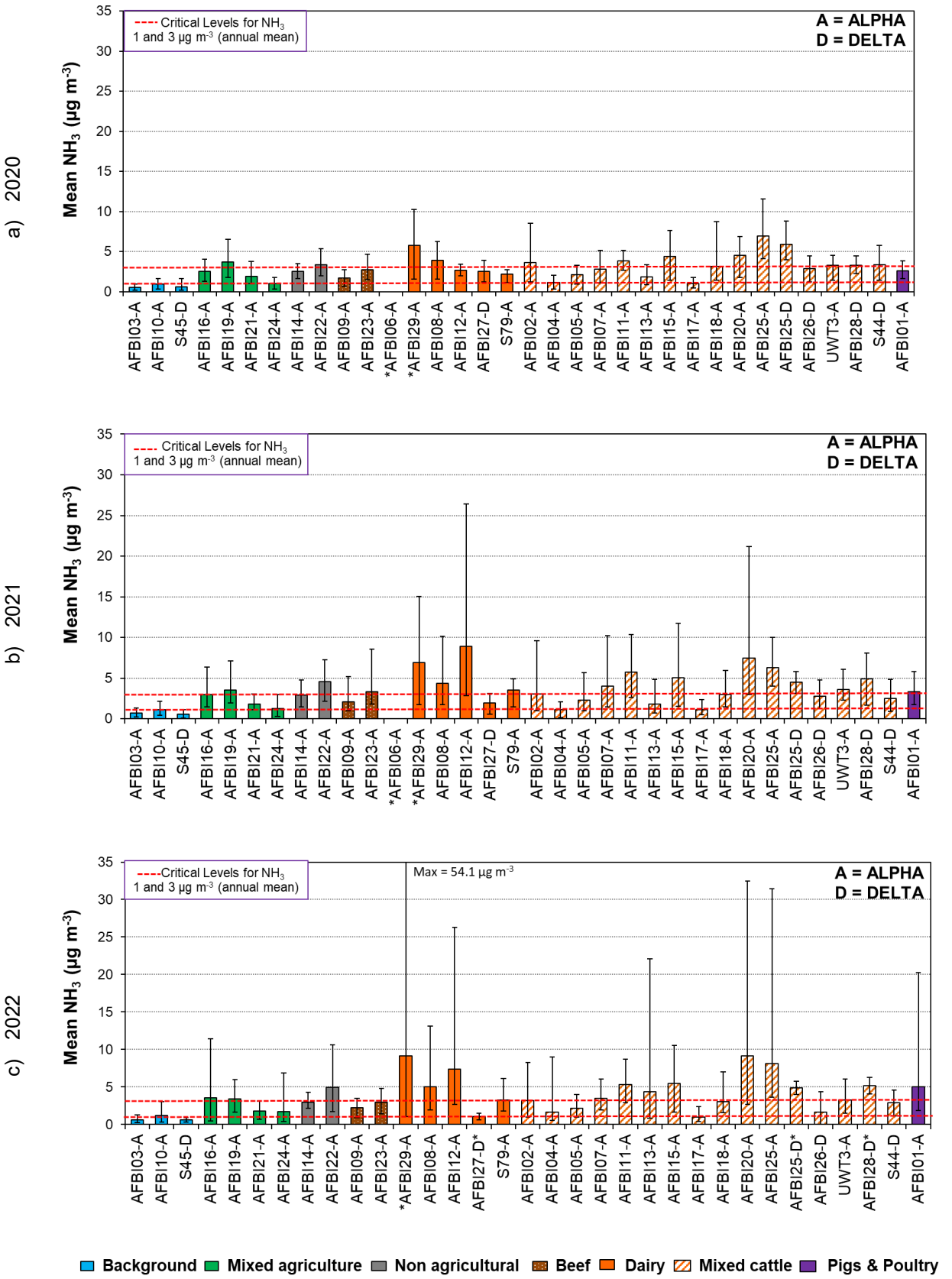


Figure 6. Comparison of annual mean monitored NH_3 concentrations in 2020 (a), 2021 (b), and 2022 (c). The whiskers in each bar display the minimum and maximum monthly values for each site in the NI ALPHA® and DELTA® network. The sites are grouped according to their dominant NH_3 emission source classifications.

3.4. Seasonal variability

The full time series of monthly NH_3 concentrations from March 2019 to December 2022 measured for 25 sites in the NI network retained in 2022, is shown in Figure 7. Sites are grouped according to their dominant emission source categories in each of the graphs.

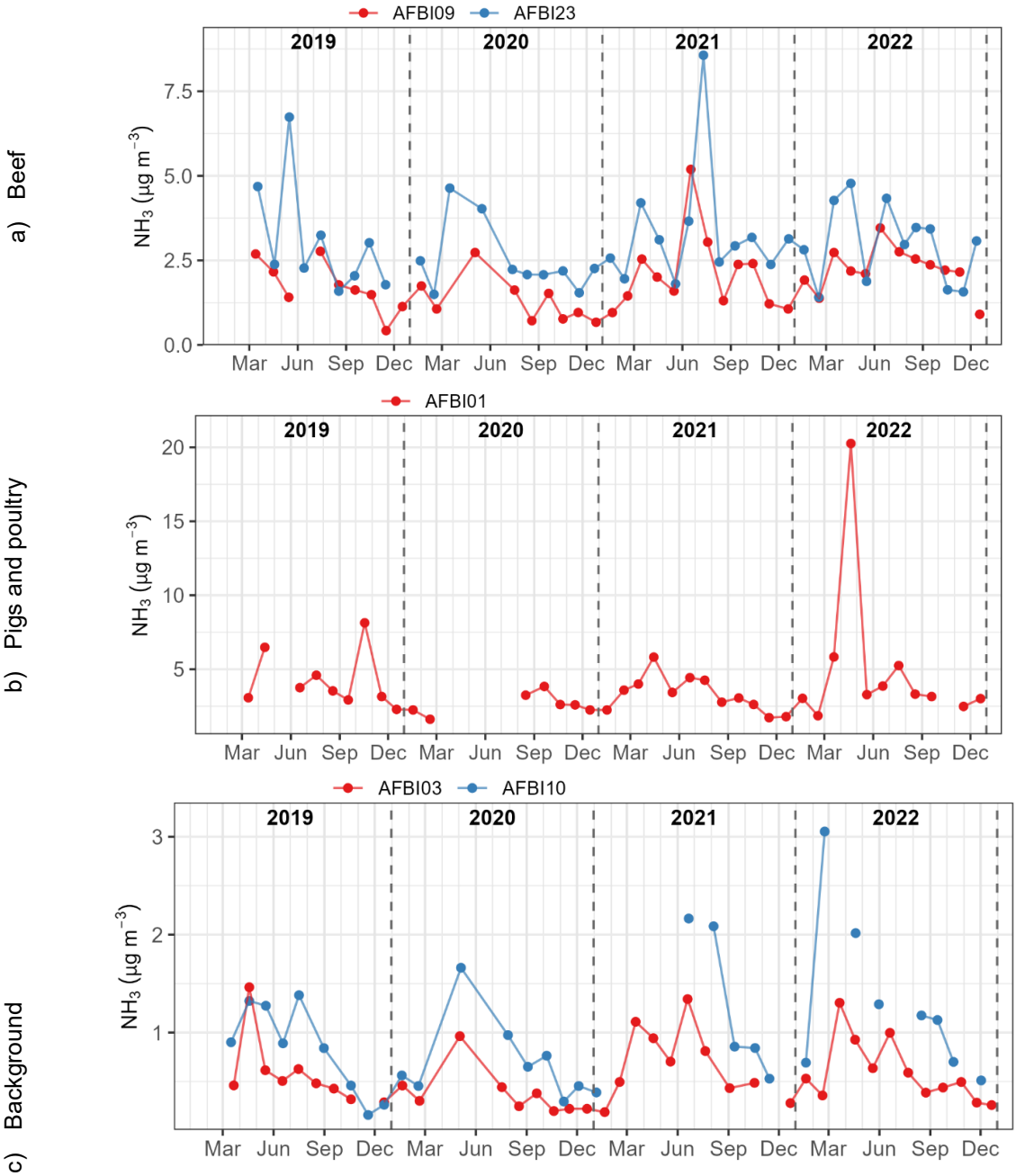


Figure 7. Time series of monthly NH_3 concentrations measured at sites (36 months of data from March 2019 to February 2022) in the ALPHA® and DELTA® networks across Northern Ireland, grouped according to dominant emission source sectors. Monthly concentrations are referenced to the mid date of their approximately monthly exposure period. Monthly concentrations nested in the middle date of their exposure period. Gaps between sampler exposures are represented by the lack of lines between markers.

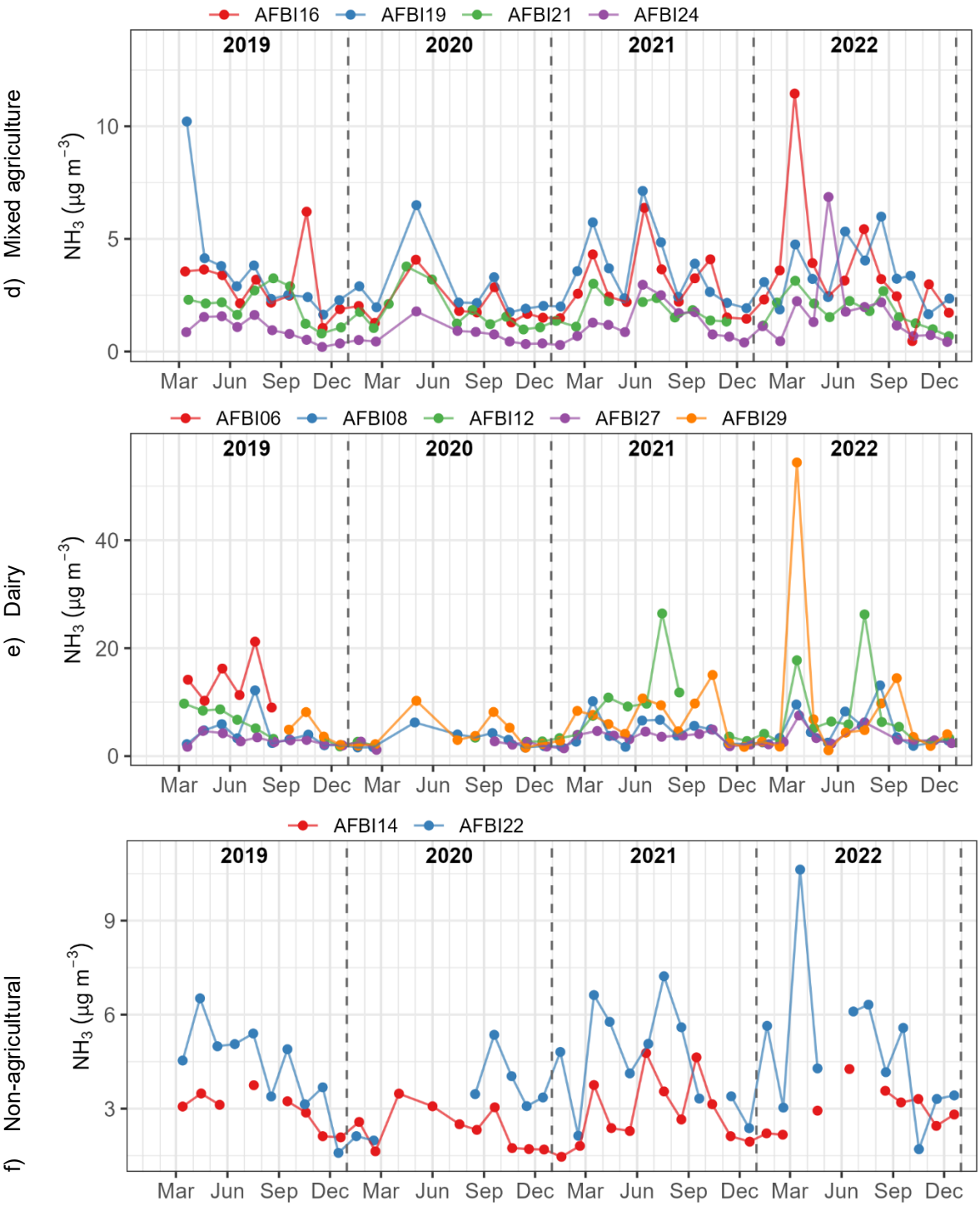


Figure 7 (cont.). Time series of monthly NH_3 concentrations measured at sites (36 months of data from March 2019 to February 2022) in the ALPHA® and DELTA® networks across Northern Ireland, grouped according to dominant emission source sectors. Monthly concentrations nested in the middle date of their exposure *period*. Gaps between sampler exposures are represented by the lack of lines between markers.

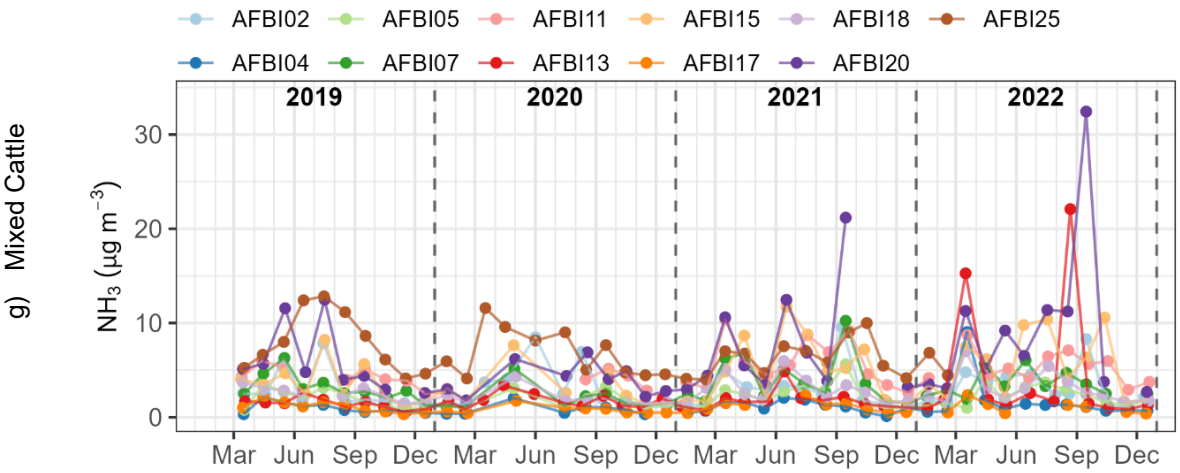


Figure 7 (cont.). Time series of monthly NH_3 concentrations measured at sites (36 months of data from March 2019 to February 2022) in the ALPHA® and DELTA® networks across Northern Ireland, grouped according to dominant emission source sectors. Monthly concentrations nested in the middle date of their exposure period. Gaps between sampler exposures are represented by the lack of lines between markers.

Ammonia concentrations in 2022 showed typical high concentration during spring and autumn months, as expected with seasonal agricultural activities. The highest concentrations in 2022 occurred during March, and to a lesser degree in April, coinciding with land spreading of manures and slurries during this period. Northern Ireland experienced a historic record of sunlight hours in March 2022, the highest number since 1927. The month was characterized by high pressure systems across the UK (Met Office, 2022b); these conditions, combined with the relatively low amount of precipitation (Figure 3), would have allowed for accumulation of NH_3 concentrations.

This pattern is also observed in the mean seasonal profiles for the different NH_3 emission source categories (Figure 8). Sites AFBI25 (Hillsborough: mixed cattle, set up close to a large emission source) and AFBI29 (Drumclamph 2: cattle dairy, only 6 months of data for the period from March 2019 – February 2020) were not included in this analysis as they were not considered representative for the wider surrounding area due to their close proximity to specific sources. Most source categories recorded maximum concentrations during March and April, when agricultural activity such as slurry spreading is typically at its peak.

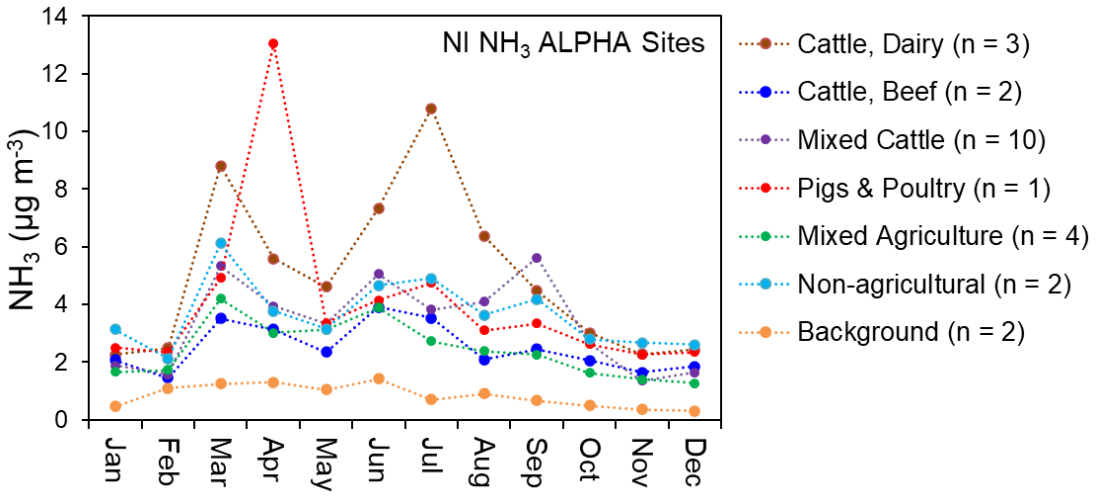


Figure 8. Seasonal cycles of NH_3 concentrations from January 2020 to December 2022 for all sites in the NI ALPHA® network (except AFBI25-A and AFBI29-A), grouped according to dominant emission source sectors.

Background (low concentration) sites

- In addition to the smaller local emission sources (such as extensive low-density sheep grazing), wider regional agricultural emissions also influence atmospheric concentrations at these more remote locations. Furthermore, the background concentration sites may be influenced meteorologically, including driving the gas-aerosol partitioning in the atmosphere. In summer, increased NH_3 emissions with an increase in temperature favour the gas phase as ammonia, while during the winter months lower concentrations were observed, most likely as a consequence of NH_3 partitioning into NH_4^+ aerosol (Tang et al., 2018a).
- Bi-directional exchange of ammonia with vegetation will also influence the reported NH_3 concentrations at background sites, where warm, dry conditions in the summer months may promote NH_3 emission from vegetation (Sutton et al., 1995; Sutton et al., 2020).

Sites in emission source areas

- Increased precipitation tends to decrease NH_3 emissions because rain events dilute the available NH_3 pool and increases the potential to wash urea and N species in solution from the surface. As NH_3 is soluble and is washed out of the atmosphere by rainfall, this is also likely to contribute to reduced atmospheric NH_3 concentrations during wet periods.

- Precipitation amounts in February 2022 were substantially above the 10-year average of 2009-2018, which likely delayed the start of land spreading until March/April.

- Livestock manure (mostly slurry-based systems in Northern Ireland, except for poultry and sheep farming) is typically spread during the spring and autumn

months and this can be related to the observed peaks in monthly NH_3 concentrations. During March and April 2022 maximum concentrations are clearly visible in the temporal profiles for all main source sectors (Figure 8) except for the mixed cattle sites, where Inch Abbey (AFBI13-A), Caddy Rd (AFBI20-A), and Hillsborough (AFBI 25-A) sites showed autumn peak at similar levels to the spring peaks.

- Most sites showed increased concentrations during July and August 2022 due to the hot and very dry summer, compared to previous years, which enhanced NH_3 emissions. The warm temperatures drive volatilization of NH_3 (e.g., high-density grazing livestock, any mineral/organic fertiliser application following silage cuts). Additionally, AFBI12-A (Ratarnet Rd) site shows clear spikes occurring in both July 2021 and 2022, most likely as a result of activity of a nearby farm.

3.5. Monitored vs modelled NH_3

Annual average NH_3 concentration data from the calendar year 2022 (January to December 2022) from the ALPHA® and DELTA® networks are compared with modelled annual mean NH_3 concentrations. Modelled NH_3 concentrations for each site's location in the ALPHA® and DELTA® network are provided by the UK European Monitoring and Evaluation Programme (EMEP4UK) model version rv5.0, an offline atmospheric chemistry transport model based on the EMEP MSC-W model with an output resolution of ~3 km x ~3 km (http://www.emep4uk.ceh.ac.uk/) (Simpson et al., 2012; Vieno et al., 2016) for the year 2022 (using 2022 emissions data published by the National Atmopsheric Emissions Inventory in 2024). Modelled NH_3 concentrations are direct model outputs and have not been calibrated. The long-term UKEAP DELTA® sites AFBI27 (Coleraine) and S44 (NAMN-Hillsborough) were included for extra coverage, to make a total of 24 observed annual average concentrations to compare with modelled concentrations in 2022.

The following sites were not used in the comparison:

- AFBI25 (Hillsborough) was excluded from this comparison since the intention of this site was to assess spatial variability at the Hillsborough high-resolution monitoring site and not to provide a monitoring location representative for the 3 km x 3 km model grid square.
- AFBI20 (Caddy Road) was excluded from the comparison due to a series of anomalously high monthly NH_3 concentrations, most likely resulting from the close proximity to strong emissions activities.
- Any site with fewer than 9 monthly observations in the calendar year were excluded due to insufficient temporal coverage (see Table 4).

Any monthly mean concentrations exceeding 3 standard deviations from the annual mean of 2022 measurements for a given site (i.e. z-score > 3) were also excluded from annual mean derivation as numerical outliers (e.g. Clougherty et al., 2013 and Dongre et al., 2025). As part of the outlier exclusion, the following data were removed from this analysis:

- March measurements for both AFBI04 (Slieve Beagh) and AFBI29 (Drumclamph 2) were removed, leaving 11 valid monthly measurements at both sites. These two monthly measurements were exceptionally high for those particular sites.
- AFBI17 (Loughmore River) was excluded due to only having 8 viable monthly measurements in 2022.

Figure 9 shows the gridded annual concentrations of NH_3 in Northern Ireland as predicted by the EMEP4UK model for 2022 (with no calibration), with an overlay of the site locations used in the model comparison. Concentrations of NH_3 from both data sources are plotted with a common colour scale.

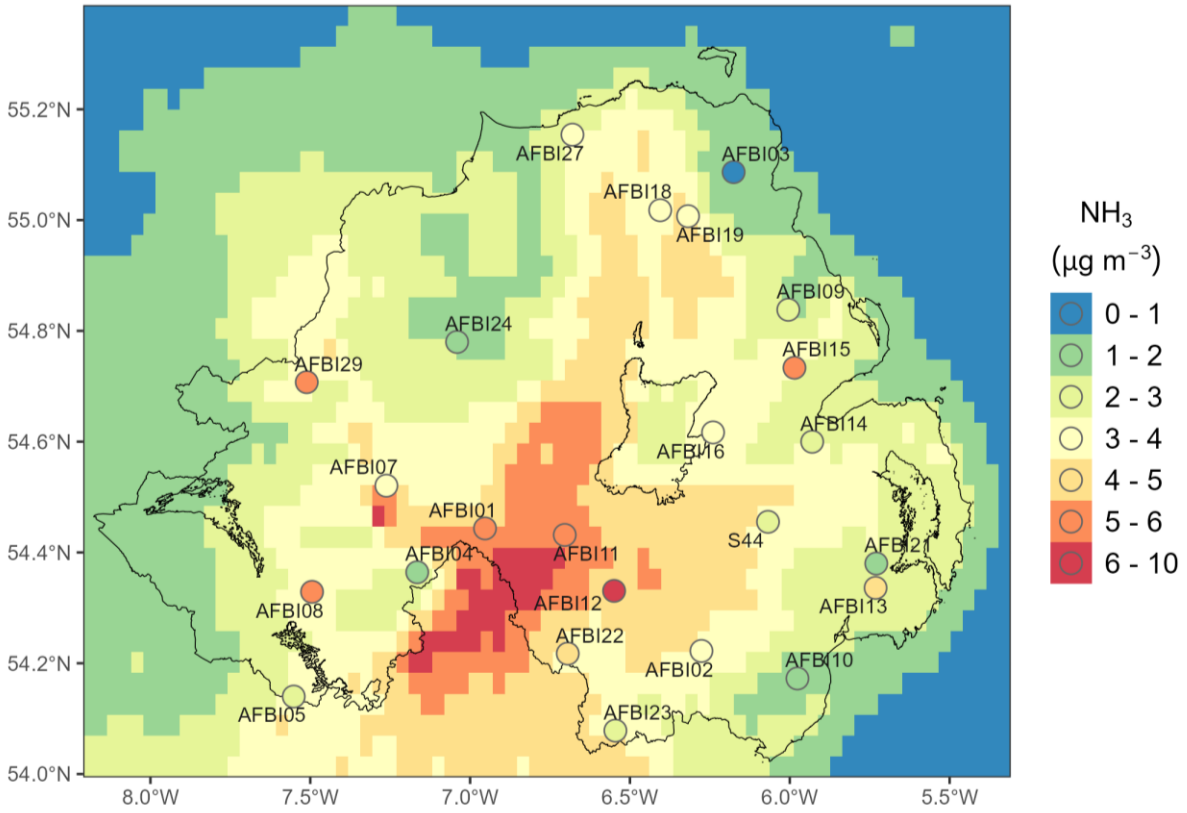


Figure 9. Comparison between annual mean modelled (shaded cells) and observed (coloured dots) NH_3 concentrations in 2022 for the NI NH_3 network.

Figure 10 shows a scatterplot comparing modelled and observed annual mean concentrations of NH_3 at the 24 locations, classified by the NH_3 dominant source emissions. Modelled values represent the corresponding ~3 km x ~3 km cell in which observed data are recorded. 22 of the 24 sites (92%) have modelled concentrations within a factor of 2 (FAC2), or between double or half of the observed annual average NH_3 concentration. This is a key metric of atmospheric model performance and should be 50% as a minimum.

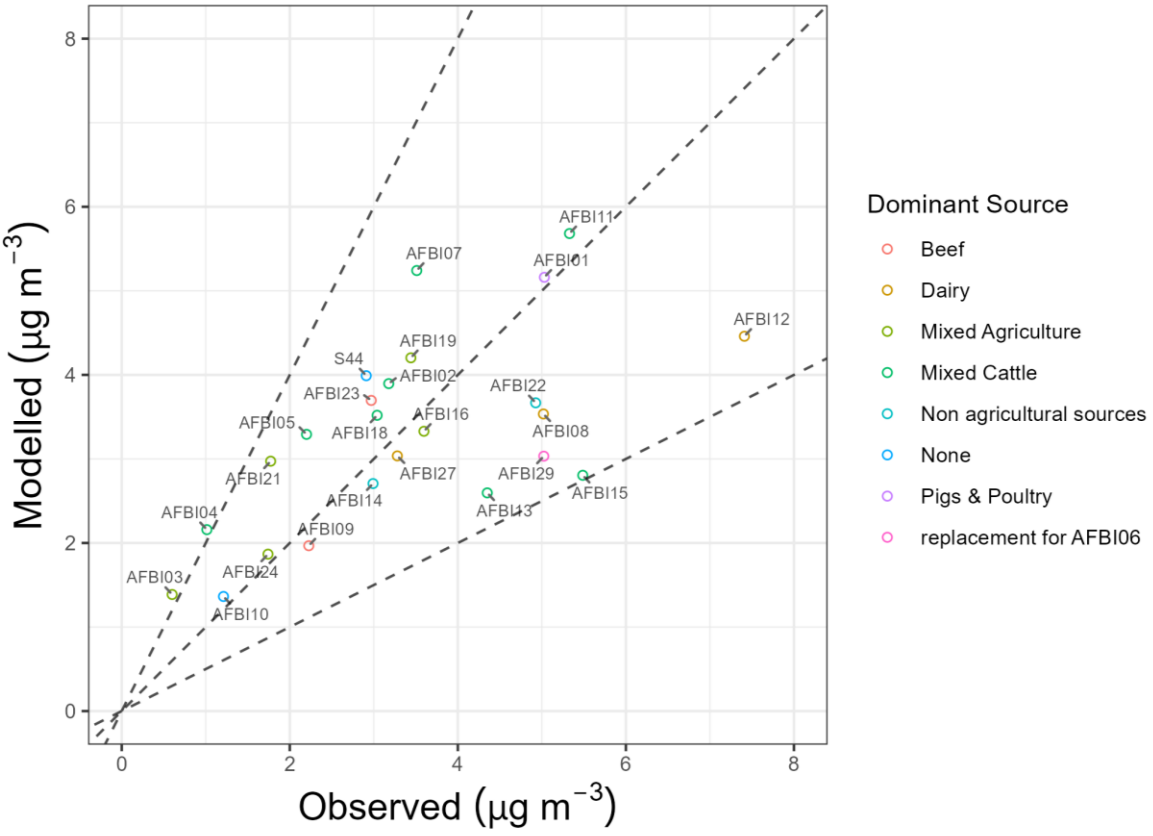


Figure 10: observed annual average NH_3 concentrations at the ALPHA® and DELTA® sites in Northern Ireland (x-axis), with annual average modelled NH_3 concentrations from the EMEP4UK model (y-axis) for 2022. The 3 diagonal dashed lines represent 1:1 (middle), 2:1 (upper) and 0.5:1 (lower) ratios, from the perspective of the modelled data. The colour of each plotted site represents the dominant source of NH_3 in the site's vicinity.

Other metrics of model performance are shown in Table 5, showing that the EMEP4UK model performed well for the 2022 calendar year, compared to observations in the network. The R^2 = 0.64 indicates a strong correlation between modelled and observed values, in conjunction with a low overall mean bias (MB) of –0.11 (units = µg m^{-3}). While this small value of MB does not, in itself, indicate good model performance (due to some cancelling of error that can be seen in Figure 10), it does indicate the model has low systematic bias. The normalised mean gross error (NMGE – the mean absolute error divided by the mean of the observations) of 29% indicates errors are small relative to the observed mean of 3.4 µg m^{-3} and the normalised RMSE (RMSE / mean observed value) is ~37%, consistent with Skoulidou et al. (2024).

Table 5. Model performance metrics for EMEP4UK against annual observations of NH_3 in 2022. FAC2 = fraction of sites modelled within a factor of 2 of measurements (min = 50%); R^2 = the (Pearson) correlation coefficient; MB = mean bias (same units as data); normalised mean gross error; RMSE = root mean square error.

Year	n. sites	FAC2	r^2	MB	NMGE	RMSE
2022	2	92%	0.64	-0.11	0.29	1.25

It is important to consider the uncertainties in both components of the model/monitoring comparison. The monitoring sites were set up to be as representative as possible across Northern Ireland, from several perspectives: geographical coverage, concentration gradient (low/medium/high) and different emission source sectors ("dominant sources"). However, the exact spatial location of each sampler influences which sources are captured over the monthly exposure period. This varies with local activities and weather conditions, both inter- and intra-annually, with closer sources being "seen" by the sampler more strongly that those further afield which are more likely to have been dispersed and diluted before the air parcels reach the sampler.
This is why representative samplers require careful site selection to avoid undue influences of individual local sources on the data. However, in areas with high levels of emitting activities, such as the Northern Irish countryside, this can be difficult due to the density of emission sources and practicalities such as landowner permissions for establishing a monitoring site etc. In addition, there are also uncertainties inherent in any monitoring technique; the UKCEH ALPHA® has an expanded uncertainty of 12% (Martin et al., 2019; Twigg et al., 2022).

The modelled concentrations are heavily influenced by the preceding emission modelling carried out under the UK's National Atmospheric Emission Inventory projects. The emission data are necessarily derived from available national and regional activity statistics (such as livestock number and crop area data, agricultural practice information, land use data for agricultural emissions; road traffic and vehicle fleet statistics, etc), and relevant "emission factors" to represent emission source strength. This means that, on average, emissions are well represented across the country, but emissions from each individual source, such as a dairy cow, or a slurry tank, will, in reality, vary considerably, depending on the individual characteristics of the source, weather conditions etc. The agricultural emission modelling also requires aggregation of individual sources to avoid breach of data agreements of the underlying agricultural statistics (where emissions from at least 5 farms need to be aggregated to preserve confidentiality), by using statistical modelling techniques.
In other words, uncertainties are inherent in both monitored and modelled atmospheric ammonia concentrations, and the analysis carried out here provides evidence that the two methods agree very well overall.

3.6. DELTA measurements

In March 2022, the DELTA® sites at Hillsborough, U of U Coleraine Met Station and Sandholes (AFBI 25, AFBI 27 and AFBI 28, respectively) were closed following a review of the network. Only January and February data were collected for those sites in 2022. These sites are included in this report for the sake of completeness of reporting in Table 6, but their interpretation can be found in the Year 3 report (Tang et al., 2022), which covers the 3rd full year (project year) of monitoring, March 2021 – February 2022). Only DELTA data from the site at Ballynahone Bog (AFBI 26-D) and the UKEAP sites at Hillsborough (S44) and Lough Navar (S45) are interpreted in this section. The Ballynahone Bog (AFBI 26-D) site did not reach the minimum number of samples for representativity (n ≥ 9) in 2022 due to issues with the airflow and damage to the samplers during shipment (Twigg et al., 2023), therefore this site's results must be interpreted with caution.

Table 6: Summary statistics for the calendar year 2022 for reactive gas and aerosol measurement data from DELTA® sites in Northern Ireland. All concentrations are expressed in µg m^{-3}. Cells in red correspond to sites whose annual statistics have been calculated with n ≤ 9 and are not considered representative of the calendar year 2022.

Species		Ballynahone Bog (AFBI26-D)	Hillsborough (S44)	Lough Navar (S45)
HNO_3	**Mean**	0.11	0.06	0.10
	Min	-0.04	0.01	-0.02
	Max	0.37	0.21	0.51
	SD	0.15	0.06	0.18
	N	6	9	9
SO_2	**Mean**	0.32	0.21	0.07
	Min	0.19	0.12	0.02
	Max	0.65	0.35	0.13
	SD	0.17	0.07	0.04
	N	**6**	10	9
NH_3	**Mean**	3.24	2.91	0.59
	Min	1.81	1.15	0.36
	Max	4.34	4.59	0.91
	SD	1.05	1.17	0.19
	N	**6**	9	7
NO_3^-	**Mean**	0.75	0.79	0.69
	Min	0.34	0.40	0.40
	Max	1.44	1.55	1.11
	SD	0.41	0.42	0.21
	N	**6**	10	9
SO_4^{2-}	**Mean**	0.58	0.42	0.53
	Min	0.05	0.05	0.31
	Max	0.92	0.68	0.73
	SD	0.29	0.22	0.16
	N	**6**	10	9
NH_4^+	**Mean**	0.58	0.68	0.32
	Min	0.32	0.19	0.14
	Max	0.87	1.44	0.71
	SD	0.18	0.39	0.18
	N	6	9	9

Table 6 (continued). Summary statistics for the calendar year 2022 for reactive gas and aerosol measurement data from DELTA® sites in Northern Ireland. All concentrations are expressed in µg m^{-3}. Cells in red correspond to sites whose annual statistics have been calculated with n ≤ 9 and which are not considered representative of the calendar year 2022.

Species		Ballynahone Bog (AFBI26-D)	Hillsborough (S44)	Lough Navar (S45)
Na^+	**Mean**	0.79	0.74	0.69
	Min	0.28	0.31	0.40
	Max	1.20	1.71	1.11
	SD	0.36	0.48	0.21
	N	6	8	9
Cl^-	**Mean**	1.35	1.59	1.18
	Min	0.91	0.59	0.69
	Max	1.87	2.42	1.66
	SD	0.38	0.67	0.33
	N	6	9	9
Ca^{2+}	**Mean**	0.14	0.12	0.12
	Min	0.09	0.00	-0.03
	Max	0.19	0.28	0.24
	SD	0.03	0.09	0.07
	N	6	9	9
Mg^{2+}	**Mean**	0.10	0.10	0.09
	Min	0.03	0.02	0.05
	Max	0.13	0.18	0.14
	SD	0.04	0.06	0.03
	N	6	9	9

Annual concentrations for the inorganic precursor gases, secondary inorganic aerosols (SIA), main sea salt and minor alkaline aerosol species are presented in Figure 11 and Figure 12. The lowest concentrations for most species were found at Lough Navar (S45), a remote site in the west of Northern Ireland away from emission sources, and where the influence of continental Europe in terms of long-range transboundary transport of pollutants is also smallest, based on modelling (see source attribution data https://www.apis.ac.uk/).

The precursor gases SO_2 and HNO_3 were present at low concentrations, with only occasional concentration peaks (see Section 3.6.1 for further discussion). SO_2 concentrations have decreased significantly in the last decades and nowadays they are approaching the limit of detection (LOD) of the DELTA® method.
Ammonium aerosols (NH_4NO_3, $(NH_4)_2SO_4$) are secondary inorganic aerosols (SIA) that are formed from reactions between precursor gases (NH_3, HNO_3 and SO_2). They have longer atmospheric lifetimes and tend to vary on a regional scale rather than a local scale. SIA concentrations are similar across all sites with ranges between 0.4 - 1.6 µg m^{-3}.

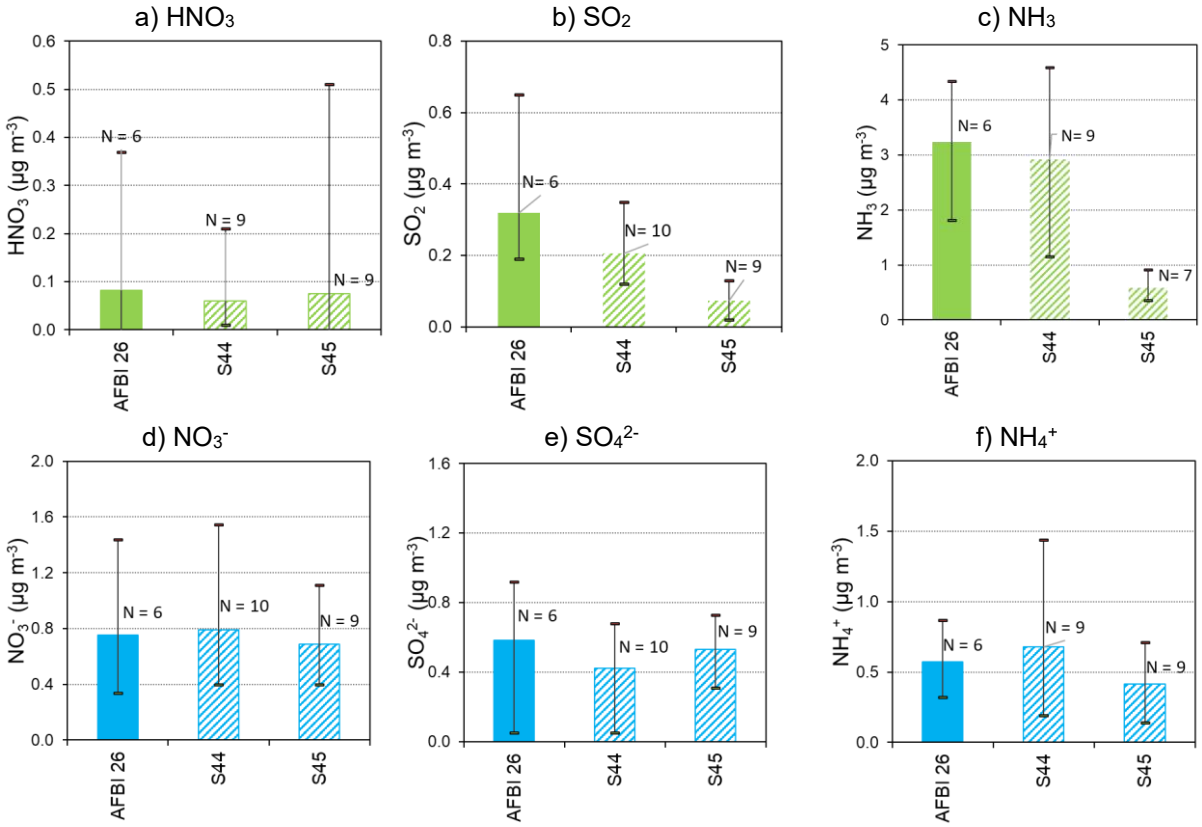


Figure 11. 2022 annual average concentrations of reactive gases (NH_3, HNO_3 and SO_2) and counterpart aerosols (NH_4^+, NO_3^- and SO_4^{2-}) at Ballynahone Bog (AFBI26), Hillsborough (S44) and Lough Navar (S45). The bar represents the annual average concentration and the whiskers the min and max monthly concentrations. The numbers next to the bars correspond to the number of valid monthly data used in the analysis.

Figure 12 shows that the minor alkaline cations (Mg^{2+} and Ca^{2+}) and sea salt components (Na^+ and Cl^-) are quite consistent across sites, although Na^+ and Cl^-concentrations at Site S44 (Hillsborough) are slightly higher than at Ballynahone Bog (AFBI26) and Lough Navar (S45), likely caused by its closer proximity to the seaside. Minor alkaline components remained within the LOD range of the DELTA® method.

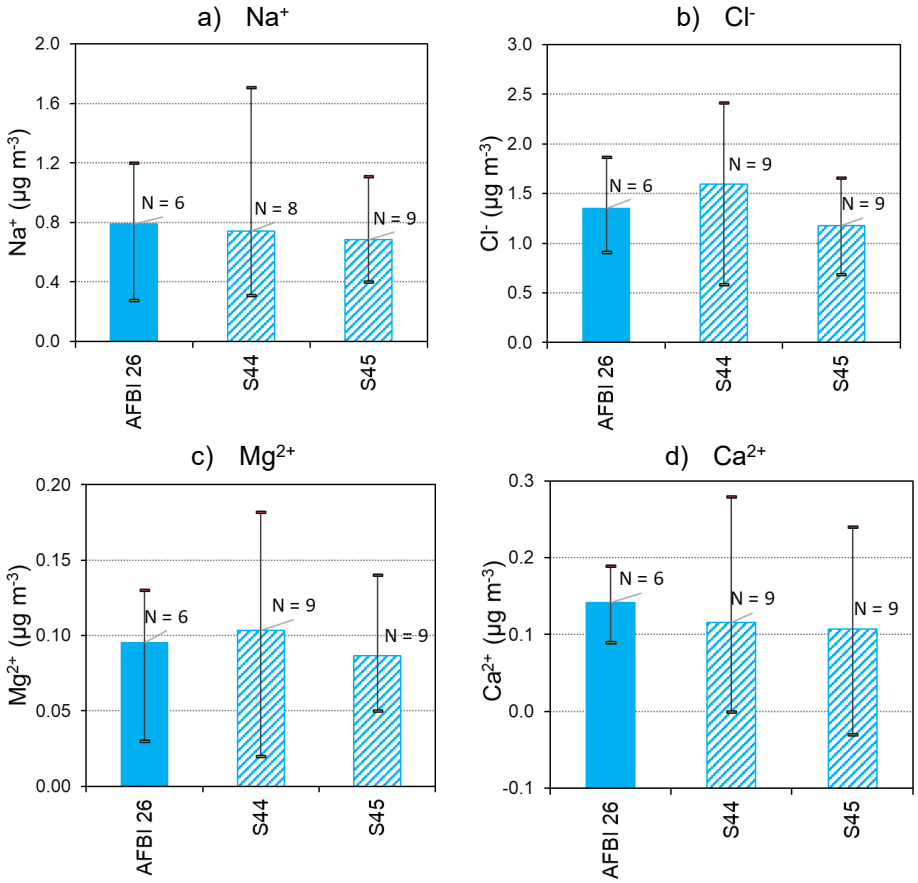


Figure 12. 2022 annual average concentrations of cations in Northern Ireland, measured using DELTA® samplers. The bars represent the average annual concentrations and the whiskers the min and max monthly concentrations. The numbers next to the bars correspond to the number of valid monthly data points used in the analysis.

Figure 13 shows the mean absolute and relative compositions of inorganic species measured in the DELTA network for 2022. NH_3 continues to dominate the inorganic gases reported (Mean DELTA NI NH_3 = 2.3 ± 1.4 µg NH_3 m^{-3}), compared to low concentrations of SO_2 (Mean DELTA NI SO_2 = 0.2 ± 0.12 µg SO_2 m^{-3}) and HNO_3 (Mean DELTA NI HNO_3 = 0.08 ± 0.01 µg HNO_3 m^{-3}). This is also reflected in the percentage composition of total mass of gas and aerosol components measured, as NH_3 (expressed as nitrogen, NH_3-N), on average accounts for 34.2% (range = 12- 44 %) of the total speciation measured, highlighting the dominance of atmospheric NH_3 in NI compared to SO_2 and HNO_3 (2% and 0.3%, respectively). SIA species contributed 19.9% of the monitored components; interestingly the proportion of NO_3^- and SO_4^{2-} at Site S45 (Lough Navar) was notably higher compared to the other two sites.

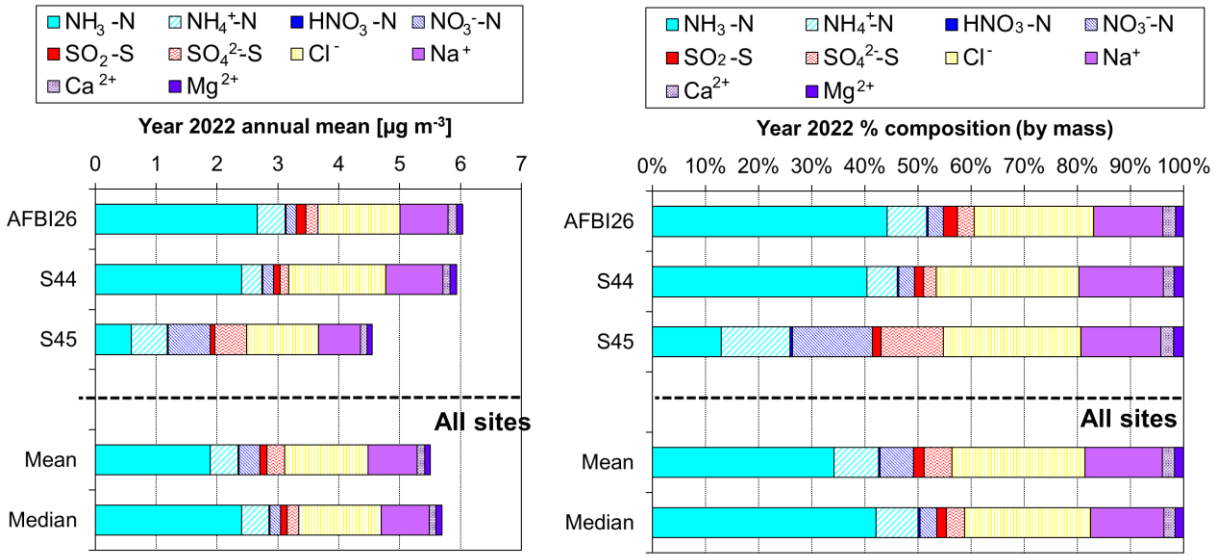


Figure 13. Atmospheric composition data for 2022 (Left) Mean gas and aerosol concentrations of sites in Northern Ireland. (Right) the same data expressed as annual average composition by total mass of both the gas and aerosol components measured.

Concentrations of NaCl accounted for 39 % of the total mass measured across sites as marine sources are located ≤100 km from the monitoring sites, while Mg^{2+} and Ca^{2+} levels were on average near LOD[4] levels and contributed less than 5% to the overall measured species pool.

3.6.1. Ionic balance and relationships between DELTA species

The validity of the DELTA measurements was assessed by checking the ion balance (IB) neutrality between the cation (Na^+, NH_4^+, Mg^{2+} and Ca^{2+}) and anion (Cl^-, NO_{3-} and SO_4^{2-}) species in nanoequivalents (neq) of charge (Twigg et al., 2015). The IB is calculated as follows:

$$Anions = \left(\frac{[NO_3^-]}{62} + \frac{2[SO_4^{2-}]}{96} + \frac{[Cl^-]}{35.5}\right) \quad \textbf{Equation 1}$$

$$Cations = \left(\frac{[NH_4^+]}{18} + \frac{[Na^+]}{23} + \frac{2[Ca^{2+}]}{40} + \frac{2[Mg^{2+}]}{24.3}\right) \quad \textbf{Equation 2}$$

Where all species concentrations are expressed as µg m^{-3} *10^3, and the numbers represent the molar mass in g mol^{-1}.Figure 14 shows the total sum of cations against the total sum of anions for the entire monitoring period (March 2019 – Dec 2022).

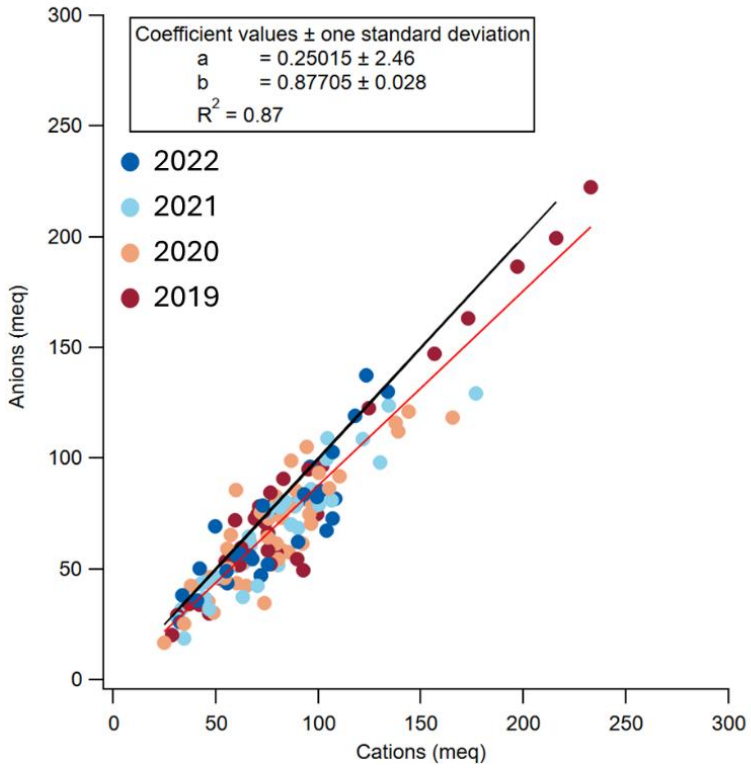


Figure 14. Ion balance for the NI DELTA network. Each year of sampling is shown with a different colour. The black line represents the 1:1 line, representing aerosol full neutrality.

The NI DELTA IB shows a good linearity coefficient (slope = 0.87) and high correlation between the cation and anion species (R^2= 0.87). This implies that particulate matter is mostly neutralized but there is a lack of acidic species (13%) to fully neutralize the alkaline aerosols. This deficit may come from the lack of acidic species in the atmosphere, however, the DELTA sampling method is not optimized to quantify all acidic species, for example organic acids, which may account for this imbalance. The high correlation between the aerosol species also provides confidence to the quality of the measurements, since any uncertainty in the measurements would propagate through to scatter in the ion balance plots. For the base cations Ca^{2+} and Mg^{2+}, there is high uncertainty in the measurements as the concentrations are mainly at or below the limit of detection of the analytical method, therefore their data must be treated with caution.

A high correlation is expected between NH_4^+ and the sum of NO_3^- and SO_4^{2-} (slope = 0.90, R^2 = 0.86; Figure 15.), as they are mostly present in the particulate phase as NH_4NO_3 and $NH_4(SO)_2$, coming from the neutralisation reaction between NH_3, HNO_3 and SO_2 oxidation products (Seinfeld and Pandis, 2016). When comparing NH_4^+ with NO_3^- (Figure 15.b) and SO_4^{2-} (Figure 15.c), NH_4^+ shows larger molar concentrations associated to NO_3^- than SO_4^{2-}. This continues the trend observed for previous years reports (Tang et al. 2022) where SIA species in Northern Ireland are more nitrate-rich than sulphate rich, similar to those observed in the wider UK (Tang et al. 2018b). This is not unexpected, given to the major reductions in SO_2 emissions since the 1980s due to effective national and international policy implementation.

Cl^- & Na^+ have an almost 1:1 relationship with high correlation (slope = 0.99, R^2 = 0.83). They are most likely related to marine sources as most of the data sits within the sea salt (ss) ratio for Na:Cl (0.85, Seinfeld & Pandis 2016; Twigg et al., 2015). In Figure 15d it can be seen that some data points are outside the marine ss ratio; this may be linked to either to depletion of Cl due to long range transport processes and subsequent acid displacement by HNO_3 to form $NaNO_3$ (Dasgupta et al., 2007; Spindler et al., 2012).

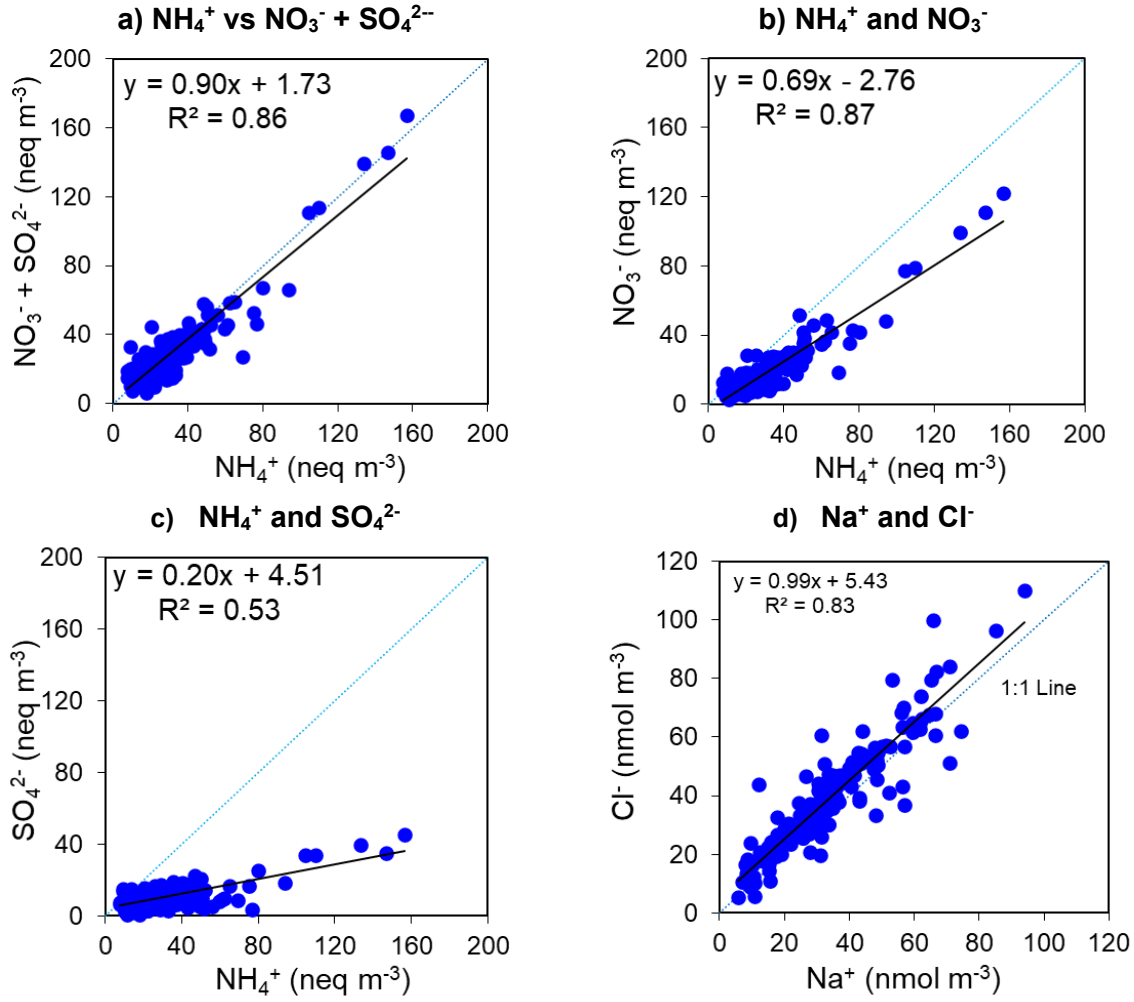


Figure 15. Scatter plots of concentrations between (a) NH_4^+ and NO_3^- + SO_4^{2--}, (b) NH_4^+ and NO_3^-, (c) NH_4^+ and SO_4^{2-}, and (d) Na^+ and Cl^- between 2019 - 2022 in the NI DELTA network.

3.6.2. Seasonal trends

Seasonal profiles were derived from the four NI DELTA® and two UK AGANet DELTA (Figure 16 - Figure 19). From March 2022 onwards only AFBI26, S44 and S45 remain. Ammonia shows consistent peak concentrations during the spring and autumn, likely related to agricultural activities discussed in Section 0. Figure 16 shows that NH_3 concentrations in 2022 were comparable to previous years, ranging from 0.4 to 6.3 µg m^{-3}. The spring peak was not well recorded in 2022 due to data losses in February and March. The relatively high NH_3 concentrations observed at S44 Hillsborough during the warm summer may have come from increased local emissions at the large nearby farm (Figure 3).

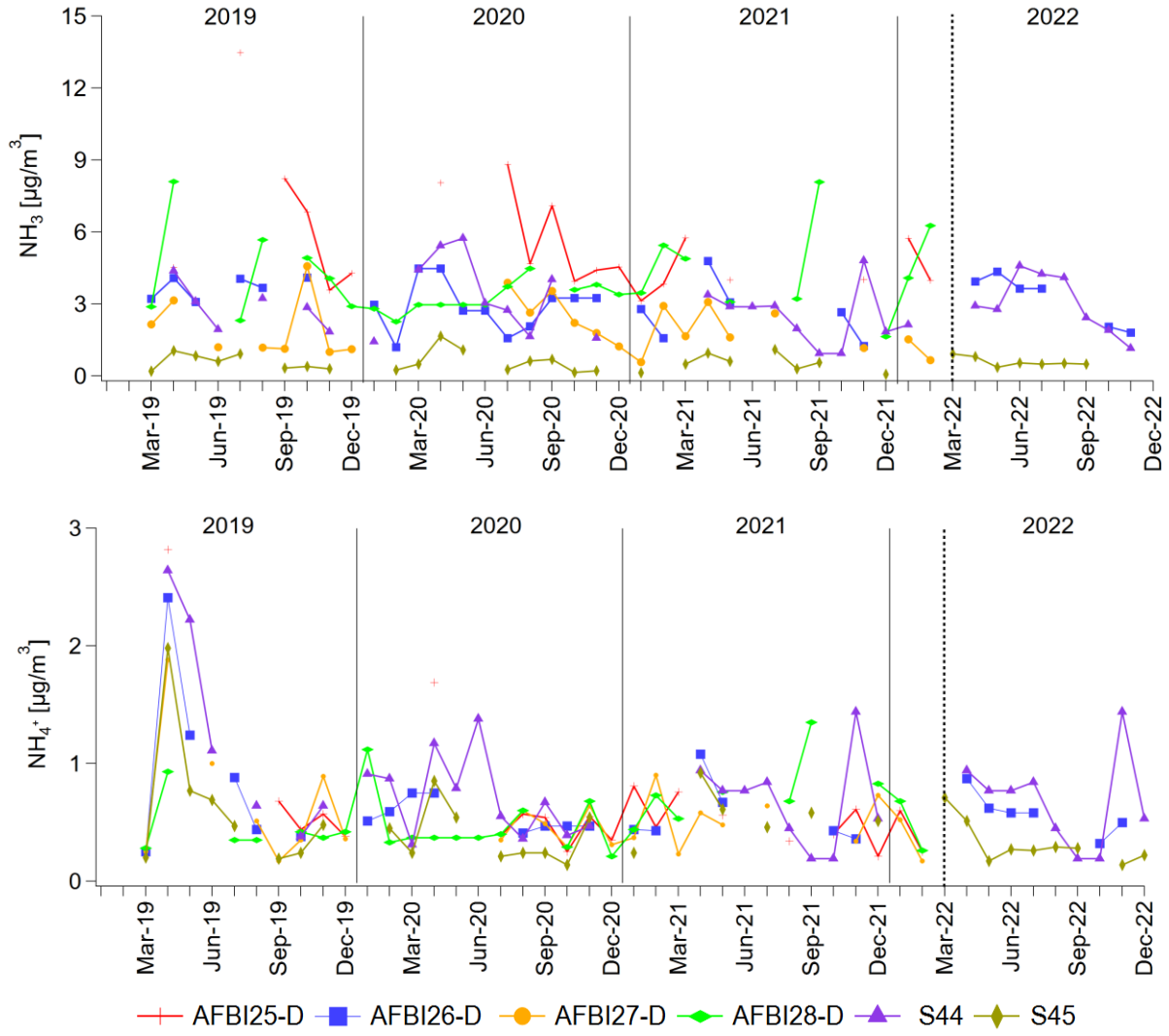


Figure 16. Time series of monthly NH_3 and associated NH_4^+ concentrations reported by the DELTA® systems in Northern Ireland. The black dashed line in March 2022 represents the closure of the monitoring sites AFBI25-D, AFBI27-D C, and AFBI28-D.

The NI DELTA® network downsize in 2022 did not change the observed pattern for NH_3 in Figure 20a, however NH_4^+ concentrations show an apparent decrease over time compared to previous years, similar to SO_4^{2-} (Figure 20c) and to a lesser degree, to NO_3^- (Figure 20e).

Future reports will provide insight whether this is an effect of the network downsize or related to changes in the atmospheric composition.

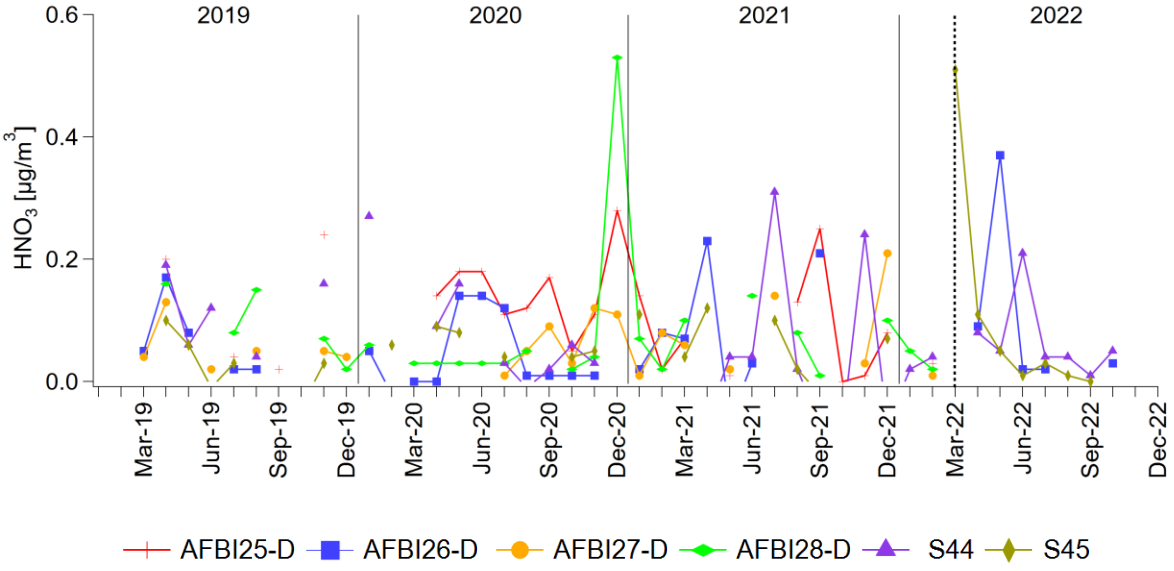


Figure 17. Time series of monthly HNO_3 and NO_3^- concentrations reported by the DELTA® systems in the Northern Ireland network. The black dashed line in March 20222 represents the closure of the monitoring sites AFBI25-D, AFBI27-D C, and AFBI28-D.

For HNO_3, the following processes influence its seasonal distribution:

i) Formation of HNO_3 from NO_x through photochemical processes (Pope et al., 2016).

ii) Removal of HNO_3 by reaction with NH_3 to form NH_4NO_3 - smaller concentrations of HNO_3 in spring and autumn due to high seasonal concentrations of NH_3 to promote aerosol formation.

iii) Temperature and humidity effects on the equilibrium between the gas phase HNO_3 (and NH_3) and aerosol phase NH_4NO_3. Cooler, more humid conditions favour the aerosol formation, whereas warmer, drier conditions will see partitioning back to the gas phase as NH_3 and HNO_3.

iv) Long-range transboundary transport of NH_4NO_3 to the sites (Vieno et al., 2014). Typically, this is observed across the UK in spring when high pressure systems result in the import of particulate matter from Europe.

In 2022, HNO_3 peaks were observed in March, May and June for S45, AFBI26 and S44 sites, respectively. March 2022 was a relatively dry month compared to previous years (Figure 3), but it also had a historical record of sunshine hours (90% greater than the long term average for the period 1991-2020; Met Office, 2022b). This was also reflected in the wider AGAnet data, where HNO_3 concentrations in March 2022 were comparable to those in the summer period, when HNO_3 formation is enhanced due to higher atmospheric oxidative capacity (Twigg et al., 2023). May and June peaks may be attributed to a combination of processes i) and iii). NO_3^- peaks were observed late spring months, when processes ii, iii) and iv) are in effect.

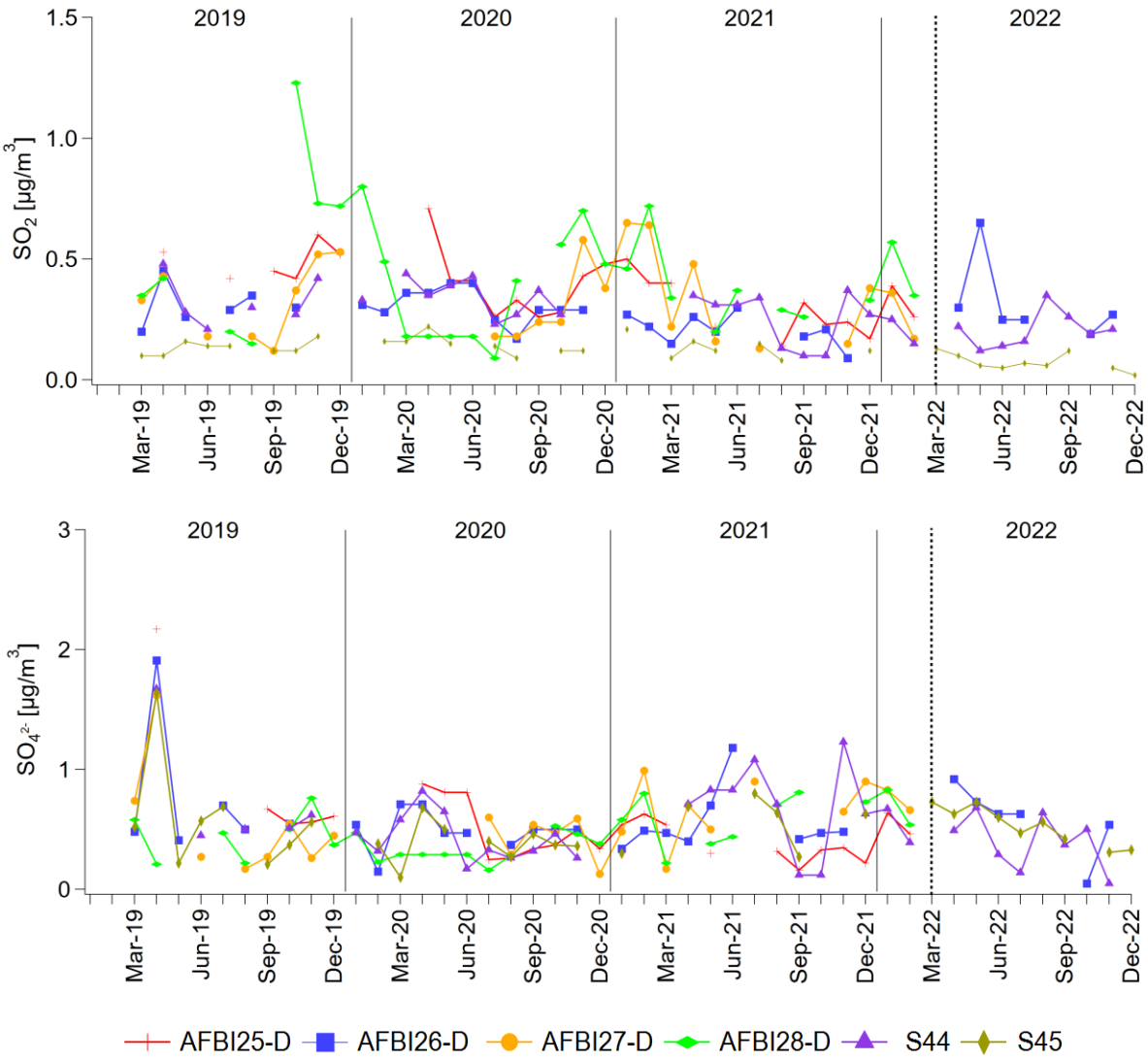


Figure 18. Time series for SO_2 and SO_4^{2-} reported by the DELTA® systems at the Northern Ireland network monitoring sites. The data is nested within the assigned exposure months for each DELTA sampler. The black dashed line in March 2022 represents the closure of the monitoring sites AFBI25-D, AFBI27-D C, and AFBI28-D.

In 2022, the highest SO_2 concentration were reported in January (Figure 18). Sulphur dioxide concentrations tend to be highest in the colder months due to seasonal combustion processes (heating), with coal burning still a considerable source of heating in Northern Ireland. The concentrations become elevated during periods where there is stable atmospheric conditions that allow the build-up of concentrations at ground level. In the case of Na^+ and Cl^-, the seasonal plots also show a clear temporal pattern (Figure 19). The largest concentrations tend to occur during winter, likely due to the increased wind speeds from storms generating more sea spray, highlighting the importance of marine sources in winter. This is especially observed during the 2021-2022 winter, when 6 named storms (Barra, Malik, Corrie, Dudley, Eunice, Franklin) occurred between December 2021 and February 2022 (Met Office, 2022).

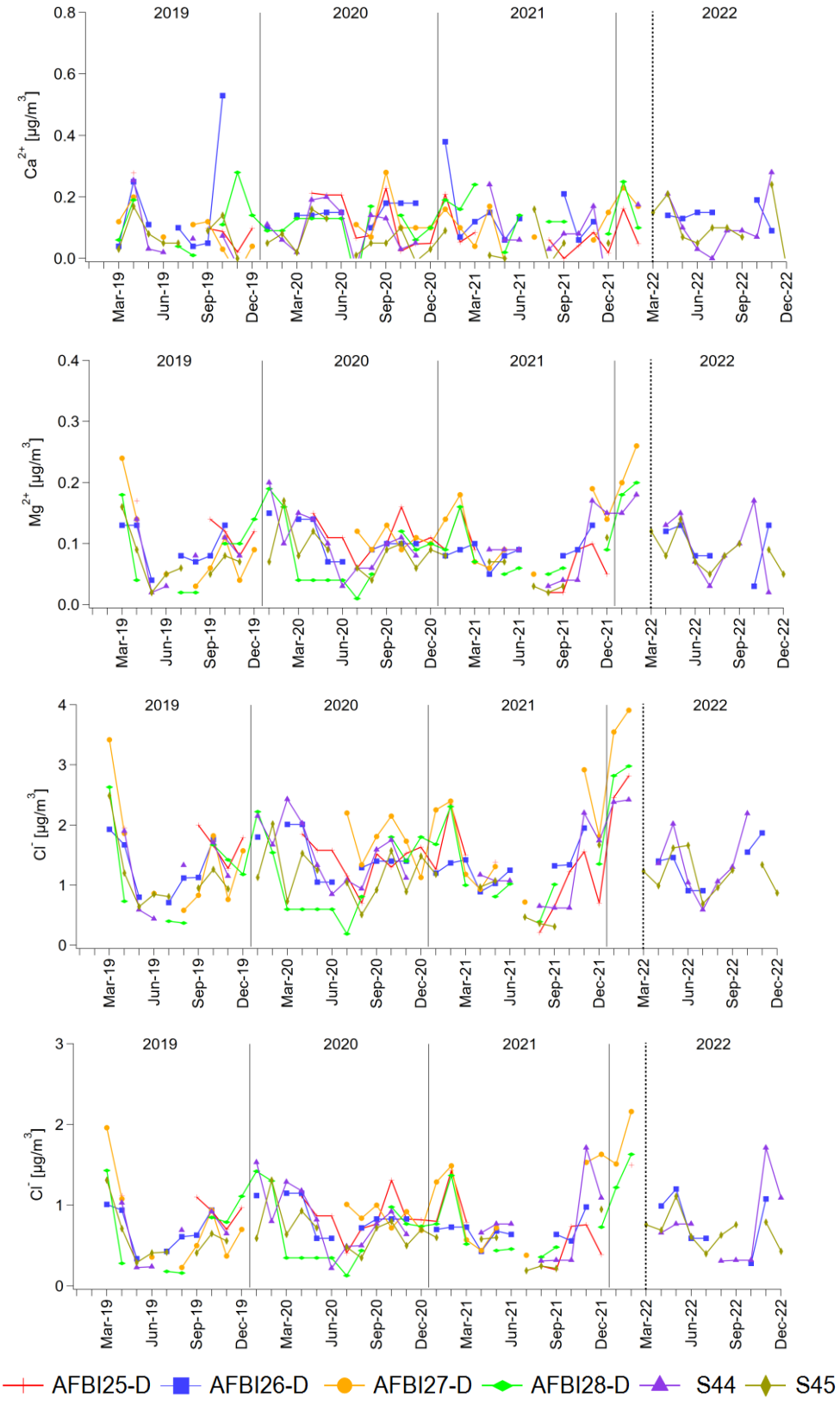


Figure 19. Time series for Na^+, Cl^-, Ca^{2+} and Mg^{2+} measured by the DELTA® sampler. The data is nested within the assigned exposure months for each DELTA sampler. The black dashed line in March 2022 represents the closure of the monitoring sites AFBI25-D, AFBI27-D C, and AFBI28-D.

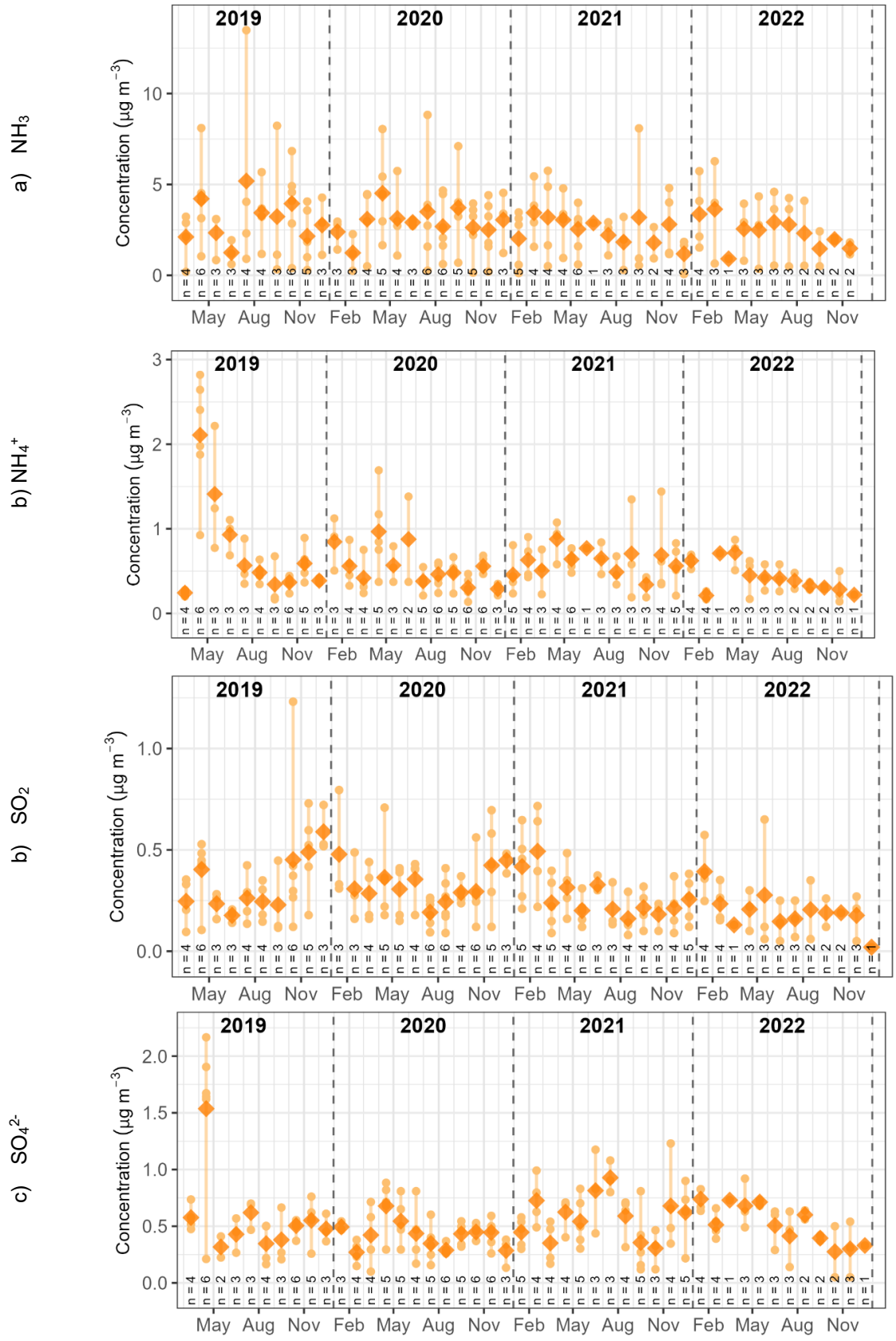


Figure 20. Mean concentrations for all DELTA samplers in the NI network. The time series represent the mean concentration and the whiskers represent the minimum and maximum concentrations recorded during the exposure month.

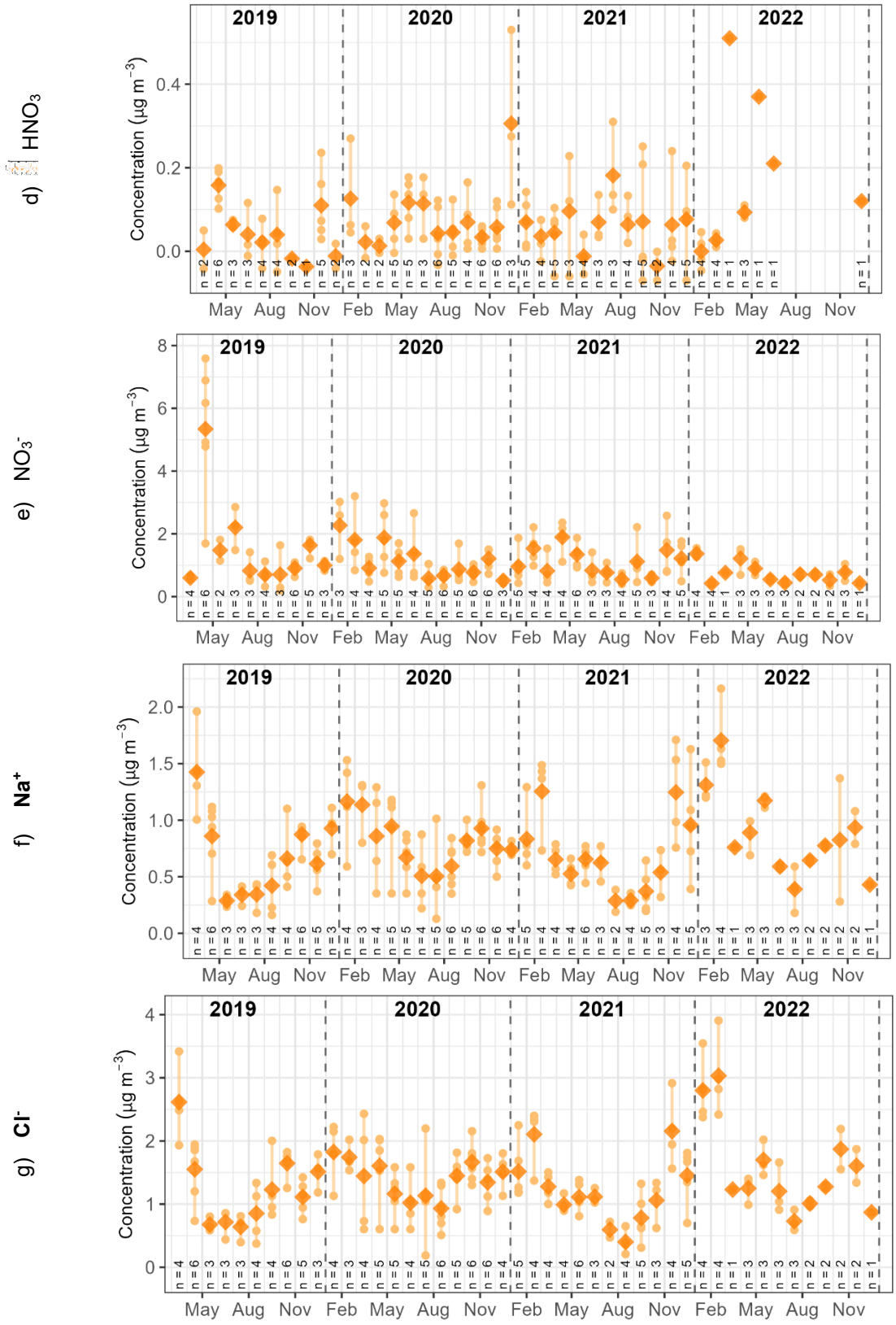


Figure 20. (cont). Mean concentrations for all DELTA samplers in the NI network. For each monitoring period, the light orange circles represent all DELTA data points, the darker orange diamonds represent the mean ammonia concentration and the whiskers represent the range (minimum and maximum) of concentrations recorded during the exposure period.

4. Conclusions and next steps

In 2022 some changes in the administration of the sites in the NI NH_3 and DELTA network were implemented; in March 2022 all of the ALPHA sites in the NI-wide network joined the UKEAP NAMM, while three of the four DELTA sites were discontinued. The remaining DELTA site (Ballynahone Bog) joined the NAMN/AGAnet.

Annual mean NH_3 concentrations in NI in 2022 showed a high spatial variability, across the 25 sites, similar to previous years. The NI NH_3 network displayed typical seasonal NH_3 patterns with key drivers related to agricultural activities, meteorological conditions and the thermodynamic partitioning of partitioning of NH_3 (g) into ammonium (NH_4^+) (p) aerosols.

The lowest NH_3 concentrations occurred at rural background sites while the highest concentration occurred in areas dominated by dairy farming. In 2022 the highest maximum monthly concentration spikes were recorded at Drumclamph 2, Caddy Rd. and Ratarnet Rd. This is due to local sources nearby, making these sites less representative of the wider surrounding area. Annual average measured NH_3 concentrations agree well with modelled predictions from the EMEP4UK CTM (R^2 = 0.64, FAC2 = 92%) in 2022.

Ammonia continues to be the largest component in the gas and aerosol measurements for the inorganic N species reported in the DELTA® network in Northern Ireland. Aerosol phase concentrations continue to be dominated by secondary inorganic aerosols (SIA) NH_4NO_3 and $(NH_4)_2SO_4$ and Na & Cl related to sea salt sources.

For the upcoming 2023 calendar year report, a similar structure to the current report will be used. An additional comparative analysis between the differences of calendar-year averages (based on calendar-month averages) vs time weighted averages for the exact monitoring periods will be provided to highlight the potential differences between methodologies. From 2023 onwards, all data from both NI NH_3 and DELTA networks are available via the Defra UK-AIR website (https://uk-air.defra.gov.uk/data/data_selector) as part of the UKEAP outputs.

5. References

Clougherty, J.E., Kheirbek, I., Eisl, H.M., Ross, Z., Pezeshki, G., Gorczynski, J.E., Johnson, S., Markowitz, S., Kass, D., and Matte T.: Intra-urban spatial variability in wintertime street-level concentrations of multiple combustion-related air pollutants: The New York City Community Air Survey (NYCCAS), Journal of Exposure Science and Environmental Epidemiology, 23, 232-240, https://doi.org/10.1038/jes.2012.125, 2013.

Dasgupta, P.K., Campbell, S.W., Al-Horr, R.S., Ullah, S.M.R., Li, J., Amalfitano, C., Poor, N.D., 2007. Conversion of sea salt aerosol to $NaNO_3$ and the production of HCl: Analysis of temporal behaviour of aerosol chloride/nitrate and gaseous HCl/HNO3 concentrations with AIM. Atmospheric Environment, (BRACE) 41, 4242–4257. https://doi.org/10.1016/j.atmosenv.2006.09.054

Dongre, P.K., Patel, V., Bhoi, U., and Maltare, N.N.: An outlier detection framework for Air Quality Index prediction using linear and ensemble models, Decision Analytics Journal, 14, 100546, https://doi.org/10.1016/j.dajour.2025.100546, 2025.

Martin, N.A., Ferracci, V., Cassidy, N., Hook, J., Battersby, R.M., di Meane, E.A., Tang, Y.S., Stephens, A.C.M., Leeson, S.R., Jones, M.R., Braban, C.F., Gates, L., Hangartner, M., Stoll, J.-M., Sacco, P., Pagani, D., Hoffnagle, J.A., Seitler, E., 2019. Validation of ammonia diffusive and pumped samplers in a controlled atmosphere test facility using traceable Primary Standard Gas Mixtures. Atmospheric Environment 199, 453–462. https://doi.org/10.1016/j.atmosenv.2018.11.038

Met Office, 2022a. UK storm season 2021/22 [WWW Document]. Met Office. URL https://www.metoffice.gov.uk/weather/warnings-and-advice/uk-storm-centre/uk-storm-season-2021-22 (accessed 2.11.26).

Met Office, 2022b. New March sunshine records [WWW Document]. Met Office. URL https://www.metoffice.gov.uk/about-us/news-and-media/media-centre/weather-and-climate-news/2022/end-of-march-statistics (accessed 2.11.26).

Pope, R. J., Butt, E.W., Chipperfield, M. P., Doherty, R. M., Fenech, S., Schmidt, A., Arnold, S. R., and Savage, N. H.: The impact of synoptic weather on UK surface ozone and implications for premature mortality. Environmental Research Letters. 11, https://doi.org/10.1088/1748-9326/11/12/124004, 2016.

Seinfeld, J.H., Pandis, S.N., 2016. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, 3rd Edition. ed. Wiley.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model – technical description, Atmospheric Chemistry and Physics, 12, 7825–7865, https://doi.org/10.5194/acp-12-7825-2012, 2012.

Skoulidou, I., Segers, A., Henzing, B., Zhang, J., Goudriaan, R., Koukouli, E., and Balis, D.: Towards integration of LOTOS-EUROS high resolution simulations and heterogenous low-cost sensor observations, Atmospheric Environment, 333, 120652, https://doi.org/10.1016/j.atmosenv.2024.120652, 2024.

Spindler, G., Gnauk, T., Grüner, A., Iinuma, Y., Müller, K., Scheinhardt, S., Herrmann, H., 2012. Size-segregated characterization of PM10 at the EMEP site Melpitz (Germany) using a five-stage impactor: a six year study. J Atmos Chem 69, 127–157. https://doi.org/10.1007/s10874-012-9233-6

Sutton, M.A., Schjørring, J.K., Wyers, G.P., 1995. Plant—atmosphere exchange of ammonia. Philos Trans A Math Phys Eng Sci 351, 261–278. https://doi.org/10.1098/rsta.1995.0033

Sutton, M.A., Tang, Y.S., Miners, B., Fowler, D., 2001. A New Diffusion Denuder System for Long-Term, Regional Monitoring of Atmospheric Ammonia and Ammonium. Water, Air, & Soil Pollution: Focus 1, 145–156. https://doi.org/10.1023/A:1013138601753

Sutton, M.A., van Dijk, N., Levy, P.E., Jones, M.R., Leith, I.D., Sheppard, L.J., Leeson, S., Sim Tang, Y., Stephens, A., Braban, C.F., Dragosits, U., Howard, C.M., Vieno, M., Fowler, D., Corbett, P., Naikoo, M.I., Munzi, S., Ellis, C.J., Chatterjee, S., Steadman, C.E., Móring, A., Wolseley, P.A., 2020. Alkaline air: changing perspectives on nitrogen and air pollution in an ammonia-rich world. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 378, 20190315. https://doi.org/10.1098/rsta.2019.0315

Tang, Y. S., Braban, C. F., Dragosits, U., Dore, A. J., Simmons, I., van Dijk, N., Poskitt, J., Dos Santos P. G., Keenan, P. O., Conolly, C., Vincent, K., Smith, R. I., Heal, M. R., and Sutton, M. A.: Drivers for spatial, temporal and long-term trends in atmospheric ammonia and ammonium in the UK. Atmospheric Chemistry and Physics, 18 (2). 705-733, 2018a.

Tang, Y. S., Braban, C. F., Dragosits, U., Simmons, I., Leaver, D., van Dijk, N., Poskitt, J., Thacker, S., Patel, M., Carter, H., Pereira, M. G., Keenan, P. O., Lawlor, A., Connolly, C., Vincent, K., Heal, M. R., and Sutton, M. A.: Acid gases and aerosol measurements in the UK (1999–2015): regional distributions and trends. Atmospheric Chemistry and Physics, 18 (22). 16293-16324. https://doi.org/10.5194/acp-18-16293-2018, 2018b.

Tang, Y., Cape, J., and Sutton, M. A.: Development and types of passive samplers for monitoring atmospheric NO_2 and NH_3 concentrations, The Scientific World Journal, 1, pp. 513-529. 2001.

Tang, Y.S., Tomlinson, S., Carnell, E.J., Williams, M., Thacker, S., Salisbury, E., Hunt, A., Guyatt, H., Smith, H., Graham, C., Simmons, I., Stephens, A.C.M., Iwanicka, A., Leaver, D., Twigg, M., Braban, C.F., Keenan, P.O., Pereira, M.G., McIlroy, J., and Dragosits, U. Atmospheric ammonia, acid gas and aerosol measurements in Northern Ireland. Year 1 report to DAERA for period March 2019 – February 2020, 2021.

Tang, Y.S., Tomlinson, S., Carnell, E.J., Williams, M., Thacker, S., Salisbury, E., Hunt, A., Guyatt, H., Smith, H., Graham, C., Simmons, I., Stephens, A.C.M., Iwanicka, A., Leaver, D., Twigg, M., Braban, C.F., Keenan, P.O., Pereira, M.G., McIlroy, J., and Dragosits, U.

Atmospheric ammonia, acid gas and aerosol measurements in Northern Ireland. Year 2 report to DAERA for period March 2019 – February 2021, 2022b.

Twigg, M.M., Berkhout, A.J.C., Cowan, N., Crunaire, S., Dammers, E., Ebert, V., Gaudion, V., Haaima, M., Häni, C., John, L., Jones, M.R., Kamps, B., Kentisbeer, J., Kupper, T., Leeson, S.R., Leuenberger, D., Lüttschwager, N.O.B., Makkonen, U., Martin, N.A., Missler, D., Mounsor, D., Neftel, A., Nelson, C., Nemitz, E., Oudwater, R., Pascale, C., Petit, J.-E., Pogany, A., Redon, N., Sintermann, J., Stephens, A., Sutton, M.A., Tang, Y.S., Zijlmans, R., Braban, C.F., Niederhauser, B., 2022. Intercomparison of in situ measurements of ambient NH_3: instrument performance and application under field conditions. Atmospheric Measurement Techniques 15, 6755–6787. https://doi.org/10.5194/amt-15-6755-2022

Twigg, M.M., Braban, C.F., Stephens, A.C.M., Tang, Y.S., Leeson, S.R., Jones, M.R., Simmons, I., Harvey, D., Yeung, K., van Dijk, N., Iwanicka, A., Duarte, F., Nemitz, E., Leaver, D., Andrews, C., Thacker, S., Keenan, P.O., Dos Santos Pereira, M.G., Guyatt, H., Hunt, A., Salisbury, E., Chetiu, N., Grant, H., Warwick, A., Rylett, D., Teagle, S., Lord, W., Bannister, G., Sutton, M.A., Conolly, C., Vincent, K., Sanocka, A., Ritchie, S., Knight, D., Donovan, B., Jackson, T., Dyer, M., Osborne, E., 2023. UK Eutrophying and Acidifying Atmospheric Pollutants (UKEAP) Annual Report 2022 [WWW Document]. URL https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2309281200_UKEAP_2022_annual_report.pdf (accessed 3.18.24).

Twigg, M.M., Di Marco, C.F., Leeson, S., van Dijk, N., Jones, M.R., Leith, I.D., Morrison, E., Coyle, M., Proost, R., Peeters, A.N.M., Lemon, E., Frelink, T., Braban, C.F., Nemitz, E., Cape, J.N., 2015. Water soluble aerosols and gases at a UK background site – Part 1: Controls of PM2.5 and PM10 aerosol composition. Atmos. Chem. Phys. 15, 8131–8145. https://doi.org/10.5194/acp-15-8131-2015

Vieno, M., Heal, M. R., Hallsworth, S., Famulari, D., Doherty, R. M., Dore, A. J., Tang, Y. S., Braban, C. F., Leaver, D., Sutton, M. A., and Reis, S.: The role of long-range transport and domestic emissions in determining atmospheric secondary inorganic particle concentrations across the UK, Atmospheric Chemistry and Physics, 14, 8435-8447, https://doi.org//10.5194/acp-14-8435-2014, 2014.

Vieno, M., Heal, M. R., Williams, M. L., Carnell, E. J., Nemitz, E., Stedman, J. R., and Reis, S.: The sensitivities of emissions reductions for the mitigation of UK PM2.5, Atmos. Chem. Phys., 16, 265–276, https://doi.org/10.5194/acp-16-265-2016, 2016.

Published datasets

EIDC-Monthly atmospheric ammonia, acid gas, inorganic aerosols, and base cation concentrations from Northern Ireland ALPHA® Ammonia Monitoring Network 2019-2020 and DELTA gas and aerosol monitoring network, 2019 – 2020

Stephens, A., Twigg, M., Braban, C., Espina Martin, P., Iwanicka, A., Duarte, F., Simmons, I., Dos Santos Pereira, G., Keenan, P., Hunt, A., Chetiu, N.-F., Guyatt, H., Salisbury, E., 2024. UKEAP (UK Eutrophying and Acidifying Atmospheric Pollutants) 2022 dataset: Acid Gas and Aerosol Network (AGANet).

Stephens, A., Twigg, M., Braban, C., Espina Martin, P., Dos Santos Pereira, G., Keenan, P., Hunt, A., Chetiu, N.-F., Guyatt, H., Leaver, D., Iwanicka, A., Simmons, I., Duarte, F., 2024. UKEAP (UK Eutrophying and Acidifying Atmospheric Pollutants) 2022 dataset: National Ammonia Monitoring Network (NAMN).



UKCEH

Our planet. Decoded.

For more information please contact:

[EMAIL US]
Enquiries@ceh.ac.uk

[LEARN MORE]
ceh.ac.uk

[FOLLOW US]
@uk_ceh