Particulate Control Efficiency of a Water Sprinkler System at a Beef Cattle Feedlot in Kansas

H. F. Bonifacio, R. G. Maghirang, E. B. Razote, B. W. Auvermann,
J. P. Harner III, J. P. Murphy, L. Guo, J. M. Sweeten, W. L. Hargrove

Abstract. *Water sprinkler systems are one method for controlling particulate matter (PM) emissions from cattle feedlots; however, limited data are available on the efficiency of these systems. This research was conducted to determine the PM control efficiency of a water sprinkler system in a cattle feedlot in Kansas. Downwind and upwind PM_{10} concentrations at the feedlot (KS1) were monitored with tapered element oscillating microbalance (TEOM) PM_{10} monitors from January 2006 to July 2009. The feedlot was equipped with a sprinkler system with a maximum water application rate of 5.0 mm d^{-1} (5.0 L m^{-2} d^{-1}). Control efficiency was determined by considering the PM_{10} data during sprinkler on/off events (i.e., the sprinkler system was operated for at least one day and was either followed or preceded by at least one day of no water sprinkling). Control efficiency equaled the percentage reduction in net PM_{10} concentration (i.e., downwind concentration - upwind concentration). PM_{10} control efficiency ranged from 32% to 80% with an overall mean of 53% (based on 24 h PM_{10} values). The effect of the sprinkler system in reducing net PM_{10} concentration lasted for one day or less. The PM_{10} concentration percentage reduction due to rainfall events was also determined at feedlot KS1 and at another feedlot (KS2). Feedlot KS2, located less than 40 km from KS1, was not equipped with a sprinkler system but practiced more frequent pen cleaning. Percentage reductions in net PM_{10} concentrations due to rainfall events were mostly in the range of 60% to almost 100% for both feedlots, with overall means of 77% for KS1 and 76% for KS2. The effects of rainfall events (with rainfall amounts >10 mm per event) lasted for 3 to 7 days depending on rainfall amount and intensity.*

Keywords. *Air quality, Cattle feedlots, PM_{10} emission, PM control, Sprinkler systems, Water application.*

Open beef cattle feedlots emit various air pollutants, including PM_{10} (i.e., particulate matter, or PM, with equivalent aerodynamic diameter of 10 µm or less) and $PM_{2.5}$ (i.e., PM with equivalent aerodynamic diameter of 2.5 µm or less). Although $PM_{2.5}$ may be more harmful than PM_{10} to human health because PM of this size can reach the lungs' alveolar regions (Mitloehner and Calvo, 2008), PM_{10} is also an important indicator of PM. PM_{10} can cause adverse health effects because it can enter the respiratory system (CARB, 2009).

The primary sources of PM in open cattle feedlots are the manure and soil on the pen surface. Other sources include unpaved roads, truck/equipment engine emissions, and feed mills. Several factors can influence PM emission from pen surfaces. Cattle activity often triggers PM emission from pen surfaces because hoof action on the dry, loose layer of soil and manure on pen surfaces generates considerable amounts of PM. The downwind concentration of PM_{10} tends to vary during the day, and concentrations typically are higher during the evening. Immediately before sunset, there is an increase in cattle activity and also an increase in stability of atmospheric conditions (Auvermann et al., 2006). Moisture content of pen surfaces also influences PM emission (Miller and Woodbury, 2003; Razote et al., 2006). The PM emission is inversely proportional to the pen surface moisture content. Moisture content of the pen surface is a function of moisture application and evaporation rates. Addition of water increases the moisture content of the pen surface, thus lowering PM emission. Sources of water include cattle urine, rain, and any water application system. However, evaporation extracts the moisture, resulting in a dry, loose pen surface prone to higher PM emission. The rate of evaporation depends on weather conditions, such as temperature, humidity, solar radiation, and wind speed. Using lysimeters with a simulated feedyard surface, Marek (2006) estimated the daily evaporation rate to be 0.9 to 4.5 mm (L m^{-2}). Marek (2006) found that evaporation at the feedlot surface was dependent on two other factors: manure profile, which influences the water transport behavior

Submitted for review in April 2010 as manuscript number SE 8525; approved for publication by the Structures & Environment Division of ASABE in December 2010. Presented at the 2009 ASABE Annual Meeting as Paper No. 097028.

Contribution No. 10-295-J from the Kansas Agricultural Experiment Station.

The authors are **Henry F. Bonifacio, ASABE Student Member,** Graduate Research Assistant, **Ronaldo G. Maghirang, ASABE Member Engineer,** Professor, and **Edna B. Razote, ASABE Member Engineer,** Research Assistant, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas; **Brent W. Auvermann, ASABE Member Engineer,** Professor, Texas A&M University Texas AgriLife Research and Extension Center, Amarillo, Texas; **Joseph P. Harner III, ASABE Member Engineer,** Department Head and Professor, **James P. Murphy, ASABE Fellow,** Professor, and **Li Guo, ASABE Student Member,** Graduate Research Assistant, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas; **John M. Sweeten, ASABE Fellow,** Research Director and Professor, Texas A&M University Texas AgriLife Research and Extension Center, Amarillo, Texas; and **William L. Hargrove,** Director, Center for Environmental Resources Management, University of Texas, El Paso, Texas. **Corresponding author:** Ronaldo G. Maghirang, Department of Biological and Agricultural Engineering, Kansas State University; 129 Seaton Hall, Manhattan, KS 66506; phone: 785-532-2908; fax: 785-532-5825; e-mail: rmaghir@ksu.edu.

  ISSN 2151-0032

between soil/manure layers, and time of day (moisture loss during the day and moisture gain at night). The nighttime increase in moisture was attributed to the hygroscopic nature of cattle manure (Marek, 2006).

Several studies have been conducted to measure PM concentrations in the vicinity of cattle feedlots. Sweeten et al. (1988) measured PM concentrations for 24 h sampling periods at three feedlots in Texas. They reported that the mean total suspended particulate (TSP) concentration was 412 $\mu g\ m^{-3}$ and the mean PM_{10} downwind concentration was 40% of the mean TSP concentration. Razote et al. (2007) reported a mean net PM_{10} concentration of 115 $\mu g\ m^{-3}$ (range from 35 to 195 $\mu g\ m^{-3}$) at a cattle feedlot in Kansas.

Methods used to control PM_{10} emissions from cattle feedlots include (1) watering pen surfaces to increase moisture content, (2) increasing stocking density, and (3) frequently harvesting manure to remove dry, loose manure from the pen surface (Auvermann et al., 2006; MWPS, 2002a, 2002b). Water application is considered an effective dust abatement measure for agricultural/industrial operations, with PM_{10} control efficiencies ranging from about 10% to about 90%, depending on the amount and frequency of application (CE, 2006). As cited in the WRAP fugitive dust handbook (CE, 2006), published PM_{10} control efficiencies include almost 90% for PM_{10} for agricultural tilling when the soil is irrigated prior to tilling, 55% for unpaved roads when water is applied on unpaved road at least twice a day, 10% to 74% for construction operations, and 50% to 90% for materials handling and transport.

Water application on pen surfaces is also considered effective in controlling PM emission from cattle feedlots (Auvermann et al., 2006); however, limited research has quantified the effectiveness of water application in controlling PM emission or reducing concentration at the feedlots. In a USEPA report, Pechan (2006) reported that watering beef cattle feedlots, either by sprinkler systems or water trucks, had a PM_{10} control efficiency of 50%; however, the basis for the efficiency value was not presented. Carroll et al. (1974) compared a sprinkled feedlot with a non-sprinkled feedlot in southern California and reported control efficiencies of 38% and 49% for TSP based on measurements within the feedlots. These values were based on two data points, however, and comparison between feedlots was difficult because management practices differed (Carroll et al., 1974). Research on a California feedlot revealed that after the water sprinkler system was turned off for two days, dust concentrations within the feedlot increased by 850% (ACFA, 2002; MWPS, 2002a); however, this study was based on limited data (only one data point) and no weather or sprinkler setting information was reported. Using a laboratory-scale chamber, Razote et al. (2006) observed that application of at least 3.2 mm of water on a simulated pen surface reduced PM_{10} emission potential by more than 80%.

Evidently, more research is needed to quantify the effectiveness of water sprinkler systems in controlling PM concentrations in cattle feedlots. The objectives of this study were to evaluate, under field conditions, the control efficiency of a water sprinkler system in reducing PM_{10} in a cattle feedlot, and to compare the sprinkler system's PM_{10} control efficiency with that of rainfall events.

Materials and Methods

Site Description

Table 1 presents characteristics of the two commercial cattle feedlots used in this study. The feedlots are located in Kansas and are within 40 km of each other. Prevailing wind directions at the feedlots are south-southeast during summer and north-northwest during winter. The first feedlot, KS1, had approximately 30,000 head of cattle and a total pen area (excluding unpaved roads, alleys, and feed mill) of about 50 ha. The cattle spacing (inverse of stocking density) was 17 m^2 $head^{-1}$. The feedlot had a water sprinkler system with an application rate of 5.0 mm d^{-1} (5.0 L m^{-2} d^{-1}). The feedlot cleaned the pens two to three times per year and removed manure from the pens at least once a year. The second feedlot, KS2, had approximately 25,000 head of cattle, a total pen area of 68 ha, and a cattle spacing of 27 m^2 $head^{-1}$. For PM control, this feedlot cleaned the pens five to six times per year and removed manure from each pen two to three times per year. Relative to KS1, KS2 had lower manure accumulation because it had a higher frequency of pen cleaning and manure harvesting.

This research focused on measurement and analysis of the dataset from the April-to-October period when the sprinkler system at KS1 was typically used. Table 1 shows that KS2 received about 15% more precipitation than KS1 in 2007 and 2008. For KS1, the total amount of water applied through the sprinkler system and the number of days the sprinkler system was operated varied from year to year depending on weather conditions. The total amount of water used by the sprinkler system in 2006, 2007, 2008, and 2009 (up to July) was 470, 333, 209, and 148 mm (L m^{-2}), respectively. The sprinkler system was operated for a total of 135 days in 2006, 102 days in 2007, 57 days in 2008, and 42 days in 2009.

Water Sprinkler System Operation

The water sprinkler system at KS1 was installed in the 1990s with an estimated cost of more than a half-million dollars. The water sprinkler system normally operated from April to October or during prolonged dry periods. The sprinkler system had a total of 179 sprinkler heads. Most of the sprinkler heads were operated in full circle with approximate wetting diameters of 55 to 88 m (equivalent wetted areas of 2,380 to 6,080 m^2); some were operated in half-circle with approximate wetting diameters of 50 to 88 m (equivalent wetted areas of 980 to 3,180 m^2). The sprinkler heads were located and operated such that there were overlaps in wetting coverage between two adjacent sprinkler heads. A group of three sprinkler heads was turned on simultaneously every 6 min, applying 1,890 L min^{-1} of water.

Table 1. Descriptions of the two feedlots.

Parameter	KS1	KS2
Capacity (head)	30,000	25,000
Area (ha)	50	68
Dust control methods		
Water sprinkler system	$\leq$5 mm d^{-1}	None
Pen cleaning[a]	2 to 3	5 to 6
Weather conditions		
Prevailing wind direction	SSE	SSE
Avg. total precipitation (mm)[b]	573	671

[a] Number of cleanings per year per pen.
[b] April to October period for 2007 and 2008.

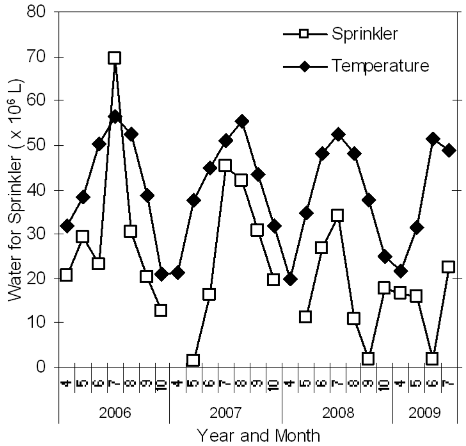

Figure 1. Sprinkler system water use and mean air temperature for the April-to-October period from 2006 to 2008 at feedlot KS1.

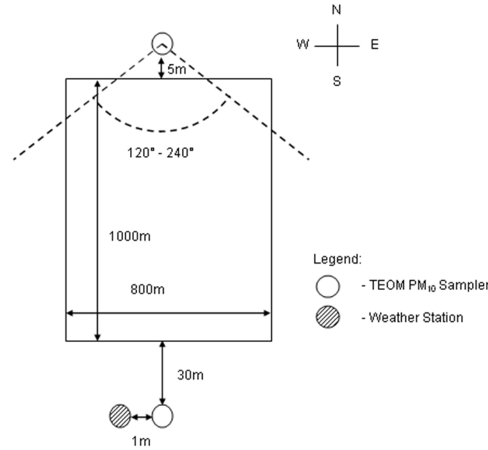

Figure 2. Schematic diagram showing locations of the samplers and weather station at feedlot KS1.

Six hours were required to cycle through all the sprinkler heads, each head applying 1.25 mm (1.25 L m^{-2}) every time it turned on; 24 h operation of the sprinkler system had an application rate of 5 mm d^{-1} (5.0 L m^{-2} d^{-1}). The water sprinkler system was operated primarily on the basis of air temperature and dusty conditions at the KS1 feedlot; a Pearson correlation coefficient of 0.61 between sprinkler water amount and air temperature suggests that sprinkler operation was indeed operated based on the observed temperature (fig. 1). Hours of operation were input daily in a computer that controlled the sprinkler system automatically. The source of the water for both the sprinkler system and waterers was an off-site well.

Measurement of PM_{10} Concentration and Weather Conditions

Mass concentrations of PM_{10} were measured at the north and south perimeters of the feedlots. Sampling locations at the feedlots were selected based on feedlot layout, power availability, and site access. For KS1, the north sampling site was approximately 5 m away from the closest pen, and the south site was approximately 30 m from the closest pen (fig. 2). For KS2, the north and south sampling locations were 40 and 60 m, respectively, away from the closest pens. These differences in distance from the pens along with differences in amount of precipitation and management practices (e.g., pen cleaning and manure harvesting frequencies, stocking density, and feeding practices) between the two feedlots prevented meaningful comparison of PM_{10} mass concentration between the sprinkled feedlot (KS1) and non-sprinkled feedlot (KS2).

The PM_{10} concentration was measured with tapered element oscillating microbalance (TEOM) PM_{10} monitors (Series 1400a, Thermo Fisher Scientific, East Greenbush, N.Y.; federal equivalent method designation No. EQPM-1090-079); the inlet was positioned 2.3 m from the ground. PM_{10} concentrations were recorded continuously at 20 min intervals. During sampling and measurement, the sampled air and TEOM filter were heated to 50°C. Maintenance of the TEOM (i.e., leak checks, flow audits, and inlet cleaning) was performed monthly. For cases of low flow audit results, either the TEOM pump was replaced or software calibration was done to correct the sampling flow rate. The TEOM collection filters were replaced if the filter loading indicated by the TEOM reached the 90% value; the TEOM in-line filters were replaced when the amount of dust collected was significant.

Each feedlot was equipped with a weather station (Campbell Scientific, Inc., Logan, Utah) to measure and record wind speed and direction (model 05103-5), atmospheric pressure (model CS100), precipitation (model TE525), and air temperature and relative humidity (model HMP45C). Measurement height was 2.5 m. Weather parameters were recorded continuously at 20 min intervals.

Data Analysis

The PM_{10} dataset from the TEOM was first screened on the basis of wind direction. Datasets that corresponded to a wind direction of 120° to 240°, in which the north sampling site was downwind of the feedlot and the south sampling site was upwind, were considered (fig. 2). Data outside this range were excluded in the analysis for the following reasons: (1) if the wind direction was from the east (i.e., 60° to 120°) or west (i.e., 240° to 300°), PM measured by the TEOM would not represent the PM emitted from pen surfaces; and (2) if the wind direction was from the north (i.e., 0° to 60° or 300° to 360°), the south sampling site would be downwind of the feedlot, and the differences in distance from the closest pens between the north and south sampling sites would make it difficult to compare the downwind concentrations. The PM_{10} concentrations were expressed as net concentrations (i.e., downwind concentration - upwind concentration). Net PM_{10} concentrations were calculated at 20 min intervals, which was the interval of data collection in the TEOM.

Negative values of PM_{10} concentrations were recorded by the TEOM in some cases (for downwind concentration, approximately 6% of KS1 datasets and 5% of KS2 datasets were negative; for upwind concentration, approximately 10% of KS1 datasets and 6% of KS2 datasets were negative). These negative values could be due to the nature of the particles or to instrument malfunction (Guo et al., 2009). In accordance with the manufacturer's recommendation, "small" negative values (i.e., 0 to -10 μg m^{-3}), which were likely due to the nature of the particles or very low concentrations, were considered in the calculation of average hourly and daily concentrations, but "large" negative values (i.e., <-10 μg m^{-3}), which were likely due to instrument malfunction, were not considered. In cases of missing upwind PM_{10} concentrations (approximately 19% of KS1 datasets and 25% of KS2 datasets), upwind concentrations were considered zero to maximize use of available downwind data.

Values from the screened dataset were selected for evaluation of the control efficiency of the water sprinkler system at KS1 and rainfall events at KS1 and KS2. Control efficiency of the water sprinkler system at KS1 was determined by selecting sprinkler on/off events. An on/off event was defined as the water sprinkler system being operated for at least one day (on) and either followed or preceded by at least one day of no water sprinkling (off). The PM_{10} control efficiency was determined by comparing the period when the sprinkler system was operated with the period when the sprinkler was not operated. The number of days for each period varied from one to four days depending on the availability of TEOM concentration and weather data. In addition, sprinkler events should not have any rainfall event seven days before and at least one day after the day selected to observe the effect of the sprinkler system because the effect of a rainfall event was observed to last for several days.

The impact of rainfall events was analyzed for days when there was no rainfall on the day prior to the rainfall event evaluated. The day after the rainfall event was not used to estimate the percentage reduction in PM_{10} concentration because of the lasting effect of rain.

Control efficiency of the sprinkler system in reducing daily net PM_{10} concentration was estimated by computing (1) the decrease in daily net PM_{10} concentration after the water sprinkler system was turned on and (2) the increase in daily net PM_{10} concentration after the sprinkler system was turned off. The efficiency, *CE*, was calculated using:

$$CE = \frac{C_{off} - C_{on}}{C_{off}} \times 100\% \qquad (1)$$

where C_{off} is the net concentration (μg m^{-3}) for the period when the sprinkler was turned off, and C_{on} is the net concentration (μg m^{-3}) for the period when the sprinkler was turned on. Control efficiency for a rainfall event was estimated by computing the decrease in daily net PM_{10} concentration after the rainfall event, that is, control efficiency for a rainfall event was calculated by:

$$CE = \frac{C_{nr} - C_{r}}{C_{nr}} \times 100\% \qquad (2)$$

where C_{nr} is the net concentration (μg m^{-3}) for the period without rainfall, and C_r is the net concentration (μg m^{-3}) for the period affected by rainfall. To account for variations in daily net concentrations, each period was represented by its average daily net concentration. The control efficiency was computed on the basis of mean values for the 24 h period and evening dust peak (EDP) period, the latter described as the time in the evening with very high PM concentrations.

Data were analyzed with SAS for Windows version 9.1.3 (SAS, 2002). In determining factors that influenced a parameter of concern (i.e., PM_{10} control efficiency, daily increase in concentration), backward selection was applied. For comparisons of mean values (i.e., control efficiencies, rainfall amount), preliminary analysis was performed to determine if the assumptions of normality and homogeneity of variance were satisfied. If these assumptions were met, standard statistical tests (e.g., standard analysis of variance, paired t-test) were used; if the assumptions were not met, nonparametric test (i.e., nonparametric one-way analysis of variance) was used together with the standard statistical test. Montgomery (1984) indicated that when the two procedures give similar results, the analysis of variance assumptions are satisfied reasonably well and the standard statistical tests are satisfactory. In all the statistical analyses, a 5% level of significance was used.

Results and Discussion

The measurement time periods were April 2006 to July 2009 for KS1 and April 2007 to July 2009 for KS2. For both feedlots, there were months that either the TEOM data or the on-site weather station data were missing because of equipment-related problems. For KS1, TEOM data were missing in three months (i.e., June, July, and September 2006). For KS2, TEOM data were missing in nine months: two months in 2007 (i.e., August and October) and seven months in 2009 (i.e., January to July). For missing on-site rainfall amounts (e.g., January 2006 to July 2007 for KS1), data from the weather station in a nearby regional airport were used. Paired t-test using the 2008 data on rainfall amounts showed that the on-site weather station and the airport weather station did not significantly differ (p = 0.64) in mean rainfall amount.

Weather Conditions and Sprinkler System Operation

Wind direction was primarily from the south (the north sampling site was downwind of the feedlot) for both feedlots. For KS1, wind directions were from the south (i.e., 120° to 240°) 52% of the time, north (i.e., 0° to 60° or 300° to 360°) 30% of the time, east (i.e., 60° to 120°) 9% of the time, and west (i.e., 240° to 300°) 9% of the time. For KS2, wind directions were from the south 49% of the time, north 28% of the time, east 12% of the time, and west 11% of the time.

Means and ranges of hourly values for temperature, relative humidity, and wind speed are summarized in table 2. Ambient temperature and relative humidity were similar at both feedlots. KS1 had higher (24%) mean wind speed than KS2. KS1 had a yearly average of 530 mm of precipitation for the months of April to October from 2006 to 2008, and mean monthly precipitation ranged from 2 to 35 mm. KS2 had an average of 671 mm of precipitation from 2007 to 2008, and mean monthly precipitation ranged from 10 to 35 mm.

Operation of the water sprinkler system at KS1 was based on air temperature and dusty conditions at the feedlot. Figure 1 shows that the trend of the amount of water used for

Table 2. Weather conditions for the April to October periods (KS1, 2006 to 2009; KS2, 2007 to 2008).

Parameter	KS1			KS2		
	Min.	Max.	Avg.	Min.	Max.	Avg.
Temperature (°C)	-9	41	20	-7	40	20
Rel. humidity (%)	10	100	64	10	100	67
Wind speed (m s^{-1})	0.00	18.33	4.64	0.00	15.87	3.74

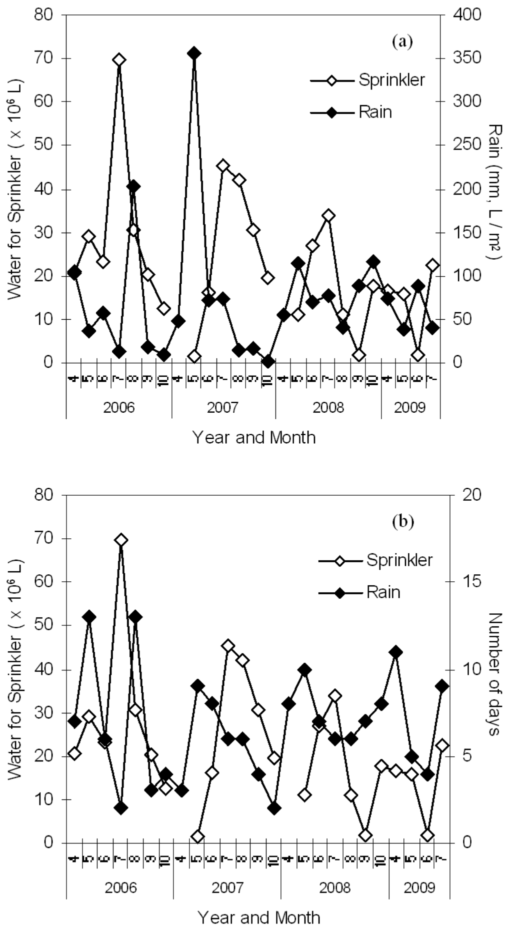

Figure 3. KS1 sprinkler system water use from 2006 to 2009: (a) sprinkler water and amount of rain, and (b) sprinkler water and number of days with rain.

the sprinkler system closely followed the trend of the air temperature. Figure 3a shows the trends for sprinkler water use and total amount of rainfall. As expected, the amount of water used for the sprinkler system was high during periods with low rainfall amounts (e.g., July 2006, August and September 2007) and low during periods with high rainfall amounts (e.g., May 2007). Figure 3b shows a comparison between the amount of water used for the sprinkler system and number of days with rainfall. In general, the amount of water used for the sprinkler system increased with decreasing number of days with rainfall events. Yearly values of rainfall variables (i.e., amount of rain and number of days) and sprinkler water use are summarized in table 3. In 2006, the amount of water used for the sprinkler system was greatest, possibly due to the relatively smaller amount of rainfall received during that period. In 2009, both rainfall amount and water consumption were low because the data represented only four months of data (i.e., April to July). In 2007 and 2008, water consumption for the sprinkler system was smaller compared to that in 2006 because rainfall amounts were greater.

PM_{10} Concentrations

The diurnal variations of the net PM_{10} mass concentration for KS1 and KS2 are illustrated in figures 4a and 4b, respectively. In general, the concentrations during any given day were smallest in the early morning hours between 0100 h and 0700 h. The concentrations were generally greatest during the hours between 1700 h and 2300 h, which is referred to in this study as the evening dust peak (EDP) period. As suggested by Auvermann et al. (2006), the following factors may be responsible for the evening dust peaks: daytime evaporation of moisture from the pen, increased social and aggressive cattle behavior during the early evening hours, and stable atmospheric conditions.

Table 3. Sprinkler water consumption and rainfall at KS1 from April to October, 2006 to 2009.

Year	Rainfall Amount (mm)	Rainfall Number of Days	Sprinkler Water Use ($\times 10^6$ L)
2006	443	48	206
2007	583	38	155
2008	563	52	102
2009[a]	354	29	57
Average[b]	530	46	154

[a] April to July.
[b] Average for 2006 to 2008.

Table 4. Measured daily PM_{10} concentrations for the two feedlots (KS1 and KS2) for the period April to October, 2006 to 2009.

	KS1		KS2	
	Daily Period (24 h)	EDP Period (1700 h to 2300 h)	Daily Period (24 h)	EDP Period (1700 h to 2300 h)
Downwind				
Number	916	726	491	377
Avg. (μg m^{-3})	168	313	85	144
SD (μg m^{-3})	264	543	135	209
Upwind				
Number	804	630	458	337
Avg. (μg m^{-3})	48	64	21	28
SD (μg m^{-3})	55	114	17	33
Net				
Number	914	724	484	375
Avg. (μg m^{-3})	136	268	71	124
SD (μg m^{-3})	235	475	129	198

Measured PM_{10} concentrations for the 24 h and EDP periods for April to October are summarized in table 4. KS1 had higher PM_{10} concentrations relative to KS2. The higher PM_{10} concentrations at KS1 could be a result of the shorter distance between the TEOM sampler and the closest pen, higher PM emission rate due to higher manure accumulation, or both; however, this could not be confirmed, since the emission rates were unknown. Comparing the two measurement periods for the two feedlots, the EDP period had higher PM_{10} concentrations than the 24 h period, as expected.

PM_{10} Control Efficiency of Water Application

For 2006 to 2009 (April to October), KS1 had 171 days with rainfall events out of 764 days in the measurement period. For KS2, there were 114 days with rainfall events out of 428 days during the measurement period (2007 to 2008). The sprinkler system at KS1 was operated for 336 out of

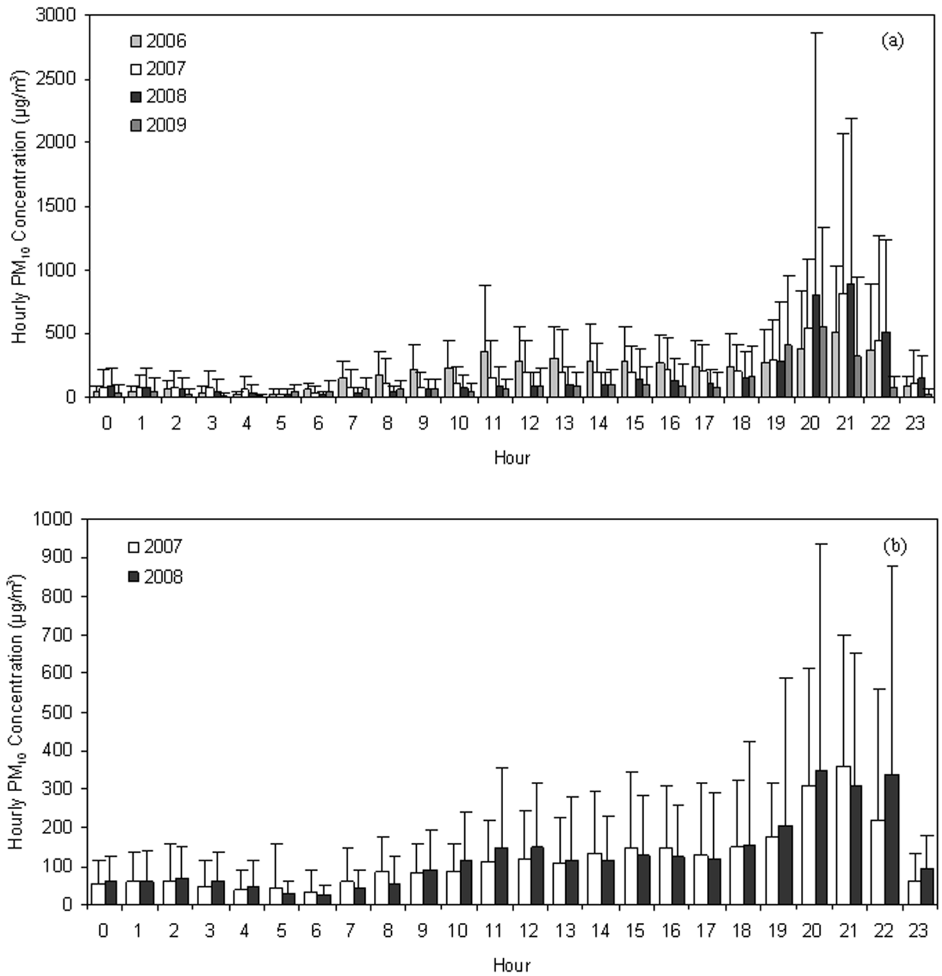

Figure 4. Average hourly PM_{10} concentration trends (April to October): (a) KS1 for 2006 to 2009 and (b) KS2 for 2007 to 2008. Error bars represent standard deviations.

764 days in the study, and there were 42 sprinkler on/off events from April 2006 to July 2009. Of these events, a maximum of 14 events could be used depending on the analysis (i.e., 24 h period and EDP period; average concentrations and maximum concentrations). Of the events that were not used, almost half had no TEOM concentration data; others were affected by rainfall events. For rainfall events at KS1 (April 2006 to July 2009), 89% (34 out of 38 events) of the data values were considered acceptable for the study. For KS2 (January 2007 to October 2008), 90% (18 out of 20 events) of the available data values were acceptable. There were more rainfall events at KS1 than KS2 because of the difference in study periods.

For the events selected, daily net PM_{10} concentrations ranged from 10 to 2,371 µg m^{-3} at KS1 and from 25 to 515 µg m^{-3} at KS2 prior to water application (i.e., sprinkler operation or rainfall event). If water was not applied, PM_{10} concentration the next day varied by ±90 µg m^{-3} and ±50 µg m^{-3} at KS1 and KS2, respectively. Daily PM_{10} concentrations decreased significantly after water application (i.e., 18 to 950 µg m^{-3} for KS1 sprinkler on/off events, 9 to 434 µg m^{-3} for KS1 rainfall events, and 5 to 98 µg m^{-3} for KS2 rainfall events). PM_{10} concentration varied by ±60 µg m^{-3}, ±40 µg m^{-3}, and ±16 µg m^{-3} the next day for KS1 sprinkler on/off events, KS1 rainfall events, and KS2 rainfall events, respectively.

Control Efficiency

Table 5 lists statistics on PM_{10} control efficiencies for the water sprinkler system and rainfall events. Tests for normality indicated that the control efficiency data for the sprinkler and rainfall events had non-normal distribution. In general, results of standard statistical tests and non-parametric tests were similar. Analysis of variance showed that the mean PM control efficiency of the sprinkler system at KS1 was significantly different from those of the rain events at KS1 ($p < 0.001$) and KS2 ($p = 0.004$); the rainfall events had higher control efficiencies, as expected. Factors that could account for the higher control efficiency for rainfall events include rainfall intensity, duration, and area coverage. Rainfall intensity and duration were generally greater than those for the sprinkler system. Possibly more important, rainfall events generally covered the whole feedlot, including the alleyways and unpaved roads. In contrast, for the sprinkler system, water was applied only on the pens. In addition, the effective pen coverage of the sprinkler system could be lower as a result of high wind speed, variable wind direction, and sprinkler design (i.e., sprinkler head type, pump operating parameters).

Table 5. PM_{10} control efficiency for sprinkler events at KS1 and for rainfall events at KS1 and KS2.

	Daily Period (24 h)			EDP Period (1700 h to 2300 h)		
	Sprinkler (KS1)	Rainfall (KS1)	Rainfall (KS2)	Sprinkler (KS1)	Rainfall (KS1)	Rainfall (KS2)
No. of Events	10	33	18	11	34	18
Avg.[a] (%)	53 a	77 b	76 b	52 a	80 c	86 c
Min. (%)	32	17	28	17	35	63
Max. (%)	80	96	95	81	98	98
SD (%)	15	16	17	21	17	11

[a] Average values followed by the same letters are not significantly different at 5%.

The control efficiency for the sprinkler system at KS1 ranged from 32% to 80% based on the 24 h concentration values and from 17% to 81% based on the concentrations for the EDP periods. Paired t-test showed that the mean control efficiency for the EDP period was not significantly different ($p = 0.82$) from that for the 24 h period (52% vs. 53%). During the 327 days (14 April 2006 to 15 July 2009) of operation, the sprinkler system was activated for at least 20 h d^{-1} on only 30% of the days and for at least 12 h d^{-1} on 70% of the days. The mean control efficiency of the water sprinkler system at KS1 was 53% (24 h) for PM_{10}; other studies reported control efficiencies of 43% for TSP (Carroll et al., 1974) and 50% for PM_{10} (Pechan, 2006).

Analysis of variance showed that KS1 and KS2 did not differ significantly ($p = 0.91$) in mean control efficiencies associated with rainfall events. Paired t-test also revealed that the mean control efficiencies for rainfall events based on the EDP and 24 h periods did not differ significantly ($p = 0.25$) for KS1. For KS2, however, non-parametric test showed that the control efficiencies of the two periods differed significantly ($p = 0.04$), with the EDP period having higher PM control efficiency.

Figures 5a and 5b show control efficiencies (sprinkler and rainfall events) plotted against the amount of water applied. The backward selection procedure did not show any significant ($p = 0.65$) effect of the amount of water applied on control efficiency of the sprinkler system, possibly because a relatively small amount of water was applied (1.5 to 5.1 mm d^{-1}). For rainfall events, the control efficiency usually exceeded 80% when the rainfall amount was more than 25 mm per event and greater than 70% when the rainfall amount exceeded 20 mm per event (fig. 5b). However, regression analysis using the backward selection procedure did not show any significant effect of rainfall amount on control efficiency ($p = 0.93$), possibly because of the effect of initial PM_{10} concentration. For example, there was a case with low control efficiency of 28% even if the rainfall amount was 120 mm. This occurred during a period when the initial net PM_{10} concentration equaled 25 μg m^{-3}, which was already low relative to the typical ambient PM_{10} concentration. Some rainfall events that had only 5 mm d^{-1} of rainfall (equivalent to the capacity of the water sprinkler system at KS1) resulted in more than 80% control efficiency (fig. 5b). High reductions achieved by these rainfall events (≤5 mm d^{-1}) might be due to the high intensity of rainfall in a short period of time and the relatively wider coverage compared to the sprinkler system.

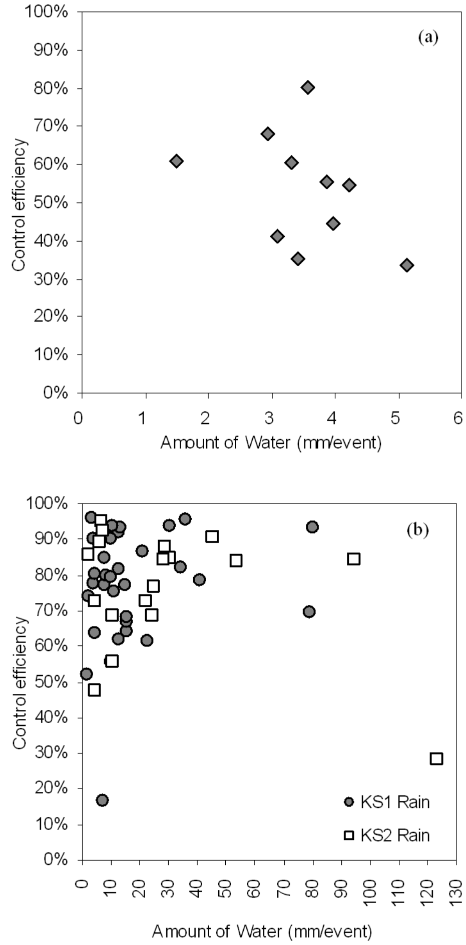

Figure 5. PM_{10} control efficiency plotted against the amount of water applied for (a) KS1 sprinkler events and (b) KS1 and KS2 rainfall events.

Figure 6 shows the control efficiencies plotted against initial net PM_{10} concentrations (i.e., no water application). Daily initial net PM_{10} concentrations at KS1 ranged from 38 to 848 μg m^{-3}; concentrations ranged from 41 to 1,471 μg m^{-3} during the EDP periods. Daily initial net PM_{10} concentrations for KS2 ranged from 25 to 471 μg m^{-3}; EDP net PM_{10} concentrations ranged from 31 to 1,018 μg m^{-3}. Statistical analysis did not show any significant correlation between control efficiency and initial PM_{10} concentration for the sprinkler ($p = 0.70$) and rainfall events ($p = 0.10$).

Decrease in PM_{10} Concentration

The decrease in PM_{10} concentration associated with the sprinkler system at KS1 ranged from 34 to 406 μg m^{-3} for the 24 h period and from 35 to 1,043 μg m^{-3} for the EDP period. For rainfall events, the decrease in concentration at KS1 ranged from 24 to 796 μg m^{-3} for the 24 h period and from 27 to 1,088 μg m^{-3} for the EDP period. The decrease in KS2 ranged from 7 to 436 μg m^{-3} for the 24 h period and from 24

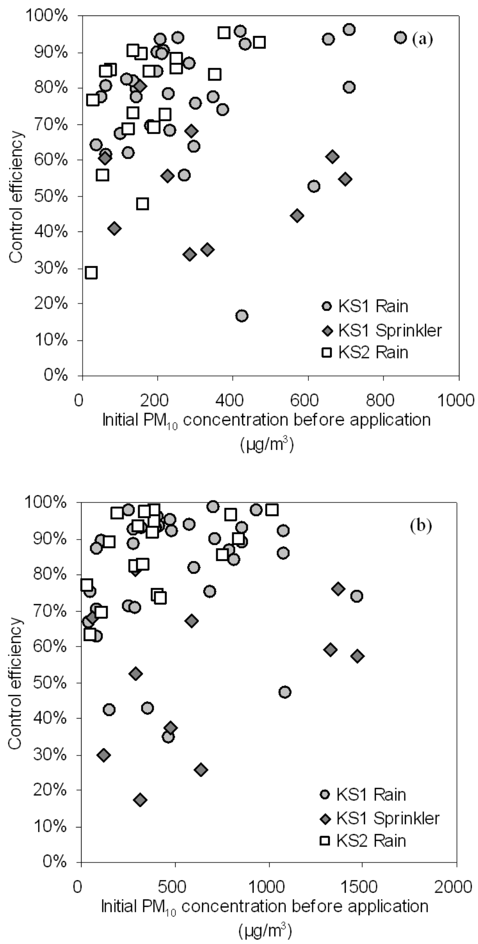

Figure 6. Plots of PM_{10} control efficiency and initial PM_{10} concentration based on (a) daily average and (b) EDP period average.

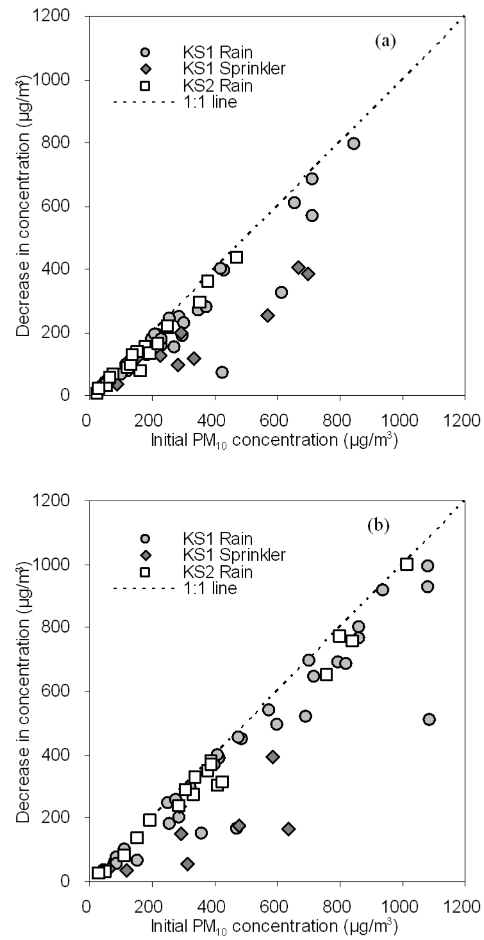

Figure 7. Effects of initial net PM_{10} concentration on the decrease in net PM_{10} concentration: (a) daily average and (b) EDP period average.

to 997 µg m^{-3} for the EDP period. For both the sprinkler system and rainfall events, statistical analysis did not show any significant correlation between decrease in concentration and amount of water applied ($p = 0.09$ for sprinkler events; $p = 0.34$ for rain events).

Figures 7a and 7b plot the decrease in net PM_{10} concentration against initial net PM_{10} concentration based on 24 h and EDP periods, respectively. In general, the higher the initial concentration, the larger the decrease in concentration was. One important trend observed from the plots was that the data points for the sprinkler on/off events at KS1 were farthest from the 1:1 (y:x) line, suggesting a much lower decrease in concentration for the sprinkler system compared to the rainfall events. An intensity of approximately 1.25 mm and shorter duration for the sprinkler system could help explain the difference in decrease in concentration for the sprinkler system compared with rainfall events. In figure 7a, there were three rainfall events that had similar initial PM_{10} concentrations (i.e., event 1: 421 µg m^{-3}, event 2: 426 µg m^{-3}; event 3: 432 µg m^{-3}). Events 1 and 3 were close to the 1:1 line, indicating very low PM_{10} concentrations (19 and 35 µg m^{-3}, respectively) measured after the rainfall events. However, event 2, which had a PM_{10} concentration of 355 µg m^{-3} after rain, was far from the 1:1 line. Events 1 and 3 had rainfall amounts of 36 and 13 mm, respectively. However, event 2 only had 2 mm of rainfall; this low amount of rainfall indicates low rainfall intensity and short duration. Thus, for water application, high intensity and long duration were important variables to have significant decrease in concentration.

Duration of the Effects of Sprinkler System and Rainfall Events

The duration of the effects of the sprinkler system and rainfall events was determined by using events with daily net PM_{10} concentration data. In general, the effect of the sprinkler system lasted for one day or less. Possible reasons for the relatively short duration of the effect of the sprinkler system include the small amount of water applied ($\leq$5 mm d^{-1}), short duration of the application (6 min every 6 h), and non-uniform distribution of application.

The duration of the effect of rainfall events generally lasted from 3 to 7 days and was possibly affected by several variables, including rainfall parameters (i.e., intensity, duration, and amount) and weather conditions (i.e., temperature, solar radiation, wind speed). To analyze the duration of the effect of rainfall, 12 rainfall events were selected from KS1 and KS2 on the basis of the completeness of net PM_{10} concentration data. Table 6 summarizes the characteristics (i.e., rainfall intensity, duration, and total amount) and net PM_{10} concentrations for these 12 events. Regression analyses on these events indicated that after rainfall events, increase in net PM_{10} concentration averaged 41 µg m^{-3} per day, ranging from 12 to 72 µg m^{-3} per day (table 6).

Table 6. PM_{10} concentrations and rainfall parameters for rainfall events (*n* = 12).

Parameter	Min.	Max.	Avg.	SD
Rainfall				
Intensity (mm h^{-1})	2.54	10.53	5.06	2.18
Duration (h)	3	19	8	6
Total amount (mm)	11	137	47	44
Net PM_{10} concentration (μg m^{-3})				
Before rain	119	895	365	268
After rain	12	74	30	21
Increase in concentration per day (μg m^{-3} d^{-1}, linear regression)[a]	12	72	41	21

[a] R2 values ranged from 0.58 to 0.95.

Regression analysis by backward selection showed that the daily increase in net PM_{10} concentration was significantly affected by the initial net PM_{10} concentration (p = 0.002) and rainfall intensity (p = 0.01): the higher the initial concentration, the faster the daily rate of increase in concentration; and the higher the rainfall intensity (≥1.25 mm h^{-1}), the lower the daily rate of increase in concentration. Figure 8 shows the daily increase in concentration plotted against initial net PM_{10} concentration.

Additional analysis was done to verify the effect of rainfall amount on the daily rate of increase in concentration based on events with almost similar initial net PM_{10} concentrations. Four events with initial PM_{10} concentrations ranging from 370 to 460 μg m^{-3} were selected. For these events, rainfall intensities were greater than 2.7 mm h^{-1} and rainfall durations were longer than 4 h. Statistical analysis showed that the increase in net PM_{10} concentration per day was inversely proportional (R^2 = 0.96) to the rainfall amount within the range of 10 to 95 mm per event (fig. 9).

The above analyses could prove useful in improving the control efficiency of the sprinkler system. The duration of the effects of rainfall, expressed as the increase in PM_{10} concentration per day after rainfall events, depended on initial PM_{10} concentration, rainfall amount, and intensity. Results suggest that the effective duration of the effects of the sprinkler system can be enhanced by manipulating either the hourly water application rate or the total daily amount of water. If the initial PM concentration can be estimated, then the daily increase in concentration after a sprinkler operation

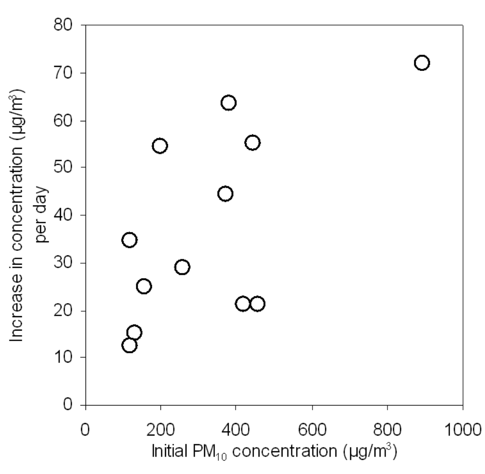

Figure 8. Increase in PM_{10} concentration (μg m^{-3}) per day plotted against initial PM_{10} concentration for rainfall events.

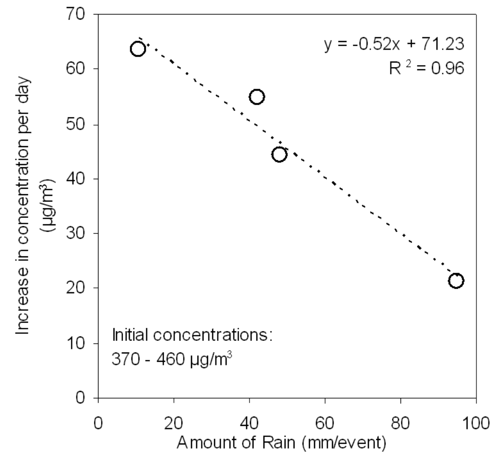

Figure 9. Increase in net PM_{10} concentration per day plotted against total rainfall amount.

or rainfall event can be predicted, and subsequent application of appropriate actions to minimize PM emission could be applied once the effect of water application recedes.

There were several limitations in this study that relate to PM_{10} measurement. The performance bias in inertial pre-separators for particulate samplers (e.g., Buser et al., 2007) and differences among PM_{10} samplers (e.g., Guo et al., 2009; Wanjura et al., 2008) are well documented. The performance bias for TEOM was not considered in this study, largely because of the lack of scientifically validated means of correcting for that bias. In addition, if the bias is not highly dependent on concentration, then its effect on control efficiency would be small. Another limitation was the single-point measurement of concentration. Because of the large area and variability in pen conditions in the feedlots, it is expected that the PM_{10} concentration would vary spatially in the feedlot and single-point measurement might not truly represent the concentration. To overcome this deficiency, it would be necessary to deploy several samplers distributed in the feedlot. It is not clear from the study what the overall effect is of single-point measurement on control efficiency.

Conclusions

Control efficiency for PM_{10} of water application, including rainfall and a water sprinkler system, was evaluated at two feedlots in Kansas by comparing PM_{10} concentrations during water application on/off events. The following conclusions were drawn:

- For the water sprinkler system at KS1, control efficiency for PM_{10} based on the 24 h mean concentrations ranged from 32% to 80% with an overall mean of 53%. Control efficiency based on concentrations during the evening dust peak (EDP) periods (1700 h to 2300 h) ranged from 17% to 81% with an overall mean of 52%.
- For rainfall events at KS1 and KS2, control efficiencies for PM_{10} ranged from 17% to 96% for the 24 h mean values and from 35% to 98% for EDP values.
- The effect of water application through the sprinkler system (≤5 mm of water d^{-1}) lasted for one day or less. The effect of a rainfall event, on the other hand, generally lasted for 3 to 7 days depending on initial net

PM_{10} concentration, and rainfall amount and intensity. After a rainfall event (>10 mm per event), the mean increase in net PM_{10} concentration was approximately 41 μg m^{-3} per day.

Results suggest that the efficiency of the water sprinkler system can be enhanced by increasing the water application rate and duration of application. The effects of sprinkler system operating variables (i.e., application rate, periods of application) on the duration of the effects of the sprinkler system require further investigation. Despite the acknowledged limitations of this study related to single-point measurement and sampler performance bias, the findings presented here could be used in estimating the PM control efficiency of a sprinkler system under field conditions and improving its performance for cattle feedlots.

Acknowledgements

This study was supported by USDA National Institute of Food and Agriculture (formerly Cooperative State Research, Education, and Extension Services) Special Research Grant "Air Quality: Reducing Air Emissions from Cattle Feedlots and Dairies (Texas and Kansas)" through the Texas Agricultural Experiment Station of the Texas A&M University System and by the Kansas Agricultural Experiment Station. Technical assistance provided by Darrell Oard, Dr. Jasper Tallada, Kevin Hamilton, Howell Gonzales, and Girly Ramirez is acknowledged. Cooperation of feedlot operators and KLA Environmental Services, Inc., is also acknowledged.

References

ACFA. 2002. Chapter 7.7: Other technologies and landscaping options. In *Beneficial Management Practices: Environmental Manual for Feedlot Producers in Alberta*. Alberta, Canada: Alberta Cattle Feeders' Association. Available at: www.agriculture.alberta.ca. Accessed 3 September 2009.

Auvermann, B., R. Bottcher, A. Heber, D. Meyer, C. B. Parnell Jr., B. Shaw, and J. Worley. 2006. Particulate matter emissions from animal feeding operations. In *Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers*, 435-468. J. M. Rice, D. F. Caldwell, and F. J. Humenik, eds. St. Joseph, Mich.: ASABE.

Buser, S. D., C. B. Parnell Jr., B. W. Shaw, and R. E. Lacey. 2007. Particulate matter sampler errors due to the interaction of particle size and sampler performance characteristics: Ambient PM_{10} samplers. *Trans. ASABE* 50(1): 229-240.

Carroll, J. J., J. R. Dunbar, R. L. Givens, and W. B. Goddard. 1974. Sprinkling for dust suppression in a cattle feedlot. *California Agric.* 28(3): 12-14.

CARB. 2009. What is particulate matter (PM_{10})? Air pollution - particulate matter brochure. Sacramento, Cal.: California Air Resources Board. Available at: www.arb.ca.gov. Accessed 21 September 2009.

CE. 2006. WRAP fugitive dust handbook. Prepared for Western Governors' Association. WGA Contract No. 30204-111. Westlake Village, Cal.: Countess Environmental.

Guo, L., R. G. Maghirang, E. B. Razote, J. Tallada, J. P. Harner, and W. Hargrove. 2009. Field comparison of PM_{10} samplers. *Applied Eng. in Agric.* 25(5): 737-744.

Marek, G. W. 2006. Determination of feedyard evaporation using weighing lysimeters. MS thesis. Amarillo, Tex.: West Texas A&M University, Program in Environmental Science.

Miller, D. N., and B. L. Woodbury. 2003. Simple protocols to determine dust potentials from cattle feedlot soil and surface samples. *J. Environ. Qual.* 32(5): 1634-1640.

Mitloehner, F. M., and M. S. Calvo. 2008. Worker health and safety in concentrated animal feeding operations. *J. Agric. Safety and Health* 14(2): 163-187.

Montgomery, D. C. 1984. *Design and Analysis of Experiments*. New York, N.Y.: John Wiley and Sons.

MWPS. 2002a. *Outdoor Air Quality.* Manure Management System Series, Section 3. Ames, Iowa: Midwest Plan Service.

MWPS. 2002b. Livestock and poultry environmental stewardship (LPES) curriculum: A national education program. Module E: Outdoor air quality; Lesson 42: Controlling dust and odor from open lot livestock facilities. Ames, Iowa: Midwest Plan Service.

Pechan. 2006. AirControlNET Version 4.1: Documentation report prepared for U.S. Environmental Protection Agency. Pechan Report No. 06.05.003/9011.002. Springfield, Va.: E. H. Pechan and Associates, Inc.

Razote, E. B., R. G. Maghirang, B. Z. Predicala, J. P. Murphy, B. W. Auvermann, J. P. Harner III, and W. L. Hargrove. 2006. Laboratory evaluation of the dust-emission potential of cattle feedlot surfaces. *Trans. ASABE* 49(4): 1117-1124.

Razote, E. B., R. G. Maghirang, J. P. Murphy, B. W. Auvermann, J. P. Harner III, D. L. Oard, D. B. Parker, W. L. Hargrove, and J. M. Sweeten. 2007. Air quality measurements from a water-sprinkled1 beef cattle feedlot in Kansas. ASABE Paper No. 074108. St. Joseph, Mich.: ASABE.

SAS. 2002. *SAS for Windows*. Ver. 9.1.3, Service Pack 4. Cary, N.C.: SAS Institute, Inc.

Sweeten, J. M., C. B. Parnell, R. S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. *Vet. Clinics of North America, Food Animal Prac.* 4(3): 557-578.

Wanjura, J. D., B. W. Shaw, C. B. Parnell Jr., R. E. Lacey, and S. C. Capareda. 2008. Comparison of continuous monitor (TEOM) and gravimetric sampler particulate matter concentrations. *Trans. ASABE* 51(1): 251-257.