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Modeling emissions from CAFO poultry farms in Poland and evaluating potential risk to surrounding populations☆

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Abstract

The world-wide use of concentrated animal feeding operations (CAFOs) for livestock production demands the need to evaluate the potential impact to public health. We estimated the exposure of various airborne pollutants for populations residing in close proximity to 10 poultry CAFOs located in Central Poland. Ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), methane (CH_4), nitrogen dioxide (NO_2), nitrous oxide (N_2O), sulfur dioxide (SO_2), and organic dust were the pollutants of interest for this study. Because no monitoring data were available, we used the steady-state Gaussian dispersion model AERMOD to estimate pollutant concentrations for the exposed population in order to calculate the hazard index (HI) for a combined mixture of chemicals. Our results indicate that while the levels of certain pollutants are expected to exceed background levels commonly found in the environment they did not result in calculated hazard indexes which exceeded unity suggesting low potential for adverse health effects for the surrounding community for the mixture of chemicals. The study was conducted through a cooperation between the Agency for Toxic Substances and Disease Registry (ATSDR) in the USA and the Nofer Institute of Occupational Medicine (NIOM) in Poland.

Keywords

Animal feeding operations; Air pollution; Emissions modeling; Mixtures evaluation

1. Background

In recent years, Poland has become one of the major producers of poultry meat in the European Union. Over the last decade, poultry production in the nation of Poland has doubled reaching an output of approximately 2.2 million MT in 2014 (USDA, 2015). This higher production of poultry meat has been stimulated by growing domestic consumption and higher export demand. To keep up with increasing demand, expansion of poultry

☆The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the Agency for Toxic Substances and Disease Registry.

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CAFOs in rural areas of Central Poland has occurred. A common complaint of residents nearby CAFOs is the malodor caused by various compounds including volatile organic compounds (VOCs), ammonia and hydrogen sulfide that arise from manure and its fermentation (NRC, 2003). In addition to the production of nuisance odors, exposure to some of these gases can produce health risks such as respiratory system irritation and inflammation and abnormal lung function test results (Von Essen and Auvermann, 2005; Heederik et al., 2007).

Numerous epidemiological studies in general populations have examined associations between exposure to air pollutants and health effects. In general, these studies have found evidence for multiple air pollutants as contributors to reported outcomes, including cardiovascular, respiratory, neurologic, and mortality end points. The joint toxic action between any of the binary combinations of the pollutants has not been fully explained mainly because of confounding exposures. However, evidence is provided from several studies of increased risks of adverse cardiovascular and respiratory outcomes in the context of ongoing cardiovascular disease (e.g., ischemic heart disease) and respiratory diseases (e.g., asthma). These studies suggest that it is likely that interactions contribute to outcomes observed in populations exposed to multiple air pollutants (EPA, 2000). While there is no one single universal approach for the assessment of human health risk from exposure to a mixture of chemicals; governmental agencies in the United States and Europe have begun using a hazard index approach to screen for the regulatory risk assessment of chemical mixtures (Sarigiannis and Hansen 2012; Wilbur et al., 2004). The hazard index (HI) of a mixture of chemicals is obtained by taking the sum of the compound-specific hazard quotients (HQi), calculated as the ratio of the exposure to the dose of no concern (i.e. the exposure above which adverse effects on human health can be expected).

AERMOD is a recommended U.S. Environmental Protection Agency (EPA) air quality regulatory modeling package that can predict or simulate the ambient concentrations of contaminants in the atmosphere. It has recently been shown to accurately predict levels of $PM_{2.5}$ and PM_{10} particulates from a poultry CAFO (Hadlocon et al., 2015) and odor causing contaminants from a swine CAFO. The goal of this study was to estimate exposures to a local community and assess the potential health risks for populations residing near 10 poultry CAFOs in the Lodz Voivodeship, Poland by using AERMOD and the hazard index approach. The present study was performed under the cooperation between the Agency for Toxic Substances and Disease Registry (ATSDR) in the USA and the Nofer Institute of Occupational Medicine (NIOM) in Poland.

2. Methods

2.1. Modeling

The air dispersion modeling was performed using AERMOD (Lake Environmental, View Version 14134), a steady-state Gaussian plume model that can model pollutant concentrations up to 50 km from the emission source and is applicable to rural or urban areas that possess flat or complex terrains and multiple sources. AERMOD utilizes two pre-processors: AERMET which is a meteorological preprocessor that prepares hourly surface data and upper air data and AERMAP which is a terrain pre-processor. Site-specific surface

roughness heights at each farm were provided by NIOM and ranged from 0.035 (Farm 9) to 1.35 m (m) (Farm1). Site-specific Albedo and Bowen ratios were not provided; therefore, they were estimated based upon land use data using default AERSURFACE values. Since no representative meteorological station was available for the 10 CAFOs, surface and upper air meteorological data for use in the AERMET pre-processor were obtained using the fifth-generation mesoscale model (MM5) for Zgierz, Poland (51.8573793 N, 19.344853 E) for the year 2011.

Several options are available within AERMOD to represent emissions from a facility. Point or flare sources are appropriate for smoke stack emissions in which the stack height, gas exit velocity, stack diameter, and gas temperature are known. Area sources are used to model ground-level area emissions that may arise from a source such as a lagoon or waste pond, while open pit sources are used to simulate fugitive emissions from below ground (e.g., coal mines). Pollutant releases from CAFO facilities are atypical of characteristic industrial emissions that may arise from a stack or flue source; however, volume sources have been shown to be effective when modeling the emissions of pollutants from CAFO buildings (Hadlocon et al., 2015; O'Shaughnessy and Altmaier 2011). Since there were no monitoring data available near the 10 CAFOs to estimate local population exposure, the estimated concentrations of pollutants were modeled using three approaches that employed volume sources: (1) a single volume source representing the farm as a whole, (2) adjacent line volume sources used to represent the rectangular dimensions of the buildings, and (3) multiple volume sources used to represent each individual vent (roof and wall) in each building contained on the farm at the specified coordinates and heights when available or estimated from Landsat imagery data.

Modeling the entire farm as a single volume source was deemed necessary since one constraint of the available data was that annual emission estimates of each pollutant were only available for the entire CAFO, even though there are multiple buildings containing multiple venting units on each farm. Because each farm consists of two or more buildings, the second modeling approach was used to treat each building within the farm as a unique volume source. Technically, volume sources in AERMOD are represented as a geometric square; however, the buildings within these farms are more rectangular in shape. To correct for these geometric structural features, each individual building was represented as a series of adjacent volume sources using the width of the building as the base size. For example, an 80 × 20 m building was represented as four adjacent 20 × 20 m volume sources; a 90 × 15 m building was characterized by six 15 × 15 m adjacent volume sources, and so forth (EPA, 1995a, 1995b). As stated above, emission rates of the chemicals were not available for individual buildings within the farms; therefore, the emission rates were linearly adjusted by considering the number of poultry housed in each building of the farm. For example, if a farm consisted of two buildings and the first building housed 70,000 poultry and the second housed 30,000 poultry, it was assumed that 70% of the emissions from the farm arose from the first building, while 30% arose from the second. For buildings consisting of several wall and roof vents with differing heights, the release height of the volume sources used to represent the building was taken as the average value of the height of the vents. The final modeling approach was to treat all of the vents (roof and wall vents) from each building as a separate unique volume source positioned at specified locations and heights of the building.

The coordinates of each vent on all the buildings were provided by NIOM or obtained from Landsat imagery data. This method is similar to the approach employed by Hadlocon et al. (2015) for modeling particulate emissions from a poultry CAFO in Ohio and represents the most elegant modeling approach since it provides the greatest spatial resolution of the emissions to the surrounding environment but was also the most time consuming approach. Given the limitations of the available emission data and lack of monitoring data this multi-tiered methodology provided a rational method to estimate the concentrations of airborne contaminants at nearby receptor sites of the farms and evaluate the sensitivity of certain modeling input parameters.

Each CAFO was initially modeled individually without regard to other possible emission sources in the general vicinity; however, Farms 6 and 7 had buildings that were only separated by a distance of approximately 200 m. Therefore, the results presented here reflect AERMOD output using the same receptor grid and modeling the emission sources jointly. Farms 2 and 3 are separated by < 1 km. Therefore, these facilities were also modeled jointly and the results presented here represent the farms modeled together using the same receptor grid. Each modeled area consisted of over 400 discrete Cartesian receptors covering approximately 25–30 km^2. Sensitive receptors (nearby homes or dwellings not associated with the farms) near the buildings of the CAFOs were identified by Landsat imagery data available from Google Earth. The concentration of pollutants at these receptors was used to estimate levels of the most exposed population.

Annual emission data were provided by NIOM for the 10 poultry farms from Lodz Voivodeship Poland. Each of the farms housed between 60,000 and 404,500 laying hens or broilers in several buildings and each building contained multiple mechanical ventilation units. These emission rates are summarized in Table 1. NIOM was unable to provide emission rates for some of the pollutants at certain farms; therefore, the modeled concentrations of pollutants will be underestimated at these locations where no data were available. All emissions were assumed to emanate from the buildings housing the poultry and not from external sources associated with the farm such as outdoor waste lagoons, spreading manure or fertilizer onto soils or the operation of outdoor farm equipment.

2.2. Risk characterization

The potential health risks to residents of the dwellings near the CAFOs were evaluated using a hazard index approach consistent with ATSDR's mixtures guidance (ATSDR, 2004a). In the hazard index approach, the estimated exposure concentration for each pollutant in the mixture is scaled by a defined level of exposure generally regarded as “acceptable” or “safe” (i.e., health-based guidance value). If the hazard index exceeds unity, there is concern for the potential health hazard and further evaluation of the mixture is warranted.

The general equation for the hazard index (*HI*) calculation is:

$$HI = \frac{ChemExposure_1}{DR_1} + \frac{ChemExposure_2}{DR_2} + \ldots + \frac{ChemExposure_n}{DR_n}$$

where $ChemExposure_1$ is defined as the level of exposure to the first chemical in the mixture and DR_1 is some defined level of exposure to the first chemical (i.e., health-based guidance value), $ChemExposure_2$ and DR_2 are the corresponding levels for chemical 2, etc. Each chemical specific ratio (e.g., $ChemExposure_1/DR_1$) is called a hazard quotient (HQ). The hazard index can be expressed as the sum of the hazard quotients.

Hazard quotients were calculated using the estimated first high 1-h concentrations for each receptor site and the 60-min AEGL-1 values or the 1-h National Ambient Air Quality Standard (NAAQS) values (Table 2). Pollutants without 1-h guidance levels (nitrous oxide, carbon dioxide, methane, and organic dust) were not included in the hazard index calculations. For pollutants (nitrogen dioxide and sulfur dioxide) with 1-h AEGL-1 values and 1-h NAAQS values, the lower of the two values was selected for the hazard quotient calculation. The HI values have been calculated using exposures due to emissions emanating from the CAFOs and do not include contributions from background levels that may typically be found in ambient air.

3. Results

3.1. AERMOD modeling

The first high 1-h concentrations at 5 residential receptors within 1 km for each farm are presented in Tables 3–10. Concentrations calculated at ground level heights are presented here as these represented the most conservative approach (levels of pollutants were approximately 10–15% lower when using flagpole heights). The 1-h contour plots of the entire grid can be accessed as supplemental information online. As summarized in the tables, good agreement was generally observed in the modeled levels of pollutants for each of the 3 approaches employed. Estimated concentrations of pollutants for receptors within the entire grid were typically within a factor of 2 for each of the three modeling approaches used in the study although greater variation was observed for some receptors located very near the farms due to differences in the coordinates and release heights of the volume sources. Due to the absence of any monitoring data, an assessment of which approach is superior is challenging; however, since the coordinates and heights of the vents on the buildings were available, it is sensible to use the results from the third method where the individual vents from each building were considered as separate unique sources.

The results indicate that modeled levels of several pollutants typically exceed background levels by a factor of 10 or more close to the farms but begin to return to normal levels at a distance of approximately 3–5 km away from the source. For example, typical ambient background levels of hydrogen sulfide are reported to range from approximately 0.11 to 0.33 ppb (0.15–0.46 μg/m3) (ATSDR 2015). Modeled levels at farm 1 exceeded 10 μg/m3 for receptors within 300 m from the buildings and approached 1 μg/m3 for residences within 1 km of the farm; however, they returned to background levels at distances of 2–3 km. Ambient atmospheric levels of ammonia can vary widely by location but a typical background concentration with no local sources is about 1 ppb (0.75 μg/m3) (ATSDR, 2004b). Estimated concentrations near the poultry CAFOs were several hundred ppb and did not drop to near background levels for several km.

3.2. Risk characterization

In the initial phase of the risk characterization, hazard quotients were calculated for each receptor site using the 1-h predicted concentrations (Tables 3–10) and the 60-min AEGL-1 values (ammonia and hydrogen sulfide) or the 60-min NAAQS values (carbon monoxide, nitrogen dioxide, and sulfur dioxide) (Table 2). The pollutant concentrations predicted using the modeling approach of treating each farm as a single volume source were utilized; this approach was considered superior to the other approaches since emission rates were only available for the entire CAFO. Table 11 summarizes the highest hazard quotient for each pollutant at a farm. Most of the hazard quotients were less than 0.1; only sulfur dioxide and nitrogen dioxide exceeded 0.1. The hazard quotients for these compounds were 0.64 and 0.21, respectively. The highest hazard quotients for ammonia, carbon monoxide, hydrogen sulfide, nitrogen dioxide, and sulfur dioxide were 0.093 at Farms 6 and 7 (combined), 0.0049 at Farms 2 and 3 (combined), 0.0015 at Farm 1, 0.21 at Farms 2 and 3 (combined), and 0.64 at Farms 2 and 3 (combined), respectively. All farms were missing emission rate data for at least one pollutant; Farms 2 and 3 (combined) had the most complete information.

Hazard indices were calculated by summing the hazard quotients for each receptor site (Table 12). The highest hazard indices for each farm ranged from 0.0024 at Farm 1 to 0.86 at Farms 2 and 3 (combined). Missing emission rates and/or the lack of 1-h guidance values resulted in hazard indices which were calculated for four or less pollutants. Ammonia, carbon monoxide, nitrogen dioxide, and sulfur dioxide were included in the hazard index calculation for Farms 2 and 3 (combined), Farm 4, and Farm 10. For Farms 6 and 7 (combined) and Farm 8, the only pollutant included in the hazard index calculation was ammonia.

4. Discussion

Hazard indices were calculated as a screening tool to assess whether the concentrations of pollutants emanating from the poultry CAFOs could pose a health risk to the surrounding communities. This approach, which is recommended by numerous U.S. agencies (ATSDR 2004a; EPA, 1986, 1989; NAS, 1974; NRC, 1989; OSHA, 1993, 2001), assumes that the chemicals in the mixture act independently, such that one does not affect the toxicity of the other; this type of joint action is called additivity. ATSDR (2004a) defines additivity in terms of dose addition and response addition. The difference between dose addition and response addition is whether the compounds in the mixture act by similar modes of action to produce similar effects (dose addition) or by different modes of action to produce similar or dissimilar effects (response addition). At most of the CAFO receptor sites, the hazard indices were low (≤0.02), indicating low risk. However, at two farms, the hazard index for the mixture of ammonia, carbon monoxide, nitrogen dioxide and sulfur dioxide was higher (0.1), but still less than 1, the point of concern. (Table 12). At Farms 2 and 3 (combined), the hazard indices at two receptor sites were 0.86; as noted previously, an emission rate was not available for sulfur dioxide at Farm 3, therefore, the predicted exposure concentration likely was underestimated. Further analysis on the contribution of the individual components to the overall hazard showed that the hazard quotient for sulfur dioxide accounted for

approximately 75% of the hazard index, and sulfur dioxide and nitrogen dioxide together accounted for approximately 99% of the total hazard index.

In assessing the toxicity of a mixture, ATSDR (2004a) uses a binary weight of evidence method which evaluates the joint action of each possible pair of chemicals in the mixture to qualitatively adjust the hazard index. For example, if the component analysis indicates that several binary combinations will have less than additive joint toxic action, the hazard index may overestimate the actual hazard presented by the exposure scenario. Given that the hazard index for Farms 2 and 3 (combined) is predominated by the hazard quotients for sulfur dioxide and nitrogen dioxide, possible joint action of these two compounds was explored. The primary target for both sulfur dioxide and nitrogen dioxide is the respiratory tract; one of the most sensitive effects is an increase in airway hyperresponsiveness in asthmatics. In a study of asthmatics exposed to 750 μg/m^3 nitrogen dioxide and/or 520 μg/m^3 sulfur dioxide for 6 h, a significant decrease in the cumulative breath units of the allergen, *Dermatophagoides pteronyssinus*, required to produce a 20% fall in forced expiratory volume in 1 s was observed when the subjects were exposed to both compounds, but not after exposure to a single compound (Devalia et al., 1994). In another controlled exposure study in asthmatics, an enhanced responsiveness to 1970 μg/m^3 sulfur dioxide was reported following exposure to 470 μg/m^3 nitrogen dioxide for 30 min (Jorres and Magnussen, 1990). Although these studies suggest some joint action, the data are not adequate to assess the nature of the additivity (i.e., additive, greater than additive or less than additive).

Due to the lack of 1-h guidance values, four pollutants (carbon dioxide, methane, nitrous oxide, and organic dust) were not included in the risk characterization. Although carbon dioxide and nitrous oxide do not have acute guidance values, occupational exposure values of 9000 mg/m^3 (NIOSH, 2015) and 90 mg/m^3 (ACGIH, 2015) have been established. The highest estimated concentrations for carbon dioxide and nitrous oxide at a residential receptor site were 0.02 and 0.001 times lower than these occupational levels suggesting that they would not likely be significant contributors to the overall hazard. Methane is a simple asphyxiant. High concentrations of methane gas (>92,000 mg/m^3) can displace the supply of oxygen in the air, especially in confined spaces (Carreon and Herrick, 2012). Methane is predicted to induce central nervous system effects in humans at 200,000 mg/m^3. The highest estimated concentration at a residential receptor site was 2.79 mg/m^3 which is substantially lower than these LOAEL values and, therefore, not likely to be a major contributor to the overall hazard. Organic dusts emanating from CAFOs can consist of various types of contaminants, and very high concentrations of pathogenic and non-pathogenic microorganisms (bacteria, fungi and viruses) as well as their derivative structures, including endotoxins, (1 → 3)-β-D-glucans and allergens (Hartung and Schulz, 2011; Schulz et al., 2005; Seedorf, 2004). Several studies have shown a high level of biological hazards (bacteria, fungi, endotoxin and (1 → 3)-β-D-glucan) associated with large-scale farming of animals in Poland (Bródka et al., 2012; Cyprowski et al., 2012; Sowiak et al., 2012a, 2012b; Szadkowska-Stańczyk et al., 2010). Bacteria of the genus of *Staphylococcus, Streptococcus,* numerous Gram-negative and Gram-positive rod-shaped bacteria, including many species of *Bacillus* genus, were found in bacterial aerosols coming from hen-houses (Vučemilo et al., 2007; Zucker et al., 2000; Oppliger et al., 2008). Respiratory and systemic symptoms and

declines in lung function have been associated with endotoxin exposure in farm workers (Heederik et al., 2007). This suggest that exposure to organic dust may have a significant impact on the health of residents living near the CAFOs; however, at this time the risk cannot be quantified. Additionally, there is a potential for organic dust components to interact with the other pollutants, particularly those affecting the respiratory tract.

To summarize, levels of pollutants in the ambient atmosphere emitted at CAFOs can be estimated from air dispersion models such as AERMOD and the potential impact these contaminants may have on the health of residents living in proximity to these and other high capacity animal operations can be assessed using the results of these models. Our modeled data suggest that odor causing pollutants such as hydrogen sulfide and ammonia can exceed background concentrations by more than an order of magnitude for residential areas within a km of the farms studied, but eventually decrease to background levels several km from the source. Greater accuracy in estimating emission factors of pollutants, site specific meteorological data, as well as, consideration of confinement and associated manure management practices of the farm would allow for better model development. Further investigation into the joint actions of the components of the mixture and additional research on organic dust would allow for a more accurate assessment of the potential health effects. Although the hazard indices used as a screening tool to assess potential health risks to the surrounding communities were below unity, the exposure to organic dust emanating from the farms may have a significant impact on the health of residents living near the CAFOs; however, their potential risk cannot be quantified at this time using the hazard index approach due to a lack of data.

Transparency document

Transparency document related to this article can be found online at http://dx.doi.org/10.1016/j.yrtph.2016.11.005.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Emission rates (megagrams per year) for the 10 CAFOs.

Pollutant	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6	Farm 7	Farm 8	Farm 9	Farm 10
NH_3	8.5745	2.64	4.125	1.8	2.175	2.288	29.03	5.94	1.575	1.289
CO	x	8.65	0.011	0.060	0.064	x	x	x	0.077	0.02
CO_2	x	2879.83	x	x	x	x	2932.15	x	x	x
CH_4	15.587	31.18	x	1.8	x	x	31.18	1.29	x	x
H_2S	0.4498	x	x	x	x	x	x	x	x	x
NO_2	x	1.82	0.082	0.495	0.480	x	x	x	0.010	0.069
N_2O	8.5240	2.08	x	x	x	x	2.08	0.63	x	x
SO_2	x	5.55	x	0.318	x	x	x	x	x	0.0001
Organic dust	3.8754	4.22	6.602	5.042	6.092	6.865	6.77	1.80	2.497	5.523

x = no data.

Table 2

1-Hour guidance levels.

	1-h acute exposure guideline level-1 (AEGL-1)[a] (μg/m^3)	1-h national ambient air quality standard (NAAQS)[b] (μg/m^3)
Ammonia	21,000	NA
Carbon dioxide	NA	NA
Carbon monoxide	Not Recommended	40,000
Hydrogen sulfide	710	NA
Methane	NA	NA
Nitrogen dioxide	940	200
Nitrous oxide	NA	NA
Sulfur dioxide	520	200
Total organic dust	NA	NA

NA = not available.

[a] AEGL-1 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic nonsensory effects. These effects are not disabling and are transient and reversible upon cessation of exposure. Source: http://www.epa.gov/oppt/aegl/pubs/compiled_aegls_update_03oct2014.pdf.

[b] Source: Primary standards developed to provide public health protection, including protecting the health of sensitive populations such as asthmatics, children, and the elderly. http://www3.epa.gov/ttn/naaqs/criteria.html.

Table 3

Estimated 1-h concentration of pollutants at five receptor sites located near farm 1.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)				
	X	Y	NH_3	CH_4	H_2S	N_2O	Dust
Single volume source							
1	393325.81	5719501.61	20.0	36.4	1.05	19.9	9.06
2	393026.52	5720394.17	17.1	31.1	0.89	17.0	7.72
3	392427.94	5720691.69	8.45	15.4	0.44	8.40	3.81
4	392727.23	5720691.69	9.96	18.1	0.55	9.90	4.50
5	392427.94	5720989.21	5.09	9.26	0.27	5.06	2.30
35 adjacent line volume sources (representing all buildings)							
1	393325.81	5719501.61	23.2	43.3	1.25	23.1	43.3
2	393026.52	5720394.17	18.4	34.3	0.99	18.3	34.3
3	392427.94	5720691.69	9.70	18.1	0.52	9.65	18.1
4	392727.23	5720691.69	11.4	21.2	0.61	11.4	21.2
5	392427.94	5720989.21	5.62	10.5	0.30	5.59	10.5
196 vol sources (all vents all buildings)							
1	393325.81	5719501.61	21.5	39.0	1.13	21.4	39.0
2	393026.52	5720394.17	16.5	30.0	0.87	16.4	30.0
3	392427.94	5720691.69	9.74	17.7	0.51	9.69	17.7
4	392727.23	5720691.69	10.8	19.6	0.57	10.7	19.6
5	392427.94	5720989.21	6.09	11.1	0.32	6.06	11.1

Table 4

Estimated 1-h concentration of pollutants at five receptor sites located near farms 2 and 3.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)							
	X	Y	NH_3[a]	CO[a]	CO_2[b]	CH_4[b]	NO_2[a]	N_2O[b]	SO_2[b]	Dust[a]
Single volume sources										
1	427367.07	5753716.09	115	179	60,300	655	38.1	43.5	116	183
2	427146.76	5753553.79	98.4	198	66,600	736	42.1	48.1	128	158
3	426750.27	5753549.28	61.4	197	66,400	733	42.0	47.9	128	98.3
4	426768.49	5753716.09	56.2	105	35,400	391	22.4	25.6	68.2	90.0
5	427615.78	5753821.02	187	114	38,400	424	24.5	27.7	74.0	299
40 adjacent line volume sources (representing all buildings)										
1	427367.07	5753716.09	74.1	106	36,900	407	23.8	26.6	71.0	118
2	427146.76	5753553.79	58.2	176	61,100	675	39.3	44.1	118	93.1
3	426750.27	5753549.28	46.3	134	46,500	513	29.9	33.6	89.4	74.0
4	426768.49	5753716.09	37.4	115	39,100	432	24.8	28.2	76.3	59.8
5	427615.78	5753821.02	123	69.2	23,800	263	15.5	17.2	45.8	197
78 vol sources (all vents all buildings)										
1	427367.07	5753716.09	76.4	115	38,800	429	24.6	28.1	74.7	122
2	427146.76	5753553.79	63.8	199	67,000	740	42.4	48.4	129	102
3	426750.27	5753549.28	51.1	145	48,800	538	30.9	35.2	93.8	81.7
4	426768.49	5753716.09	36.7	117	38,400	424	24.2	27.7	73.7	58.7
5	427615.78	5753821.02	158	79.2	26,700	295	16.9	19.3	51.3	253

[a]Includes emissions from Farms 2 and 3.

[b]Includes emissions solely from Farm 2.

Table 5

Estimated 1-h concentration of pollutants at five receptor sites located near farm 4.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)					
	X	Y	NH_3	CO	CH_4	NO_2	SO_2	Dust
Single volume source								
1	425770.83	5775443.63	43.1	1.43	43.1	11.9	7.61	121
2	426069.62	5775443.63	61.4	2.04	61.4	16.9	10.8	172
3	426069.62	5776280.03	49.3	1.64	49.3	13.5	8.70	138
4	426368.41	5776280.03	39.3	1.31	39.3	10.8	6.93	110
5	426667.20	5776280.03	26.2	0.87	26.2	7.20	4.63	73.4
19 adjacent line volume sources (representing all buildings)								
1	425770.83	5775443.63	59.3	1.97	59.3	16.3	10.5	166
2	426069.62	5775443.63	61.0	2.03	61.0	16.8	10.8	171
3	426069.62	5776280.03	48.6	1.62	48.6	13.3	8.58	136
4	426368.41	5776280.03	41.5	1.38	41.5	11.4	7.32	116
5	426667.20	5776280.03	24.2	0.81	24.2	6.57	4.28	67.9
40 vol sources (all vents all buildings)								
1	425770.83	5775443.63	49.4	1.64	49.4	13.6	8.72	138
2	426069.62	5775443.63	67.4	2.24	67.4	18.5	11.9	189
3	426069.62	5776280.03	48.4	1.61	48.4	13.3	8.54	135
4	426368.41	5776280.03	40.8	1.36	40.8	11.2	7.21	114
5	426667.20	5776280.03	24.3	0.81	24.3	6.67	4.93	68.1

Table 6

Estimated 1-h concentration of pollutants at five receptor sites located near farm 5.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)			
	X	Y	NH_3	CO	NO_2	Dust
Single volume source						
1	424655.57	5776482.33	53.6	1.55	11.8	150
2	425433.17	5776683.93	24.2	0.71	5.32	67.6
3	425238.77	5776885.53	63.4	1.87	14.0	177
4	424655.57	5777087.13	81.9	2.41	18.0	229
5	424461.17	5777288.73	36.9	1.09	8.13	103
22 adjacent line volume sources (representing all buildings)						
1	424655.57	5776482.33	46.1	1.36	10.2	129
2	425433.17	5776683.93	25.6	0.76	5.63	71.7
3	425238.77	5776885.53	44.2	1.30	9.76	123.8
4	424655.57	5777087.13	40.2	1.18	8.86	112.5
5	424461.17	5777288.73	31.7	0.93	6.99	88.7
42 vol sources (all vents all buildings)						
1	424655.57	5776482.33	31.7	0.94	7.02	88.6
2	425433.17	5776683.93	26.8	0.80	5.97	75.7
3	425238.77	5776885.53	36.6	1.08	8.08	102.2
4	424655.57	5777087.13	34.6	1.03	7.68	97.5
5	424461.17	5777288.73	30.4	0.90	6.76	85.7

Table 7

Estimated 1-h concentration of pollutants at five receptor sites located near farms 6 and 7.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)				
	X	Y	NH_3[a]	CO_2[b]	CH_4[b]	N_2O[b]	Dust[a]
Single volume source							
1	385941.66	5745745.22	1450	146,000	1550	103	354
2	386542.02	5745947.46	788	74,100	788	52.5	334
3	385941.66	5746149.70	1950	196,000	2090	139	468
4	385141.18	5746351.94	619	59,500	632	42.1	226
5	385341.90	5746351.94	715	69,300	737	49.1	245
33 adjacent line volume sources (representing all buildings)							
1	385941.66	5745745.22	1390	140,000	1490	99.1	343
2	386542.02	5745947.46	577	55,900	595	39.7	206
3	385941.66	5746149.70	2070	209,000	2220	148	494
4	385141.18	5746351.94	551	52,700	560	37.4	210
5	385341.30	5746351.94	640	61,600	655	43.7	234
124 vol sources (all vents all buildings from Farms 6 and 7)							
1	385941.66	5745745.22	1260	127,000	1350	90.1	312
2	386542.02	5745947.46	514	50,600	539	35.8	187
3	385941.66	5746149.70	2590	261,000	2790	186	611
4	385141.18	5746351.94	543	51,900	552	36.7	210
5	385341.30	5746351.94	640	61,600	654	43.5	239

[a]Includes emissions from Farms 6 and 7.

[b]Includes emissions solely from Farm 7.

Table 8

Estimated 1-h concentration of pollutants at five receptor sites located near farm 8.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)			
	X	Y	NH_3	CH_4	N_2O	Dust
Single volume source						
1	386844.72	5703537.91	99.5	21.6	10.5	30.1
2	386641.48	5703746.28	129	28.0	13.5	39.0
3	385828.52	5703954.65	184	40.2	19.4	55.8
4	386031.76	5703954.65	417	90.7	43.8	126
5	386438.24	5703954.65	413	89.8	43.4	125
8 adjacent line volume sources (representing all buildings)						
1	386844.72	5703537.91	127	27.7	13.8	38.4
2	386641.48	5703746.28	86.0	18.7	9.06	26.0
3	385828.52	5703954.65	241	52.5	25.4	72.9
4	386031.76	5703954.65	460	100	48.4	139
5	386438.24	5703954.65	438	95.4	46.1	132
16 vol sources (all vents in all buildings)						
1	386844.72	5703537.91	73.0	15.9	7.75	22.1
2	386641.48	5703746.28	141	30.7	15.0	42.7
3	385828.52	5703954.65	203	44.2	21.6	61.5
4	386031.76	5703954.65	480	104	50.9	145
5	386438.24	5703954.65	465	101	49.3	140

Table 9

Estimated 1-h concentration of pollutants at five receptor sites located near farm 9.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)			
	X	Y	NH_3	CO	NO_2	Dust
Single volume source						
1	392683.60	5765511.13	128	6.23	0.80	202
2	392889.25	5765718.09	171	8.35	1.08	271
3	392889.25	5766132.01	182	8.90	1.16	288
4	392889.25	5766338.97	130	6.37	0.83	206
5	393094.90	5766338.97	150	7.32	0.95	237
14 adjacent line volume sources (representing all buildings)						
1	392683.60	5765511.13	112	5.50	0.71	178
2	392889.25	5765718.09	128	6.27	0.81	203
3	392889.25	5766132.01	143	6.99	0.91	226
4	392889.25	5766338.97	160	7.84	1.01	254
5	393094.90	5766338.97	129	6.33	0.82	209
24 vol sources (all vents all buildings)						
1	392683.60	5765511.13	123	6.02	0.78	196
2	392889.25	5765718.09	158	7.70	1.00	250
3	392889.25	5766132.01	171	8.38	1.09	272
4	392889.25	5766338.97	85.4	4.17	0.54	135
5	393094.90	5766338.97	146	7.14	0.93	232

Table 10

Estimated 1-h concentration of pollutants at five receptor sites located near farm 10.

Receptor	Universal transverse mercator		First high 1-h concentration (μg/m^3)				
	X	Y	NH_3	CO	NO_2	SO_2	Dust
Single volume source							
1	394916.68	5768278.45	17.3	0.26	0.92	0.001	74.1
2	394322.34	5768572.79	22.1	0.34	1.18	0.002	95.0
3	394619.51	5768867.13	51.1	0.79	2.73	0.004	219
4	394916.68	5769161.47	81.5	1.26	4.35	0.006	350
5	395213.85	5769161.47	57.7	0.90	3.08	0.004	248
9 adjacent line volume sources (representing all buildings)							
1	394916.68	5768278.45	15.1	0.25	0.81	0.002	65.0
2	394322.34	5768572.79	30.0	0.46	1.60	0.002	129
3	394619.51	5768867.13	73.3	1.14	3.91	0.006	314
4	394916.68	5769161.47	70.5	1.09	3.77	0.004	303
5	395213.85	5769161.47	49.7	0.77	2.66	0.004	213
33 vol sources (all vents all buildings)							
1	394916.68	5768278.45	14.3	0.22	0.77	0.001	61.5
2	394322.34	5768572.79	25.7	0.40	1.37	0.002	110
3	394619.51	5768867.13	79.7	1.24	4.26	0.006	342
4	394916.68	5769161.47	64.8	1.01	3.47	0.005	278
5	395213.85	5769161.47	53.5	0.83	2.86	0.004	230

Table 11

Hazard quotients based on the highest estimated 1-h concentrations and 1-h guidance levels.

	NH_3[a]	CO_2	CO[b]	H_2S[a]	CH_4	NO_2[b]	N_2O	SO_2[b]	Organic dust
Farm 1	0.00095	_[c]		0.0015	NG[d]	–	NG	–	NG
Farms 2 and 3	0.0089	NG	0.0049	–	NG	0.21	NG	0.64	NG
Farm 4	0.0029	–	0.000051	–	NG	0.084	–	0.054	NG
Farm 5	0.0039	–	0.000060	–	–	0.09	–	–	NG
Farms 6 and 7	0.093	NG	–	–	NG	–	NG	–	NG
Farm 8	0.020	–	–	–	NG	–	NG	–	NG
Farm 9	0.0087	–	0.00022	–	–	0.0058	–	–	NG
Farm 10	0.0039	–	0.000031	–	–	0.022	–	0.00003	NG

[a] Calculated using the 1-h AEGL-1 value.

[b] Calculated using the 1-h NAAQS value.

[c] – indicates that no emission rates were available.

[d] NG indicates no 1-h guidance values were available.

Table 12

Hazard indices based on the 1-h estimated concentrations and 1-h guidance values.

	Pollutants included in hazard index	Receptor Site				
		1	2	3	4	5
Farm 1	NH_3, H_2S	**0.0024**[a]	0.0021	0.0010	0.0012	0.00062
Farms 2 and 3	NH_3, CO, NO_2, SO_2	0.78	**0.86**	**0.86**	0.46	0.50
Farm 4	NH_3, CO, NO_2, SO_2	0.099	**0.14**	0.11	0.090	0.060
Farm 5	NH_3, CO, NO_2	0.062	0.028	0.073	**0.094**	0.042
Farms 6 and 7	NH_3	0.069	0.037	**0.093**	0.029	0.034
Farm 8	NH_3	0.00476	0.0061	0.0088	**0.020**	**0.020**
Farm 9	NH_3, CO, SO_2	0.010	**0.014**	**0.014**	0.010	0.012
Farm 10	NH_3,CO, NO_2, SO_2	0.0054	0.0070	0.016	**0.026**	0.018

Note: Missing emission rates and/or the lack of 1 h guidance values resulted in indices with different number of pollutants in the equations.

[a]Bold indicates the receptor site with the highest hazard index.