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Particulate matter dynamics in naturally ventilated freestall dairy barns

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HIGHLIGHTS

► Particulate matter concentrations and ventilation rates in dairy barns were monitored for two years.
► Concentrations of $PM_{2.5}$, PM_{10}, and TSP, exhibited non-normal positively skewed distributions.
► The respective emission rates of $PM_{2.5}$, PM_{10}, and TSP ranged between 1.6–4.0, 11.9–15.0, and 48.7–52.5 g d^{-1} cow^{-1}.
► Concentrations of $PM_{2.5}$ and PM_{10} increased with ambient air temperature ($R^2 = 0.60–0.82$).
► Concentrations of TSP (but not of $PM_{2.5}$ and PM_{10}) tended to increase with cattle activity.

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ABSTRACT

Particulate matter (PM) concentrations and ventilation rates, in two naturally ventilated freestall dairy barns, were continuously monitored for two years. The first barn (B1) housed 400 fresh lactating cows, while the second barn (B2) housed 835 non-fresh lactating cows and 15 bulls. The relationships between PM concentrations and accepted governing parameters (environmental conditions and cattle activity) were examined. In comparison with other seasons, PM concentrations were lowest in winter. Total suspended particulate (TSP) concentrations in spring and autumn were relatively higher than those in summer. Overall: the concentrations in the barns and ambient air, for all the PM categories ($PM_{2.5}$, PM_{10}, and TSP), exhibited non-normal positively skewed distributions, which tended to overestimate mean or average concentrations. Only concentrations of $PM_{2.5}$ and PM_{10} increased with ambient air temperature ($R^2 = 0.60–0.82$), whereas only concentrations of TSP increased with cattle activity. The mean respective emission rates of $PM_{2.5}$, PM_{10}, and TSP for the two barns ranged between 1.6–4.0, 11.9–15.0, and 48.7–52.5 g d^{-1} cow^{-1}, indicating similar emissions from the two barns.
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1. Introduction

In general, the size of particulate matter (PM) suspended in air is dependent upon the level of energy input into the producing process. Relatively higher energy processes, such as combustion, produce finer particles, while lower energy processes, for instance crushing or grinding, produce coarser particles (Auvermann et al., 2006). Particulate matter from animal feeding operations (AFOs) therefore includes both fine particles, from engine exhaust of farm vehicles, and coarse particles, from hoof action on dry manure and soil or feed grinding. In contrast to PM in urban areas, however, coarse PM dominate AFO emissions because most are generated by lower energy mechanical processes (Auvermann et al., 2006).

Particulate matter from AFOs may also contain harmful substances (heavy metals, VOCs, nitrates, sulfates, etc) and bioactive components (pathogens, endotoxins, antibiotics, allergens, dust mites, etc) that could exacerbate respiratory diseases and mortality in the herd, in addition to adversely affecting the health of farm workers, farm residents, and neighbors in the vicinity of these facilities (Cambra-Lopez et al., 2010; Matkovic et al., 2009; Hamscher et al., 2003). Epidemiological studies, for instance, have reported strong associations between adverse cardiopulmonary and respiratory conditions and human exposure to air-suspended PM_{10} (Schartz, 2001; Anderson et al., 1995; Pope et al., 1995;

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Oberdorster and Yu, 1990). Other studies have indicated significantly more human mortality and morbidity in summer because of higher temperatures and PM_{10} emissions, which increase cardiovascular and respiratory diseases (Hansen et al., 2012; Yi et al., 2010). Evaluations of PM concentrations at AFOs, therefore, are important for assessing the quality of air with respect to both human and animal health.

Relationships between emissions and key governing parameters (environmental conditions and cattle activity) are invaluable tools for dairy and similar operations because they allow mitigation efforts to be directed to specific times of the day or season which will have the most effect. In general, emission of PM is a function of the prevailing environmental conditions. Past studies indicate an inverse relationship between PM emission and relative humidity, and a positive correlation between PM emissions and ambient air temperature (Charron et al., 2004; Yang, 2002; Chang et al., 2001). Cattle activity and wind conditions are other factors that could potentially influence PM emissions from soil, feed, bedding, and manure at a dairy. Cambra-Lopez et al. (2010), for instance, reported good correlations between PM_{10} emissions and bird activity in broiler houses. In naturally ventilated buildings, wind speeds had direct influence on the ventilation rates (Wu et al., 2012; Norton et al., 2009; Snell et al., 2003), which in turn could potentially affect the PM emissions from the buildings.

Although a few studies of PM emissions from naturally ventilated dairy barns have been conducted (Marchant et al., 2011; Zhao et al., 2007; Schmidt et al., 2002), and there is no information on the relationships between PM emissions from such facilities and causative parameters. The objectives of this study were to conduct long term studies to: (i) determine emission rates (g d^{-1} cow^{-1}) of $PM_{2.5}$, PM_{10}, and TSP from naturally ventilated freestall dairy barns, and (ii) analyze the correlations between these emissions and the principal governing parameters.

2. Experimental methods

2.1. Dairy site description

Washington State is located in the United States Pacific Northwest, where ambient temperature ranges from approximately −10 to 40 °C with humid winters and dry summers. The dairy on which this research was conducted consisted of six symmetrically distributed freestall naturally ventilated freestall barns, with manure storage and treatment facilities (lagoons, settling basins, drying ponds, and composting pads) located at the southeast quadrant of the farm. The two barns selected for emissions monitoring were located at the northeast corner of the farm complex. All the barns were oriented east-west lengthwise (Fig. 1). Barn 1 (B1) was 183 × 31 m and housed 250 cows in freestalls in the south pen. The north pen of B1, on the other hand, was open (no stalls) and housed a birthing area on the west end. The north sidewall of B1 was completely open at all times, allowing approximately 200 cows (50% of the herd in B1) to freely move in and out of the north pen and the dry lot to the north. Barn 2 (B2) was 213 × 39 m, and housed 835 cows and 15 bulls, all in freestalls. Barns B1 and B2 were 55 m apart and the area between the two barns was fenced to contain about 100 replacement heifers. The on-farm instrument shelter (OFIS) was located in this area midway between B1 and B2 (Fig. 1).

The 4.3 m high sidewalls of the barns were either open to allow natural ventilation or partially closed to reduce ventilation in cold weather. To accomplish this, sidewalls had dual curtains; the top and bottom curtains covered 81 cm and 147 cm, respectively, when fully closed. The one exception to this configuration was the north sidewall of B1, which was completely open without curtains. The curtains were either fully open or fully closed, and the top curtain was always closed before the bottom one. The bottom curtain was closed in windy and/or cold conditions. When both curtains were closed, a 40 cm opening between the top curtain and the roof remained. The west and east gable sidewalls of the barns were always open. The respective openings were 31 m wide and 3.7 m high for B1 and 39 m wide and 3.8 m high for B2. The only other openings in the barns were the ridges, which were 157 and 185 cm in B1 and B2, respectively. The ridge openings were not covered.

2.2. Instrumentation

The $PM_{2.5}$ concentrations were measured during winter (Jan. 29–Feb. 7, 2008) and summer (Jul.10–23, 2008), while TSP concentrations were monitored for approximately one week in each of the four seasons (Apr. 10–15, Jun. 12–18, Sept. 12–18, 2008, and Feb. 26–Mar. 04, 2009) each year. Concentrations of PM_{10} were

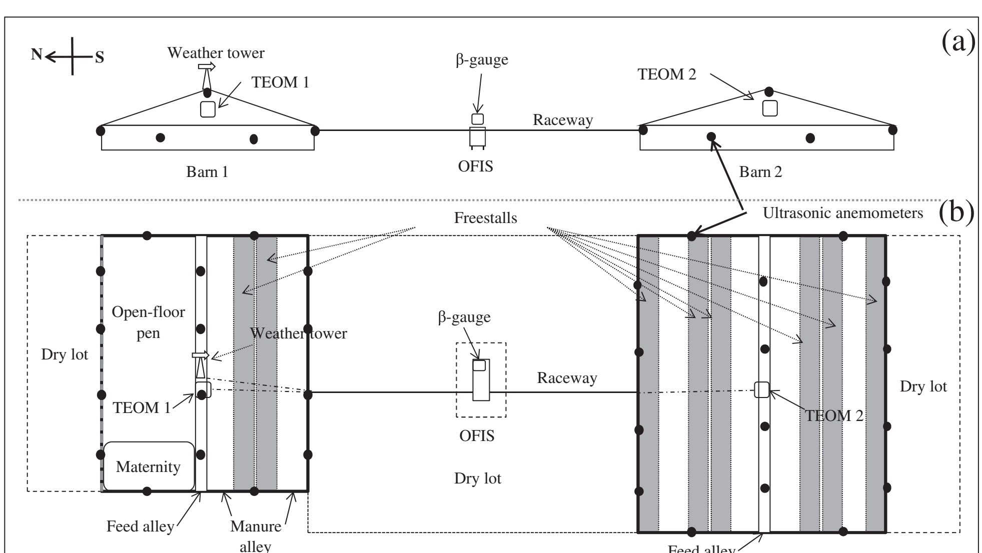

Fig. 1. Layout of the barns, on-farm instrument shelter (OFIS), and monitoring locations: (a) end view; (b) plan view.

monitored during all other periods of the study (Dec. 16, 2007–Feb. 11, 2009).

The mass concentrations of $PM_{2.5}$, PM_{10}, and TSP in the barns were monitored using tapered element oscillating microbalances (TEOM; Model 1400a, Rupprecht & Patashnick, Albany, NY). With a PM_{10} inlet installed, the U.S. EPA had designated the TEOM as an equivalent method for PM_{10} measurement (EPA Designation No. EQPM-1090-079). The PM_{10} and TSP inlets were installed in front of the flow splitter, while the $PM_{2.5}$ inlet was installed behind the PM_{10} inlet. In this arrangement, the TEOM is designated an equivalent method for measurement of $PM_{2.5}$ (EPA Designation No. EQPM-0609-181). The TEOM, including the air sampling head, the sensor unit, and the temperature sensor were installed near the center of each barn, approximately 1.5 m below the ridge opening. The TEOM controller units and vacuum pumps were installed in the instrument shelter. The TEOM was operated at a total air flow of 16.67 L min^{-1}, a sample air flow of 3.00 L min^{-1}, an oven temperature of 50 °C, and filter loadings ranging between 17% and 50%.

The ambient PM concentrations on the other hand, were monitored using a beta ray attenuation particle monitor (Model FH62C14, Thermo Electron Corporation, Franklin, MA), which is referred to as 'β-gauge' in this article. For a given measurement period, the same type of inlets for monitoring $PM_{2.5}$, PM_{10}, and TSP concentrations in the barns were also used in the β-gauge to monitor the respective concentrations in ambient air outside the barns. In similar configurations to that described for TEOM, U.S. EPA had designated β-gauge as equivalent methods for PM_{10} (EPA Designation No. EQPM-1102-150) and $PM_{2.5}$ (EPA Designation No. EQPM-0609-183). The β-gauge sampling head and temperature sensor were installed on the roof of the instrument shelter, while the controller unit and vacuum pump were installed inside the shelter. The β-gauge total airflow rate was 16.67 L min^{-1}, while the sampling tube was maintained at 50 °C.

The TEOM filters were replaced when the filter loading percentage exceeded 50%. The filter paper in the β-gauge was automatically rotated to a new filter position each day. Periodic calibrations of the TEOMs and the β-gauge, with respect to airflow, mass, temperature, and barometric pressure, were performed to ensure quality of data.

To monitor ventilation rates of each barn, 16 three-dimensional sonic anemometers (Model 81000, R.M. Young Co., Traverse City, MI) were installed at selected locations in the study barns. To achieve this, each barn was divided lengthwise into four equal sections. The sidewall anemometers were installed at approximately the midpoints of each of the four sections. In addition, these four anemometers were mounted such that the sensors were in the middle of the opening between the upper curtain and the eave. The four anemometers in the ridge opening were installed with their sensors positioned at the centers of each of the four sections. Each of the end walls was divided into two equal sections and two anemometers were mounted at the horizontal and vertical midpoints of each section (Fig. 1). Positive air velocities perpendicular to the respective openings designated air inflows, while negative velocities indicated air outflows from the barns (Ndegwa et al., 2009).

Local environmental conditions (wind direction, wind velocity, and air temperature) were monitored using a weather tower station installed midway lengthwise on the ridge of B1 (Fig. 1). The air temperatures were measured using solar radiation shielded RH/temperature probes (NOVUS Model RHT-WM, Novus Electronics, Porto Alegre, Brazil), while a wind anemometer (Model 03002VM Wind Sentry, R.M. Young, Traverse City, MI) measured wind speed and direction. The two TEOMs and the β-gauge had temperature sensors, which allowed continuous temperature measurements, under their respective sampling inlets. Three activity sensors (Passive Infrared Detector, model SRN-2000N, Visonic Inc., Bloomfield, CT) were installed in each barn to monitor cow and vehicle movement. Each activity sensor produced a direct current voltage (VDC), proportional to motion strength, but inversely proportional to the distance from the detected moving objects. One sensor each monitored cattle activity in the east-and west halves of the barn, while a third sensor was pointed to the central feed alley of the barn to monitor vehicle traffic. The maximum coverage was 18 × 18 m which ensured detection of activity occurring within 18 m of the sensor and almost within the entire width of each pen. The two sensors for monitoring activity within the pens were located adjacent to water and feed areas where they faced the maximum number of animals.

2.3. Data acquisition

Measurement data from all on-line instruments and sensors, including the TEOMs, β-gauge, weather sensors, (sonic anemometers) and activity sensors, were acquired every second and averaged every 15 s and 60 s. The averaged data were saved in a desktop computer located in the OFIS. Custom developed software for Air Emissions Data Acquisition and Control (AirDAC) (Ni and Heber, 2010) was used. The software was written in LabVIEW programming language (National Instruments Corporation, Austin, TX). It was compatible with data acquisition and control hardware from two manufacturers: National Instruments Co. and Measurement Computing Co., Norton, MA. In addition to the analog output data acquired and averaged by AirDAC, the TEOMs and β-gauge internally stored 30 min average PM concentration data, which were periodically downloaded and stored in the OFIS computer.

2.4. Data processing and analysis

The PM data obtained during either filter changes or equipment downtime, and other obvious outlier data points were omitted for the data analyses. The respective usable data, as percentages of total concentration data collected, were 98.5% for PM_{10}, 92.6% for $PM_{2.5}$, and 95.5% for TSP. The daily average fluxes were calculated by multiplying the daily average 30 min concentrations (μg m^{-3}) by the daily average ventilation rates (m^3 d^{-1}) of the barn (Ndegwa et al., 2009). The annual average herd size was used in the computations of the respective emission rates (μg d^{-1} cow^{-1}).

To analyze the relationships between PM emissions and temperature or cattle activity, the average data were first sorted with respect to temperature, from lowest to highest. The mean emissions within 2 °C intervals were then computed to reduce data points to a reasonable number for figure plotting purposes. The activity sensor voltage outputs ranged from 0.3 to 0.9 VDC. For the analyses of relationships between emissions and cattle activity, the mean PM concentrations were averaged at 0.1 V intervals within this range (0.3–0.9 V) for figure plotting purposes.

3. Results and discussion

3.1. Particulate matter concentrations and emissions

The box plots of seasonal profiles of PM concentrations and temperatures in the barns and outside air, showing the: minimum, 10th percentile, median, 90th percentile, and maximum values, are presented in Figs. 2–4, while the respective mean concentrations are shown in Table 1. The PM concentrations were less spread out in winter than in the other seasons. The observed stability of PM concentrations in winter was attributed to the closed curtains, which perhaps reduced external influences. The PM concentrations, for all seasons, were not normally distributed but positively

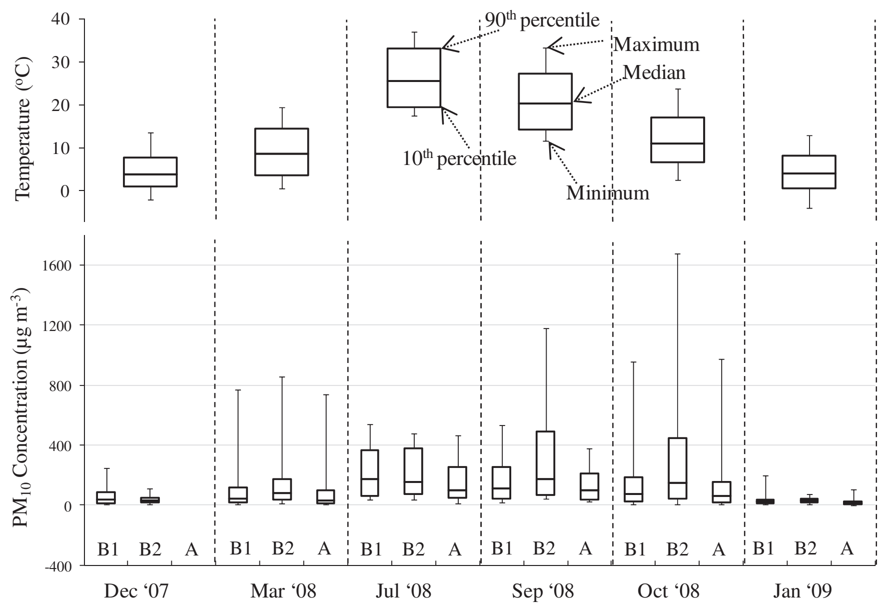

Fig. 2. Concentrations of PM_{10} in barn 1 (B1), barn 2 (B2), and in ambient air (A) and the respective temperatures during each measurement period.

skewed. Relatively more outliers were, therefore, observed at the long-tail ends of concentration distributions, which tended to overestimate mean concentrations. This bias was evident when the means (Table 1) were compared with the median values shown in Figs. 2–4. For instance, the respective median PM_{10} concentrations in B1, B2, and outside air, in July, were approximately 170, 150, and 100 μg m^{-3} compared with mean concentrations of 195, 195, and 127 μg m^{-3}, while the respective median TSP concentrations, in September, were approximately 420, 1020, and 200 μg m^{-3} compared with mean concentrations of 514, 1320, and 278 μg m^{-3}. The average PM concentrations should, therefore, be interpreted with caution because of lack of normality in the data distribution. In contrast, the temperatures were relatively normally distributed during each measurement period suggesting that temperature fluctuations during each measurement period were probably not the cause for the observed non-normal distribution of PM concentrations.

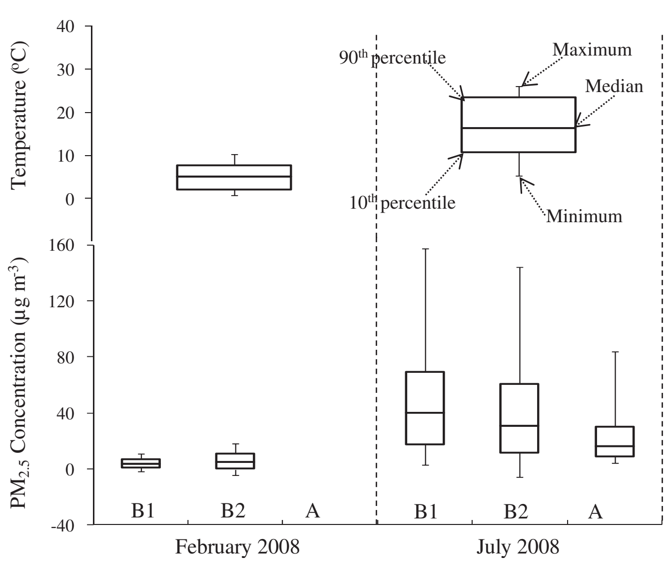

Fig. 3. Concentrations of $PM_{2.5}$ in barn 1 (B1), barn 2 (B2), and ambient air (A) and the respective temperatures during each measurement period.

In general, daily mean PM_{10} concentrations in the barns were lowest (22–29 μg m^{-3}) in winter but averaged between 64 and 240 μg m^{-3} in the other seasons. The concentrations of PM_{10} and $PM_{2.5}$ in summer were approximately 10 times higher than in winter. Schmidt et al. (2002) reported respective PM_{10} concentrations of 60 and 370 μg m^{-3} in winter and summer, in a naturally ventilated dairy barn, which were similar to concentrations observed in this study. Average $PM_{2.5}$ concentrations in the barns were approximately 4 μg m^{-3} in winter, but averaged between 35 and 44 μg m^{-3} in summer. The mean TSP concentrations, in the barns, ranged between 150 and 1320 μg m^{-3}, which was relatively lower than the range of concentrations (900–1500 μg m^{-3}) observed in other naturally ventilated dairy barns in Ohio (Zhao et al., 2007). The average TSP concentrations obtained in this study, however, were similar to 24 h average winter and summer concentrations (150 and 570 μg m^{-3}, respectively), observed in a naturally ventilated dairy in Minnesota (Schmidt et al., 2002). In general, however, mean TSP concentrations in spring and fall were higher than in summer; suggesting that other factor(s) beside air temperature probably had more influence on TSP concentrations. The higher TSP concentrations in spring and autumn than in winter were perhaps caused by greater cattle activity in spring and autumn that occurred with more comfortable temperatures.

The diurnal profiles of hourly mean PM concentrations in the barns and ambient air are shown in Fig. 5. Overall, PM_{10} and $PM_{2.5}$ concentrations were highest around late evening, and lowest from midnight to mid-morning. No particular diurnal trend, however, was observed with the TSP concentrations. The changes in hourly mean PM_{10} and $PM_{2.5}$ concentrations corresponded to changes in temperature; higher PM_{10} concentrations were observed during periods of elevated temperatures and vice versa (see Figs. 5 and 6 also). In contrast, temperature changes did not seem to influence the hourly mean TSP concentrations. These PM concentration patterns have been attributed to increased cattle activity due to comfortable temperatures and relatively calm wind conditions during these periods (Bonifacio et al., 2012; McGinn et al., 2010; Auvermann et al., 2006; Sweeten et al., 1998). Smaller peaks were also observed during mornings, possibly during feeding times; this is consistent with previous studies (Hiranuma et al., 2011).

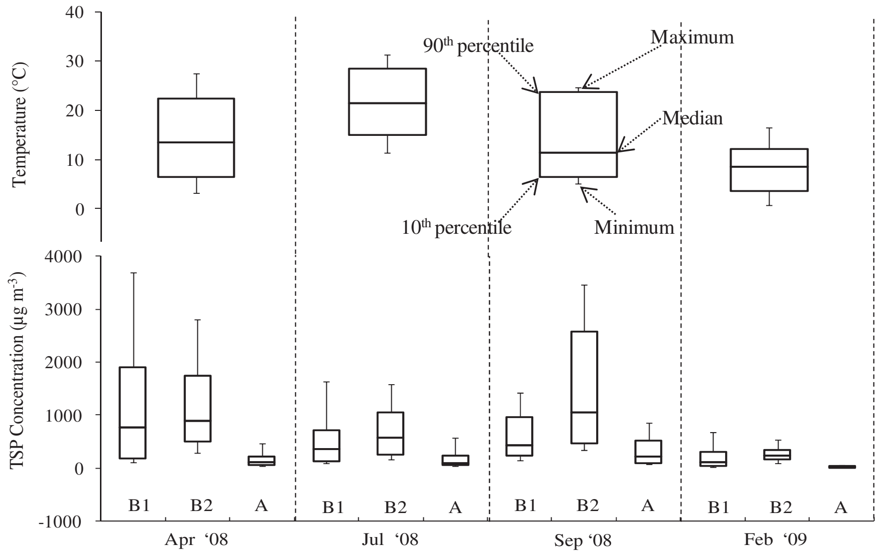

Fig. 4. Concentrations of TSP in barn 1 (B1), barn 2 (B2), and ambient air (A) and the respective temperature during each measurement period.

The average 30-min PM concentrations and PM emission rates (g d^{-1} cow^{-1}) for the two barns are presented in Table 2. The average 30 min mean concentrations of PM_{10} and TSP in B2 were approximately two times higher than in B1. The concentrations of $PM_{2.5}$, on the other hand, were similar in both barns. The average ventilation rates from spring, 2008 to late winter, 2009, were 886 and 883 m^3 s^{-1} in B1 and B2, respectively. The product of the respective average ventilation rates and PM concentrations yielded emission rates of 1.6–4.0, 11.9–15.0, and 48.7–52.5 g d^{-1} cow^{-1} for $PM_{2.5}$, PM_{10}, and TSP, respectively. The emission rates of PM_{10} were significantly higher than those obtained in winter and summer in a naturally ventilated dairy barn in Minnesota, which ranged between 0.1 and 2.0 g d^{-1} cow^{-1} (Schmidt et al., 2002). The TSP emissions rates observed in the current study, however, were within the range of 49–135 g d^{-1} cow^{-1} reported for a naturally ventilated freestall dairy in California (Marchant et al., 2011). In general, a comparison of PM emissions across different geographical and climate regions is, however, complicated because of the differences in environmental conditions, animal feed, feed and manure management, bedding material, amongst others.

3.2. Relationships between PM concentration and temperature

The linear regressions between hourly mean $PM_{2.5}$, PM_{10}, and TSP concentrations and hourly mean ambient air temperature are presented in Fig. 6. The $PM_{2.5}$ and PM_{10} concentrations in the barns correlated relatively well with temperature, with correlation coefficients (R) ranging between 0.8 and 0.9. The correlations between TSP concentrations and temperature, however, were, relatively, poor ($R = 0.0$–0.5). In general, TSP concentrations were higher in autumn and spring, when temperatures were between 5 and 20 °C, than in summer when temperatures were significantly higher. These results suggest that the concentrations of $PM_{2.5}$ and PM_{10}, possibly, were predominantly a function of temperature while other factors, besides temperature and operation parameters, most probably, had higher influence on concentrations of PM larger than PM_{10} (TSP minus PM_{10}). Higher temperatures are usually associated with drier and more dispersed particles of feed, bedding, manure, and soil, which are more amenable to suspension in the air. The higher correlations between concentrations of $PM_{2.5}$ and PM_{10} and temperature, therefore, may be attributed to this phenomenon.

3.3. Relationships between PM concentration and wind conditions

The prevalent wind directions in each season and the diurnal-cycle mean wind speeds at the research site are presented in Fig. 7. The prevailing wind direction was from the southwest throughout the year (Fig. 7a). Wind speeds were, in general, highest in winter and spring and lowest in autumn and summer (Fig. 7b).

Table 1
Seasonal average hourly mean PM concentrations and temperature (mean ± standard deviation).

Season	Month	PM range	B1 (μg m^{-3})	B2 (μg m^{-3})	Ambient (μg m^{-3})	Temperature (°C)
Spring '08	Apr.	TSP	433 ± 217	1011 ± 504	133 ± 85	13.9 ± 5.7
	Mar.	PM_{10}	64 ± 86	103 ± 99	53 ± 87	8.8 ± 4.0
Summer '08	Jul.	TSP	420 ± 281	626 ± 357	132 ± 102	21.7 ± 5.2
	Jul.	PM_{10}	195 ± 124	195 ± 115	127 ± 88	25.9 ± 5.0
	Jul.	$PM_{2.5}$	44 ± 24	35 ± 23	19 ± 12	16.7 ± 4.9
Fall '08	Sep.	PM_{10}	134 ± 87	240 ± 196	111 ± 69	20.7 ± 5.0
	Sep.	TSP	514 ± 295	1320 ± 833	278 ± 182	13.1 ± 6.1
	Oct.	PM_{10}	95 ± 88	203 ± 189	86 ± 91	11.4 ± 4.1
Winter '08	Feb.	$PM_{2.5}$	3.6 ± 2.4	4.4 ± 4.2	–	5.0 ± 1.9
Winter '07	Dec.	PM_{10}	20 ± 13	29 ± 14	–	4.0 ± 2.6
Winter '09	Jan.	PM_{10}	24 ± 17	31 ± 10	12 ± 10	4.1 ± 3.2
Winter '09	Feb.	TSP	152 ± 117	244 ± 80	15 ± 10	8.5 ± 3.4

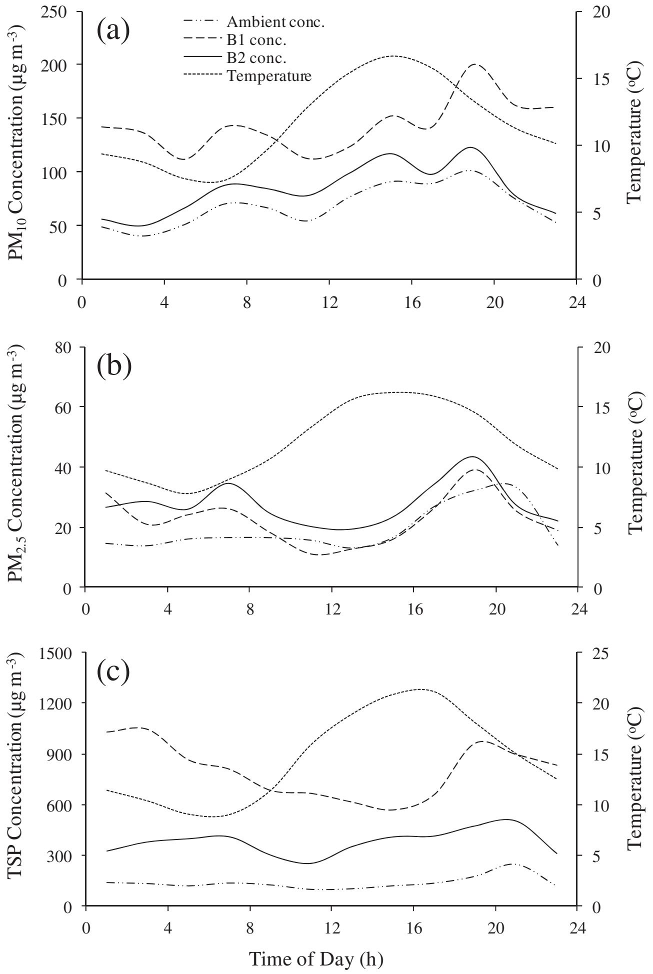

Fig. 5. Profiles of average diurnal particulate matter concentrations in barn 1 (B1), barn 2 (B2) and ambient air (Ambient) and mean ambient air temperature.

Wind speed peaks were observed between: 1:00 and 5:00 pm in winter; 2:00 and 7:00 pm in spring; 8:00 and 11:00 pm in summer; and 1:00 and 6:00 pm in autumn. Previous studies have indicated strong positive correlations between ventilation rate and wind speed, in naturally ventilated dairy barns, but no correlation between ventilation rate and wind direction (Wu et al., 2012; Snell et al., 2003). Barn ventilation, on the other hand, impacts PM concentrations in the barn in several ways: (1) inflowing air may carry PM into the barn, (2) high ventilation rates increase removal of PM from the barn and vice versa, and (3) strong winds increase turbulence which promotes longer durations of PM suspension in the air.

In the current study, except during winter when the curtains were either partially or completely drawn, barn ventilation rates would have been proportional to wind speed because wind direction was predominantly from the southwest throughout the year. The average wind speeds in autumn and summer were similar. The average TSP concentrations in summer in B1, B2, and ambient air (Table 1), which averaged 420, 626, and 132 μg m^{-3}, respectively, however, were lower than the respective average TSP concentrations of 514, 1320, and 278 μg m^{-3} in autumn. On the other hand, the wind speeds were significantly higher in spring than in summer. The TSP concentrations, however, were not significantly different during these two seasons. These data do not indicate any correlation between wind speed and TSP concentrations in either the barns or ambient air. In contrast, the respective mean

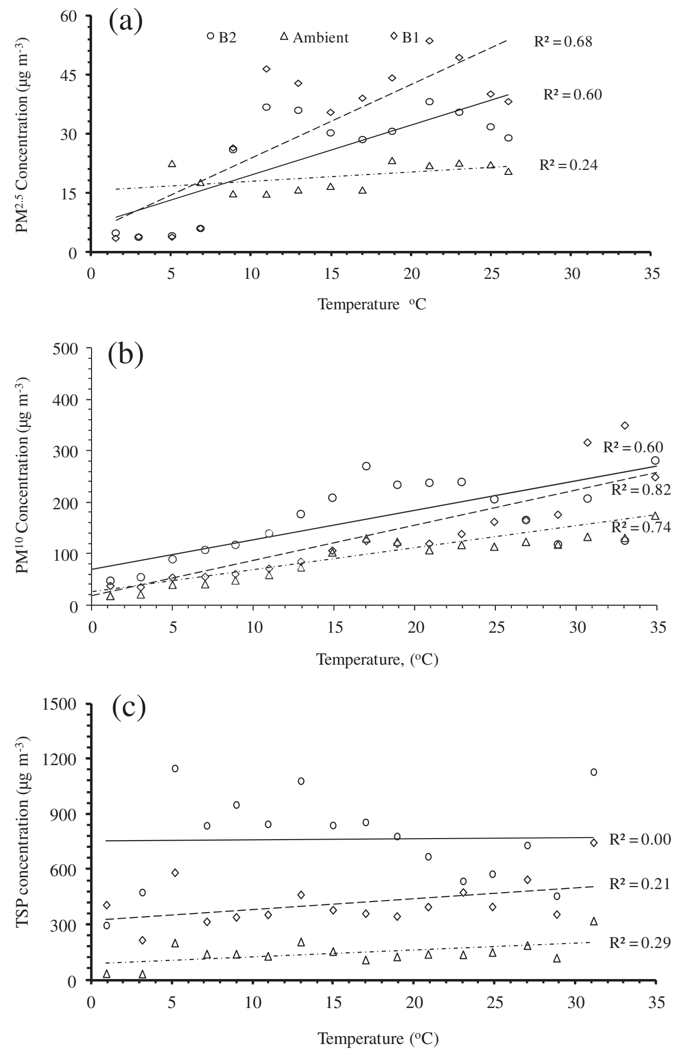

Fig. 6. Relationships between particulate matter concentrations in barn 1 (B1), barn 2 (B2), and ambient air (Ambient) and average ambient temperature: (a) $PM_{2.5}$; (b) PM_{10}; and (c) TSP.

concentrations of PM_{10} in B1, B2, and ambient air at 195, 195, and 127 μg m^{-3} in summer were significantly higher than in spring at 64, 103, and 53 μg m^{-3}, respectively, although the wind speeds were significantly lower in summer than in spring. Similarly, therefore, this data also points to other factors besides wind speeds being responsible for the observed PM_{10} concentrations in the barns and ambient air. The effects of wind speeds on PM (TSP or PM_{10}) concentrations were perhaps masked by other competing factor(s) such as temperature and cattle activity.

3.4. Relationships between PM concentration and cattle activity

Only data from B2 were used for determining the relationship between PM concentrations and cattle activity. The significantly

Table 2
Average 30-min mean PM concentrations and emission rates for the two barns.

	$PM_{2.5}$		PM_{10}		TSP	
	B1	B2	B1	B2	B1	B2
30 min averages (μg m^{-3})	21	17	78	133	274	543
Emission rates (g d^{-1} cow^{-1})	4.0	1.6	15.0	11.9	52.5	48.7

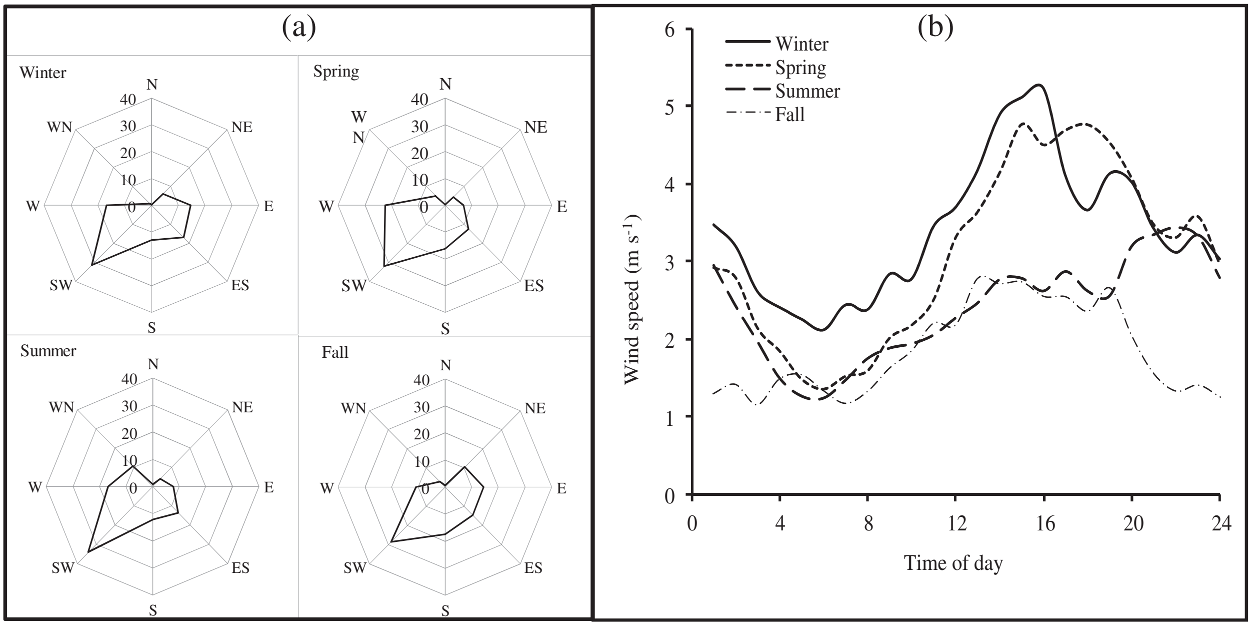

Fig. 7. Wind conditions profiles: (a) prevailing seasonal direction (% frequency); (b) mean daily wind speed averaged over 15 days during each season.

heavier vehicle traffic through the feed alley of B1 relative to B2 was one reason. The unique unlimited movement of cows in and out of the north pen of B1 to the north dry lot was the other basis for excluding data from B1 in the analyses.

3.4.1. Concentrations of TSP versus cattle activity

The average TSP concentrations and the corresponding cattle activity in B2 during the corresponding monitoring periods are shown in Table 3. The average cattle activity in all four seasons ranged from 0.49 to 0.70 V. Based on data presented in Table 3, there was no significant correlation between TSP concentrations and cattle activity levels. The average cattle activity was, for example, lowest in spring but the average TSP concentrations were 3.5-fold higher than in winter when cattle activity was highest. Similarly, although the average cattle activity (0.64 V) in summer was higher than the average cattle activity (0.59 V) in autumn, the average TSP concentration was significantly (2×) higher in autumn than in summer.

The scatter plots of TSP emissions versus cattle activity during the hottest (summer) and the coldest (winter) seasons are shown in Fig. 8. The summer data were grouped together and is encompassed within the larger, dotted line oval while the winter data is enclosed in the smaller, solid line, oval. The average cattle activity in both summer (0.66 V) and winter (0.68 V) were not significantly different. In contrast, however, the average TSP concentrations were significantly higher in summer at 564 μg m^{-3} than in winter at 278 μg m^{-3}. These results suggest that cattle activity was not responsible for the higher concentrations of TSP in summer compared with winter. Within the same season, when other competing factors were equal, there is some indication (the scatter plots rise to the right in both groups) that TSP concentrations increased, to some extent, with cattle activity. The TSP concentrations in winter displayed a narrower range of distribution (relative standard deviation (RSD = 30%) than the distribution of TSP concentrations (RSD = 70%) in summer. This observation is best explained by examining the general temperature spread in summer and winter. In general, the day to night temperature spread in winter was also smaller, as opposed to summer when daytime temperatures were likely to be higher than overnight temperatures (Table 1).

Table 3
Average hourly mean cattle activity and total suspended particulate (TSP) concentration in barn 2 (mean ± standard deviation).

Season	Average cattle activity (V)	TSP ± SD (μg m^{-3})
Spring	0.49 ± 0.14	878 ± 458
Summer	0.64 ± 0.16	564 ± 387
Fall	0.59 ± 0.15	1139 ± 737
Winter	0.70 ± 0.08	278 ± 89.7

3.4.2. Concentration of PM_{10} and $PM_{2.5}$ and cattle activity

The average concentrations of PM_{10} and $PM_{2.5}$ and the corresponding cattle activity levels during the respective monitoring periods are shown in Table 4. The average cattle activity levels were distributed between 0.44 and 0.69 during measurements of PM_{10} and between 0.69 and 0.70 during $PM_{2.5}$ measurements. The

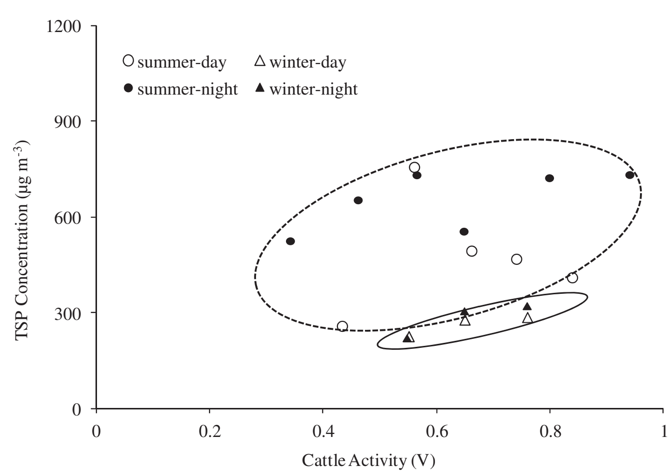

Fig. 8. Relationships between TSP concentrations and cattle activity in barn 2 during day and night in both summer and winter.

Table 4
Seasonal average PM_{10} and $PM_{2.5}$ concentrations and average cattle activity in barn 2 (mean ± standard deviation).

Season	Cattle activity (V)	PM_{10} ($\mu g\ m^{-3}$)	Cattle activity (V)	$PM_{2.5}$ ($\mu g\ m^{-3}$)
Spring	0.44 ± 0.21	150 ± 208		
Summer	0.62 ± 0.25	221 ± 126	0.69 ± 0.22	60 ± 201
Fall	0.69 ± 0.21	285 ± 160		
Winter	0.52 ± 0.23	30 ± 46	0.70 ± 0.19	7 ± 4

concentrations of PM_{10}, on the other hand, ranged from 30 $\mu g\ m^{-3}$ in spring to 285 $\mu g\ m^{-3}$ in autumn, while the concentrations of $PM_{2.5}$ ranged from 7 $\mu g\ m^{-3}$ in winter to 60 $\mu g\ m^{-3}$ in summer.

The scatter plots of hourly mean PM_{10} concentrations in the barn versus cattle activity, during summer and winter seasons, are shown in Fig. 9. Although the average cattle activity level in winter was higher than in summer, PM_{10} concentrations in the barns, in general, were significantly higher in summer (upper oval) than in winter (lower oval), during both days and nights. The vertical scatter of the PM_{10} concentrations in summer, however, was wider, indicating a wider range of PM_{10} concentrations in a typical summer day. The converse was true during winter, when the activity during the day was higher than at night. The average PM_{10} concentrations in the barns, however, were not significantly different between day and night. These observations further affirm that, other factors, besides cattle activity impact PM_{10} concentrations in the barn more significantly than activity. The relationships between PM_{10} concentrations and temperature presented earlier indicated significant positive correlations. Because temperatures were significantly higher in summer than in winter, the correlation of PM_{10} concentrations with cattle activity reaffirms the impact of temperature on PM_{10} concentrations.

The scatter plot of hourly mean $PM_{2.5}$ concentrations against the corresponding cattle activity levels is shown in Fig. 10. Daytime cattle activity levels were lower during summer than winter. However, this did not result in correspondingly lower $PM_{2.5}$ concentrations. Similarly, higher cattle activity during winter days did not result in higher $PM_{2.5}$ concentrations during winter nights. On the other hand, cattle activity levels during summer and winter nights were similar, but the corresponding $PM_{2.5}$ concentrations were not; nighttime summer $PM_{2.5}$ concentrations were higher than those in winter. The cattle activity levels during day and night in summer were similar, as opposed to winter when cattle activity was generally higher during the day than at night. Daytime and nighttime $PM_{2.5}$ concentrations were similar, as with $PM_{2.5}$

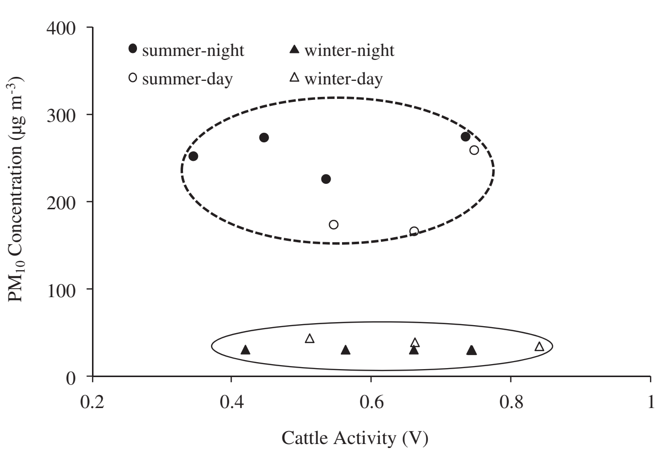

Fig. 9. Relationships between PM_{10} concentrations and cattle activity in barn 2 during day and night in summer and winter.

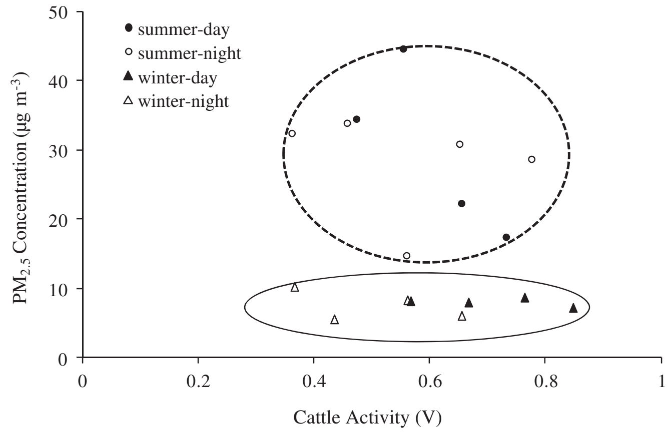

Fig. 10. Relationships between $PM_{2.5}$ concentrations and cattle activity in barn 2 during day and night in summer and winter.

concentrations during winter. The overall trends depicted in Fig. 10 suggest that cattle activity influence on $PM_{2.5}$ generation in naturally ventilated systems was not significant. The higher $PM_{2.5}$ concentrations in summer, day or night, can only be attributed to another factor, most probably temperature. These observations are in line with theory and past research. The fine particles are mainly produced from activities other than those associated with cattle activity because cattle activity mainly results in production of coarse particles rather than fine particles (Auvermann et al., 2006).

4. Conclusions

Concentrations and emission rates of PM from naturally ventilated freestall dairy barns were monitored for two years. The average PM emission rates from barns ranged between: 1.6–4.0 g d^{-1} cow^{-1} for $PM_{2.5}$; 11.9–15.0 g d^{-1} cow^{-1} for PM_{10}; and 48.7–52.5 g d^{-1} cow^{-1} for TSP. Season-wise, the PM_{10} concentrations were highest in summer, while TSP concentrations were highest in fall. The concentrations of $PM_{2.5}$ in summer, in barns, were on average about 10-fold higher than the concentrations in winter. In general, concentrations of all PM categories ($PM_{2.5}$, PM_{10}, and TSP) were lowest in winter. The concentrations of $PM_{2.5}$ and PM_{10} increased with temperature, while TSP concentrations were not influenced by temperature. Overall: the concentrations in the barns and ambient air, for all the PM categories ($PM_{2.5}$, PM_{10}, and TSP), exhibited non-normal positively skewed distributions, which tended to overestimate mean concentrations. To a limited extent, TSP concentrations increased with cattle activity; while cattle activity did not exert a significant effect on concentrations of finer dust particles ($PM_{2.5}$ and PM_{10}).

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