OPEN-PATH TRANSMISSOMETRY TO DETERMINE ATMOSPHERIC EXTINCTION EFFICIENCY ASSOCIATED WITH FEEDYARD DUST

J. K. Upadhyay, B. W. Auvermann, A. N. Paila, N. Hiranuma

ABSTRACT. *Open-lot, concentrated animal feeding operations (CAFOs) in the southern High Plains, such as cattle feedyards and open-lot dairies, emit fugitive particulate matter (PM) that occasionally reduces downwind visibility. The long-path visibility transmissometer (LPV) can be used to measure changes in total atmospheric extinction, a direct measure of path-averaged visibility impairment. To our knowledge, no researchers have used transmissometry as a surrogate to estimate aerosol concentrations downwind of open-lot livestock facilities. We compare time-resolved PM mass concentrations ($\mu g\ m^{-3}$) and atmospheric extinction coefficients (km^{-1}) measured simultaneously along the downwind boundary of a commercial cattle feedyard to compute "extinction efficiency," the change in atmospheric extinction that results from a unit change in PM mass concentration. Expected values for the in-situ extinction efficiency of total suspended particulate (TSP) and its fraction less than 10 microns (PM_{10}) aerodynamic equivalent diameter (AED) are 0.2 to 0.5 $m^2\ g^{-1}$ and 0.4 to 0.8 $m^2\ g^{-1}$, respectively. Determination of the atmospheric extinction efficiency of feedyard dust will enable transmissometry to be used as an intuitive, real-time surrogate for measuring time-averaged PM_{10} and/or TSP concentrations.*

Keywords. *Atmospheric extinction, Feedyard, Fugitive dust, PM_{10}, Transmissometry, TSP.*

The atmospheric extinction coefficient, B_{ext}, is a measure of the light attenuation in the atmosphere resulting from the absorption and scattering of light by gases and particles. Expressed in units of inverse distance (e.g., km^{-1}), B_{ext} comprises the sum of the absorption and the scattering coefficients (Malm and Johnson, 1984):

$$B_{ext} = B_{scat} + B_{abs} = B_{Ray} + B_{s,p} + B_{a,g} + B_{a,p} \qquad (1)$$

In equation 1, the subscripts *scat* and *abs* refer to total scattering and total absorption, respectively; *g* and *p* refer to gases and particles, respectively; and B_{Ray} refers to Rayleigh scattering, the wavelength-dependent scattering by native gases in the earth's atmosphere. The value of B_{Ray} is zero in the limit as barometric pressure tends to zero; its value in clear air at sea level is approximately 0.010 to 0.012 km^{-1} (Malm et al., 1986).

The extinction coefficient may be used to compute the radiant intensity at any point some distance from a radiant source of known intensity (Persha, 2002), as in:

$$I(r) = \left(\frac{K \cdot I_0}{r^2}\right) e^{-B_{ext} r} \qquad (2)$$

in which $I(r)$ is the irradiance detected at a given location ($W\ km^{-2}$), I_0 is the radiant intensity (W) of the source, r is the linear distance (km) between the source and detector, and K is a dimensionless parameter defined by the beam geometry of the radiant source.

Two methods are available to estimate B_{ext}. (1) An open-path transmissometer can be used to measure the path-averaged value of B_{ext} directly. In this case, the transmissometer installation fixes K, I_0, and r; it then measures $I(r)$ at the detector and infers B_{ext} from equation 2. (2) Aerosol mass-concentration measurements can be used to estimate the atmospheric extinction if the "atmospheric extinction efficiency" (Sisler, 1996) and mass fraction of each independent aerosol component are known. The atmospheric extinction efficiency (originally referred to as "extinction/mass ratio;" see Malm and Johnson, 1984) of an aerosol component is defined as:

$$\varepsilon_i = 10^3 \cdot \frac{\partial B_{ext}}{\partial C_i} \qquad (3)$$

where C_i is the mass concentration ($\mu g\ m^{-3}$) of each aerosol component (denoted by the subscript i), B_{ext} is as previously defined, ε_i is the extinction efficiency ($m^2\ g^{-1}$) of aerosol component i, and 10^3 is a units-conversion constant ($\mu g\ km\ g^{-1}\ m^{-1}$). Provided that all of the aerosol components i are independent, the total extinction efficiency, ε_T, is then calculated as:

$$\varepsilon_T = \sum_{i=1}^{n} w_i \varepsilon_i \qquad (4a)$$

in which

$$w_i = \frac{C_i}{\sum_{j=1}^{n} C_j} \qquad (4b)$$

Submitted for review in November 2007 as manuscript number SE 7272; approved for publication by the Structures & Environment Division of ASABE in June 2008.

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  ISSN 0001-2351

is the mass fraction of independent component *i* in the combined aerosol, *n* being the number of independent aerosol components (Malm and Johnson, 1984).

The independence of the aerosol components is vital to the process of reconstructing the total extinction efficiency of the combined aerosol using equations 4a and 4b. For example, it would be incorrect to reconstruct ε_T from a combination of the extinction efficiencies of sulfate, organic carbon, and urban $PM_{2.5}$ or fine particles (particles having an aerodynamic equivalent diameter, or AED, of 2.5 microns or less) because the typical urban $PM_{2.5}$ fraction already contains a significant proportion of sulfate and organic carbon aerosol. Likewise, it would be incorrect to reconstruct ε_T from $PM_{2.5}$ and PM_{10} (particles less than 10 microns AED) concentrations because the PM_{10} fraction contains the $PM_{2.5}$ fraction by definition. Ignoring for the moment the important issue of performance bias in the inertial preseparators of federal reference method $PM_{2.5}$ and PM_{10} monitors deployed in agricultural settings (Buser et al., 2007), the correct way to establish the independence of the summands in equation 4a would be to compute the $PM_{10-2.5}$ or PM coarse (particles with AED between 2.5 and 10 microns) concentration by difference and apply the appropriate extinction efficiency to that fraction.

Regulatory and Industrial Significance

The federal government does not currently regulate visibility impairment caused by episodic, fugitive dust emissions specifically from confined animal feeding operations (CAFOs). According to the U.S. Environmental Protection Agency (40 CFR 122.23), an animal feeding operation (AFO) is defined as a "lot or facility" where animals "have been, are, or will be stabled or confined and fed or maintained for a total of 45 days or more in any 12-month period and crops, vegetation, forage growth, or post-harvest residues are not sustained in the normal growing season over any portion of the lot or facility." Because the interpretive difficulties surrounding PM monitoring, sampler bias, and time-averaged measurements are nuanced and somewhat arcane to the public at large and to the CAFO community in particular, we intend to build on the work herein reported to develop more intuitive, visibility-based surrogate measurements that can inform routine CAFO management decisions (Auvermann, 2000; Razote et al., 2006).

Technical Objective

We designed this study to determine the atmospheric extinction efficiencies associated with the fugitive total suspended particulate (TSP) and PM_{10} from a commercial cattle feedyard. As a reference value, Malm (1999) published a value of 0.6 $m^2\ g^{-1}$ for the extinction efficiency of dry, generic coarse particles.

Experimental Design

Field studies were conducted at a commercial beef cattle feedyard (capacity 45,000+) in the Texas Panhandle. Mass concentrations ($\mu g\ m^{-3}$) of PM_{10} and TSP and B_{ext} (km^{-1}) were simultaneously measured along the downwind boundary of the feedyard continuously from September 2005 to July 2006 (fig. 1). The concentration and extinction data were acquired at one-minute intervals and then integrated to 5-minute averages for data reduction and analysis.

Monitoring Equipment

The long-path visibility transmissometer (LPV; model LPV-3, Optec, Inc., Lowell, Mich.) measures the total extinction (scattering + absorption) of green (λ = 540 nm) light by atmospheric gases and particles along a path between a transmitter and a photometer (Persha, 2002). The transmissometer compares the luminous intensity of a narrow beam of light with the intensity that would have been measured at the same location in an aerosol-free vacuum. The ratio of the measured and expected values of light intensity is an indirect measure of the path-averaged atmospheric extinction, B_{ext}, between the transmitter and photometer (Young, 2000).

The tapered-element, oscillating microbalance (TEOM; model 1400a, Thermo Scientific, Inc, Waltham, Mass.) is a quasi-real-time aerosol monitor in which aerosol particles impinge on a filter attached to a vibrating element. As the mass of particles retained on the filter increases, the characteristic frequency of the element decreases, and the change in frequency over time is a measure of the particle mass deposited on the filter during that time interval. TEOMs may be configured with a variety of inertial, size-selective inlets to measure any PM size fractions of interest. Numerous studies have shown that TEOMs have yielded biased PM concentrations under a range of conditions (Gehrig et al., 2005; Hitzenberger et al., 2004; Wanjura et al., 2005).

Figure 1 shows the experimental design for this study. We calibrated the LPV at a path length of 300 m per the manufacturer's specifications and deployed it on an E-W path along the northern perimeter of the feedyard corrals. The transmitter was installed at a height of 10 m atop a large water tank on the NE corner of the feedyard, and the photometer was installed at a height of 1 m on a short pillar at the NW corner of the feedyard (fig. 1). Under prevailing winds from the S-SSW, this LPV measured the downwind extinction resulting from the combination of the background aerosol load (assumed negligible; upwind land use was predominantly native range-land) and the fugitive emissions of particulate matter from the feedyard surface. The path length from transmitter (location A) to receiver (location B) was approximately 900 m. PM mass concentrations were measured at one upwind and one down-wind location (locations D and C, respectively). One TEOM was installed at location D with a TSP size-selective inlet on the upwind side. Two TEOMs were installed at location C, one with a TSP inlet and one with a size-selective inlet for PM_{10}. The TEOMs at location C were assumed to approximate the path-averaged aerosol concentrations corresponding to the LPV's open path, although that assumption is subject to criticism. To validate that assumption would require multiple, additional TEOMs distributed along the LPV path, which at the time of the research was cost-prohibitive.

In addition to the visibility and PM concentration measurements, we deployed an automatic weather station at location C to measure wind speed and direction, rainfall, temperature, solar radiation, relative humidity, and barometric pressure. Although the full suite of weather data will be useful for dispersion modeling to infer emission rates from the ground-level, area source (GLAS), in this case we used only the wind-direction data as a basis for removing out-of-sector data from our regression analysis.

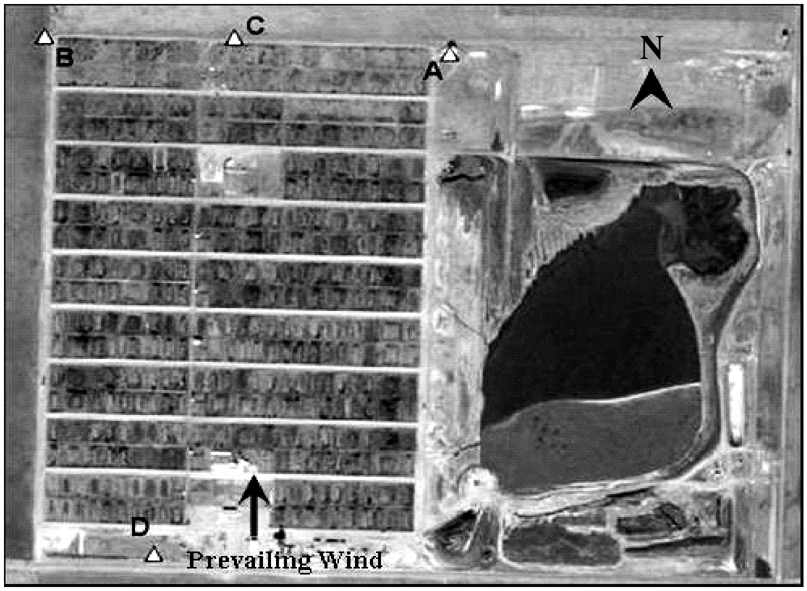

Figure 1. Overhead photograph of the cooperating feedyard. Instruments were deployed so that we could measure PM_{10} and TSP mass concentration and atmospheric extinction simultaneously measured along the downwind boundary of the feedyard. Transmitter is at A, receiver (photometer) is at B, upwind TEOM is at D, and downwind TEOMs are at C.

The equation of simple linear regression model was:

$$B_{ext} = mC_i + B_{Ray} + e \quad (5)$$

where m is the slope of the regression line $\frac{\partial B_{ext}}{\partial C_i}$ (known also as the extinction efficiency, ε_T), B_{Ray} is the intercept or Rayleigh scattering coefficient, and e is a random error term. Because B_{Ray} is known to good approximation and may therefore be treated as a physical constant, equation 5 may be rewritten as:

$$B_{ext} - B_{Ray} = mC_i + e \quad (6)$$

Equation 6 implies that the regression equation (eq. 5) may be forced through the origin if the B_{ext} measurements are corrected for Rayleigh extinction, which agrees fundamentally with the logic of Malm and Johnson (1984). Consequently, we subtracted B_{Ray} = 0.010 km^{-1} from all of our B_{ext} measurements and forced our subsequent regression intercepts to equal zero. After computing the regression coefficients for all data sets, we reformulated the regression equations according to equation 5, with B_{Ray} = 0.01 km^{-1}.

Objective Criteria for Data Filtering

Because of the relative placement of the TEOMs and the LPV's open path, we removed from the regression analysis all data collected while the wind direction was outside the 90° sector subtended by the SE and SW vectors. In addition, occasionally the dust concentrations along the downwind boundary of the source area were so great that the LPV photometer did not measure any of the transmitted light. In such cases, the LPV returned an extinction value of 0 km^{-1}, and those data were also removed from the analysis. Truck traffic along the downwind feed alley intermittently created transient road-dust spikes in the TEOM data. Because our primary focus was the fugitive, manure-derived dust from the open lots, we excluded the data points that were clearly associated with vehicle traffic. We also excluded all zero values associated with extinction (B_{ext}), PM_{10}, and TSP in our analyses. From the remaining data, we plotted 5-minute average B_{ext} values against the PM_{10} and TSP mass concentrations. We then subjected daily ensembles of those data to simple, linear regression to estimate the extinction efficiencies of PM_{10} and TSP. The slope of the regression analysis was considered as the extinction efficiency (ε_T). Because we were unable to measure the upwind B_{ext} as a reference value, we assumed that the regression intercept was equal to B_{Ray}, which for Big Bend National Park (BBNP) is approximately 0.01 km^{-1} (IMPROVE, 2006). The elevations of our experimental site and the transmissometer at BBNP are 1,062 and 1,075 m, respectively.

Daily estimated extinction efficiencies of PM_{10} and TSP reported here were based on the analyses of two datasets: 24-hour period (0000 h to 2400 h), and dust-peak period (1800 h to 2400 h). The rationale for the additional analysis was to isolate the dust derived primarily from cattle activity on dry manure surfaces (i.e., during the evening peak) from the undifferentiated dusts that arise from other sources such as feed milling, hay grinding, vehicle exhaust, and traffic on unpaved roads, nearly all of which predominate during the morning and early afternoon labor shifts. The 24-hour datasets were sorted to extract the data from the evening dust-peak period only (1800 h to 2400 h) to determine whether the dust-peak extinction efficiency (ε_T) differs markedly from the 24-hour value of ε_T.

Results and Discussion

Five-minute average values of B_{ext}, PM_{10}, and TSP from September 2005 through July 2006 were plotted to estimate daily extinction efficiencies of PM_{10} and TSP during these months. TSP concentrations from December 2005 to February 2006 were not available.

Figure 2 is an example of the raw data collected by our TEOMs and LPV on 5 September 2005. Vehicle traffic on a nearby, unpaved road is clearly visible in the extinction data; because the TEOMs are located at a single point, vehicle dust

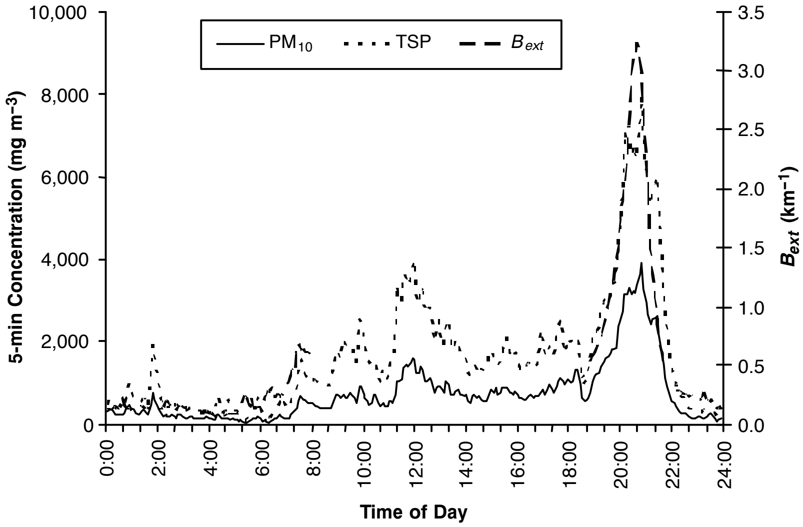

Figure 2. Diurnal variation of PM_{10} and TSP concentrations and B_{ext} for a typical day downwind of the feedyard.

plumes that show up within the 900 m LPV path do not necessarily envelop the TEOMs every time. Vehicles responsible for those spikes in atmospheric extinction include the night watchman's pickup truck (generally between 1700 h and 0600 h), feed trucks (0500 h to 1300 h), and feedyard management and consultants (0800 h to 1700 h). The diurnal peaks in dust concentrations and atmospheric extinction characteristic of cattle feedyards occur, as usual, between 1800 h and 2400 h, and they coincide nicely (fig. 3).

One of the more obvious features of the daily scatter plots is the hysteretic "looping" behavior of B_{ext}/concentration scatter plots (fig. 4). Simple, linear regressions (cf. eq. 5) fit the data well, and coefficients of determination (R^2) are excellent (0.87 for PM_{10} and 0.82 for TSP). The significance levels of the overall regression fits were alpha less than 0.05 ($\alpha < 0.05$) in both cases. However, the looping behavior highlighted by the arrows in figure 4 is *prima facie* evidence that, in plotting two time-series data sets against each other, we have violated one of the major assumptions in linear regression, to wit, that errors are assumed to be independent. In this case, rather, the data are clearly *autocorrelated* or *serially correlated*, which we plan to address with more powerful analytical techniques in a subsequent article. Nevertheless, the potential predictive value of the current regression models is beyond serious question; only the absolute values of the mean extinction efficiencies are likely to change as a result of the more rigorous analysis, not their orders of magnitude.

Figure 5 shows the frequency distribution of daily extinction efficiencies (ε_T) of PM_{10} during 24-hour intervals and dust-peak periods for September 2005 to July 2006. The distribution of values is in the range 0.2 to 3.6 $m^2\ g^{-1}$, with approximately 65% of extinction efficiency values in the range of 0.4 to 0.8 $m^2\ g^{-1}$. We observed no significant variation in the distribution pattern between the two cases. For PM_{10}, extinction efficiencies ranged from 0.4 to 0.8 $m^2\ g^{-1}$, as compared to Malm's (1999) reference value of 0.6 $m^2\ g^{-1}$ for the dry extinction efficiency of generic "coarse particles."

Again, the extinction efficiencies of TSP were estimated during each month following the same regression procedure. In figure 6, the daily extinction efficiency (ε_T) of TSP is distributed between 0.1 and 0.8 $m^2\ g^{-1}$ for 24-hour interval

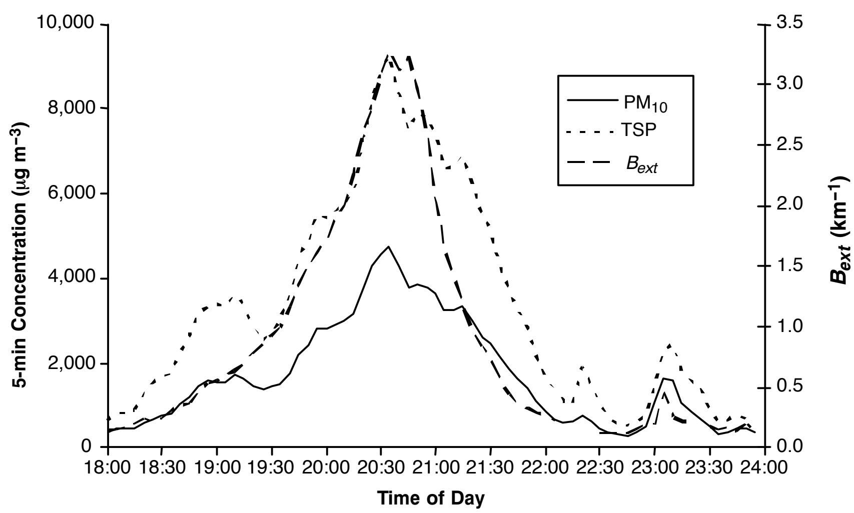

Figure 3. Variation of PM_{10} and TSP concentrations and B_{ext} during the six-hour period often known as the "evening dust peak" at cattle feedyards.

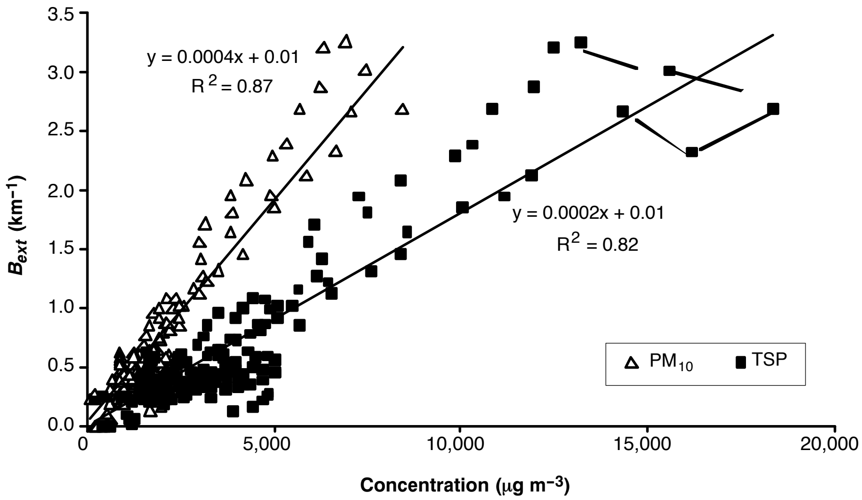

Figure 4. Correlation between extinction coefficient (B_{ext}) and 5-minute downwind particulate matter concentrations on a typical day at the experimental feedyard. The data points at high concentrations (>6,000 µg m^{-3} TSP, >3,000 µg m^{-3} PM_{10}) exhibit a pronounced, clockwise, looping behavior over time in both data series. Note also that the regression equations are forced through an intercept equal to B_{Ray} = 0.01 km^{-1} (Malm and Johnson, 1984).

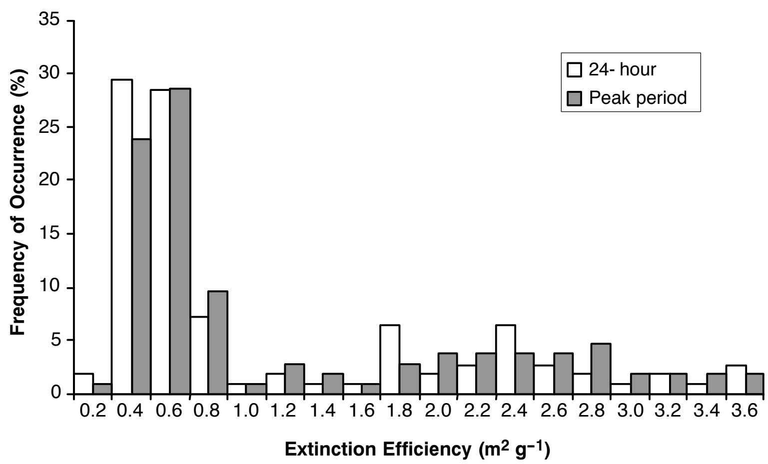

Figure 5. Frequency distribution of extinction efficiency (m^2 g^{-1}) for downwind PM_{10} computed from both the 24-hour and dust-peak data ensembles from September 2005 to July 2006.

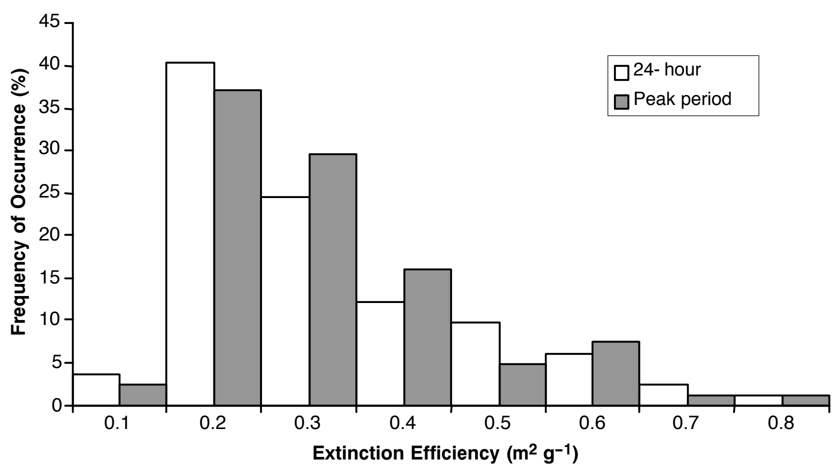

Figure 6. Frequency distribution of extinction efficiency (m^2 g^{-1}) for downwind TSP during 24-hour intervals and dust-peak periods from September 2005 to July 2006.

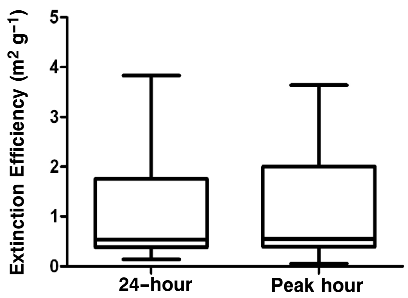

Figure 7. Stem-and-box plots of the estimated extinction efficiency of feedyard PM_{10}, using measured data from 24-hour intervals (left) and the evening dust peak (right).

measurements. Nearly 85% of the extinction values are in the range of 0.2 to 0.5 m^2 g^{-1}. Figure 6 also depicts the frequency distribution of ε_T of TSP during the dust-peak period for September 2005 to July 2006. Extinction efficiencies are in the range 0.1 to 0.8 m^2 g^{-1}. More than 80% of the values are between 0.2 and 0.5 m^2 g^{-1}. The range of values (0.1 to 0.8 m^2 g^{-1}) for the dust-peak data was similar to the range for the 24-hour data. As will be shown below with statistical tests, the dust-peak values of ε_T for feedyard TSP do not differ dramatically from the corresponding 24-hour values, and they agree well with Malm's reference value of 0.6 m^2 g^{-1} for generic coarse mass (Malm, 1999).

We are interested in knowing whether or not our estimates of the extinction efficiencies of feedyard PM_{10} and TSP depend on the time interval over which the concentration and extinction data are collected (i.e., 0000 h to 2400 h data vs. 1800 h to 2400 h dust-peak data). Figures 7 and 8 show the respective distributions of ε_T estimates in stem-and-box plots. To verify the apparent visual conclusions, i.e., that using different time intervals has little to no effect on the distribution of the estimated extinction efficiencies, we subjected the ε_T data to the nonparametric Kolmogorov-Smirnov and Mann-Whitney tests (Steel et al., 1997) for data sets having unequal sample sizes. The null hypothesis for both the M-W and K-S tests was that the distributions of 24-hour and dust-peak estimates extinction efficiency of a given PM size fraction were identical.

In the case of PM_{10}, the M-W unpaired test for 24-hour and peak-dust hour ε_T values yielded a P-value of 0.481, which is much greater than the threshold P-value of 0.05. The higher P-value suggested that the medians of two groups are not significantly different. The K-S test statistics showed that the maximum difference between the two cumulative distributions was 0.072 (P = 0.937). In both cases, we concluded that the distributions of extinction efficiencies of PM_{10} under both cases are not significantly different.

Similarly, the significance test of distributions of extinction efficiency (ε_T) of TSP for 24-hour and peak-dust were carried out using M-W unpaired test and K-S test, respectively. The M-W test suggested that the difference in medians of two groups are not statistically significant (P = 0.441); with the K-S test, the maximum difference between the two cumulative distributions was 0.096 (P = 0.832). Again, the P-values were greater than the threshold P-value (0.05) in each case, suggesting that the 24-hour and dust-peak data sets yield virtually identical estimates of extinction efficiency for a given PM size fraction.

The test statistics and P values are shown in table 1. We conclude from these statistics that we may reliably use only the dust-peak data between 1800 h and 2400 h for our estimates of extinction efficiency without introducing additional biases beyond those already noted.

The computed daily extinction efficiencies of PM_{10} and TSP were used to compute the monthly extinction efficien–cies from September 2005 to July 2006. The variation of monthly extinction efficiencies of PM_{10} and TSP for 24-hour intervals is shown in figure 9. The ε_T values range from 0.3 to 2.5 m^2 g^{-1} for PM_{10} and from 0.2 to 0.5 m^2 g^{-1} for TSP with means at 1.0 and 0.4 m^2 g^{-1}, respectively. Sim-ilarly, figure 10 shows the monthly extinction efficiencies of PM_{10} and TSP as inferred from the dust-peak data only. The extinction efficiency ranges from 0.3 to 2.7 m^2 g^{-1} for PM_{10} and from 0.2 to 0.5 m^2 g^{-1} for TSP. The mean values of PM_{10} and TSP extinction efficiencies are 1.0 and 0.3 m^2 g^{-1}, respectively. The fact that the extinction efficiency of feedyard TSP is numerically less than the extinction efficiency of feedyard PM_{10} is consistent with the well documented observation that, gram for gram, smaller particles have a relatively greater effect on visibility and visual contrast than larger particles (Malm, 1999).

Figure 11 shows the frequency distribution of the mass concentration ratio, TSP/PM_{10}, for all measured data from September 2005 to July 2006. Nearly 75% of the TSP/PM_{10} ratios are in the range of 2.0 to 3.0. The ratio of TSP to PM_{10} in the months of October and November is 5.0 to 7.0, which is significantly higher as compared to the rest of the months when the TSP/PM_{10} ratio is between 2.0 to 3.0. It has been

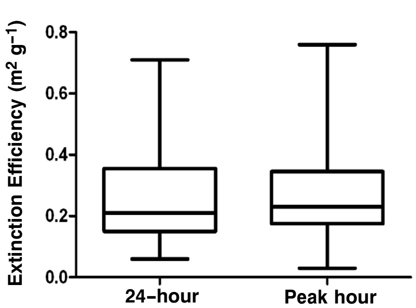

Figure 8. Stem-and-box plots of the estimated extinction efficiency of feedyard TSP, using measured data from 24-hour intervals (left) and the evening dust peak (right).

Table 1. Summary of Mann-Whitney and Kolmogorov-Smirnov test statistics comparing extinction efficiencies derived from 24-hour and dust-peak data. Results are shown for both PM_{10} and TSP dust fractions.[a]

Parameter	PM_{10} 24 Hour	PM_{10} Dust Peak	TSP 24 Hour	TSP Dust Peak
Number of data values	109	105	82	81
Mean (ε_T)	1.070	1.148	0.266	0.275
Median (ε_T)	0.530	0.550	0.210	0.230
Standard deviation (ε_T)	1.010	1.020	0.144	0.142
Mann-Whitney unpaired test				
P-value	0.481		0.441	
Kolmogorov-Smirnov test				
P-value	0.937		0.832	
D[b]	0.072		0.096	

[a] 24 hour = 0000 h to 2400 h, dust peak = 1800 h to 2400 h.
[b] D = difference between cumulative distributions.

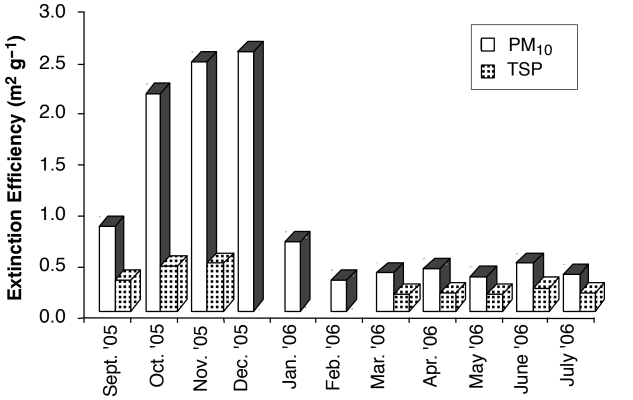

Figure 9. Extinction efficiency (m^2 g^{-1}) of feedyard dust for each month using 24-hour datasets.

reported that the ratio of TSP to PM_{10} is typically in the range of 4.0 to 5.0 for agricultural aerosols (Parnell et al., 2005) when inferred from particle-size distributions of feedyard TSP samples. Because the preseparator bias documented by Buser et al. (2007) yields artificially high PM_{10} measurements, the discrepancy between the low TSP/PM_{10} ratios we are reporting and those reported by Parnell et al. (2005) may be explained by the fact that our artificially high PM_{10} measurements are in the denominator of the TSP/PM_{10} ratio calculation.

The extinction efficiency of PM_{10} from October to December 2005 was always high (>2.0 m^2 g^{-1}) for both 24-hour and peak-only datasets (figs. 9 and 10). At present, we do not have any specific explanation for this anomaly in the estimated extinction efficiency of PM_{10} during October-December 2005. It appears that PM_{10} concentrations measured during those three months were abnormally low, but it is not clear whether they were a result of instrument malfunction or some fundamental change in the feedyard aerosol.

Effect of Humidity

Our daily extinction efficiencies, calculated from extinction measurements using the LPV, represent the optical properties of feedyard aerosols as they exist in the environment (in situ), as contrasted with the extinction efficiencies published by Malm (1999) for dry aerosol particles. This distinction is particularly important for hygroscopic aerosols such as feedyard dust. It appears likely that hygroscopicity and deliquescence are responsible, in part, for the variation in optical properties that shows up as an experimental variation in extinction efficiency (Hiranuma et al., 2008). Relative humidity (specifically, its effect on particle size, shape, and optical properties via hygroscopic adsorption and deliquescence behavior) is likely to be an important co-factor in exploiting the predictive relationships between extinction and mass concentration in the feedyard setting (Brooks et al., 2005).

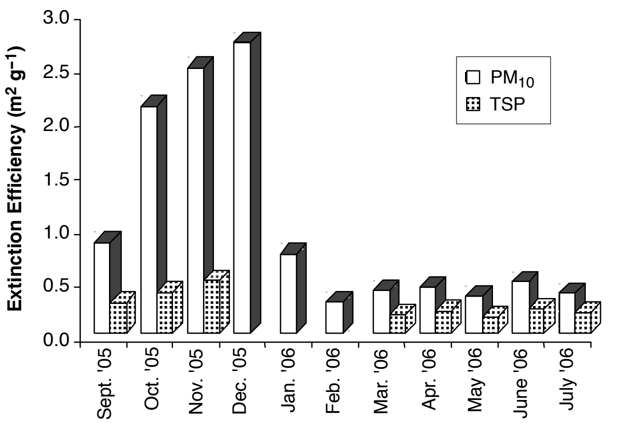

Figure 10. Extinction efficiency (m^2 g^{-1}) of feedyard dust for each month, computed solely from data collected during the evening dust peaks (1800 h to 2400 h).

Effect of Sampler Bias

The performance bias in inertial preseparators for gravimetric PM monitors (e.g., Buser et al., 2007), including the TEOM, has been ignored in the present analysis because no systematic, scientifically validated means of correcting for that bias has been adopted for federal or state compliance monitoring. It is not our purpose here to propose an algorithm for correcting for that bias. However, the bias is significant and necessarily results in a quantitative error in any physical quantities or parameters calculated from concentration data measured with devices in which the bias is present.

That is certainly the case here; in the foregoing, we have calculated an optical property (extinction efficiency) of feedyard aerosols from the aerosol mass concentration as measured by gravimetric monitors with inertial PM_{10} preseparators. The reader should be aware, therefore, that the absolute values of the extinction efficiency of PM_{10} presented here are contingent; that is, the absolute value of the PM_{10} extinction efficiency will eventually need to be corrected for the preseparator bias if and when a valid correction algorithm is adopted by the regulatory community.

Effect of Precipitation Events

Another possible source of variation in our estimates of extinction efficiency is the natural variation in the TSP/PM_{10} ratio, that is, the variation that occurs without regard to oversampling bias or other monitor-specific phenomena. For example, Parnell et al. (2005) showed that the particle-size distribution (PSD) of feedyard dust shifts dramatically after a precipitation event, reducing the mass median diameter (MMD) of the aerosol and decreasing its TSP/PM_{10} ratio.

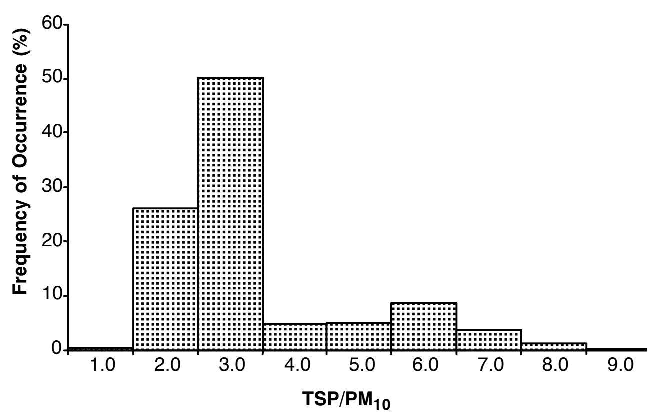

Figure 11. Frequency distribution of TSP/PM_{10} ratio for all measured data.

INFLUENCE OF EXPERIMENTAL GEOMETRY

There are two distinct but related weaknesses in our experimental design, which correlated point measurements of aerosol mass with path-averaged extinction measurements. Both weaknesses relate to the spatial nonuniformity of mass concentration along the plume transect represented by the transmissometer beam. First, during the last ten years of field research on cattle feedyard dust, we have frequently observed that the plume cross-section along the downwind corral boundary consists of a variable number of eddies and discrete plumes. Those nonuniformities are instantaneously path-averaged by the transmissometer measurement, but the TEOM at the midpoint of the transmissometer path is incapable of averaging the aerosol concentration along that same path. Because the distribution and location of eddies and discrete plumes within the overall plume are most likely random phenomena, it is not clear what the overall effect is on the extinction efficiency. Secondly, however, assuming (in the ergodic sense) that the mass concentration in the plume cross-section is Gaussian or quasi-Gaussian, we may infer that the aerosol concentration measured at the midpoint of the cross-section is the maximum value along the transmissometer path. If that is the case, the path-averaged mass concentration is by definition less than the concentration along the plume centerline. The net effect of that phenomenon would be a downward bias in (i.e., underestimating) the extinction efficiencies of both PM_{10} and TSP. To overcome this experimental bias rigorously would require deployment of multiple TEOMs distributed along the transmissometer path with their inlets at elevations corresponding to the beam's changing elevation along its path.

CONCLUSIONS

To infer the extinction efficiencies associated with fugitive TSP and PM_{10} emitted from cattle feedyards, we measured aerosol mass concentrations and atmospheric extinction coefficients in quasi-real time along the downwind boundary of a large, commercial feedyard from September 2005 to July 2006. Daily extinction efficiencies derived from 24-hour data sets were observed to range from 0.4 to 0.8 m^2 g^{-1} for PM_{10} and from 0.2 to 0.5 m^2 g^{-1} for TSP. We observed similar extinction efficiencies using only the visibility and concentration data from the evening dust peak. The TSP/PM_{10} ratios throughout the project were usually in the range ~2.0 to 3.0.

Real-time, nearly instantaneous changes in the atmospheric extinction coefficient along the downwind perimeter of feedyard corrals appear to be reliably predicted by aerosol mass concentrations measured by TEOM. On the basis of "goodness of fit" considerations, changes in mass concentration of PM_{10} explain a greater proportion of variations in B_{ext} than do changes in TSP concentration. As expected, changes in PM_{10} concentration have a significantly greater influence on B_{ext} than changes in TSP concentration. Our use of time-series data from mass concentration and atmospheric extinction measurements results in autocorrelated regression errors, and we plan to refine our analytical technique to resolve the interpretive and predictive difficulties posed by that autocorrelation.

Despite the acknowledged limitations of our study related to (1) point vs. line-averaged measurements and (2) the performance bias of inertial preseparators, the PM_{10} extinction efficiencies presented here are a valid basis for predicting the mass concentration of PM_{10}, *as measured by gravimetric monitors currently approved for use in compliance monitoring along the centerline of the feedyard dust plume*. Our estimates of the extinction efficiency of feedyard dust are numerically close to Malm's (1999) reference value for generic, coarse dust. Results from this article may provide livestock producers and feedyard managers with a lower-cost, more intuitive means by which to estimate PM concentrations, facilitating the timely implementation and retrospective evaluation of best management practices (BMPs).

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