TECHNICAL PAPER

ISSN: 1047-3289 *J. Air & Waste Manage. Assoc.* **61**:1026–1035
DOI: 10.1080/10473289.2011.599282
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Concentrations of Particulate Matter Emitted from Large Cattle Feedlots in Kansas

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ABSTRACT

Particulate matter (PM) emitted from cattle feedlots are thought to affect air quality in rural communities, yet little is known about factors controlling their emissions. The concentrations of PM (i.e., $PM_{2.5}$, PM_{10}, and total suspended particulates or TSP) upwind and downwind at two large cattle feedlots (KS1, KS2) in Kansas were measured with gravimetric samplers from May 2006 to October 2009 (at KS1) and from September 2007 to April 2008 (at KS2). The mean downwind and net (i.e., downwind – upwind) mass concentrations of $PM_{2.5}$, PM_{10}, and TSP varied seasonally, indicating the need for multiple-day, seasonal sampling. The downwind and net concentrations were closely related to the moisture content of the pen surface. The $PM_{2.5}/PM_{10}$ and $PM_{2.5}$/TSP ratios at the downwind sampling location were also related to the moisture content of the pen surface, humidity, and temperature. Measurement of the particle size distribution downwind of the feedlot with a cascade impactor showed geometric mean diameter ranging from 7 to 18 μm, indicating that particles that were emitted from the feedlots were generally large in size.

IMPLICATIONS

This work characterized the total suspended particulates (TSP), PM_{10}, and $PM_{2.5}$ concentrations emitted from large cattle feedlots in Kansas, providing baseline information on concentrations and size distribution of particulates emitted from feedlots in the Great Plains. As expected, high dust events were observed during the spring and summer; dust control strategies should target those potential dust events. PM emitted from the feedlots was dominated by coarse particles; as such, development and evaluation of dust control strategies, including water sprinkling, shelterbelts, etc., might have to focus more on the coarse particles. The moisture content of the pen surface was one of the most significant factors affecting PM concentrations in cattle feedlots; by controlling the moisture content, it would be possible to control dust emissions.

INTRODUCTION

The increasing size and geographic concentration of animal feeding operations, including beef cattle feedlots, has led to public concern about emissions of particulate matter (PM), ammonia, volatile organic compounds, and odor. Open beef cattle feedlots generate fugitive dust, including TSP (total suspended particulates), PM_{10} (PM with equivalent aerodynamic diameter of 10 μm or less), and $PM_{2.5}$ (PM with equivalent aerodynamic diameter of 2.5 μm or less). Although there have been no direct study on feedlot personnel health problems, several researchers indicated that dust generated from cattle feedlots has the potential to cause a number of health hazards in humans and livestock.[1–3] Sweeten et al.[4] indicated that dust from cattle feedlot surfaces, alleys, and roads can annoy neighbors and irritate feedlot employees. In addition, particulates with bound ammonia and odorous compounds can be emitted from feedlots to nearby residences and can cause actual or perceived health effects.[5,6] As more stringent air quality standards are developed, there is a need to characterize PM emissions from cattle feedlots and to assess the effectiveness of abatement measures for mitigating those emissions.

Particle size is important in characterizing the physical behavior and potential health effects of PM. Removal processes, atmospheric residence times, and contribution of light scattering to visibility degradation are affected by particle size.[7,8] The formation and growth of particles might be influenced by several processes, and they are sensitive to a number of environmental parameters including humidity, temperature, reactive trace gas concentrations,[9,10] and possibly wind speed. Therefore, it is necessary to understand the particle size distribution and mass concentrations at critical size ranges for investigating health effects posed by PM emissions from cattle feedlot and monitoring the transport and fate of PM. Moreover, to develop or improve control methods, it is necessary to know factors that influence PM emissions.

Dry, warm conditions and active cattle behavior are the principal contributors to dust emission from cattle feedlots.[11] In general, fugitive dust emitted from feedlots

is mainly from the uncompacted and pulverized manure layer associated with animal activity, especially from late afternoon to early evening. Other sources of dust include feed mills, loading and unloading of feed trucks, vehicle exhaust, unpaved roads, and winds.[12–15] Cattle feedlots may contribute to secondary PM by emissions of ammonia and nitric oxide that subsequently leads to secondary aerosol formation,[2,11,16] although there is little evidence showing this occurs at the local scale.[17] Information on the spatial, temporal, and physical characteristics of the emission sources are needed to distinguish their contributions to ambient particulate matter concentrations. Accurate emission inventories are also needed to provide accurate inputs to air quality modeling.

Currently, there is little information on either concentration or particle size distribution of PM from cattle feedlots and almost all of the published data have been from Texas.[18–20] Based on cattle feedlots in Texas, the mean net TSP was 412 $\mu g/m^3$ (15 events measured seasonally in 1987), with PM_{10} concentrations of 19% to 40% of TSP.[18,19] In a related study, Purdy et al.[20] reported that the downwind $PM_{2.5}/PM_{10}$ ratio was close to 10%. From the limited data available, dust from cattle appears to be large with over half larger than PM_{10}. However, more measurements are needed to further characterize and understand PM emissions from open-lot beef cattle feedlots.[21] The objectives of this study were to (1) measure the mass concentration and size distribution of PM emitted from two large cattle feedlots in Kansas and (2) determine the effects of weather conditions and pen surface moisture content on the mass concentrations.

MATERIALS AND METHODS

Feedlot Description and Sampling Locations

Two large cattle feedlots in Kansas (i.e., KS1 and KS2) were considered in this study. The feedlots were within 40 km of each other. The first feedlot, KS1, had approximately 30,000 head of cattle and a total pen area of about 50 ha. It had a water sprinkler system for dust control with an application rate of 5 mm/day (5 $L/m^2 \cdot day$). The system was normally operated from April to October and during prolonged dry periods. It had a total of 179 sprinkler heads; a group of three sprinkler heads was turned on simultaneously every 6 min and 6 hr were required to cycle through all sprinkler heads. In addition, pens at KS1 were scraped two to three times per year and manure was removed from the pens at least once a year. The second feedlot, KS2, had approximately 25,000 head of cattle and a total pen area of 68 ha. Pens were also scraped five to six times per year and manure was removed from each pen two to three times per year. For both feedlots, feed was processed and mixed in the feed mill, loaded on feed trucks, and delivered to the pens three times a day. Prevailing wind directions at the sites were south in summer and north in winter (Figure 1a). Annual mean values of precipitation at KS1 and KS2 were approximately 573 and 671 mm, respectively.

Particulate samplers (2100 Mini-Partisol; Thermo Fisher Scientific, Franklin, MA) were set up at the north and south perimeters of each feedlot (Figure 1b). For KS1, the north sampling location was about 5 m away from the closest pen and the south sampling location was about

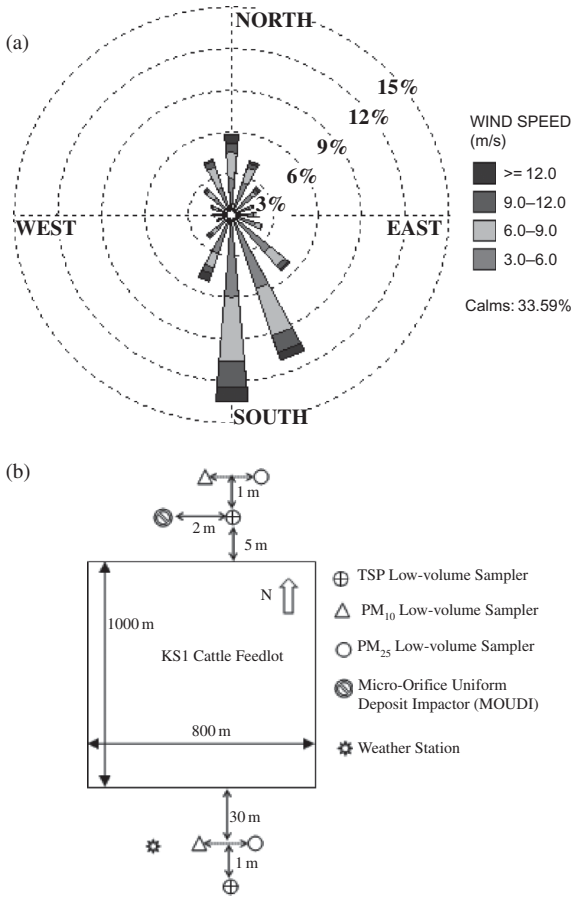

Figure 1. (a) Wind rose statistics from May 2006 to October 2009 (hourly data from total time period); (b) schematic diagram showing sampler locations at feedlot KS1.

30 m away from the closest pen (Figure 1b). For KS2, the north and south sampling locations were approximately 40 and 60 m away from the closest pens, respectively. These locations were selected so that samplers are able to capture particulates coming from the feedlots; in addition, power availability, and access to the sampling locations were considered.

Each feedlot was equipped with a weather station (Campbell Scientific Inc., Logan, UT) to measure and record at 20-min intervals wind speed, wind direction, pressure, temperature, precipitation, and relative humidity. Weather data from a local weather station were also collected. In addition to the low-volume samplers, a Micro-Orifice Uniform Deposit Impactor or MOUDI (Model 100/110; MSP Corp., Shoreview, MN) was set up in the prevailing downwind location of KS1 to measure the particle size distribution.

Air Sampling and Measurement

The mass concentrations of TSP, PM_{10}, and $PM_{2.5}$ were measured with low-volume samplers (air sampling flow rate of 5 L/min) equipped with size-selective inlets for TSP, PM_{10}, and $PM_{2.5}$. Samplers were placed side by side with a minimum distance of about 1 m from each other (Figure 1b). These samplers are gravimetric samplers that yield time-integrated mass concentration of PM. During measurement, ambient air is drawn into the size-selective

inlet of the sampler using a vacuum pump and PM is collected on the collection filter. The mass of the collected PM is determined by subtracting the gross weight of the filter from its tare weight. The mass of PM is then divided by the sampling flow volume to get the mass concentration of PM. Flow rate is critical for particle fractionation and calculation of mass concentration. For the samplers, the flow control system uses a temperature and pressure compensated mass flow control scheme to maintain a constant volumetric flow rate of 5 L/min.[22] Filters used for low-volume samplers were either a Pallflex TX40 or a Polytetrafluoroethylene (PTFE) filter (Whatman Inc., Clifton, NJ). All filters were conditioned in a laboratory conditioning chamber (25 °C, 40% relative humidity) for 24 hr before weighing, before and after sampling, to minimize the effect of humidity.

Particle size distribution at the prevailing downwind sampling location of KS1 (generally, the north sampling location) was measured with the MOUDI. The MOUDI[23] is an eight-stage cascade impactor that is based on the principle of inertial impaction using multiple-nozzle stages in series. It was operated with air sampling flow rate of 30 L/min. It used 34-mm aluminum foils for the impaction stages and 34-mm PTFE filters for the bottom stage. In accordance with the manufacturer's recommendation, the aluminum foils were sprayed with thin layer of grease to minimize particle bounce and then heated for about 90 min in an oven with temperature of 65 °C.

Field sampling events were conducted monthly from May 2006 to October 2009 at KS1 and from September 2007 to April 2008 at KS2. Since 2007, 15 and 3 5-day intensive sampling events were conducted at KS1 and KS2, respectively. The 5-day sampling events were conducted mostly from March to November (13 out of 15 events for KS1). Each sampling event normally included from 2 to 10 sampling runs. For each sampling run, sampling duration was generally 12 hr. In cases when expected concentrations were small (e.g., winter or after rain events), sampling duration was 24 hr to ensure that measurable amounts of PM were collected on the filters. The total numbers of sampling runs for the low-volume samplers were 185 and 40 for KS1 and KS2, respectively. Because of sampler malfunctions and/or power outages, the actual numbers of sampling runs ranged from 126 to 177 for KS1 and from 1 to 39 for KS2. The MOUDI sampler was used from July 2007 to July 2009 for a total of 43 sampling runs (each run had a duration of 24 hr).

During each sampling run, manure samples were collected from three to five different pens for the determination of moisture content (MC) of pen surfaces in the feedlots. These samples were normally taken right after the start of each sampling run and when the sprinkler heads in the pens from which samples were being collected were not running. Approximately 2.5 to 5 cm upper layer of manure was collected from two to three spots between the center of the pen to the feed apron. The collected samples from each pen were placed in a zipped plastic bag. The MC of the manure sample was determined using the ASTM D 2216-98 oven-drying method.[24]

Data on the operation of the sprinkler system, including when the system was operated and the daily amount of water used for sprinkling, were obtained from the feedlot operator. In this research, the water sprinkler system at KS1 was operated during 60 sampling runs out of 185 total sampling runs. The amount of water applied ranged from 0 to 5.2 mm for each run.

Data Analysis

Measured PM values were first screened on the basis of wind direction. Because the samplers were strategically set up north and south of the feedlots, measured values were considered acceptable if the wind direction was from 120° to 240° (i.e., the north sampling site was the downwind location) at least 80% of the time.[25] If the wind direction was within the 120° to 240° range but less than 80% of the time or outside the 120° to 240° range at least 20% of the time, the PM data were excluded in the analysis. Tables 1 and 2 summarize the numbers of acceptable sampling runs.

All PM concentration data were converted to standard conditions of temperature (25 °C) and pressure (760 mm Hg). From the screened data, the $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP ratios for each sampling run at each sampling location were calculated. The frequency distribution, which is the tabulation of raw data obtained by dividing it into size ranges and computing the number of data elements falling within each size range,[26] was used to describe the population of these ratios within certain ranges. In addition, from the prescreened data, the corresponding

Table 1. Numbers of acceptable sampling runs and 24-hr values for the low-volume samplers.

		Feedlot KS1		Feedlot KS2	
		Number of Acceptable Sampling Runs	Number of 24-hr Values	Number of Acceptable Sampling Runs	Number of 24-hr Values
Downwind (typically north sampling location)	$PM_{2.5}$	47	21	11	3
	PM_{10}	69	28	10	3
	TSP	71	28	6	3
Upwind (typically south sampling location)	$PM_{2.5}$	44	20	6	2
	PM_{10}	61	28	10	3
	TSP	59	27	0	0
Net (downwind − upwind)	$PM_{2.5}$	30	15	4	2
	PM_{10}	49	25	8	2
	TSP	49	25	0	0

Table 2. Numbers of acceptable sampling runs for each month for feedlot KS1.

	TSP		PM_{10}			$PM_{2.5}$				
Month	Downwind	Net	Downwind	Net	24-hr Concentration $\geq$150 μg/m^3	Downwind	Net	24-hr Concentration $\geq$35 μg/m^3	With Rain	With Sprinkling
01	1	0	1	1	0	1	1	0	0	0
02	1	1	1	1	0	0	0	0	0	0
03	4	3	4	3	1	2	2	1	0	0
04	3	3	4	1	0	2	1	0	0	0
05	7	5	7	5	1	5	4	1	1	3
06	7	5	7	4	0	2	1	0	0	6
07	16	8	15	9	1	11	7	1	0	17
08	12	9	10	8	1	10	7	1	1	7
09	7	5	7	6	0	6	2	0	1	4
10	6	6	7	6	0	4	3	0	1	2
11	4	4	4	4	0	2	2	0	0	0
12	3	0	2	1	0	2	0	0	0	0
Total	71	49	69	49	4	47	30	4	4	39

24-hr mass concentrations were calculated by taking into account the mass concentrations in successive runs within 24 hr. Then, from the 24-hr data sets, the net concentration (i.e., difference between downwind and upwind concentrations) was determined. Table 1 also shows the numbers of acceptable data set for the 24-hr means and the net concentrations for the low-volume samplers.

Particle size distribution data from the MOUDI were also screened for acceptability in the analysis based on wind direction. There were 14 acceptable sampling runs (out of 43 total sampling runs) for the MOUDI sampler. For each of the MOUDI data set, the geometric mean diameter (GMD) and geometric standard deviation (GSD) were obtained using eqs 1 and 2, respectively.[7]

$$\mathrm{GMD} = \exp\left(\frac{\sum (m_j \ln d_j)}{\sum m_j}\right) \tag{1}$$

$$\mathrm{GSD} = \exp\left(\frac{\sum \left\{ m_j \left[\ln\left(\frac{d_j}{\mathrm{GMD}}\right)\right]^2 \right\}}{\sum m_j}\right)^{0.5}, \tag{2}$$

where GMD is the geometric mean diameter of the sample, μm; d_j is the geometric mean diameter of particles in the jth stage of the MOUDI, μm; m_j is the mass fraction of particles in the jth stage of the MOUDI; and GSD is the geometric standard deviation.

The following statistical analyses were conducted using SAS (version 9.1.3; SAS Institute Inc., Cary, NC) and Excel (Microsoft Corp., Redmond, WA):

(1) Paired t test procedure to determine significant difference between the upwind and downwind sampling locations in PM concentrations and ratios (i.e., $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP).
(2) The CONTRAST statement in SAS GLM procedure was used to contrast the mean concentrations and ratios between the day and evening sampling.
(3) Correlation analysis on mass concentrations (i.e., $PM_{2.5}$, PM_{10}, and TSP) and PM ratios (i.e., $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP).
(4) Correlation analysis on log-transformed PM concentrations as well as PM ratios with weather conditions (i.e., humidity, temperature, wind speed, and precipitation), and amount of water applied by the water sprinkler system. Log-transformed PM concentrations provided better correlation with factors, including pen surface MC, compared with untransformed concentrations.
(5) Regression analysis using the backward selection procedure to identify the factors that could predict the mass concentration.

For all analyses, a 5% level of significance was used except for the regression analysis of backward selection, which used 10% significance level.

RESULTS AND DISCUSSION

Particle Size Distribution

The mean GMD of the particles as measured by the MOUDI at the downwind sampling location of KS1 was 13.0 μm, ranging from 7.0 to 18.2 μm. The relatively large GMD value indicates that the PM emitted from feedlot KS1 was dominated by coarse particles. The mean GSD was 2.4, ranging from 2.1 to 3.8, indicating a relatively broad particle size distribution. The observed size distribution is similar to those in previous research on cattle feedlots. Hamm[27] reported an average mass median diameter of 16 μm with average GSD of 2.1, whereas Sweeten et al.[18] reported mean GMD of 9.5 (standard deviation [SD] = 1.5) μm and mean GSD of 2.1 (SD = 0.06); both studies were from cattle feedlots in Texas and Coulter Counters were used for the analysis of particle size distribution.

PM Mass Concentrations and Ratios

The PM concentrations at the upwind and downwind sampling locations of the feedlots varied with season, with the highest concentrations observed between

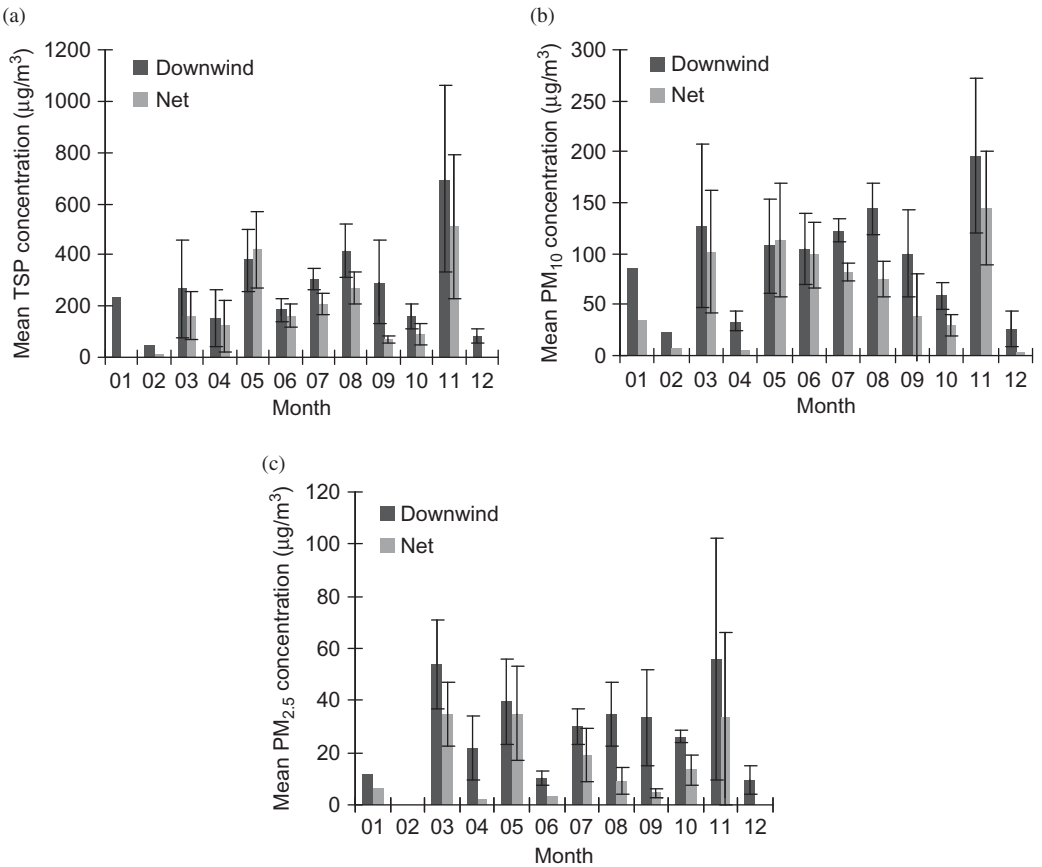

Figure 2. Mean monthly PM concentrations of (a) TSP, (b) PM_{10}, and (c) $PM_{2.5}$ at feedlot KS1.

Table 3. Downwind and upwind 24-hr PM concentration values.

		Feedlot KS1			Feedlot KS2		
		n[a]	Mean (μg/m³)	SE[b] (μg/m³)	*n*[a]	Mean (μg/m³)	SE[b] (μg/m³)
Downwind	$PM_{2.5}$	21	34	7	3	24	9
Sampling	PM_{10}	28	105	14	3	88	12
Location	TSP	28	262	42	3	185	23
Upwind	$PM_{2.5}$	20	16	1	2	11	7
Sampling	PM_{10}	28	39	5	3	73	55
Location	TSP	27	58	7	—	—	—
Net (downwind – upwind)	$PM_{2.5}$	15	25	13	2	17	4
	PM_{10}	25	76	16	2	80	13
	TSP	25	201	40	—	—	—

Notes: [a]*n* represents the number of 24-hr values. [b]SE represents the standard error.

March and November (Figure 2). Overall mean downwind concentrations were 34, 105, and 262 μg/m³ for $PM_{2.5}$, PM_{10}, and TSP, respectively, at KS1, whereas they were 24, 88, and 185 μg/m³, respectively, at KS2 (Table 3). These values were within the ranges of published values for cattle feedlots. Sweeten et al.[19] reported mean downwind concentrations of 700 μg/m³ (range of 97–1685 μg/m³) and 285 μg/m³ (range of 11–866 μg/m³) for TSP and PM_{10}, respectively. Purdy et al.[20] reported mean upwind and downwind PM_{10} concentrations of 94 and 269 μg/m³, respectively, and corresponding $PM_{2.5}$ concentrations of 14 and 25 μg/m³, respectively, from four cattle feedlots in Texas.

The primary and secondary 24-hr national ambient air quality standards (NAAQS) for PM_{10} is 150 μg/m³ and is not exceeded more than once per year on average over a 3-yr period. The $PM_{2.5}$ 24-hr concentration must not exceed 35 μg/m³ over a 3-yr period.[28] In 4 out of 28 samples for PM_{10} and 4 out of 21 samples for $PM_{2.5}$, the measured 24-hr concentration exceeded the NAAQS (Figure 3). These cases occurred in March, May, July, and August when pen surfaces were generally dry (Table 2), with pen surface

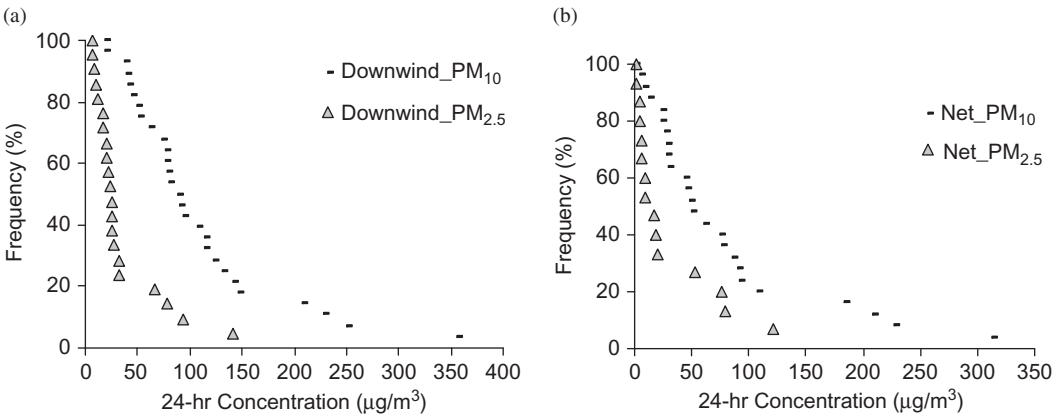

Figure 3. Cumulative frequencies of 24-hr concentration versus 24-hr concentration for (a) downwind values and (b) net values at feedlot KS1.

MC generally less than 16%. Note that the sampling locations were 5 m from the closest pen in KS1, representing a worst case. If measurements were carried out at the property lines, a few hundred meters further away from the pens, it is likely that the concentrations would be considerably lower because of particle dispersion and settling.[29]

Table 3 also presents the net concentrations, which are the downwind concentrations adjusted for upwind or background concentrations to reflect the contribution of the feedlot only.[19] Overall mean net mass concentrations of $PM_{2.5}$, PM_{10}, and TSP at KS1 were 25, 76, and 201 μg/m^3, respectively. For KS2, only two cases of 24-hr net mass concentrations were obtained; the upwind TSP data were not available because of TSP sampler malfunction. Net mass concentrations of PM_{10} and $PM_{2.5}$ at KS2 were 80 and 17 μg/m^3, respectively.

The PM mass concentrations during the day and night sampling periods for KS1 were also compared. Results showed that there were no significant differences in mean concentrations between the day and night sampling periods ($P = 0.09$) except for TSP ($P = 0.04$) (Table 4). The mean net concentration of TSP during the day (6 a.m. to 6 p.m.) was less than that at night (6 p.m. to 6 a.m.). However, earlier research using high-resolution sampling has shown that the highest concentrations of dust occurs between 6 p.m. and 11 p.m.,[11,18,21] during which cattle are generally more active and atmospheric conditions are relatively stable.

Previous research indicated that PM ratios may allow estimation of fine PM concentrations using available TSP or PM_{10} data.[30,31] For KS1, mean $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP ratios at the downwind sampling location were significantly ($P < 0.05$) smaller than the corresponding ratios at the upwind sampling location (Table 5). The frequency distribution of PM ratios at the downwind locations showed smaller ratios occurred more often than upwind sampling location in which frequencies were distributed more uniformly (Figure 4a and b). $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP ratios with ranges of 0.1–0.3, less than 0.1, and 0.3–0.4, respectively, had higher frequency observed. These results suggest that the contribution of fine and coarse particles from the feedlot was not as equally distributed compared with the upwind areas and that the PM emitted from the feedlots was dominated by coarse particles. This finding was consistent with the MOUDI results, in which the mean GMD was 13.0 μm and consistent with previous studies that reported GMD ranging from 9.5 to 16.0 μm.[18,19]

In comparison, PM measurements in urban areas showed the $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP ratios typically run higher with average of 0.54, 0.30, and 0.50, respectively.[31,32] Studies in Swiss and Asian regions also

Table 4. Descriptive statistics of PM concentrations during the day and night sampling periods for feedlot KS1.

		Day Sampling Period (6 a.m. to 6 p.m.)			Night Sampling Period (6 p.m. to 6 a.m.)		
		n	Mean (μg/m^3)	SE (μg/m^3)	*n*	Mean (μg/m^3)	S.E. (μg/m^3)
Downwind	$PM_{2.5}$*	23	25[a]	6	22	36[a]	7
Sampling	PM_{10}*	37	104[a]	13	30	111[a]	18
Location	TSP*	39	286[a]	50	30	322[a]	57
Upwind	$PM_{2.5}$*	22	21[a]	5	21	17[a]	2
Sampling	PM_{10}*	38	57[a]	12	22	37[a]	6
Location	TSP*	36	124[a]	34	23	77[a]	18
Net (downwind – upwind)	$PM_{2.5}$*	11	13[a]	6	16	19[a]	6
	PM_{10}*	27	71[a]	12	21	74[a]	18
	TSP*	27	202[a]	50	23	237[b]	47

Note: *Row means followed by the same letter are not significantly different at the 0.05 level of significance.

Table 5. Descriptive statistics of PM ratios at the downwind and upwind sampling locations for feedlot KS1.

		Feedlot KS1		Urban Areas (Published Data)
		Downwind	Upwind	
$PM_{2.5}/PM_{10}$	*n*	46	44	
	Mean*	0.29[a]	0.44[b]	0.54[31]
	SE	0.02	0.04	
$PM_{2.5}/TSP$	*n*	46	42	
	Mean*	0.10[a]	0.28[b]	0.30[31]
	SE	0.01	0.03	
PM_{10}/TSP	*n*	67	55	
	Mean*	0.41[a]	0.54[b]	0.50[32]
	SE	0.02	0.03	

Note: *Row means followed by the same letter are not significantly different at the 0.05 level of significance.

showed that fine PM had greater portion in urban and industrial areas, [30,33,34] primarily because the major source of PM in these areas is burning of fossil fuels by transportation and industrial sources.

The data from KS2 were limited and may not be representative of the long trend of PM ratios. The mean $PM_{2.5}/PM_{10}$, $PM_{2.5}/TSP$, and PM_{10}/TSP ratios obtained at the downwind sampling location of feedlot KS2 were 0.38, 0.18, and 0.53, respectively. Only the $PM_{2.5}/PM_{10}$ ratio was available at the upwind sampling location of feedlot KS2.

The $PM_{2.5}/PM_{10}$, $PM_{2.5}/TSP$, and PM_{10}/TSP ratios at KS1 were also analyzed by sampling period (i.e., day vs. night). There were no significant differences between daytime (6 a.m. to 6 p.m.) and nighttime (6 p.m. to 6 a.m.) sampling periods in mean values of $PM_{2.5}/PM_{10}$ ($P = 0.7$) and $PM_{2.5}/TSP$ ($P = 0.3$), indicating that the fraction of fine and coarse particles varied only slightly between day and night.

Statistical analysis showed significant correlations among $PM_{2.5}$, PM_{10}, and TSP concentrations at both the downwind and upwind sampling locations of KS1 (Table 6). There was also strong correlation between the $PM_{2.5}/PM_{10}$ and $PM_{2.5}/TSP$ ratios at both the downwind and upwind sampling locations (correlation coefficients of 0.71 and 0.82, respectively) as well as $PM_{2.5}/TSP$ and PM_{10}/TSP ratios (correlation coefficients of 0.51 and 0.60, respectively), whereas there were no significant correlations for the other PM ratios. The ratios had significant correlations with PM mass concentrations for $PM_{2.5}/TSP$ and PM_{10} as well as TSP at the upwind sampling location, and for PM_{10}/TSP and $PM_{2.5}$ at the downwind sampling location.

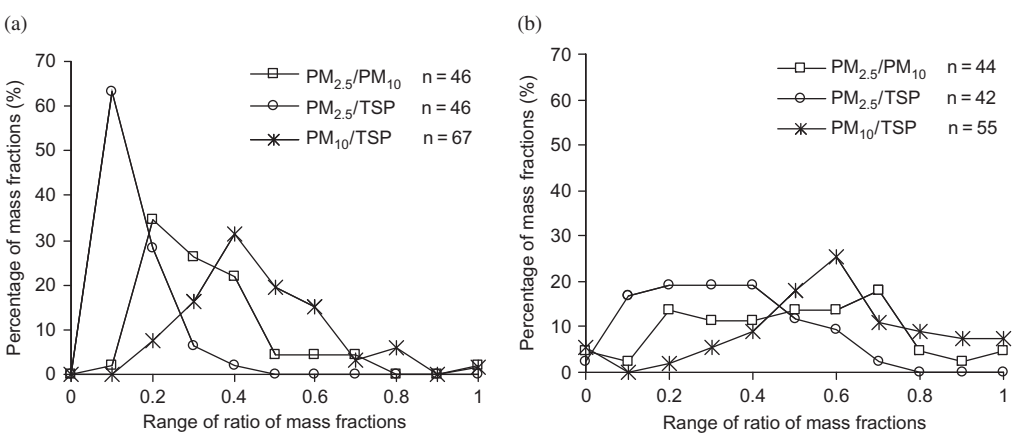

Figure 4. Frequencies of mass fractions at the (a) downwind and (b) upwind sampling locations of feedlot KS1.

Table 6. Correlation matrix of concentrations and ratios for the downwind and upwind sampling locations of feedlot KS1.

		$PM_{2.5}$	PM_{10}	TSP	$PM_{2.5}/PM_{10}$	$PM_{2.5}/TSP$	PM_{10}/TSP
Downwind	$PM_{2.5}$	1.00	0.89*	0.91*	0.21	0.02	−0.33*
	PM_{10}		1.00	0.91*	−0.17	−0.26	−0.14
	TSP			1.00	0.03	−0.26	−0.40
	$PM_{2.5}/PM_{10}$				1.00	0.71*	−0.16
	$PM_{2.5}/TSP$					1.00	0.51*
	PM_{10}/TSP						1.00
Upwind	$PM_{2.5}$	1.00	0.74*	0.89*	0.25	−0.02	−0.30
	PM_{10}		1.00	0.69*	−0.26	−0.46*	0.15
	TSP			1.00	−0.14	−0.39*	−0.25
	$PM_{2.5}/PM_{10}$				1.00	0.82*	0.10
	$PM_{2.5}/TSP$					1.00	0.60*
	PM_{10}/TSP						1.00

Note: *Significant at the 0.05 level.

Effects of Weather Conditions and Pen Surface Moisture Content

The PM mass concentrations and ratios would likely depend on weather conditions and feedlot pen surface characteristics. In general, the PM emitted from cattle feedlots results from hoof action on the dry, uncompacted, pulverized layer of manure on the corral surface.[12,13] As such, weather conditions and pen surface characteristics (i.e., depth, degree of compaction, and moisture content) are important determinants of the PM emission potential of the pen surface.[12,35] To identify factors associated with variation of PM concentrations, the weather conditions (i.e., humidity, temperature, wind speed, and precipitation), moisture content of the pen surface, and the amount of water applied by the water sprinkler system were further analyzed. For the acceptable sampling runs at the downwind sampling location of feedlot KS1, average temperature was 21 °C (range of −13 to 40 °C), average relative humidity was 57% (range of 20% to 91%), and average wind speed was 6 m/sec (range of 1 to 22 m/sec). There were 4 runs in which there was rainfall (maximum amount of 3 mm) and 39 runs in which the water sprinkler system was operated (maximum amount of water applied was 5 mm) (Table 2).

Pen surface MC showed significant correlation with the log-transformed PM concentrations and ratios except for PM_{10}/TSP (Table 7). The amount of water used by sprinkler system was significantly and positively correlated to the log-transformed PM_{10} and TSP concentrations, possibly because the sprinkler system was normally operated when dust events were occurring or expected to occur. For weather conditions, significant correlation was observed between wind speed and ln(TSP), temperature and ln(TSP), humidity and ln(TSP), temperature and ln(PM_{10}), and humidity and ln(PM_{10}). Precipitation was not significantly correlated with concentrations and ratios. The lack of significant correlation between precipitation and concentrations or ratios could be due to relatively small number of cases in this study; however, a rainfall event, depending on the amount and intensity, can reduce the PM concentration due to reduction in emission rate from the wet surface and also the wash-out process in the near-surface atmosphere.[36]

The backward variable selection procedure in regression analysis was used to determine the independent predictors of the concentrations and PM ratios.[37,38] The R^2 values, parameter estimates, and intercept of the multivariable regression models are summarized in Table 8. Factors that significantly influenced TSP concentration included pen surface MC and wind speed; those that influenced PM_{10} concentration were humidity, temperature, pen surface MC, and amount of water used by sprinkler. Pen surface MC was the only factor that significantly influenced the $PM_{2.5}$ concentration. For the $PM_{2.5}/PM_{10}$ ratio, humidity and pen surface MC were the significant factors; and for $PM_{2.5}$/TSP ratio, pen surface MC and amount of water used by sprinkler were the significant parameters.

Statistical analysis indicated that the pen surface MC had the greatest effect on PM concentrations, particularly PM_{10} and TSP, which were reduced when MC was increased. The decrease in concentration with increasing MC of the pen surface is likely due to reduction in emission rates from the pen surfaces. The presence of moisture in the manure surface is expected to enhance the strength of surface crusts and also

Table 7. Correlation of concentrations and ratios for the downwind sampling location of feedlot KS1 with weather conditions and amount of water applied by the sprinkler system.

	n	Humidity (%)	Temperature (°C)	Wind speed (m/sec)	Precipitation (mm)	Pen Surface Moisture Content (%)	Amount of Water Used by Sprinkler (mm)
ln($PM_{2.5}$)	47	−0.02	0.01	0.20	0.22	−0.40*	0.28
ln(PM_{10})	69	−0.38*	0.33*	0.23	−0.11	−0.67*	0.39*
ln(TSP)	71	−0.29*	0.24*	0.27*	−0.13	−0.60*	0.37*
$PM_{2.5}/PM_{10}$	46	0.37*	−0.15	0.09	0.18	0.43*	−0.14
$PM_{2.5}$/TSP	46	0.24	−0.01	0.08	0.02	0.49*	−0.04
PM_{10}/TSP	67	−0.04	0.12	−0.18	0.09	0.04	−0.13

Note: *Significant at the 0.05 level.

Table 8. Factors selected in backward selection model for the concentrations and ratios at the downwind sampling location of feedlot KS1.[a]

			Parameter Estimates				
	R^2	Intercept	Humidity (%)	Temperature (°C)	Wind Speed (m/sec)	Pen Surface Moisture Content (%)	Amount of Water Used by Sprinkler (mm)
ln($PM_{2.5}$)	0.16	3.6	—	—	—	−0.03	—
ln(PM_{10})	0.51	6.1	−0.01	−0.02	—	−0.05	0.2
ln(TSP)	0.44	5.8	—	—	0.05	−0.05	—
$PM_{2.5}/PM_{10}$	0.24	−2.3	0.01	—	—	0.02	—
$PM_{2.5}$/TSP	0.22	−3.0	—	—	—	0.03	0.1

Note: [a]All variables left in the regression models are significant at the 0.1 level.

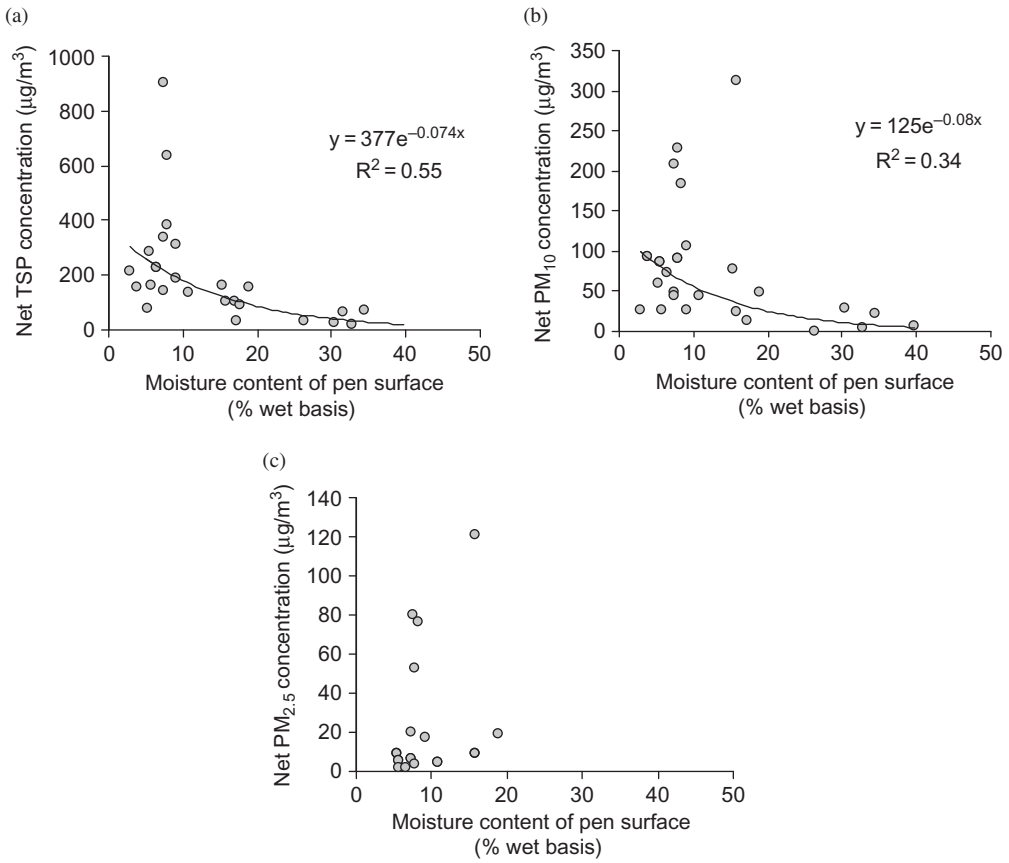

Figure 5. Net 24-hr mass concentrations of (a) TSP, (b) PM_{10}, and (c) $PM_{2.5}$ versus pen surface moisture content at feedlot KS1.

increase the mass of particles and surface tension, thereby decreasing particle suspension and transport. Figure 5a, b, and c plot the net concentrations of TSP, PM_{10}, and $PM_{2.5}$, respectively, as a function of pen surface MC. In general, net TSP and PM_{10} concentrations decreased exponentially with increasing MC. The relationship between net $PM_{2.5}$ concentration and pen surface MC was not as clear, possibly because pen surface MC was <20% for all of the acceptable sampling runs for net $PM_{2.5}$ concentration.

Results indicate that the threshold value of pen surface MC for PM control is about 20% (Figure 5). Comparison of the mean net concentrations in cases in which MC $\geq$20% and MC <20% showed mean percentage difference of over 80% for TSP and PM_{10}; for net $PM_{2.5}$ concentrations, all acceptable cases has MC <20% (Figure 5). When downwind concentrations were considered (data not shown), comparison of cases in which MC $\geq$20% and MC <20% resulted in mean percentage differences or reductions of 79%, 72%, and 78% for TSP, PM_{10}, and $PM_{2.5}$, respectively. The critical threshold MC of 20% is similar to previous findings and recommendations. Sweeten et al.[18] indicated that the MC should be in the range between 26% and 41% depending on surface conditions, whereas Miller and Berry,[39] from laboratory experiments, determined moisture contents above 35% best in controlling dust but noted that organic matter content of the feedlot surface also played a large role.[39,40] Other researchers have also suggested that the pen surface MC should be maintained at 20% to 40% on the basis of odor and dust control as well as the economy of treatment.[12,39,41]

CONCLUSIONS

The following conclusions can be drawn from this research:

- The downwind and net mass concentrations of $PM_{2.5}$, PM_{10}, and TSP as well as their ratios varied seasonally, indicating the need for multiple-day, seasonal sampling. The mass concentration of TSP and PM_{10} were closely related to the pen surface moisture content. The mass concentration of $PM_{2.5}$ also was related to the moisture content, but not to the same degree. For PM control, the moisture content of pen surface should be at least 20%.
- The ratios of $PM_{2.5}/PM_{10}$, $PM_{2.5}$/TSP, and PM_{10}/TSP at the downwind sampling location were generally less than those upwind. In addition, measurement of the particle size distribution at the downwind edge of the feedlot with a cascade impactor (MOUDI) showed geometric mean diameter ranging from 7 to 18 μm, indicating that particles that are emitted from the feedlots were generally large in size.

ACKNOWLEDGMENTS

This project is supported by grant no. 2007-35112-17853 from the U.S. Department of Agriculture (USDA) National Institute of Food and Agriculture. The project is also supported by the Kansas Agricultural Experiment Station and the USDA

Agricultural Research Service (ARS). The cooperation of the feedlot managers/operators and KLA Environmental Services is highly acknowledged. Technical assistance provided by Darrell Oard, Henry Bonifacio, and Emad Almuhanna of Kansas State University is acknowledged.

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