



Measurement report: Long-Term Mapping of Ammonia Near Swedish Livestock Farms Reveals Key Local Drivers of Concentration Patterns

Sofie Hellsten^{1*}, Sofie Petersson¹, Maddalena Tigli², Audric Vigier², Cristina Martin Hernandez², Åsa Hedmark³, William J. Bealey², Ågot K. Watne^{1*}

¹IVL Swedish Environmental Research Institute, Gothenburg, P.O. Box 53021, SE-400-14 Gothenburg, Sweden

²UK Centre for Ecology & Hydrology, Edinburgh, Bush Estate, Penicuik, Midlothian, EH26 0QB, UK

³Länsstyrelsen Skåne, Malmö, SE-205 15 Malmö, Sweden

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*These authors contributed equally to this work

Correspondence to: Sofie Hellsten (sofie.hellsten@ivl.se)

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Abstract. Ammonia (NH_3) emissions from agriculture contribute significantly to air pollution and nitrogen deposition, with implications for human health and sensitive ecosystems. However, long-term field observations comparing NH_3 concentration patterns among different livestock production systems in northern Europe remain limited. This study aimed to quantify temporal and spatial variations in NH_3 concentrations around pig, poultry, and dairy farms and identify the influence of temperature, management practices, and distance from emission sources.

Monthly average concentrations were recorded from June 2023 to May 2024 across nine spatially distributed sampling locations around each farm. Annual mean NH_3 concentrations ranged from 1.8–17.0, 5.2–22.5, and 4.0–23.7 $\mu\text{g m}^{-3}$ at the poultry, pig, and dairy farms, respectively. These levels were consistently above nearby background concentrations of 0.44–0.45 $\mu\text{g m}^{-3}$ and exceeded the 1 $\mu\text{g m}^{-3}$ critical level for lichens and mosses at all sites.

Concentrations decreased with distance from livestock housing and were positively correlated with ambient temperature at all three farms. The pig and dairy farms showed greater temporal variability than the poultry farm, mainly reflecting manure handling, housing conditions, and other management activities. An April peak at the pig farm was likely related to slurry spreading. These findings show that both continuous housing emissions and episodic manure application elevate NH_3 concentrations near farms. The findings provide a robust observational basis for refining agricultural NH_3 emission inventories and supporting mitigation efforts under national and European air quality and environmental policies.

1 Introduction

Ammonia (NH_3) emissions represent a significant environmental concern due to their wide-ranging ecological and human health impacts. Agricultural activities have been estimated to be responsible for 86% of global atmospheric NH_3 emissions (van Damme et al., 2021), and in Sweden, agricultural emissions contribute 90% (Swedish EPA, 2025). Ammonia has a relatively short atmospheric lifetime of approximately 24 hours (Wichink Kruit et al., 2012) and is associated with large dry deposition velocities to vegetation (Sutton and Fowler, 2002; Fowler et al., 2009). Hence a large amount of NH_3 released into the air can be deposited to vegetation near the agricultural facility, impacting local natural and semi-natural ecosystems. Elevated NH_3 concentrations can cause acute local-scale problems, particularly on nature reserves situated within intensive agricultural landscapes (Hallsworth et al., 2010). Excessive nitrogen inputs can lead to the decline of nitrogen-sensitive plant species, fostering competitive dominance of nitrogen-tolerant species and reducing overall biodiversity (Bobbink et al., 2010; Krupa et al., 2003). Ammonia deposition can also lead to soil acidification and eutrophication of water bodies, impairing biodiversity and disrupting ecosystem services (Bobbink et al., 2010). The quantitative threshold of nitrogen levels, critical levels, below which no long-term harmful effects on ecosystems are expected is 1 $\mu\text{g NH}_3 \text{ m}^{-3}$ for lichens and mosses and 3 $\mu\text{g NH}_3 \text{ m}^{-3}$ for higher plants (UNECE, 2017; Umweltbundesamt, 2023). Furthermore, ammonia contributes to the formation



of fine particulate matter ($PM_{2.5}$), which poses severe human health risks to respiratory and cardiovascular health (Lelieveld et al., 2015; Wyer et al., 2022).

Efforts to mitigate ammonia emissions are critical for achieving sustainable agricultural practices and ensuring compliance with environmental regulations. For instance, the UNECE Gothenburg Protocol has resulted in efforts to decrease anthropogenic emissions of nitrogenous compounds in Europe (UNECE, 1999). However, the reduction in ammonia emissions in Europe has been less significant to other pollutants (Aas et al., 2024), and many countries, including Sweden, have difficulties to achieve the emission targets of ammonia set up in the National Emissions Ceilings Directive (2016/2284/EU). Furthermore, the revised Industrial and Livestock Rearing Emissions Directive (IED 2.0), requires permit applications to assess impacts of large pig and poultry farms, above stated size thresholds (livestock units, LSU), ca 350 LSU for pigs and ca 300 LSU laying hens / 280 LSU broilers.

Intensive agricultural husbandry operations, such as pig and poultry farms, are significant point sources of ammonia emissions (e.g. Skiba et al., 2006; Jones et al., 2013; Baker et al., 2020). Ammonia emissions from agricultural facilities arise mainly from volatilisation during manure storage, handling, and field application (Monteny and Erisman, 1998). The emissions arise from multiple stages of manure management, including livestock housing, manure storage, land application (spreading), and excreta deposited during grazing, and can substantially impact downwind environments, leading to alterations in nearby vegetation communities (Pitcairn et al., 1998; Skiba et al., 2006; Jones et al., 2013). In addition, emission rates are not constant over time but show clear seasonal variability, largely driven by temperature-dependent volatilisation processes and seasonal management practices, with generally higher emissions during warm summer months and manure spreading periods, and lower emissions during colder winter periods (Tang et al., 2018; Pedersen et al., 2021; Kelleghan et al., 2021a). The transport of ammonia in the atmosphere depends on meteorological conditions, such as wind speed, temperature, and humidity, and interannual variability in weather patterns significantly influences ammonia dispersion and deposition dynamics (Ge et al., 2023). In addition to meteorological conditions, ammonia concentrations also fluctuate seasonally and vary spatially in the landscape depending on source strength and land use (Tang et al., 2018, Theobald et al., 2001).

On-site measurements yield direct data on ambient NH_3 concentrations, capturing the influence of real-world emissions under prevailing environmental conditions. Such data are essential for improving our understanding of the factors that drive ammonia variability, including the effects of intensive agricultural operations. However, there is a notable lack of long-term monitoring near livestock facilities. Most studies in the literature rely on short-term campaigns, targeted measurement periods, or long-term datasets collected either at background sites or for the purpose of estimating emissions. Very few studies have characterised spatial and temporal concentration patterns in the immediate vicinity of farms, despite this being where gradients and variability are often most pronounced. Extended monitoring close to emission sources is therefore needed to identify seasonal trends and to more accurately evaluate the long-term environmental impacts of agricultural NH_3 emissions.

Understanding how ammonia spreads from livestock housing is critical for safeguarding nearby sensitive ecosystems. (Sutton et al., 2009). The objective of the study is to evaluate local drivers of ammonia concentration variability near livestock facilities, including proximity to emission sources, agricultural activities and meteorological conditions. To meet the objective of the



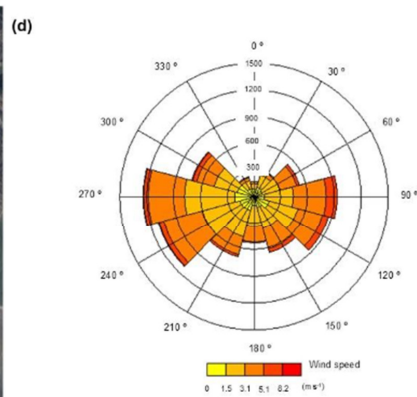
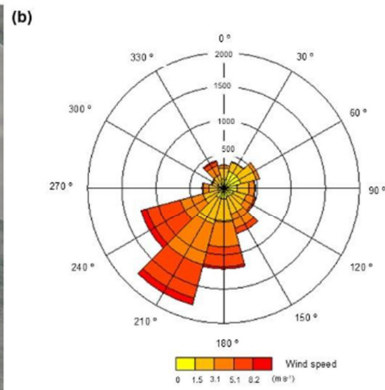
study we pose the following hypotheses. First, even in an agricultural intensive area, intensive livestock facilities are point sources and will contribute significantly to the background concentrations of ammonia. Second, temporal variability in ammonia concentrations is strongly influenced by farm management activities. Because these activities differ between production systems, the magnitude and pattern of variability also differ. For instance, on poultry farms, where housing operates as a relatively closed and mechanically controlled system, management activities have a limited and more predictable influence on emissions. In contrast, dairy farms typically exhibit greater spatial and temporal variation due to open housing structures and a wider range of daily activities occurring across the farmyard. Third, as the emissions of ammonia are temperature dependent, the concentration variations in the vicinity of the farms will depend on the ambient temperature. To test these hypotheses, we present measurements of NH_3 concentrations conducted at varying distances from three types of livestock housing operations: dairy, pig and poultry. Passive samplers were deployed at nine locations per farm over a 12-month period to capture a comprehensive picture of concentration patterns. This approach offers possibility for comprehensive mapping, both regarding spatial resolution and time. Furthermore, as this approach disentangles the impact of different local factors impacting the ambient ammonia concentration in the near vicinity of livestock facilities, the results offers a valuable basis for identifying effective management strategies to reduce local emissions and their environmental impacts.

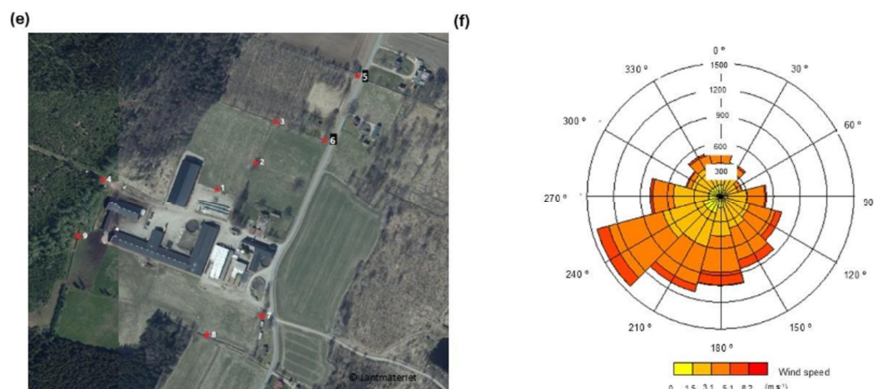
2 Method

2.1 Site selection

Three large-scale commercial farms, located in southern and southwestern Sweden, were selected for this study (Fig. 1). These farms represent distinct types of intensive livestock operations and were chosen because they are not situated in close proximity to other livestock farms or major ammonia emission sources. Further details about each farm and the surrounding landscape are provided in Table 1.

At each farm, nine sampling sites were strategically selected to capture the spatial variability in ammonia concentrations. The sites were positioned in key directions around the housing facilities and spanned a range of distances from 35 to 563 meters, ensuring comprehensive spatial coverage (see Fig. 1 and Table 2). For each farm, a typical meteorological year (TMY) was constructed to represent climatological conditions to identify the prevailing wind directions. The TMY comprises individual months selected from the period 1989–2019 based on daily classification of synoptic-scale circulation patterns using the Lamb weather type methodology, following the implementation by Chen (2000). Meteorological input parameters including wind speed, wind direction, temperature, precipitation, and global solar radiation were sourced from the nearest representative weather stations operated by the Swedish Meteorological and Hydrological Institute (SMHI). Care was taken to ensure that at least three sites were positioned along the transect of the prevailing wind direction. Site selection was also guided by practical considerations: locations needed to be compatible with ongoing farm operations, e.g. avoiding the centre of cultivated fields, and permit easy and rapid access for sampler replacement by farm personnel.





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Figure 1. Aerial photos (©Lantmäteriet, 2023) and wind rose for typical meteorological year of the poultry farm (a,b), pig farm (c,d) and dairy farm (e,f) displaying the locations of all passive samplers.

Table 1. Description of the three farms included in the study, detailing the type of livestock, the maximum number of livestock per category under the measurement period, distance to NH₃ background station and meteorological station.

Livestock type	Number of livestock	Description	Distance to NH ₃ background station (km)	Distance to met. station (km)
Poultry	65 000 laying hens	The poultry farm is located in an open and flat landscape. The farm has two livestock units, where the first unit has natural ventilation in the form of 21 chimneys on the roof, and the other unit has mechanical ventilation on the southern wall.	30	16
Pigs	3 680 finishing pigs, 440 sows, and 1 700 piglets	The pig farm is located in a rolling landscape with a mix of open fields and forest. The farm has seven livestock units of varying sizes and for different purposes related to pig farming. All the livestock units have natural ventilation on their roofs.	24	14
Dairy cows	393 dairy cows, 242 young heifers, 179 pregnant heifers, 30 suckler cows, 40 steers*	The dairy farm is located in a forest environment surrounded by a lot of high trees.	45	27

*Additional livestock unit for approx. 400 calves was built and set in operation in February 2024.



2.2 Study design and measurement techniques

At each site, monthly mean NH_3 concentrations were measured using diffusive passive samplers developed by IVL Swedish Environmental Research institute (Ferm et al., 2005). Samplers were installed at approximately 1.5 meters above ground level. To ensure unobstructed airflow and representative measurements, most samplers were mounted on free-standing posts in open areas. However, due to practical constraints at some locations, a few samplers were mounted on trees or buildings. All samplers were protected from rain, wind and bird droppings, using protective covers equipped with anti-bird spikes, in accordance with the approach of Tang et al. (2018). Two of the nine sampling sites were equipped with three replicate samplers, to assess measurement uncertainty.

The measurements were conducted over a 12-month period, from June 2023 to May 2024. While the exact date of sampler replacement varied slightly between farms due to logistical factors, all samplers at a given farm were changed simultaneously, ensuring consistent measurement periods within each site. However, the sampling periods are not perfectly aligned across the three farms. Detailed information on sampling periods and instances of missing data is provided in Table A1, A2 and A3 in Appendix A.

Meteorological parameters during the measurement period were obtained from the same meteorological stations used for the reference meteorological year. The corresponding data are presented in Appendix 2. Background concentrations of ammonia were obtained from the nearest available monitoring stations, the Hensbacka and Hissmossa sites, which are part of the Swedish Throughfall Monitoring Network (Pihl Karlsson et al., 2024).

2.3 Statistical Analysis and Data Assessment

Data cleaning involved the removal of outliers and data gaps caused by sampler loss or contamination. As wet samples do not provide valid measurements, all samples identified as wet were excluded from the analysis, resulting in the removal of 22 samples in total. This included a subset of 7 samples that were part of triplicate sets. Additionally, at one pig farm site, the sampling equipment had fallen over, leading to large discrepancies among the three replicate measurements. These samples were deemed invalid and excluded from further analysis.

Monthly and yearly averages were calculated per location using only the samples retained after data cleaning. Farm-wide averages were calculated for all samples at each farm. In some months, while the measurements were valid, the concentrations fell below the detection limit. In such cases, the detection limit value was used in the statistical analysis to ensure consistency. For a few samples that were valid but yielded reported concentrations below approximately $1 \mu\text{g m}^{-3}$ or $2 \mu\text{g m}^{-3}$, a concentration of $1 \mu\text{g m}^{-3}$ and $2 \mu\text{g m}^{-3}$ was assumed in the calculations, respectively. This approach was applied to avoid underestimation of concentrations in the dataset and to maintain comparability across all sampling occasions.

The spatial decrease of ammonia concentrations was analysed by plotting mean NH_3 concentrations against distance from the nearest livestock housing (used as a proxy for emission source distance). As each farm included multiple housing facilities,



the farms were not a source with a single point source, but rather several point sources. All active housing facilities were
155 considered when evaluating spatial concentration gradients. However, since the facilities housed different numbers and types
of livestock, emission strengths likely varied between them, which may have influenced the observed concentration patterns.
Notably, as a new housing facility was built and put into operation during the measurement period, this altered the actual
distance between one measurement site (site 4) and nearest housing when it became operational. For the purpose of analysis,
however, the original 'distance to housing' was retained throughout the entire study period.

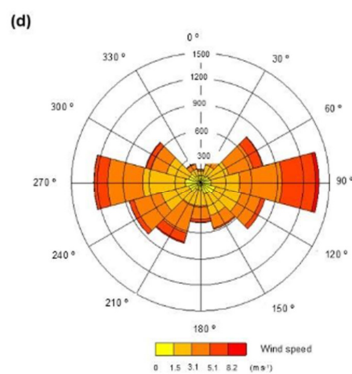
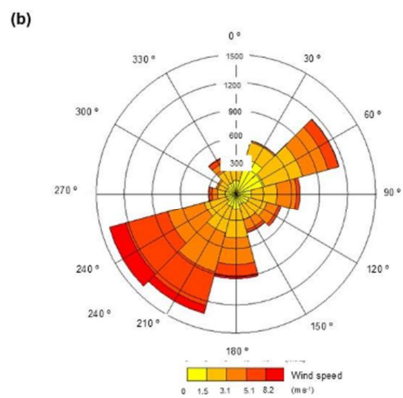
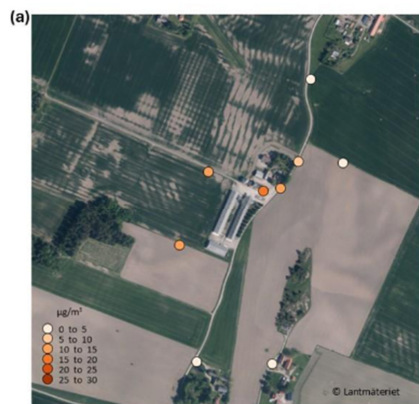
160 Time series of monthly average NH_3 concentrations were calculated per site and per farm, to assess monthly variation in NH_3
concentrations. These time series were used to visualize temporal trends, showing how concentrations varied throughout the
year (June 2023–May 2024).

The relationship between monthly average temperature and ammonia concentrations was assessed by plotting mean NH_3
concentrations (aggregated monthly) against corresponding mean ambient temperatures, including only months with valid
165 measurements at all sites. Linear regression analysis was applied for evaluation of the temperature dependence of NH_3
concentrations.

3 Results and discussion

3.1 Spatial Distribution of Ammonia Concentrations

Annual NH_3 concentrations measured at all sites on the three farms are shown in Fig 2. Concentrations varied both between
170 farms and among sites within each farm, but at all sites the concentrations were above the critical level of $1 \mu\text{g}/\text{m}^3$. Mean
annual NH_3 levels ranged from 5.2 to $22.5 \mu\text{g}/\text{m}^3$ near the pig farm, from 1.8 to $17.0 \mu\text{g}/\text{m}^3$ near the poultry farm, and from
 4.0 to $23.7 \mu\text{g}/\text{m}^3$ near the dairy farm (Table 2). In general, the highest concentrations were observed at sites located closest to
livestock housing, highlighting the strong influence of source proximity on ambient levels. Distance from emission sources
was the primary factor governing the spatial variation in ammonia concentrations. In addition, prevailing wind direction is also
175 important, as sites situated downwind of livestock housing typically exhibit higher concentrations compared with those located
upwind or crosswind relative the source (Tang et al., 2005).



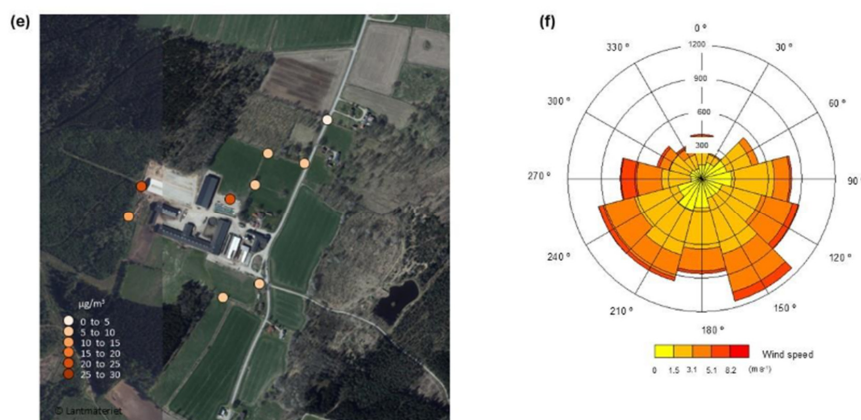


Figure 2. Aerial photos (© Läntmetriet, 2024) and wind rose for the measurement period of the poultry farm (a,b), pig farm (c,d) and dairy farm (e,f) displaying annual mean NH₃ concentration at all sites.

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Annual mean NH₃ concentrations at all measurement sites near the farms were higher compared with background levels, including at the sites located furthest from the livestock facilities (Table 2). At Hensbacka, situated approximately 45 km from the dairy farm and 30 km from the poultry farm, the annual mean concentration during the measurement period was 0.44 µg/m³. In comparison, the lowest concentrations recorded at the dairy and poultry farms were 4.0 and 1.8 µg/m³, respectively.

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Similarly, at Hissmossa, located 24 km from the pig farm, the annual mean concentration was 0.45 µg/m³, while the lowest value observed at the pig farm was 5.2 µg/m³.

Table 2. Summary of measured NH₃ concentrations by site, including distance to the nearest livestock housing along with statistical parameters: mean, median, standard deviation (Std), maximum (Max), and minimum (Min) concentrations over the monitoring period. Bold values indicate sites included in the transect in the prevailing wind direction.

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	Site number	Distance to housing (m)	Mean (µg m ⁻³)	Median (µg m ⁻³)	Std (µg m ⁻³)	Max (µg m ⁻³)	Min (µg m ⁻³)
Poultry	1	39	17.0	12.0	14.5	50.0	2.9
	2	73	10.6	7.9	8.8	30.0	2.1
	3	154	5.4	4.8	3.9	14.0	1.0
	4	347	3.1	3.3	1.5	5.5	1.0
	5	243	3.8	3.2	2.1	7.8	1.0
	6	327	2.0	2.2	1.1	4.2	1.0
	7	314	3.8	2.4	4.3	15.0	1.3
	8	84	13.6	15.0	5.4	21.0	6.0

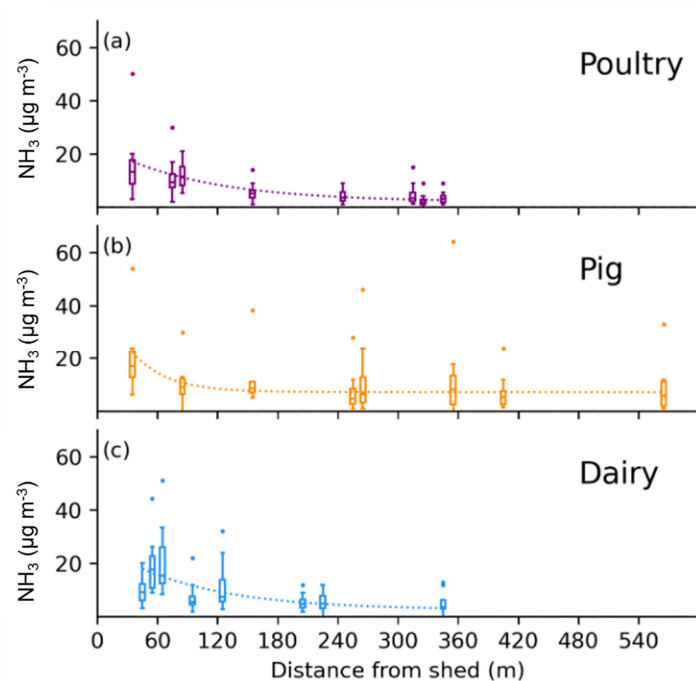


	9	80	11.0	10.0	8.0	28.0	3.1
Pig	1	35	22.5	19.3	14.6	54.0	6.4
	2	153	11.3	7.3	11.1	38.3	5.1
	3	258	5.2	3.3	7.4	28.0	1.0
	4	563	7.1	2.3	11.1	33.0	1.0
	5	358	10.2	3.0	18.4	64.0	1.0
	6	405	5.2	2.8	6.2	24.0	1.5
	7	90	10.6	7.2	8.0	30.0	2.0
	8	268	5.5	3.9	5.3	20.0	1.0
	9	264	7.9	3.9	12.3	46.0	1.6
Dairy	1	60	21.7	20.3	10.1	44.3	9.0
	2	123	8.7	8.2	3.5	13.0	3.4
	3	201	5.0	4.7	1.8	9.0	2.3
	4	65	23.7	16.0	15.0	51.0	8.4
	5	345	4.3	3.5	3.0	13.0	1.9
	6	230	5.5	4.8	2.9	12.0	2.0
	7	124	7.7	5.0	8.1	32.0	2.8
	8	99	6.3	5.0	5.4	22.0	1.9
	9	41	10.0	8.6	5.2	20.0	3.2

3.2 Declining NH₃ Concentrations with Distance from Housing

Our measurements show a consistent decline in NH₃ concentrations with distance from livestock facilities. As illustrated in Fig. 2, concentrations are highest adjacent to housing and decrease steeply within the first 100–150 meters at all three farms.

195 This pattern reflects localized emissions from livestock housing and related operations and aligns with the known atmospheric behaviour of NH₃, which has a short lifetime due to rapid dry deposition and low atmospheric persistence as well as dilution of the emissions. Beyond approximately 150–200 meters, concentrations tend to stabilize, reflecting a transition from point-source influence to a broader background signal shaped by regional emissions and atmospheric mixing.



200 **Figure 3. Boxplots of monthly NH_3 concentrations as a function of distance from livestock housing, based on 12 months of measurements from nine sites across the poultry (a), pig (b) and dairy (c) farms. Each box represents the distribution of monthly concentrations at a given distance, aggregated across all sites and farms. Median values, interquartile ranges (IQR), and outliers are indicated. Regression curves fitted using the function $y=ae^{-bx}+c$ are included to guide the reader's interpretation.**

205 All sites exhibited steep NH_3 concentration gradients with distance (Fig. 3), consistent with findings from previous studies (e.g. Tang et al., 2005; Fairchild et al., 2009; Jones et al., 2013; Souhar et al., 2022). For example, Tang et al. (2005) observed a reduction in NH_3 from $39 \mu\text{g}/\text{m}^3$ at 20 m to $\sim 7 \mu\text{g}/\text{m}^3$ at 320 m downwind of broiler houses in Northern Ireland. Similarly, our data show a 4–5-fold decrease between 40 m and 300 m at all farms. These rapid declines underscore the limited transport range of NH_3 and its propensity for near-source deposition and dispersion (Sutton et al., 1998; Ge et al., 2023).

210 Among the three sites, the pig farm (Fig. 3b) consistently showed higher NH_3 concentrations at intermediate to far distances, particularly beyond 200 meters, where levels remain elevated. This is likely attributable to its location in Skåne, a region characterized by more intensive agriculture, higher livestock densities, and frequent manure application. These factors contribute to elevated regional background levels of NH_3 . In contrast, the poultry and dairy farms, located in Västra Götaland, are situated in areas with lower agricultural intensity, resulting in lower ambient NH_3 concentrations. This contrast highlights

215 the importance of considering regional agricultural context when interpreting concentration data or modelling emissions.

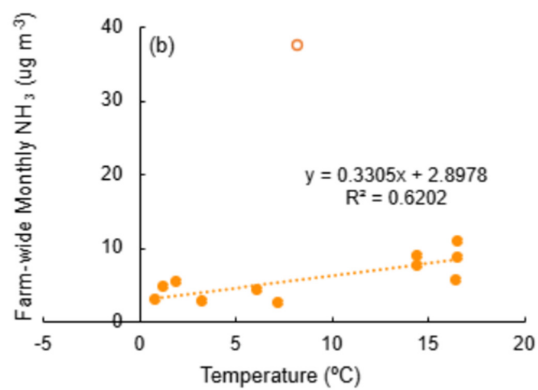
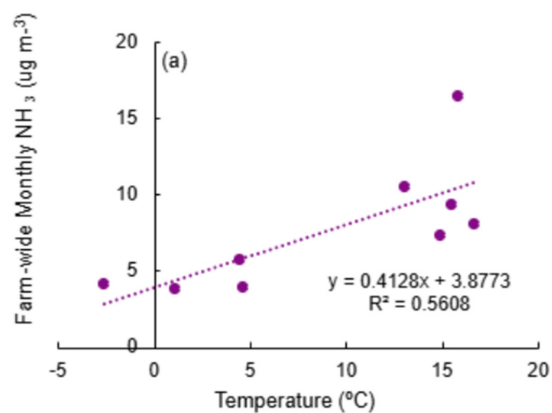


Satellite observations by Epps et al. (2025) show that NH_3 column enhancements (ΔNH_3) can persist several kilometres downwind of pig operations, especially under hot and calm conditions. While their data represent vertically integrated concentrations across the atmospheric boundary layer, our passive samplers capture near-surface levels, offering finer resolution of spatial variability close to the source. Together, these approaches reveal that NH_3 emissions from intensive
220 livestock operations can significantly impact local air quality. Ground-based measurements remain essential for resolving fine-scale gradients and complementing satellite data, thereby improving our understanding of emission dynamics and informing targeted mitigation strategies.

3.3 Influence of Distance and Temperature on NH_3 Concentrations

Ammonia (NH_3) concentrations near livestock housing exhibit high variability, largely influenced by farm activities, which
225 complicates the identification of temporal trends. In contrast, conditions become more stable with increasing distance from the source, allowing clearer detection of seasonal patterns and long-term trends (Fig. 3).

Figure 4 shows that the measured monthly farm-wide NH_3 concentrations are overall correlated with ambient temperature at all three farms. During the monitoring period, mean monthly temperatures ranged from just below -5°C to nearly 20°C . At the pig farm, data from April were excluded from the correlation analysis, as this month exhibited anomalously high
230 concentrations likely attributable to manure spreading activities in the surrounding area (Fig. 4b). Excluding this outlier strengthens the observed relationship between temperature and NH_3 concentrations at the pig farm. These results align with and support earlier research describing seasonal and operational influences on ammonia concentrations. Warmer periods promote increased ammonia volatilization, resulting in elevated NH_3 concentrations both near the source and downwind. For example, Kelleghan et al. (2021b) found a clear correlation between ammonia concentrations and ambient temperature across
235 multiple sites in Ireland, and Tang et al. (2005) reported higher NH_3 concentrations during summer near broiler houses in Northern Ireland. Furthermore, Souhar et al. (2022) demonstrated elevated NH_3 levels in intensive livestock landscapes during warm seasons in western France. Kelleghan et al. (2021a) observed substantial seasonal variations in emission rates from an intensive laying hen facility in Ireland, indicating a likely temperature-driven seasonal pattern in ammonia concentrations. Similarly, Hellsten et al. (2007) and Pedersen et al. (2021) emphasized the role of temperature and seasonal manure
240 management practices in driving emission dynamics.



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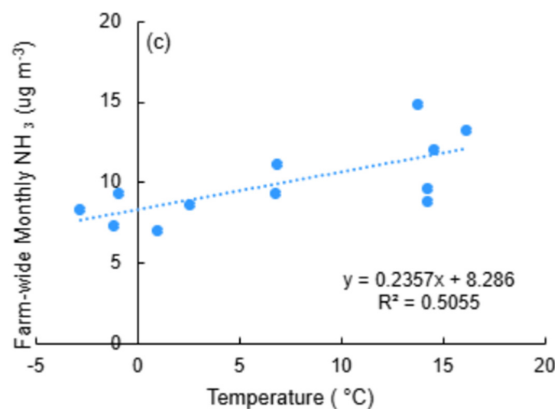
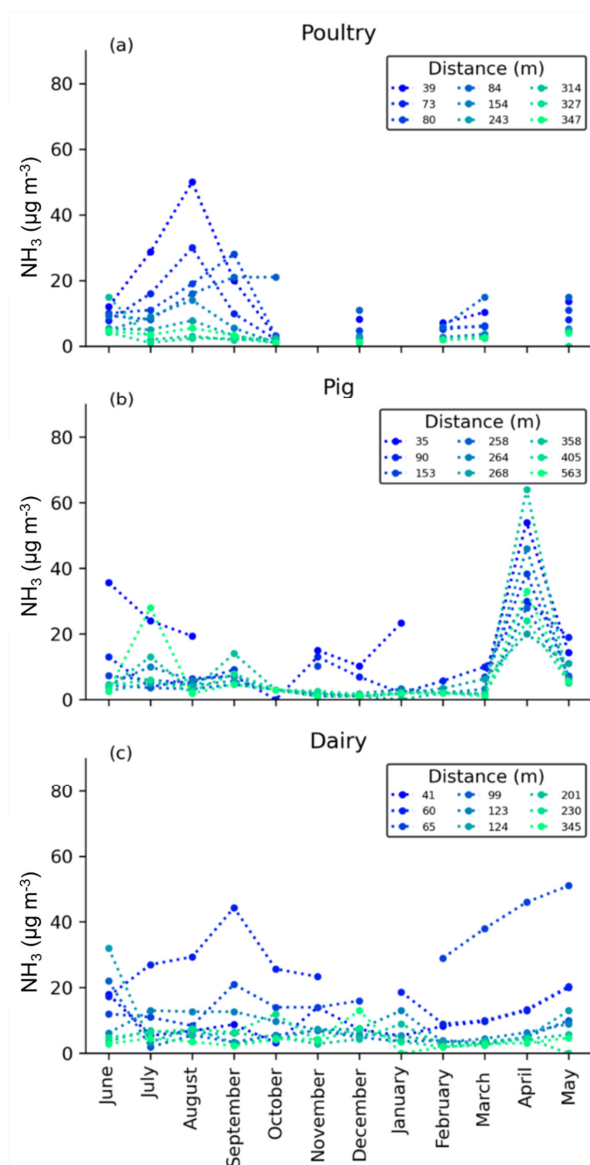


Figure 4. Relationship between monthly average ambient temperature and farm-wide NH₃ concentrations at (a) the poultry farm, (b) the pig farm (excluding April (the hollow dot) due to outlier effects from manure spreading), and (c) the dairy farm.

250 3.4 Local Drivers of Ammonia Concentration Variability Near Livestock Housing

Figure 5 shows that monthly NH₃ concentrations at all measurement sites vary with distance to livestock housing across all three farms. Larger fluctuations were observed close to the housing facilities, while measurements at more distant sites generally exhibited smaller month-to-month changes, reflecting more stable background conditions. In this context, stability refers to the degree of temporal consistency in measured NH₃ concentrations at a given site, excluding major emission events such as house cleaning or manure spreading. These large, short-term activities introduce sharp peaks in concentration that are important to document but do not represent the farm's typical emission dynamics over longer time scales.

Poultry farms tend to exhibit more stable NH₃ emissions over time compared to other types of livestock operations, such as dairy or pig farms. This stability is primarily due to the relatively controlled and uniform conditions under which poultry are housed. Poultry are typically kept indoors throughout the production cycle, with consistent feeding, housing, and manure accumulation patterns. As a result, the emission dynamics are largely driven by internal factors such as litter quality, ventilation rates, and housing temperature. However, poultry farms can also display cyclical emission patterns, as housing units are periodically emptied, cleaned, and restocked with new birds. The poultry farm in this study contains two poultry houses operating on different production cycles, where this process occurred in August/September for one of the poultry houses and in January for the other. As shown in Fig. 5a, the emission changes associated with this process are clearly reflected in the concentration data, with higher levels observed at sites nearest the source in August compared with September. In January, however, it was not possible to evaluate the impact of emission changes from the livestock facilities due to a data gap.



270 **Figure 5.** Monthly NH_3 concentrations at all measurement sites for the poultry farm (a), pig farm (b) and dairy farm (c) with colour indicating distance from the livestock housing. Each point represents a monthly value at a specific site, allowing visualization of temporal trends and spatial gradients simultaneously.



On pig farms, the timing of livestock movements (e.g., weaning, finishing, slaughter) can lead to short-term spikes or drops in emissions depending on manure accumulation and ventilation dynamics. At the pig farm, one sampling location (site 1) stands out with significantly higher NH_3 concentrations compared to the other measurement points (Fig. 5b). This sampler was positioned in an open area approximately 40 meters from the livestock unit door, and the elevated readings may be attributed to its proximity to emission sources and specific local conditions during the sampling period. As shown in Table 2, the concentration differences at this location are particularly pronounced during the summer months, likely due to increased ventilation and opening doors, which facilitate greater emission dispersal through the open doors. Overall, the data indicate that elevated NH_3 levels are primarily associated with large-scale livestock operations as a whole, rather than emissions from housing alone.

The dairy farm exhibits greater variability in the measured concentrations compared with the two other farms, likely due to a higher degree of influence from on-farm activities. On dairy farms, ammonia levels fluctuate seasonally due to changes in livestock housing (indoor vs. pasture), manure handling, and temperature. During the summer, cattle may graze outdoors, leading to a spatial redistribution of emissions and reduced in-barn NH_3 levels, whereas winter housing concentrates emissions around the housing and manure storage facilities. Notably, during the measurement period at the dairy farm, a new housing facility was constructed and became operational in February 2024, housing 400 calves. This development is reflected in the data as a marked increase in NH_3 concentrations at the sites closest to housing from February and onward (Fig. 5c). The impact of the new livestock unit is also observable at adjacent measurement sites, indicating localized changes in emission patterns and dispersion.

Although this study primarily focused on emissions originating from housing facilities, contributions from surrounding manure spreading operations activities cannot be overlooked. Notably transient increases in NH_3 concentrations were observed even at the sites furthest away from the housing facilities, especially during spring. This pattern was particularly prevalent for the pig farm (Fig. 5b), where concentrations peaked in April across all measurement locations. This event likely coincides with field spreading of manure or slurry, which is a known episodic contributor to elevated NH_3 concentrations (Misselbrook et al., 2005; Kamp et al., 2024). Episodic peaks in spring were also observed by Epps et al. (2025), likely linked to manure spreading activities. As the poultry farm also is surrounded by open agricultural fields, we expected to observe a similar seasonal pattern in NH_3 concentrations as seen at the pig farm; however, this trend is not evident. One possible explanation is the length of the measurement period at the poultry farm, which spanned both March and April. This can potentially have averaged out seasonal contrasts. Differences in management practices, e.g. deep litter vs slurry, or local weather conditions may also have played a role. Additionally, it is possible that the pig farm is more influenced by transboundary ammonia transport from outside Sweden. However, based on the available data, the underlying reason for the deviation remains uncertain. Nevertheless, the overall patterns in NH_3 concentrations remain clearly discernible. Despite the elevated levels for the pig farm in April from manure spreading in the surrounding area, it is still possible to see the contribution from the livestock farm as the levels are generally decreasing with the distance from the source. This is indicated by the general decrease in concentrations with increasing



distance from the source, as shown by the transect data (site 1-4) in Table 2. Hence, while acute episodes are often associated with field spreading, our results underscore that continuous emissions from livestock housing facilities also play a substantial role in sustaining elevated background levels throughout the year. These findings support previous work demonstrating that both source activity and atmospheric conditions shape the spatio-temporal distribution of NH₃ in agricultural landscapes (Tang et al., 2018).

3.5 Measurement Uncertainties and Limitations

Ammonia (NH₃) measurements in agricultural environments are subject to multiple sources of uncertainty, stemming from both methodological and environmental factors. At two locations on each farm, three samplers were deployed in parallel to evaluate the accuracy and consistency of the measurements. Good agreement was observed among triplicates at the same location, except in cases where samplers were reported as wet or other anomalies were noted (see Table A1 and A2 in Appendix A for details).

In this study, passive diffusive samplers were used to obtain time-integrated concentration estimates over monthly periods. The monthly integration period used in this study cannot capture short-term fluctuations in emissions that result from farm management activities (e.g., manure handling or ventilation changes) or meteorological variability (e.g., sudden shifts in wind direction or temperature). Consequently, peak emission events may be underrepresented. These limitations are partially mitigated by the year-long monitoring period and by the spatial distribution of samplers around each farm, which provides a robust assessment of seasonal trends and dispersion under a broad range of weather conditions.

Wind speed and direction, in particular, have a strong impact on observed NH₃ concentrations, underscoring the importance of meteorological factors in short-range dispersion and deposition (Ge et al., 2023; Kamp et al., 2024). By placing samplers around each farm in all wind directions, the influence of wind direction on individual measurements was minimized when calculating farm-wide average concentrations. As a result, the farm-wide concentration reflects the overall emission signal from the farm, independent of the prevailing wind direction during the measurement periods.

4 Conclusions

This study investigated spatial and temporal variability in atmospheric NH₃ concentrations around pig, poultry, and dairy farms in Sweden using passive samplers deployed at 27 locations over a 12-month period. Annual mean concentrations ranged from 1.8–17.0 µg m⁻³ at the poultry farm, 5.2–22.5 µg m⁻³ at the pig farm, and 4.0–23.7 µg m⁻³ at the dairy farm. Concentrations exceeded nearby background levels (0.44–0.45 µg m⁻³) at all sites and declined by approximately 4–5-fold between about 40 m and 300 m from livestock housing. These results support our hypothesis that intensive livestock facilities act as strong local point sources of atmospheric NH₃, even within agricultural landscapes where regional ammonia levels are already elevated.



335 The measurements further demonstrated that temporal variability is strongly influenced by farm management and meteorological conditions. NH_3 concentrations were positively correlated with ambient temperature at all three farms, while episodic peaks were associated with farm-specific activities such as slurry spreading and changes in livestock housing. The pig and dairy farms showed greater temporal variability than the poultry farm, reflecting differences in housing systems, manure management, and livestock practices. Together, these findings confirm that both continuous emissions from livestock housing and short-term management activities contribute to observed NH_3 concentration patterns.

The observed spatial gradients and seasonal behaviour are consistent with previous studies reporting elevated NH_3 concentrations near livestock operations and rapid declines with distance from emission sources (e.g. Tang et al., 2005; Jones et al., 2013; Souhar et al., 2022). However, relatively few studies have combined year-long monitoring with high spatial resolution around multiple livestock production systems. By comparing pig, poultry, and dairy farms using a common measurement approach, this study extends current understanding of how production systems, farm management, and local environmental conditions interact to influence near-source NH_3 concentrations.

Several limitations should be considered when interpreting the results. The passive sampling approach provides monthly mean concentrations and therefore cannot resolve short-term emission events or meteorological fluctuations. In addition, the study was based on three farms and one year of measurements, limiting the ability to assess interannual variability. Nevertheless, the consistency of the observed spatial gradients and seasonal patterns across sites provides confidence in the overall conclusions.

These findings have important implications for understanding the behaviour of atmospheric NH_3 in agricultural landscapes. The results demonstrate that elevated concentrations can persist hundreds of metres from livestock housing and remain substantially above regional background levels, increasing the potential for local nitrogen deposition to sensitive ecosystems. The strong influence of temperature and management activities also highlights the need for emission inventories, atmospheric models, and mitigation strategies to account for both climatic and operational controls on NH_3 emissions. Long-term, spatially resolved monitoring near livestock facilities can therefore provide critical information for improving assessments of agricultural nitrogen pollution and supporting environmental policy development under frameworks such as the NEC Directive and the Industrial Emissions Directive.

Code, data, or code and data availability

360 All data generated and analysed during this study are presented within the article and its Appendix. The figures are based exclusively on the measurement data reported herein. No additional unpublished datasets were used. The dataset supporting this study is openly available via Zenodo: *One year measurements of ammonia levels at three Swedish farms* (Watne et al., 2026), <https://doi.org/10.5281/zenodo.19495370>. All external datasets applied in the analysis (e.g. background concentrations



and meteorological data) are openly accessible through their respective national or international data providers and are cited
365 in the manuscript with appropriate references.

Author contributions

S.H. and Å.K.W. were responsible for Conceptualization and Methodology of the study. S.P. and Å.K.W. carried out the
Investigation and Data curation, including field measurements and quality control of ammonia concentration data. S.H. and
Å.K.W. performed the Formal analysis and Validation of the results. W.J.B., M.T., A.V., C.M.H. and Å.H. contributed to
370 Methodology, Visualization, and interpretation of results. S.H., Å.K.W. and S.P. prepared the Writing, original draft, with
contributions from all co-authors. All authors contributed to Writing, review and editing, discussed the results, and approved
the final manuscript. Project administration and Supervision were led by S.H.

Competing interests

The authors declare that they have no known financial or personal relationships that could have appeared to influence the work
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Although the tool is intended to support environmental permitting and may be used by regulatory authorities and consultants,
the authors have no commercial interests associated with its application. The funders had no role in study design, data
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385 also to synthesize the conclusions in a structured manner. After using this tool/service, the author(s) reviewed and edited the
content as needed and take(s) full responsibility for the content of the published article.

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Appendix A –Timeline and measurement data of Farm Monitoring Activities (2023–2024)

Table A1: Sampling periods conducted at the three farms across a 12-month timeframe (June 2023 – June 2024). Each row corresponds to a calendar month, listing the start and end dates for data collection at each farm type.

Month	Pig Farm	Poultry Farm	Dairy Farm
June	31 May – 25 Jun 2023	30 May – 3 Jul 2023	29 May – 28 Jun 2023
July	25 Jun – 1 Aug 2023	3 Jul – 7 Aug 2023	28 Jun – 31 Jul 2023
August	1 Aug – 30 Aug 2023	7 Aug – 7 Sep 2023	31 Jul – 3 Sep 2023
September	30 Aug – 17 Oct 2023	7 Sep – 13 Oct 2023	3 Sep – 25 Sep 2023
October	17 Oct – 2 Nov 2023	13 Oct – 16 Nov 2023	25 Sep – 8 Nov 2023
November	2 Nov – 8 Dec 2023	-	8 Nov – 30 Nov 2023
December	8 Dec – 9 Jan 2024	16 Nov – 24 Jan 2024	30 Nov – 8 Jan 2024
January	9 Jan – 8 Feb 2024	-	8 Jan – 8 Feb 2024
February	8 Feb – 8 Mar 2024	24 Jan – 22 Feb 2024	8 Feb – 9 Mar 2024
March	8 Mar – 15 Apr 2024	22 Feb – 1 May 2024	9 Mar – 5 Apr 2024
April	15 Apr – 6 May 2024	-	5 Apr – 8 May 2024
May	6 May – 11 Jun 2024	1 May – 7 Jun 2024	8 May – 15 Jun 2024



Table A2: Monthly ammonia concentrations ($\mu\text{g m}^{-3}$) on the nine measurement sites of the three farms.

Livestock	Site	June	July	August	September	October	November	December	January	February	March	April	May
Poultry	1	12.0	28.7	50.0	20.0	2.9	***	8.2	***	7.1	10.3	***	13.7
	2	7.7	16.0	30.0	9.9	2.1	***	**	***	5.1	6.3	***	8.1
	3	4.8	9.0	14.0	5.5	1.0	***	3.0	***	2.7	3.7	***	5.3
	4	4.7	3.4	5.5	3.3	1.0	***	1.2	***	2.0	2.6	***	4.0
	5	5.4	5.0	7.8	3.2	1.0	***	2.5	***	2.0	2.8	***	4.7
	6	4.2	1.0	2.4	2.3	1.0	***	1.0	***	2.0	2.4	***	***
	7	15.0	2.0	3.0	1.9	2.4	***	1.3	***	2.0	2.6	***	4.3
	8	9.3	8.1	16.0	21.0	21.0	***	11.0	***	6.0	15.0	***	15.0
	9	10.0	11.0	19.0	28.0	3.1	***	4.8	***	5.8	5.9	***	11.0
Pig	1	35.7	24.0	19.3	*	**	15.0	10.3	23.3	**	6.4	54.0	14.3
	2	7.3	5.9	5.1	9.2	**	10.2	*	****	**	6.9	38.3	7.2
	3	4.3	3.6	3.2	4.6	3.0	1.0	1.0	3.3	2.0	1.8	28.0	6.5
	4	2.5	28.0	1.9	4.6	3.0	1.0	1.0	2.0	2.0	1.0	33.0	5.5
	5	3.7	13.0	2.7	14.0	3.0	1.8	1.0	****	2.0	1.7	64.0	5.1
	6	4.3	6.0	2.5	7.9	3.0	2.6	1.6	2.0	2.0	1.5	24.0	5.4
	7	13.0	3.7	6.4	7.2	**	13.0	6.9	2.0	5.7	10.0	30.0	19.0
	8	2.6	5.0	4.3	5.7	3.0	2.1	1.0	1.8	3.4	6.3	20.0	11.0
	9	4.5	10.0	5.9	7.2	3.0	1.6	1.8	3.1	2.0	3.2	46.0	6.2
Dairy	1	17.3	27.0	29.3	44.3	25.7	23.3	****	18.7	9.0	10.0	13.3	20.3
	2	6.2	13.0	12.7	12.7	9.8	7.2	7.4	13.0	3.4	4.5	6.3	8.9
	3	3.7	6.9	5.6	6.1	5.0	2.9	4.3	9.0	2.3	3.8	4.3	5.7
	4	12.0	11.0	8.4	21.0	14.0	14.0	16.0	>250 ^a	29.0	38.0	46.0	51.0
	5	2.9	4.6	3.5	2.3	4.3	4.3	13.0	****	1.9	2.9	3.1	4.7
	6	4.8	6.4	7.3	6.4	12.0	3.7	7.6	3.5	2.0	2.5	4.6	****
	7	32.0	3.4	7.6	3.1	4.1	7.3	5.8	5.2	3.7	2.8	4.8	13.0
	8	22.0	1.9	5.5	3.4	5.5	6.9	4.9	3.6	3.9	3.1	5.0	10.0
	9	18.0	5.4	6.8	8.8	3.2	14.0	7.3	5.3	8.3	9.7	13.0	20.0

* Sampling equipment being dislodged by strong winds

**Wet filter

***Overlapping measurement period

515 ****Sample missing

^a Sample valid, but it has been excluded from the analysis as it was influenced by the commissioning of the shed.



520 **Table A3: Standard deviation ($\mu\text{g m}^{-3}$) of the three samplers measured in parallel at two sites on the poultry, pig and dairy farm.**

	June	July	August	September	October	November	December	January	February	March	April	May
Poultry 1	1.0	1.2	2.6	1.7	0.1	**	0.3	**	0.2	0.6	**	1.2
Poultry 2	0.1	0.0	2.0	0.0	0.3	**	17.2	**	0.5	0.2	**	0.6
Pig 1	0.6	1.0	2.1	*	9.9	2.6	0.6	1.2	20.0	0.5	**	0.6
Pig2	0.4	0.4	0.1	0.7	*	5.3	*	*	10.0	1.3	4.7	0.8
Dairy 1	0.6	1.0	1.5	1.5	0.6	3.5	0.0	1.2	0.3	0.0	0.6	2.1
Dairy2	0.1	0.0	0.6	1.2	0.4	4.2	2.1	1.0	0.2	0.2	0.1	0.3

* Sampling equipment being dislodged by strong winds

**Overlapping measurement period

***Sample missing

525