Atmospheric Pollutants and Trace Gases

Atmospheric Ammonia, Volatile Fatty Acids, and Other Odorants near Beef Feedlots

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ABSTRACT

Intensive livestock operations can release odorous gases from stored or land-applied manure. We measured concentrations of dust and 14 odor-causing gases at increasing distances from four feedlots near Lethbridge, southern Alberta, Canada. Concentration was determined from the amount of total dust or gas accumulated in the samplers, and the volume of air sampled. Adjacent the feedlots, the maximum concentration of many volatile fatty acids exceeded reported odor detection thresholds; the maximum ammonia concentration was close to the threshold. Ammonia and butyric acid approached or exceeded their individual odor thresholds as far as 200 m downwind of the feedlots. Highest concentrations were measured adjacent to land where manure was being applied. None of the odorant concentrations exceeded their irritation threshold. There was a positive relationship between ammonia concentration and odor intensity as well as dry deposition. Much of the emitted ammonia was deposited to soil immediately downwind, enough to supply all the nitrogen needed for crop growth. Odorant concentrations declined sharply with distance, though measurable odor occasionally persisted to 1 km from the feedlot, beyond the minimum separation guidelines (Alberta) for a single residential dwelling. The weekly averaged total suspended particulates (>5 μm) were below the Alberta guideline criterion except for one period. Differences among feedlots in odorant plume concentrations were partly related to the stocking density of feedlots, which presumably affects manure moisture and amount of volatiles within the pens.

Animal manure is a valuable source of plant nutrients, but hauling it long distances is costly, so it is often applied at high rates near intensive livestock operations. Partly because of this land-applied manure, the area surrounding feedlots may be affected by offensive odors. These gaseous emissions can affect nearby residents in two ways, when concentrations exceed threshold levels: (i) sensory irritation and (ii) health hazards. Determining these threshold levels is made more difficult by uncertainty about the effects of mixtures of gases; the effects of individual odorants may be additive, subtractive, synergistic, or counteractive (Mackie et al., 1998). Furthermore, the odor intensity is also affected by dust in the air; Powers (1999), for example, reported that removing dust reduced odor intensity by 40 to 70%.

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Emissions from livestock can affect human and animal health. For example, Thu et al. (1997) reported that in poorly ventilated swine (*Sus scrofa*) barns, high emissions coincided with symptoms associated with toxic or inflammatory effects on the respiratory tract of the workers. In addition, residents living downwind may show increased eye irritation, nausea, weakness, or, in some instances, psychological responses (Thu et al., 1997; Schiffman et al., 1995). High concentrations of ammonia inside barns can reduce animal production (Drummond et al., 1980) and airborne particles in feedlots coincide with a higher incidence of pneumonia in cattle (*Bos taurus*) (MacVean et al., 1986).

Livestock operations are prominent sources of atmospheric ammonia (Isermann, 1994). In Canada, agriculture accounts for some 90% of industrial ammonia emissions, and most of that (81%) is attributed to livestock manure (Janzen et al., 1999). Once volatilized, the ammonia can harm the environment in several ways. It reacts with acids (nitric, sulfuric, and hydrochloric), forming aerosols that can be transported long distances before being washed out. It may cause acidification of ecosystems by enhancing sulfur dioxide capture in clouds, which is then deposited to land and water surfaces (ApSimon et al., 1987). Ammonia deposited to land can damage vegetation (van der Eerden, 1982; van der Eerden et al., 1998; Holtan-Hartwig and Bøckman, 1994) and reduce plant biodiversity in natural ecosystems (van Dam et al., 1986; Heil and Bruggink, 1987; Sutton et al., 1993), especially when critical loads are exceeded (Fangmeier et al., 1994). Most crops grown near intensive livestock facilities are tolerant of ammonia, but sensitive crops, such as some vegetables, may be affected (van der Eerden et al., 1998). Because ammonia is a major form of N loading of nontargeted ecosystems and is released mostly from agriculture (Asman et al., 1998), the European Community has adopted a code of practice to reduce agriculture's ammonia emissions (United Nations Economic Commission for Europe, 2001). For instance, incorporating manure spread on the surface into soil can reduce ammonia volatilization by as much as 90%.

The concentration of gases in the air diminishes with distance from their source. One way of reducing odor

Abbreviations: DT, dilutions to threshold; MDS, minimum distance separation; TSP, total suspended particulates; VFA, volatile fatty acid.

nuisances, therefore, is to establish guidelines for minimum distance separation (MDS, or "setback" criteria) between livestock operations and residential areas. These guidelines may take into account many factors, such as animal type and weight, number of animals, manure handling practices, stocking density, land use, terrain, animal housing, and odor annoyance. For example, MDS guidelines have been reported for Alberta, Canada (Alberta Agriculture, Food and Rural Development, 1999), Australia (Sweeten and Rodriguez-Akabani, 1994), Austria (Schauberger and Piringer, 1997), and the USA (Jacobson et al., 2000), but all use different approaches.

To establish effective MDS criteria, we need first to know the distribution of odor-causing gases downwind of the source. The objective of our study was to relate odor to specific gas concentrations, the distance from the source, weather, and management at beef feedlots.

MATERIALS AND METHODS

In all, 14 volatile compounds, odor intensity, and dust were measured around feedlots. Their concentration adjacent the feedlot was assumed to reflect air quality typically encountered by feedlot workers and the livestock, while the downwind concentrations reflected potential exposure of nearby neighbors. In addition, information on ammonia deposition rates was also documented.

Measurement Sites

The Lethbridge North Irrigation District (LNID) in southern Alberta is one of the most concentrated beef feedlot areas in Canada. In 1995, farms in this district, encompassing 71 000 ha, fed about 291 000 beef cattle as well as other livestock: 12 600 dairy, 63 000 swine, and 499 000 poultry (Bennett and McCarley, 1995). Four feedlot sites in the LNID, with capacities of 6000, 12 000, and two with 25 000 head, were selected for the study. At one of the 25 000-head feedlots, only dust and ammonia deposition were measured. Like most in the region, these feedlots were situated on a level landscape where the surrounding land was planted to a uniform crop. Within each feedlot, pens were sloped allowing runoff water to drain into a holding lagoon. Each pen is normally cleaned twice yearly at the time cattle are moved to market (spring and fall). The solid manure accumulated in the pens is applied directly to fields and can be incorporated. In addition to feedlot air quality, we also collected some data on air quality adjacent to land amended with feedlot manure.

Air Quality Measurements at Feedlots

Odor and gas concentrations near feedlots were measured from 23 Mar. to 24 Sept. 1999. A main tower was located approximately 3 m east of the eastern perimeter of three feedlots allowing simultaneous measurements. During the monitoring period, additional downwind towers and instrumentation were located at the 12 000-head feedlot (between 22 May and 14 June) and the 25 000-head feedlot (between 18 June and 3 August).

Main Tower Measurements

The main towers were equipped with a datalogger (Model CR21X; Campbell Scientific, Logan, UT), two digital flow meters (Model GFM1700; Aalborg Instruments and Controls, Monsey, NY), anemometer (Model 014; MetOne, Grants Pass, OR), wind vane (Model 013, MetOne), and an unshielded thermocouple (junction 0.003-inch [0.076-mm] diameter, Model COCO-003; Omega Engineering, Stamford, CT). Samplers on each main tower included passive denuder samplers for ammonia concentration, a sorbent sample tube for organic compound concentrations, Tedlar bags (DuPont, Wilmington, DE) for air sampling (analyzed for odor intensity), and dust cassettes for total suspended particulates.

Ammonia concentration was measured with passive (ventilated by the wind) samplers (Schjoerring et al., 1992; McGinn and Janzen, 1998) that accumulated ammonia over a 2- to 3-d period. The samplers consisted of glass tubes (10-cm length and 0.6-cm inner diameter) coated on the inside surface with 3% oxalic acid. Two tubes (referred to as a sampling unit) were joined in series and one end was capped with a stainless steel disk having a 1-mm-diameter opening in the center to reduce airflow through the tubes. Two sampling units (four tubes in total) were mounted on a wind vane (Model 013; MetOne) so that the opening always pointed upwind. The mean wind speed was measured using an anemometer mounted at the same height on the tower as the passive samplers. The rate of airflow inside the tubes was calculated from wind speed, as described by Schjoerring et al. (1992). At the end of the sampling period, the ammonia sampler was capped and brought to the laboratory. The tube was flushed with a fixed volume of water and ammonia N in this solution was determined using a salicylate method (Kempers and Zweers, 1986). Ammonia concentration was measured in both tubes of each sampling unit to determine whether the first in the series had become saturated. The mean ammonia concentration over the sampling period was calculated from the accumulated ammonia divided by the accumulated volume of air (duration $\times$ airflow rate).

Concentrations of organic compounds were determined by pumping air, using a 12-V DC pump (Model TD3LS7; Brailsford and Company, Rye, NY), through a sorbent tube (Orbo 507; Supelco, Bellefonte, PA). The airflow was regulated to 0.4 L min^{-1} and monitored periodically with a digital flow meter (Model GFM-1700; Aalborg Instruments and Controls). After exposure for 2 to 3 d, the sorbent tubes were sealed and taken to the laboratory where gases in the absorbent (activated silica gel) were desorbed with 10 mL acetonitrile. The extract was analyzed using a gas chromatograph (GC) (Model 5890; Hewlett-Packard, Palo Alto, CA) for seven volatile fatty acids (VFAs: acetic, propionic, butyric, isobutyric, isovaleric, valeric, and caproic acids), *o*-, *m*-, and *p*-cresol, phenol, indole, and skatole. The GC conditions for VFAs included splitless injection; helium gas carrier; Nukol column (0.32-mm i.d. $\times$ 30-m length, 1-μm film thickness, no. 24207; Superlco); and split/splitless 4-mm liner packed with deactivated glass wool (no. 24270; Supelco). The GC oven temperature program was as follows: hold at 50°C for 1 min, then increase from 50 to 150°C at 20°C min^{-1} and from 150 to 195°C at 4°C min^{-1} and hold for 5 min; a flame ionization detector was used. The mean VFA concentration over the sampling period was calculated as for ammonia.

Total suspended particulates (TSP) were monitored using a polyvinyl chloride filter with a pore size of 5 μm. Air was drawn through the filter (#225-8-01-1; SKC Ltd., Eighty Four, PA) at 2.5 L min^{-1} using a 12-V DC pump (Model TD3LS7; Brailsford and Company); a blank cassette with no airflow was mounted next to the sample cassette to correct for moisture accumulation. The dust cassettes were changed weekly and weighed to within 1 μg, and quantity of dust collected was calculated as the difference in weight between cassettes. Airflows for the particulate samplers were monitored continu-

ously with electronic flow meters (Model GFM-1700; Aalborg Instruments and Controls) and recorded using a datalogger (Model 21x; Campbell Scientific). The TSP was reported in units of micrograms per cubic meter of air ($\mu g\ m^{-3}$).

Air samples were taken to evaluate odor intensity using established protocols (Sweeten and Rodriguez-Akabani, 1994; O'Brien, 1995). An inert Tedlar sample bag (10 L), previously purged three times with nitrogen gas, was placed inside a chamber constructed from a 19-L plastic pail with a sealed latching lid (M&M Industries, Chattanooga, TN). The inlet of the bag was connected to outside air via a Teflon tube passing through the chamber wall, and a regulated 12-V DC pump (Model TD3LS7; Brailsford and Company) evacuated the chamber, thus filling the sample bag. When the bag reached about 80% capacity, the pump was turned off and the bag inlet valve was closed. This approach allowed the sample bags to be filled without contamination from air passing through the pump.

Air samples were shipped to the Alberta Research Council laboratory in Vegreville, Alberta and analyzed within 24 h of collection using a dynamic dilution olfactometer (Model AC'SCENT Beta 5; St. Croix Sensory, Lake Elmo, MN) in accordance with international standards for odor measurement (E6779-91; ASTM International, West Conshohocken, PA). The unit of measurement was dilutions to threshold (DT). The olfactometer was capable of controlled dilutions of 1:100 000 down to 1:10, with 14 dilution levels within this range. The higher the dilution ratio where odor is detected (higher DT value), the greater is the odor intensity. For our samples, if no member of the odor panel detected an odor at the minimum 1:10 dilution level, it was assumed all members would detect an odor if a 1:5 dilution ratio were made. Since only half of the members detecting odor is required to set the DT value, the sample in this case would receive a DT value of 7 (minimum).

Downwind Tower Measurements

To examine dispersion of gases from the 12 000- and 25 000-head feedlots, two towers were placed 100 and 200 m downwind of the main tower. At each downwind tower, ammonia, organic compounds, and odor intensity were monitored similar to those on the main tower. Wind speed was monitored using an anemometer attached to a digital pulse accumulator that recorded wind run. Flow rate for the sorbent tube was regulated with a flow controller (#224-26-01; SKC Ltd.) whose calibration was periodically checked with a flow meter.

Real-Time Measurements of Ammonia

An open-path laser (GasFinder; Boreal, Spruce Grove, AB, Canada) was set up 200 m downwind of the 12 000- and 25 000-head feedlots to monitor ammonia concentration continuously, with 5-min averaging periods, over a 200-m path length (north–south). The laser was generally situated east of the feedlot and data were used when winds were westerly. In addition, samples were periodically collected for odor intensity, using methods reported earlier, and ammonia was measured at the same time with a chemiluminscence-type ammonia analyzer (Model 17; Thermo Environmental Instruments, Franklin, MA). Both units were on a truck with the intakes at a height of 2 m, and air was sampled for 5 min. This mobile unit allowed for simultaneous measurement of odor intensity and ammonia concentration at varying distances downwind of a feedlot source, regardless of the wind direction.

Dry Deposition of Ammonia

The deposition of dry ammonia was monitored using soil traps at the location of the instrumented towers. At each site, three open Petri dishes each holding 20 g of oven-dried soil (Typic Haplustolls) were positioned on the ground under a rain shelter (open on all sides). After exposure to ambient air for 7 to 14 d, the soil was retrieved and analyzed in the laboratory. Unexposed soil was used as the control. The soil moisture was determined and a KCl extract of the soil was analyzed for ammonium concentration using the salicylate method (Kempers and Zweers, 1986).

Statistical Analysis

Regression analysis was conducted using linear models to describe the relationship of ammonia and VFA concentrations to stocking densities. The correlations between odorant concentration and wind speed, ammonia concentration and odor intensity, and dry deposition of ammonia and ambient concentration were also evaluated. The averaged ammonia, VFA, and TSP concentration, odor intensity, and dry deposition of ammonia, which were associated with different size feedlots, were analyzed as a completely randomized design using the MIXED procedure of SAS (SAS Institute, 1996).

RESULTS AND DISCUSSION

Weather during the Sampling Period

With the fixed towers, wind direction was monitored to extract sampling periods when towers were downwind of the feedlots. From April to July 1999, the wind direction was westerly more than 60% of the time, but this proportion fell slightly in August and September (Table 1).

Monthly temperatures and precipitation during the sampling period were similar to the long-term means, though July precipitation was unusually high (Table 1). Most of the rainfall resulted from several well-defined low-pressure systems accounting for the larger rainfall events; between April and September, there were eight days with 10 mm or more rainfall and three days with 20 mm or more. Rain prevented sampling and data collection during these periods.

Table 1. Weather conditions during the 1999 feedlot trial.

	Temperature							1961–1990 Normal	
Month	Maximum	Minimum	Mean	Precipitation	Wind speed	Wind run	Percent westerly winds	Mean temperature	Precipitation
	°C			mm	km h^{-1}	km	%	°C	mm
April	12.8	−0.6	6.1	41.5	17.6	12 695	63.3	5.6	34.8
May	17	3.5	10.3	58.3	18.4	13 677	61.3	11.1	48.6
June	21	8.1	14.6	65.1	17	12 245	66.7	15.6	64.6
July	23.5	9.3	16.4	64.2	16.4	12 170	64.5	18.1	39.8
August	25.9	11.6	18.8	39.3	13.5	10 053	45.2	17.4	44.7
September	20.1	5.6	12.9	10.8	13.7	9 870	56.7	11.9	42.7

Table 2. Air quality measurements (averaged) during concurrent periods of westerly winds for three feedlots of varying capacities. Weather parameters were averages over the sampling periods.

Period ending	Ammonia concentration			Volatile fatty acids (VFAs)			Temperature	Wind direction	Wind speed
	Capacity (animals)								
	6 000	12 000	25 000	6 000	12 000	25 000			
	μg NH_3–N m^{-3}			μg m^{-3}			°C	° westerly	m s^{-1}
19 May	138	498	503	24.7	101.2	–	12.4	261	3.5
26 May	66	324	183	16.1	177.6	47.7	16.9	257	6.2
7 June	119	674	255	–	45.3	18.5	14.5	236	5.3
21 June	86	897	212	12.8	51.8	25.1	19.0	236	5.7
23 June	103	702	224	12.9	37.8	17.4	14.7	256	5.1
21 July	205	1488	1050	24.4	40.4	19.3	18.8	264	2.4
23 July	155	878	603	45.0	108.6	24.0	21.1	252	3.8
28 July	166	1043	641	26.2	25.1	26.2	21.0	268	2.4
Average	130a†	813b	459c	23.2x	73.5y	25.5x	17.3	254	4.3
SD	45	357	302	11.2	51.8	10.4	3.2	12	1.5

† Different letters (a, b, and c for NH_3–N and x and y for VFAs) in the same row indicate a significant difference at $p < 0.05$.

Air Quality Adjacent to a Feedlot

Ammonia

Of all the 2- to 3-d periods sampled, only eight periods were associated with continuous westerly winds (Table 2). Average ammonia concentrations over these eight periods ranged from 130 μg NH_3–N m^{-3} at the 6000-head feedlot to 813 μg NH_3–N m^{-3} at the 12 000-head feedlot (all significantly different at $p < 0.05$). The largest feedlot coincided with the median value (459 μg NH_3–N m^{-3}). Concentrations were not directly correlated with feedlot size, perhaps because of variations in stocking densities: 13.3 m^2 $animal^{-1}$ for the 12 000-head feedlot, 20 m^2 $animal^{-1}$ for the 6000-head feedlot, and 25.6 m^2 $animal^{-1}$ for the 25 000-head feedlot (where areas included roads and alleys between pens). The more crowded 12 000-head feedlot is speculated to result in more urine and hence more ammonia volatilized per unit area. The regression of ammonia concentration (Y) adjacent to a feedlot against stocking density (X), where $Y = -30.7X + 1070$, explained a small amount of variance in ammonia concentration between feedlots ($r^2 = 0.17$).

The total loss of ammonia presumably is related not only to concentration within the plume but also to the size of the plume. Therefore, the largest feedlot (in area) with a corresponding larger plume, might therefore have the highest losses even though concentrations in the plume are lower. Further investigation using dispersion modeling (e.g., Flesch et al., 1995) would help resolve this issue.

The ammonia concentrations in Table 2 are much higher than values reported for pristine regions (<1 μg NH_3–N m^{-3}; European Centre for Ecotoxicology and Toxicology of Chemicals, 1994), urban areas (16 μg NH_3–N m^{-3}; European Centre for Ecotoxicology and Toxicology of Chemicals, 1994), or in regions with livestock (17–24 μg NH_3–N m^{-3}; Allen et al., 1988). Luebs et al. (1974) measured a 24-h average ammonia concentration near a 600-cow dairy of 540 μg NH_3–N m^{-3}. In a previous study in the Lethbridge region, Alberta Environment (2000) measured a maximum ammonia level (one-hour exposure) adjacent a feedlot of approximately 789 μg NH_3–N m^{-3}, a concentration below the Alberta one-hour exposure guideline of approximately 1200 μg NH_3–N m^{-3}.

Organic Compounds

The recovery of VFAs from the standards analyzed along with the samples indicate a 5% precision and 10 to 20% accuracy of detection. The highest total VFA concentration, of the eight periods having westerly winds, was associated with the 12 000-head feedlot at 73.5 μg m^{-3}. This concentration was significantly different ($p < 0.05$) from the 25 000- and 6000-head feedlot concentrations at 25.5 and 23.2 μg m^{-3}, respectively (Table 2). As with ammonia, differences among site were partly related to stocking density. The best fit linear model $Y = -4.1X + 120$, where Y is the VFA concentration and X is the stocking density, accounted for more of the variance in VFAs between feedlots ($r^2 = 0.29$) than was the case for ammonia.

Acetic acid accounted for the largest proportion of the VFA compounds measured, followed by similar levels of propionic acid and butyric acid (Fig. 1). Concentrations of the other VFA compounds (isobutyric, valeric, isovaleric, and caproic acid) were comparatively low. The relative abundance of VFA compounds in air was similar to that found in swine slurry by Kirchmann and Lundvall (1993).

The concentrations of *m*-, *o*-, and *p*-cresols, phenol, indole, and skatole were close to the background levels. For the periods with westerly wind directions, the average concentrations ranged from 0.0030 to 0.0181 μg m^{-3} for *p*-cresol, and from 0.0009 to 0.0111 μg m^{-3} for phenol. For another sampling period with predominately easterly winds (no air flow over feedlot between 10 and 13 August), *p*-cresol concentration averaged 0.0019 μg m^{-3} and that of phenol was 0.0007 μg m^{-3}. For both *p*-cresol and phenol, the highest averaged concentrations were associated with the 12 000-head feedlot. There were only two sampling periods when *m*-cresol was measured (average 0.0082 μg m^{-3} across all feedlots) and only one sample were skatole was detected (0.098 μg m^{-3} at the 12 000-head feedlot).

Maximum Odorant Concentration

Highest ammonia concentrations were observed at the 12 000-head feedlot, where the maximum value of

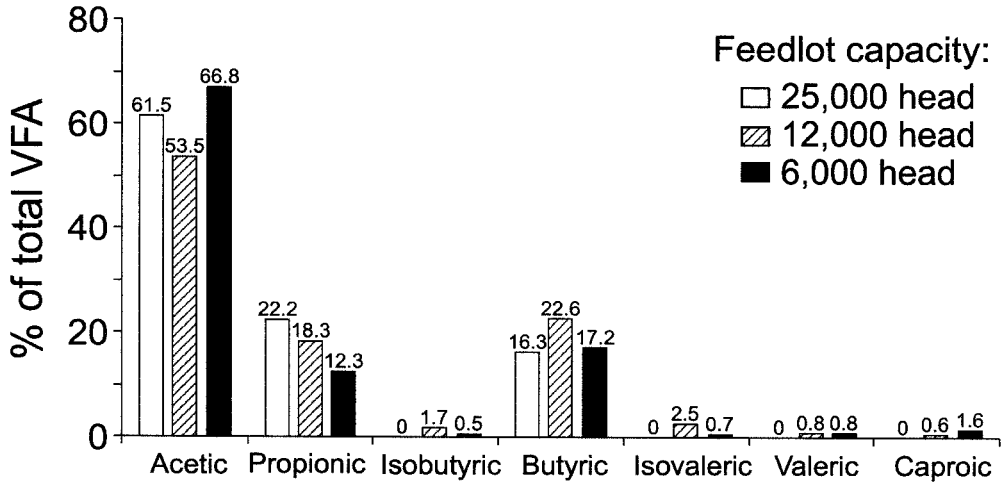

Fig. 1. Contribution of individual volatile fatty acid (VFA) compounds to total VFAs at three feedlots.

1805 μg NH_3–N m^{-3} (during pen cleaning) approached the odor threshold (Table 3). Since this value is an average over 2 to 3 d, the odorant concentration was probably much higher during times of low atmospheric mixing, common at night and early morning. Luebs et al. (1974) found that ammonia concentrations were 20 and 60 times greater in the early morning and evening, respectively, than in the mid- to late afternoon period.

Maximum concentration of butyric acid ranged from 6.5 to 33.6 μg m^{-3} adjacent the feedlots (Table 3). These maximum values were above the reported detection threshold values (2.5–3.7 μg m^{-3}). In addition to butyric acid, odor detection threshold was exceeded for acetic acid at the 12 000-head feedlot, and for isobutyric, isovaleric, valeric, and caproic acids at all feedlots. Zahn et al. (2001) reported much higher values at swine lagoons for all VFAs, for example, acetic (270 μg m^{-3}) and butryic (590 μg m^{-3}). Of all the feedlots, the 12 000-head feedlot recorded the highest value for most of the VFA compounds (the exception was valeric acid), perhaps because of more anaerobic conditions in the manure pad. The 12 000-head feedlot also was associated with the highest maximum concentrations of *o*- and *p*-cresol, and phenol (0.029, 0.039, and 0.434 μg m^{-3}, respectively).

The maximum values of the 2- to 3-d averaged concentrations of all measured gases were well below the reported irritation threshold (Table 3). The concentration of these compounds would probably not have exceeded irritation threshold even during periods when dispersion was low, except perhaps for ammonia. Unlike the other compounds measured, the irritation level for ammonia is only fivefold the odor detection limit, plac-

Table 3. Maximum gas concentrations measured adjacent three feedlots and a field where manure was recently spread. Each measured value is the average over a 2- to 3-d sampling period. Also listed are some reported odor detection and irritation threshold concentrations. Values in parentheses were measured during pen cleaning.

	Maximum concentration					
	Feedlot capacity (animals)					
Compound	6000	12 000	25 000	Spreading	Odor threshold†	Irritation threshold†
	μg m^{-3}					
Acetic	25.8	114.1	31.8	54.1	100‡, 2500§	25 000§
Propionic	8.7	34.2	7.3	60.0	25‡, 86¶	–
Butyric	9.1	33.6	6.5	104.5	2.5‡, 3.7§#	18 300§
Isobutyric	1.4	4.5	1.2	16.6	0.72††	–
Isovaleric	1.9	6.6	1.7	28.9	0.17††	–
Valeric	6.3	5.6	2.6	8.5	0.26††	–
Caproic	2.4	5.7	2.7	5.8	2.0††	–
o-Cresol	0.004	0.029	0.003	0	–	–
p-Cresol	0.003	0.039	0.020	0.002	4.5#	22 460#
m-Cresol	0.002	0.014	0.014	0	–	–
Phenol	0.003	0.434	0.154	0.100	20# (230–380)††	19 570#
Indole	0	0	0	0	1.9††	–
Skatole	0	0.098	0	0	–	–
Ammonia N	205	1488 (1805)	1050	–	2730#	14 500#

† In a population exposed to a gas concentration greater than these thresholds, 50% of the individuals will detect an odor or show signs of physical irritation.
‡ Data from Zahn et al. (1997).
§ Data from Hasimoglu (1998). Units were converted from ppm to μg m^{-3} with the equation (μg m^{-3}) = (ppm,M1000P/RT), where M is the molecular weight, P is the pressure (1 atm), R is the universal gas constant (0.08205 L atm/mol K), 1000 is a conversion factor (1000 L = m^3), and T is the temperature (293 K).
¶ Data from Hellman and Small (1974). Data were converted from ppm to μg m^{-3}.
# Data from Mackie et al. (1998). Units were converted from ppm to μg m^{-3}.
†† Data from Zahn et al. (2001).

ing ammonia at the forefront of potential odorants that could affect human and livestock health.

Odor Intensity

Odor was generally detected in the "blank" samples (containing ultrapure nitrogen) that accompanied each day's olfactometer analysis (DT between 8 and 13). Blank samples with a DT above 7 may be attributed to (i) bag odor despite purging with nitrogen and no recycling, (ii) residual odors in the instrument, and (iii) variability in human detection limits.

Concurrent odor intensity values adjacent the three feedlots were available for seven periods. However, for these seven concurrent periods, the sampling duration varied from five minutes to four hours. The average odor intensity was significantly higher ($p < 0.05$) at the 12 000-head feedlot (42 ± 12 DT) than at the 25 000- (28 ± 12 DT) and 6000-head feedlot (20 ± 6 DT).

Our results are comparable with those of other studies. Sweeten et al. (1977) reported typical DT values of 31 (moderately strong odor) for a 4000-head feedlot in Texas, though the DT value of odor ranged from 1.5 (weak odor) to nearly 170 (very strong odor). Sweeten and Miner (1993) reported an average DT value of 45 for a 2000-head feedlot, though DT values varied widely with location; for instance, low-lying pens with standing water yielded the highest reading of 170 DT.

Total Suspended Particulates

Average TSP values for all sampling periods ranged from 25.3 to 97.2 μg m^{-3} (Table 4) at four feedlots. Highest average values occurred at the second 25 000-head feedlot, perhaps because of road dust (significantly different from the rest at $p < 0.05$). The other three feedlots were farther from high traffic roads and may better reflect typical feedlot dust levels (overall average of 37.9 μg m^{-3}). At these three feedlots, the averaged TSP value at the 6000-head feedlot (25.3 μg m^{-3}) was significantly different ($p < 0.05$) from that at the 12 000-head feedlot (53.6 μg m^{-3}).

Peak TSP values were probably much higher than evident from our weekly averages. Sweeten et al. (1988) observed highest TSP levels near feedlots between 1900 and 2200 h, probably coinciding with periods of low wind speed and dispersion from surface heating. In the feedlots of our study, dust plumes were sometimes observed in the evening hours, reflecting boundary layer conditions and increased cattle activity at dusk.

Other studies, using shorter duration measurements, have reported higher TSP values than those in our study. In the Lethbridge area, Alberta Environment (2000) recorded a maximum TSP level near a feedlot (about one-hour average) of 490 μg m^{-3} in the evening hours, with an average of 179 μg m^{-3}. Sweeten et al. (1988) reported average net dust concentrations (difference between up- and downwind air samples) of 412 μg m^{-3}.

Apart from the second 25 000-head feedlot where road dust was suspected, only one (weekly averaged) measurement exceeded 100 μg m^{-3}, the Alberta 24-h exposure guideline.

Our estimates of TSP did not include particles of <5 μm and therefore may underestimate the effects on livestock health; for example, particles from 2.0 to 3.3 μm may be most important as a cause of pneumonia (MacVean et al., 1986). Particulates between 5 and 10 μm are the upper limit of respired dust (Dunlea and Dodd, 1994).

Table 4. Averaged total suspended particulates monitored on the downwind perimeter of feedlots (n = 5–14).

Feedlot capacity	Average TSP†	Standard deviation
animals	μg m^{-3}	
6 000	25.3c‡	14.5
12 000	53.6b	29.1
25 000A	34.9bc	25.7
25 000B§	97.2a	44.9

† Total suspended particulates.
‡ Different letters in the same column indicate a significant difference at $p < 0.05$.
§ Road dust is suspected to be a contributing factor at this feedlot.

Air Quality Downwind of a Feedlot

Odorant Concentration Dispersion

Ammonia concentrations, measured at the fixed towers when wind direction was westerly, were highest next to the feedlot and then fell asymptotically with increasing distance from the feedlot (Fig. 2A). At the 200-m distance, the ammonia concentration was reduced to between 65 to 82% of the concentration adjacent the feedlot.

A decline in concentration with distance was also observed in measurements using the mobile unit (Fig. 2B). However, concentrations were much higher

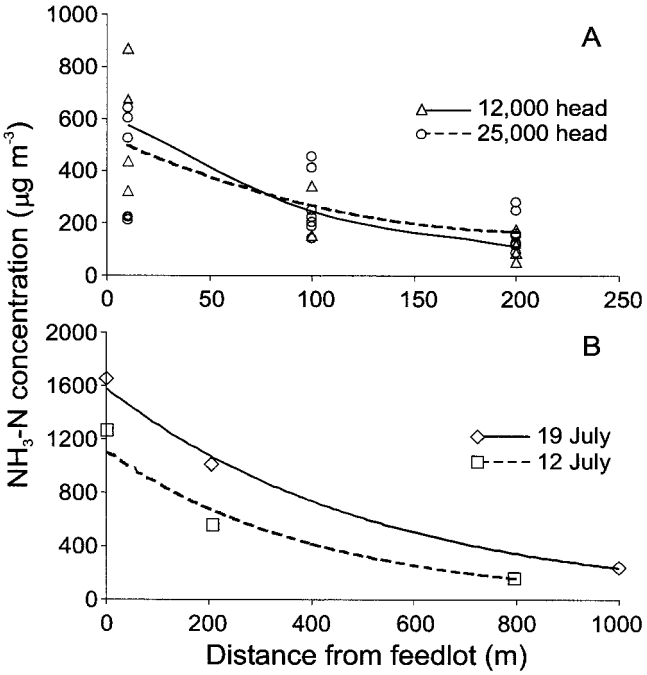

Fig. 2. Average ammonia concentration at distances downwind of the (*A*) 12 000- and 25 000-head feedlots measured over two-day sampling durations at fixed tower locations, and (*B*) dispersion measured with a portable analyzer using a 5-min sample duration. Different symbols denote different sampling periods.

because of the short (5 min) sampling taken during calm evening (1930 h) conditions when conditions for dispersion were poor. Measurements from the open-path laser operating continuously (5-min averages) indicated that ammonia concentrations 200 m downwind of a feedlot fluctuated as much as 15-fold over the day (Fig. 3). On some days the diurnal variability coincided with a dilution effect of high wind speed (Fig. 3A), while on other days (Fig. 3B) the relationship to wind speed was not as clear.

The total concentration of VFAs also declined with distance downwind from the feedlots (Fig. 4). Concentrations were higher and more variable at the 12 000-head feedlot than in the 25 000-head feedlot, perhaps reflecting differences in sampling times: the 12 000-head feedlot was sampled earlier, between 25 May and 11 June (with maximum values on 25–26 May) while the 25 000-head feedlot was sampled between 18 June and 28 July. The VFA concentration during the last sampling period at the 12 000-head feedlot was similar to that found at the 25 000-head feedlot throughout the remaining summer. Presumably, a high VFA concentration early in the measurement season would coincide with a flush of VFAs accumulated in the pens over winter.

For the averaged data in Fig. 4, total VFA concentration at the 12 000-head feedlot declined by 77% over the 200 m downwind of the feedlot. The corresponding reduction at the 25 000-head feedlot was 46%.

Acetic, propionic and butyric acid accounted for most of the VFAs measured (Fig. 1). Of these, only butyric acid was generally detected at concentrations exceeding its odor threshold value, and then usually only next to the feedlot. On two occasions, butyric acid concentrations 100 and 200 m downwind of the feedlots exceeded the odor detection threshold level. Highest butyric acid concentrations were in the earliest sample (25–26 May at the 12 000-head feedlot): 24.8, 7.5, and 3.0 $\mu g\ m^{-3}$ adjacent the feedlot and at 100 and 200 m, respectively. The other occurrence was recorded in 21–23 July at the 25 000-head feedlot: 6.1, 4.4, and 3.1 $\mu g\ m^{-3}$ at the feedlot and at 100 and 200 m downwind, respectively.

Odor Intensity Dispersion

Of the 18 odor sampling days in 1999 only six had wind conditions that allowed collection of downwind air samples at the fixed towers (Fig. 5). Upwind samples typically ranged from 8 to 11 DT except on 19 July at the 12 000-head feedlot when DT values at all locations were higher, coinciding with manure spreading in the general vicinity. On most sampling days, DT values decreased with distance from the feedlot, approaching upwind levels within 1000 m of the 12 000-head feedlot.

The persistence of DT values out to 1000 m on 27 May and 19 July, may be a result of a number of interacting factors including high background concentrations (as found on 19 July), poor dispersion, and the presence of dust that can enhance the odor intensity. The Code of Practice for Alberta recommends a MDS for a 12 000-head feedlot of 942 m for a single residence and 2515 m for a town. Conditions like those on 27 May would have created an odor nuisance for a single residence located within 1000 m of this feedlot, but the steady dispersion of the odor intensity beyond 1000 m would presumably have negated the odor nuisance at 2515 m.

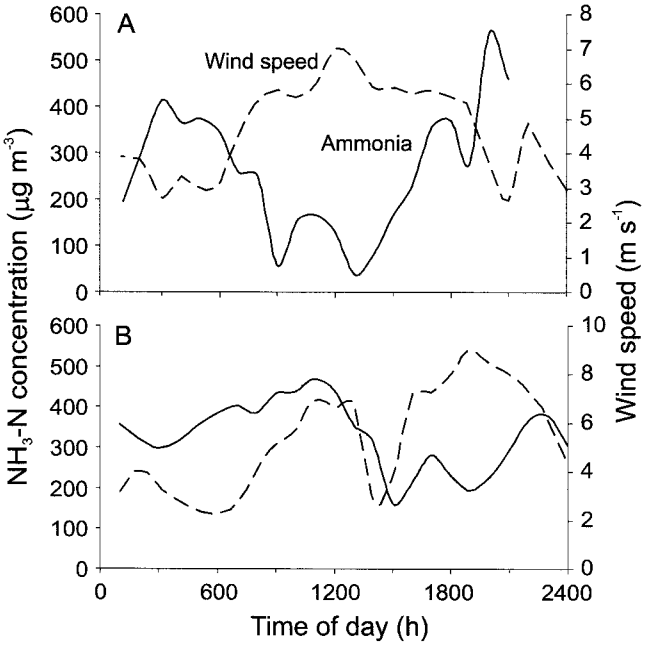

Fig. 3. Diurnal variability in ammonia concentration and wind speed recorded 200 m downwind of a feedlot using an open-path laser on (*A*) 16 June at the 25 000-head feedlot and (*B*) 28 June at the 12 000-head feedlot.

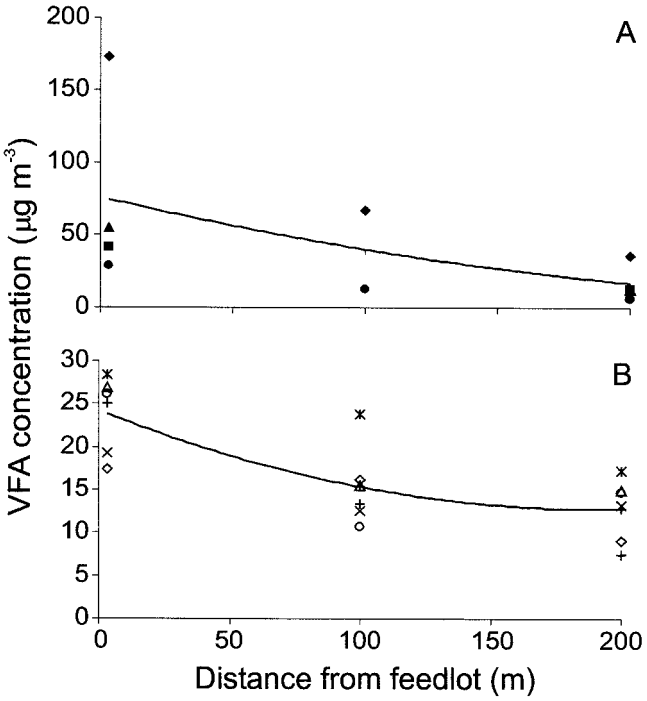

Fig. 4. Volatile fatty acid (VFA) concentration at distances downwind of the (*A*) 12 000- and (*B*) 25 000-head feedlots measured over two-day sampling periods (different symbols) at fixed tower locations.

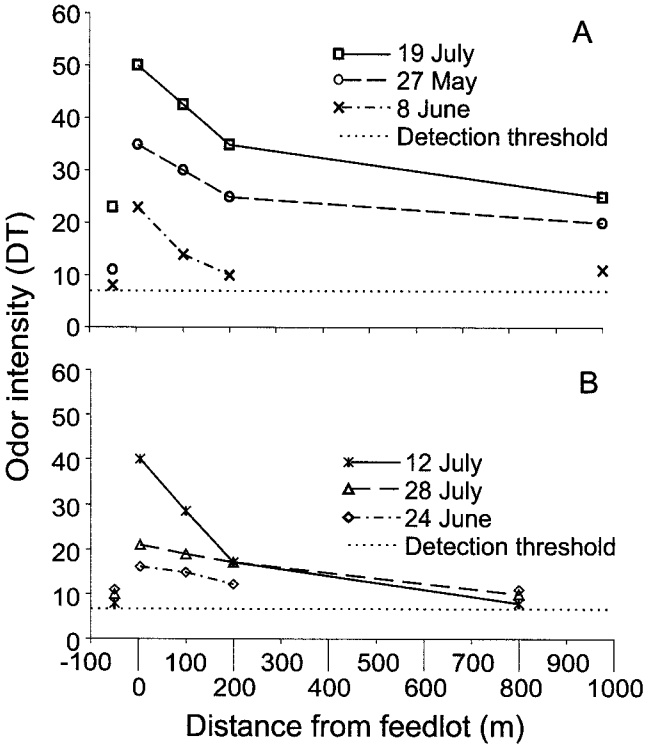

Fig. 5. Odor intensity (measured with an olfactometer) at distances downwind of the (*A*) 12 000- and (*B*) 25 000-head feedlots measured over 5-min sampling durations. Upwind value is represented at a distance of −50 m.

Air Quality Adjacent Manure Spreading Operations

Measurements after application of cattle manure from the 25 000-head feedlot to the field showed high concentrations of VFAs. Most obvious VFAs were propionic, butyric, isobutyric, isovaleric, valeric, and caproic acids, which exceeded a reported odor detection threshold by approximately 2-, 28- to 42-, 23-, 170-, 33-, and 3-fold (Table 3). These high concentrations may reflect the release of VFAs accumulated in the deeper, anaerobic layers of the manure bed. The high concentrations released during cleaning and spreading, however, are probably transitory. Butyric acid was below the irritation threshold while other VFA irritation thresholds were not identified.

Wind Speed and Odorant Concentration

For the eight days shown in Table 2, ammonia concentration adjacent the feedlots was inversely related to wind speed, where the correlation coefficients (r) at the 6000-, 12 000-, and 25 000-head feedlots were 0.94, 0.69, and 0.91, respectively. High wind speed is expected to enhance the mechanical mixing (turbulence) of the airflow over the feedlot and dilute downwind concentrations. However, wind speed is expected to have little effect on ammonification (source strength), which may account for the variability in the relationship (e.g., Fig. 3B). The link between wind speed and ammonia concentration suggests that downwind exposure can be reduced by cleaning pens or applying manure when wind speed is high (e.g., Gordon et al., 2000) or under unstable atmospheric conditions that promote dispersion. However, high wind may also enhance the surface transfer of other gases (e.g., VFAs) and dust.

Although the highest VFA concentrations adjacent the 12 000- and 25 000-head feedlots (Table 2) coincided with a period when wind speed was greatest (6.2 m s^{-1}), there was considerable variability, as was the case for ammonia. For instance, for the period ending on 21 June (Table 2) the wind speed average was 5.7 m s^{-1} but the 12 000-head feedlot VFA concentration was only 29% of that associated with the 6.2 m s^{-1} wind speed. Using the averaged wind and 2- to 3-d sampling durations may contribute to the inconsistencies in this relation. The correlation between wind speed and VFA concentration (Table 2) was not as strong as it was for ammonia; r values at the 6000-, 12 000-, and 25 000-head feedlots were 0.59, 0.39, and 0.45, respectively. However, unlike that for ammonia, the ambient VFA concentration increased with increasing wind speed, suggesting that, in contrast to that of ammonia, the transport of VFAs from the manure surface is a key factor controlling VFA loss. The source strength in manure may be influenced by other factors such as precipitation events (Lunney and Lott, 1995) and thickness and moisture content of the manure in the feedlot.

Correlation between Concentration and Odor Intensity

Ammonia concentration, measured with the chemiluminescence analyzer (mobile unit), was positively correlated with odor intensity (r = 0.84, n = 42). Although this relationship does not imply that ammonia is the cause of the odor, it does suggest that ammonia concentration is a useful indicator of odor intensity: as ammonia concentration increases, so does the concentration of other odorous compounds. The relationship is confounded since many of the odorous components are a result of anaerobic decomposition of the manure, whereas the majority of ammonia from livestock manure is generated from the hydrolysis of urea in the urine (although some denitrification of nitrate is possible). Previous studies have also demonstrated the role of volatile organic acids and ammonia concentrations as indicators of odor intensity from dairy slurry (Barth et al., 1974), and a link between *p*-cresol and odor intensity from swine slurry (Spoelstra, 1980).

Local Dry Deposition of Ammonia

Deposition of ammonia and ammonium (NH_x) takes two forms: (i) dry deposition of ammonia close to the

Table 5. Average dry deposition rates of ammonia N to land adjacent various-sized feedlots over eight sampling periods.

Feedlot capacity	NH_3–N deposition	Standard deviation
animals	mg m^{-2} d^{-1}	
6 000	23.0a†	7.2
12 000	84.4b	17.8
25 000A	37.5c	12.5
25 000B	55.8d	9.0

† Different letters in the same column indicate a significant difference at $p < 0.05$.

source and (ii) wet deposition of NH_x (ammonium aerosols) at larger distances (Asman, 1994). In our study, ammonia dry deposition for eight concurrent sampling periods at four feedlots varied from 23 to 84 mg NH_x–N m^{-2} d^{-1} at the tower adjacent the feedlots (Table 5). These values were significantly different ($p < 0.05$) between feedlots. The highest dry deposition was at the 12 000-capacity feedlot, which also recorded the highest plume concentrations (Tables 2 and 3). In fact, the rate of dry deposition was correlated ($r = 0.85$) with ambient ammonia concentration (Fig. 6). Although the upper measured level of ammonia N of 750 μg m^{-3} in Fig. 6 was below the odor detection threshold (Table 3), it was still associated with a high deposition rate of about 100 mg m^{-2} d^{-1}.

Assuming westerly winds (northwest to southwest) throughout the year 56% of the time (Lethbridge climate normals), the amount deposited to land immediately east of the feedlots was 47 to 172 kg NH_x–N ha^{-1} yr^{-1} and at 200 m downwind the deposition was 29 to 41 kg NH_x–N ha^{-1} yr^{-1}. Nitrogen deposition at these rates would supply much or all of the crop N demands in the affected area, since common inorganic N fertilization rates in this region range from 50 (dryland) to 100 (irrigation) kg N ha^{-1} yr^{-1}.

The rate of dry deposition diminished with increasing distance from the feedlot, coinciding with trends in ammonia concentration (Fig. 7). Our estimated rates of dry deposition at 100 m (20–23 mg m^{-2} d^{-1}) are similar to estimates of wet deposition by Berendse et al. (1988) at 75 m from a poultry barn of 19 mg m^{-2} d^{-1} (assuming a constant rate throughout the year).

CONCLUSIONS

Although odorants from feedlots were effectively dispersed, with concentrations decreasing rapidly with distance, their concentrations fluctuated throughout the day. Consequently, further research on short-term fluctuations is needed to more accurately determine MDS to alleviate odor complaints. One possible practice identified to reduce odorant concentration from the feedlot was to increase the stocking density (area per head).

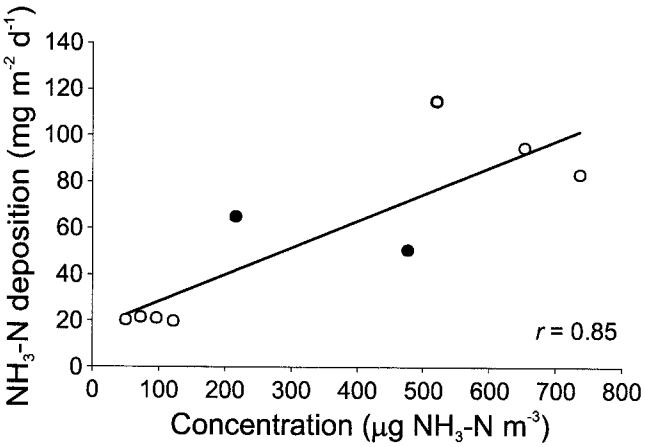

Fig. 6. Relationship between ammonia concentration and ammonia deposition downwind of feedlots.

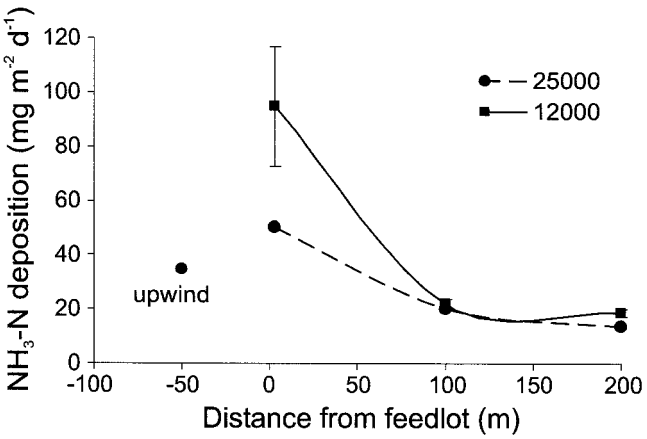

Fig. 7. Decrease in ammonia dry deposition with distance from the 12 000- and 25 000-head feedlots. Upwind value is represented at a distance of −50 m. Only one sample period was used at the 25 000-head feedlot (20 July to 3 August) while five (between 8 June and 20 July) were measured at the 12 000-head feedlot.

Although the specific odorants in our study never exceeded their irritation threshold even adjacent the feedlot, ammonia and VFAs occurred at concentrations that may contribute to a odor nuisance problem, especially when the manure was handled during pen cleaning and application to land. Our findings also suggest that ammonia concentration may be a useful indicator of odor intensity. The dry deposition of ammonia adjacent to feedlots was large enough to account for a large portion of crop N needs, suggesting that it should be included in development of fertilizer recommendations. In addition, the role of dust in enhancing odor needs to be clarified, that is, the role of dust in enlarging the MDS requirement for a commercial feedlot operation.

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