INCREASING STOCKING DENSITY REDUCES EMISSIONS OF FUGITIVE DUST FROM CATTLE FEEDYARDS

K. J. Bush, K. R. Heflin, G. W. Marek, T. C. Bryant, B. W. Auvermann

ABSTRACT. *The moisture and compaction dynamics of an open-lot corral surface in a cattle feedyard depend strongly on the spatial density at which the animals are stocked. Because the moisture content and bulk density of the corral surface directly influence its intrinsic dust susceptibility, emission of fugitive dust from a feedyard surface should be sensitive to changes in stocking density. In the summer of 2012 we measured airborne dust concentrations upwind and downwind of feedyard pens stocked at two different densities, 718 (control) and 1,435 hd* ha^{-1}*, over a 160-d feeding period. Doubled stocking density was achieved in two different ways, by (A) confining cattle to half the pen area using electric cross-fencing and (B) doubling the number of cattle in the pens. Path-averaged dust concentrations were measured upwind and downwind of feedyard pens using an optical particle sizer (OPS model 3330, TSI Inc., Shoreview, Minn.) and an earlier-model optical sensor (model DUSTTRAK II 8530, TSI Inc., Shoreview, Minn.) mounted on mobile monitoring platforms. Because the monitoring platforms used different instruments, during the data analysis phase DUSTTRAK data were compared only to DUSTTRAK data, and OPS data were compared only to OPS data. Downwind 1-min concentrations of dust varied from 1 to 4,478* $\mu g\ m^{-3}$ *for the control pens, 1 to 2,431* $\mu g\ m^{-3}$ *for the pens with cross-fencing (treatment A), and 1 to 2,872* $\mu g\ m^{-3}$ *for the pens with twice as many cattle as the control pens (treatment B). Dispersion modeling using AERMOD revealed that the apparent dust-emission fluxes from treatments A and B were 79.4% and 80.6% lower, respectively, than the apparent emission flux from the control pens (23.45* $\mu g\ m^{-2}\ s^{-1}$*). We conclude that stocking-density manipulation is likely to be a viable Beneficial Management Practice (BMP) for controlling fugitive dust from open-lot cattle feedyards but that improved, path-averaged monitoring techniques appropriate to the feedyard source geometry are needed.*

Keywords. *Abatement, AERMOD, Cattle spacing, Cross-fencing, Emission factor, Emission flux, Emissions, Feedlot, Feedyard, Fugitive dust, Particulate matter, Reduction, Stocking density.*

Fugitive dust emissions are a high-profile environmental concern for open-lot cattle feedyards in arid and semi-arid climates. Dust from feedyard surfaces may create nuisance conditions, health hazards, and traffic hazards on adjacent highways (Sweeten, 1982). Offensive odors are often associated with high dust concentrations (Von Essen and Auvermann, 2005) and can lead to an increase in neighbor complaints and a decrease in property values (Rahman et al., 2008). Feedyard dust includes particles from manure, urine, soil, hair, plant material, and insects. It often harbors fungi, bacteria, and biologically derived toxins (Purdy et al., 2004), and can carry ammonia, hydrogen sulfide, and several volatile organic compounds (VOCs) (Wyatt et al., 2007).

Bacterial endotoxins associated with Gram-negative organisms may impair both animal and human health (Wilson et al., 2002). Gram-positive bacteria appear to be the most prevalent bacteria in feedyard dust, as Gram-negative bacteria are more susceptible to warm, dry air and less likely to survive downwind transport (Wilson et al., 2002; Purdy et al., 2004). However, Wilson et al. (2002) suggest that environmental stress conditions and microbial collection methods may result in Gram-negative bacteria that are viable but not culturable, effectively causing their presence in feedyard dust samples to be underestimated. Veterinary researchers also suppose that the effect of endotoxins, in conjunction with the allergic and irritant properties of dust, could predispose cattle to illness. MacVean et al. (1986) found that incidence of cattle pneumonia was positively associated with dust concentrations, especially among younger cattle within two to three weeks of delivery to the feedyard, implying that the inhaled

---

Submitted for review in March 2014 as manuscript number SE 10681; approved for publication by the Structures & Environment Division of ASABE in July 2014.

The authors are **Kevin Jack Bush,** Research Associate, **Kevin R. Heflin**, Research Associate, Texas A&M AgriLife Research, Amarillo, Texas; **Gary. W. Marek**, **ASABE Member,** Research Agricultural Engineer, Conservation and Production Research Laboratory, USDA-ARS, Bushland Texas; **Tony C. Bryant**, Staff Nutritionist and Research Manager, JBS Five Rivers Cattle Feeding, Greeley, Colorado; and **Brent W. Auvermann, ASABE Member,** Professor, Biological and Agricultural Engineering Department, Texas A&M AgriLife Research, Amarillo, Texas. **Corresponding author:** Kevin Jack Bush, Texas A&M AgriLife Research, Amarillo, TX 79106; phone: 806-677-5600; e-mail: kjbush@ag.tamu.edu.

dust stresses the respiratory system and leaves the animal more vulnerable to infection by other pathogens. Bovine respiratory disease, of which dust may be among the etiologic factors, is thought to be the most important cause of cattle mortality in U.S. feedlots (Loneragan et al., 2001).

The effects of feedyard dust on adjacent communities have not been extensively studied, and few publications exist on the health effects on feedyard workers (Von Essen and Auvermann, 2005). Wyatt (2007) found that persons exposed to feedlot dust exhibited more respiratory complaints and had elevated lung inflammatory mediators. Exposure to high concentrations of agricultural dust may be associated with organic dust toxic syndrome (ODTS), a short-lived illness with flu-like symptoms such as fever, chills, headache, and cough (Purdy et al., 2004; Von Essen and Auvermann, 2005).

Dust emissions from feedyard surfaces are a function of pen surface conditions and animal activity. High winds, high temperatures, and low humidity accelerate drying rates of manure on feedyard surfaces, increasing its dust potential. Light winds and temperature inversions in the late evening combined with increased animal activity may result in extreme, short-term, ground-level dust concentrations. This phenomenon, commonly known as the evening dust peak (EDP), may result in short-term (1-min averaged) dust concentrations 15 times the daily average (Auvermann and Romanillos, 2000). Feedyards employ a wide range of dust-suppression methods, most of which fall under four main categories: feed management, surface amendments, manure harvesting, and moisture management. Feed-management practices involve manipulating feed timing in order to reduce the magnitude of dust peaks during the day. For example, the last feeding of the day might be timed such that cattle would recline and ruminate in the late evening, reducing animal hoof action during periods of decreased boundary-layer turbulence. Increasing fat intake may decrease the dust potential of excreted manure. Chemical amendments that are widely used for e.g. road-dust suppression (emulsions, oils, and resins) might also be added directly to the feedyard surface to control dust but, like increasing dietary fat, the efficacy of such additives remains conjectural, the costs are likely to be high, repeated applications are likely to be necessary, and the implications for animal health and occupational safety are of great concern. Most related research has been conducted in laboratory settings with varying results (Rahman et al., 2008) and therefore does not yet present a compelling account of the cost-effectiveness of such chemical amendments. Where water resources are at a premium, increasing the frequency of manure harvesting from corral surfaces is perhaps the most effective dust suppression method, especially under extremely hot, dry conditions (Auvermann et al., 2000). In this approach, uncompacted manure is carefully harvested from the pen surface, leaving behind a hard, well compacted layer comprising a dense mixture of manure and the (normally clayey) mineral soil. Standard recommendations are to maintain uncompacted manure depths less than 50 mm (2 in.) (Rahman et al., 2008; Auvermann and Casey, 2011).

Moisture management is an important aspect of dust control on feedyard surfaces. The application of supplemental moisture to feedlot surfaces during dry periods has been shown to reduce dust potential dramatically (Sweeten, 1982; Sweeten and Lott, 1995; Bonifacio et al., 2011). This has been achieved historically via (a) mobile tankers fitted with pumps and spray nozzles and, more recently, (b) solid-set sprinkler systems. However, these systems are high in initial cost, require frequent maintenance, and require low wind speeds for uniform application. In addition, the long-term depletion of water tables may call into question the use of high quality groundwater for feedyard dust suppression.

As an alternative, increasing stocking density is a passive form of moisture management and dust suppression whose capital and operating costs may be much lower than those of active water-application methods. By increasing the stocking density, three distinct changes interact to produce the desired, dust-suppressive effect. First, assuming no significant change in drinking-water intake or respiration by the cattle, the effective depth of urine excreted onto the corral surface is increased. Second, the proportion of the pen area shaded from solar radiation is increased, reducing the corral-surface temperature and, correspondingly, the local evaporative demand. Third, to the extent that the spatial intensity of vertical (i.e., compactive) hoof action increases with increased stocking density, along with the higher moisture content, an increase may be expected in the bulk density of the corral surface. In this study, we evaluated the dust-control efficacy (as measured by changes in dust concentrations and emissions fluxes) of doubling the stocking density in a portion of a commercial-scale feedyard in the Texas Panhandle.

MATERIALS AND METHODS

This study was conducted on a 60,000 head feedyard located in the Texas Panhandle. The feedyard was selected primarily for the east-west orientation of its feeding and working alleys, which were nearly orthogonal to prevailing south to southwest winds, allowing for treatment-segregated, upwind and downwind monitoring. The study area consisted of a rectangular block of 38 pens (2 × 19) bounded by feed alleys and separated by a single, earthen working alley (fig. 1). One pen in each row was twice the size of the others, resulting in an effective study area equivalent to 20 pens of equal dimension and area within each row. The eastern half of each row, consisting of nine pens each (including the outsized pen), was designated the experimental control and was stocked at a conventional rate of 718 hd ha^{-1} (equivalent to a cattle spacing of 150 ft^2 hd^{-1}). The western half of each row was stocked at a rate of 1,435 hd ha^{-1} (75 ft^2 hd^{-1}). The increased stocking density was accomplished in two ways. Treatment A pens were stocked with the same number of cattle as the control pens, but each of the pens in Treatment A was cross-fenced with temporary, electric “hot wire” to reduce the effective size of the pen by half. Treatment B retained the full, original pen area but was stocked with twice the number of cattle per pen.

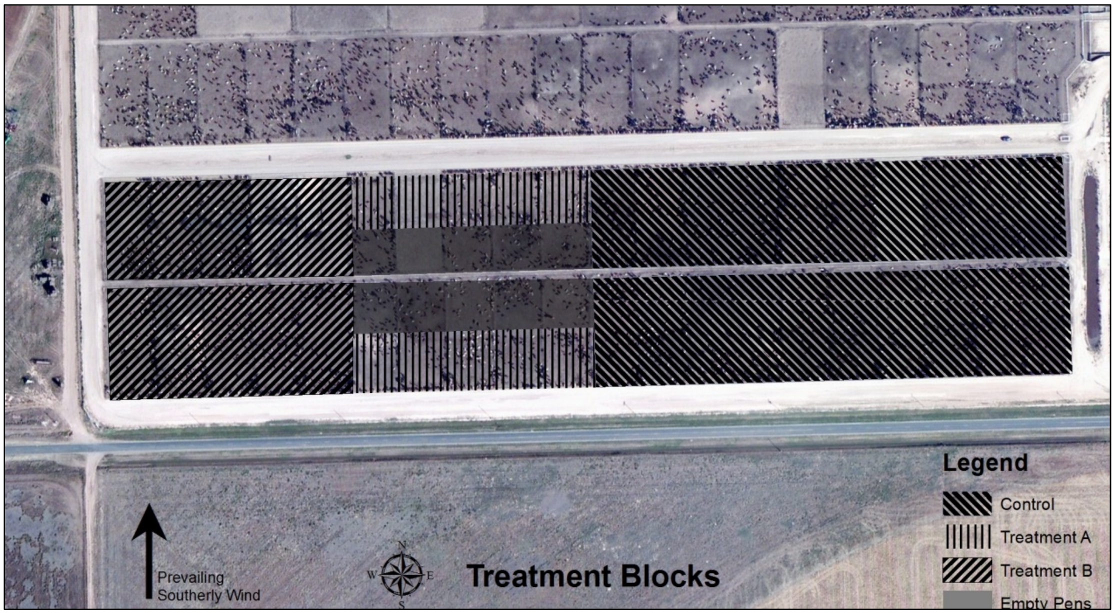

Figure 1. Treatment block orientation in the southern end of the study feedlot. The eastern half of the study area contained a stocking density of 718 hd ha^{-1} (150 ft^2/hd^{-1}) and the western half 1,435 hd ha^{-1} (75 ft^2/hd^{-1}).

Dust concentrations were measured using an optical particle sizer (OPS model 3330, TSI Inc., Shoreview, Minn.) and an earlier model aerosol monitor (DUSTTRAK II model 8530, TSI Inc., Shoreview, Minn.). Each device was mounted to a mobile monitoring platform on the front of a dedicated all-terrain vehicle (ATV). The sample inlet on each monitor was positioned at 55.9 cm (22 in.) above the ground to ensure that the inlet remained within the ground-level dust plume generated by hoof action. Monitors were mounted on the front of each ATV to prevent any tire-generated dust from entering the sampling inlet. Dust concentrations were recorded as 1-min averages, and both monitoring platforms were equipped with identical, synchronized, GPS devices (Garmin Dakota 20, Garmin LTD, Olathe, Kans.). The GPS coordinates were recorded every 5 s to track the location of each dust measurement. The accelerators on each ATV were modified to achieve a target ground speed of 1.6 kph (1.0 mph) to prevent them from disturbing the ground surface and entraining extra dust into the air. The southern row of pens (the "J row") was always monitored using the OPS; the combined effect of the J row and the northern row of pens (the "K row") was only monitored using the DUSTTRAK II (fig. 2). Each monitoring run began at the northwest corner of each row of pens. The ATVs were driven in a single, continuous, clockwise loop around their respective study areas during a given 30-min cycle. Each 30-min loop comprised approximately 15 min of downwind and 15 min of upwind measurements. The extremely low ground speed of the J-row monitoring platform was visually confirmed to ensure that the vehicle's operation contributed negligibly to the dust plume measured by the K-row monitor.

Monitoring events were scheduled to coincide with forecasted weather conditions conducive to high dust emissions and ground-level concentrations. Scheduling specifications included light (0-16 kph) winds from the southwest to southeast (225°-135°) and dusty pen-surface conditions. Monitoring took place during the late afternoon and evening to take advantage of the EDP, thereby increasing the method's signal-to-noise ratio. Wind speed, wind direction, temperature, relative humidity, precipitation, and solar radiation were recorded as 1-min averages during the entire study using an automatic weather station (Campbell Scientific, Inc., Logan, Utah).

Dispersion Modeling

The AERMOD View (Lakes Environmental, Waterloo, Ontario) dispersion model was used to estimate dust emission fluxes from the feedlot surface. AERMOD is the current EPA-preferred regulatory dispersion model (CFR, 2005). The model is a steady-state, Gaussian plume model that consists of two data pre-processors and the dispersion

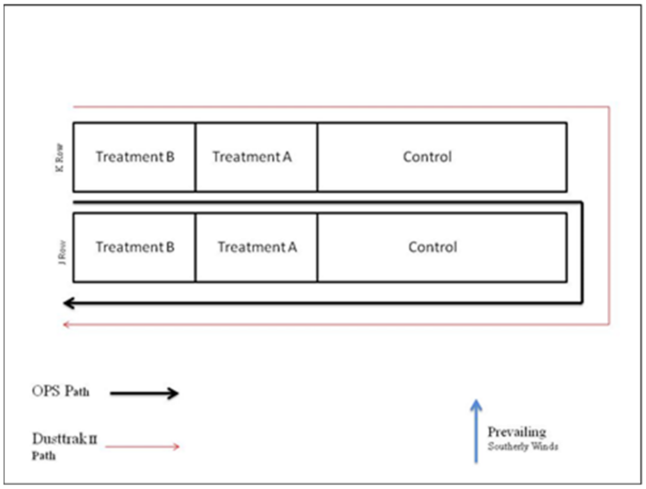

Figure 2. OPS and DUSTTRAK II PM$_{10}$ monitor paths. Dust from the southern row of pens (J row), was monitored using the OPS, while the combined effect of the J row and the northern row of pens (K row) was monitored using the DUSTTRAK II.

model. AERMET is the processor that provides boundary-layer data and mixing parameters for the model. AERMAP addresses the temporal and spatial aspects of the model by characterizing the terrain and creating a grid for receptors and sources in three dimensions (Cimorelli et al., 2004).

AERMET requires surface and upper-air weather data for the modeled area. Surface data for this study were measured by the onsite weather station. Upper-air "pseudodata," which were obtained from Lakes Environmental (Waterloo, Ontario), were estimated using the Fifth Generation Penn State/NCAR Mesoscale model (MM5) following the approach of Dai et al. (2003). Surface characteristics were entered into AERMOD/AERMET according to US EPA AERSURFACE guidelines (U.S. EPA, 2008). Locations of source-area vertices and receptors were specified in the input files by latitude and longitude.

A reference emission flux of 10 μg m^{-2} s^{-1} was specified for each non-zero source area in AERMOD. The model uses the reference emission flux to predict downwind dust concentrations. Although the scaling technique used to infer emission flux is not sensitive to the magnitude of the reference flux – for a fixed source/receptor geometry and a given set of weather data, net downwind concentration at a given receptor is purely proportional to flux, so any reference flux will generate the same inferred flux – this value was chosen because it falls within the range of emission fluxes seen in similar studies (Bonifacio et al., 2012). The following parameters were assumed for each model run: study pens were the only area sources, the reference emission flux was uniform and constant, the emission flux from the empty sections of cross-fenced pens was identically zero, and the receptor height was set at 55.9 cm (22 in.), equal to the inlet heights on the mobile monitoring platforms. AERMOD then predicted one-hour-average dust concentrations at the center (i.e., with respect to the prevailing wind vector drawn through the centroid of the emitting area) of the downwind side of each treatment block.

Pen Surface Assessment

In addition to dust measurement, a qualitative pen-surface assessment was conducted by all project personnel who visited the feedyard. The conditions of individual pen surfaces were rated on a scale from "A" (low dust potential) to "F" (high dust potential) based on the apparent intrinsic dust susceptibility of the surface (table 1). A rating of "W" indicated wet, muddy conditions covering >25% of the pen surface area.

All pens in the study were rated on each visit, whether or not the dust-monitoring platforms were to be run. These assessments were conducted to corroborate dust measurements and to evaluate the surface assessment as a dust-management tool.

Experimental Design

This study was a repeated-measures design with one replication per monitor type. The experimental unit was defined as a block of pens. There were 5 pens in the Treatment A and Treatment B blocks and 9 pens in the control block for the J pen monitor (OPS). For the J+K row monitor (DUSTTRAK), there were 10 pens in each treatment block and 18 pens in the control block (figs. 1 and 2).

Table 1. Corral surface assessment classifications and descriptions.

Corral Surface Condition	Description
A	Little to no uncompacted manure visible on the corral surface; hard and smooth, may be moist to dry
B	Well compacted surface easily visible; small clods of uncompacted manure present
C	Compacted surface sparsely visible, nearly covered with small manure clods
D	Compacted layer not visible, completely covered with dry, uncompacted manure in chunks and/or clods
E	Completely covered with <1 in. of finely textured, dry, uncompacted manure "fluff"
F	Completely covered with >1 in. of finely textured, dry, uncompacted manure "fluff"
W	Wet; sloppy and/or uneven surface >25% of corral area

Data Analysis

To be as conservative as possible with respect to detecting differences among treatments, downwind PM concentrations were used instead of net downwind concentrations. Deriving absolute estimates of emission flux from mass concentration data requires the use of *net* downwind concentrations, computed as the difference between measured downwind and upwind concentrations, to isolate the source area's contribution to the aerosol load. However, because we are concerned primarily with relative differences in the fluxes between control and treatment source areas, we may neglect background concentrations, provided that we understand that in so doing we are producing conservative estimates of the treatment's effectiveness. A mathematical justification follows.

Consider two adjacent treatment areas of arbitrary shape, A_1 and A_2, subjected to precisely the same weather conditions. Their emission fluxes are Q_1 and Q_2, respectively. The background mass concentration of aerosol common to both treatments is C_0, and we measure path-averaged mass concentrations C_1 and C_2, respectively, downwind of each area.

According to the fundamentals of Gaussian dispersion modeling, for a fixed site geometry (which includes the area and orientation of the source as well as the relative location of the downwind receptors) and a common set of weather conditions, the relationship between emission flux and downwind concentration is essentially linear, such that an equation can be written for any source i,

$$Q_i = k_i\left(C_i - C_0\right) \tag{1}$$

in which $k_i>0$ is a constant of proportionality that lumps together the combined effects of source geometry, weather, and the relative position of the receptor. If that equation is written for this study with two source areas, A_1 and A_2, then the resulting equations are,

$$Q_1 = k_1\left(C_1 - C_0\right) \tag{2}$$

and

$$Q_2 = k_2\left(C_2 - C_0\right) \tag{3}$$

Although the two sources experience the same weather conditions and the same background concentration, the constants of proportionality k_1 and k_2 differ due to their different geometries of source area and receptor positions. An equation can now be written to show the relative difference in flux between the two sources,

$$E_{12} = \frac{Q_2 - Q_1}{Q_1} \tag{4}$$

which treats source area A_1 as the reference area and its emission flux Q_1 as the reference flux. (Under the sign convention we have implicitly adopted, E_{12} is negative if the treatment effectively reduces the emission flux, or $Q_2<Q_1$.) Interpreting the source area A_1 as the "control" treatment in our experiment, E_{12} represents the fractional change in emission flux that is attributable to the abatement measure being used on source area A_2.

Inserting equations 2 and 3 into equation 4 and simplifying,

$$E_{12} = \left[\frac{k_2}{k_1}\right]\left\{\frac{C_2 - C_0}{C_1 - C_0}\right\} - 1 \tag{5}$$

We may now define a similar term, $E_{12,G}$, which is the value of E_{12} assuming that the background concentration $C_0=0$:

$$E_{12,G} = \left[\frac{k_2}{k_1}\right]\left\{\frac{C_2}{C_1}\right\} - 1 \tag{6}$$

We may now write an expression for the difference E_{12}-$E_{12,G}$ and ask what its sign will be for the range of values of k_1, k_2, C_0, C_1, and C_2 that are of interest in this study:

$$E_{12} - E_{12,G} = \left[\frac{k_2}{k_1}\right]\left\{\frac{C_2 - C_0}{C_1 - C_0} - \frac{C_2}{C_1}\right\} \tag{7}$$

Because $k_i>0$ strictly, the ratio k_2/k_1 is also strictly positive. Consequently, recalling that $E_{12}<0$ if $Q_2<Q_1$, a sufficient condition to ensure that E_{12}-$E_{12,G}$ is negative – which is to say, *to ensure that the estimate of treatment 2's abatement effectiveness is conservative*, or understated – is that,

$$\left\{\frac{C_2 - C_0}{C_1 - C_0} - \frac{C_2}{C_1}\right\} < 0 \tag{8}$$

Second, we note that whenever air quality conditions permit the evaluation of an abatement measure, we must have both $C_0<C_1$ and $C_0<C_2$, ensuring that the first quotient in equation 8 is also positive. Then we may rewrite the sufficiency condition (eq. 8) as:

$$\frac{C_2 - C_0}{C_1 - C_0} < \frac{C_2}{C_1} \tag{9}$$

which, because all of the mass concentrations C_i are strictly positive, reduces to the statement $C_1>C_2$.

We may therefore say that, for circumstances in the field under which evaluating an area-source abatement measure is practically meaningful, we are ensured that *neglecting the background concentration and basing our analysis on gross downwind concentrations will always produce a conservative (understated) estimate of the actual treatment effectiveness whenever the mass concentration downwind of the reference area, C_1, is numerically greater than the mass concentration downwind of the treatment area, C_2.* The condition $C_1>C_2$ was obtained consistently in our experiment.

The preceding development assumed a single, upwind mass concentration C_0 applicable to all three treatments. Indeed, the very notion of a "background" concentration implies that C_0 is spatially uniform upwind of the source area. Because of the labor- and equipment-intensive nature of the study, however, it is reasonable to question the assumed uniformity of C_0 upwind of the study area and the consequent validity of the preceding development based on that assumption. Generalizing equations 1-9 to accommodate different values of C_0 for the control area and a treatment area confirms the overall logic if the background concentration for one of the treatment areas is greater than the background concentration for the control area; in that case, the estimate of abatement effectiveness is even more conservative if upwind concentrations are neglected than if C_0 were actually uniform. In fact, the only circumstance in which the logic does not hold, and therefore in which the abatement effectiveness is rendered ambiguous by neglecting upwind concentrations, is if the background concentration for the control area is greater than that of the treatment area to which it is being compared. As will be shown in the results and discussion, upwind concentrations during our study were consistent with conditions that yield reliably conservative estimates of abatement effectiveness. As a result, background concentrations have been neglected throughout the following discussion.

Because the monitoring platforms used different instruments, during the data analysis phase DUSTTRAK data were compared only to DUSTTRAK data and OPS data were only compared to OPS data. This was done in order to avoid confounding associated with dissimilar monitor performance. Further, inferences were drawn only from relative concentration differences within a single monitor's dataset.

Downwind measured dust concentrations were filtered using wind direction and wind speed to rank the data quality objectively. Wind speeds had to be greater than 1 m sec^{-1}, and wind direction had to be such that each data point would be downwind of only one treatment block. Each data point was geolocated as the midpoint of the segment travelled during the one-minute averaging period for each measurement. All valid, one-minute data during a one-hour period for each treatment block were then averaged. This one-hour average was then compared to the AERMOD-predicted, one-hour averages as described previously, using the corresponding surface and upper-air weather data.

Emission fluxes were calculated using a standard scaling approach using the equation:

$$Q_O = \frac{Q_A}{C_A} \times C_O \tag{10}$$

in which Q_O is the calculated emission flux (µg m^{-2} s^{-1}), Q_A is the reference emission flux (10 µg m^{-2} s^{-1}), C_A is the

AERMOD-predicted 1-h dust concentration (μg m^{-3}) associated with the reference emission flux, and C_0 is the measured 1-hr dust concentration (μg m^{-3}) (Bonifacio et al., 2012).

Emission factors were calculated as the mass of dust emitted per 1000 hd per day (kg $(1000\ hd)^{-1}\ d^{-1}$) using the estimated emission fluxes. It is important to note that this does not yield, nor is it intended to yield, daily emission factors as the term is ordinarily used in the regulatory context. Our emission factors were calculated using emission fluxes from the dustiest time of the day and would therefore greatly overestimate the dust actually emitted during a full 24-h period. The emission factors are only calculated (a) to compare the effectiveness of the stocking-density treatments during the EDP and (b) to put the emissions rates on the appropriate scaling basis given the dominant mechanism responsible for the emissions: hoof action.

Pen surface assessments were entered into a Microsoft Access (2007) database. The frequency of each rating was calculated for each treatment group, and a histogram was created. Dust-concentration data were analyzed using an analysis of variance (ANOVA) and Tukey *post-hoc* test using IBB SPSS Statistics 21.0 (August 2012).

RESULTS AND DISCUSSION

UPWIND (BACKGROUND) CONCENTRATION DATA

To ensure that neglecting upwind concentrations was acceptable to simplify data analysis and generate conservative (i.e., under-) estimates of abatement effectiveness, upwind concentration data from both monitors were segregated by treatment block. As shown in figure 3, dust concentrations upwind of both Treatments A and B were consistently greater than or equal to dust concentrations upwind of the control pens. Based on the mathematical development above, we were justified in using only downwind data to infer fluxes, emission factors, and abatement effectiveness, and the estimates of abatement effectiveness may be reliably interpreted as conservative estimates.

Downwind Concentration Data

A total of 1,706 one-min averaged concentrations were measured. These data were filtered using measured wind speed and wind direction to insure that only data points that represented concentrations from a single treatment (i.e., only downwind of one treatment) were used for analysis. The resulting numbers of acceptable data are shown in table 2. The remaining one-minute data were averaged to obtain one-hour averages for use in AERMOD. The numbers of one-hour averages are shown in table 3.

One-minute averaged dust concentrations measured downwind of the J pens using the OPS ranged from 0 to 4,478 μg m^{-3} for the control pens, 0 to 2,430 for Treatment A, and 1 to 2,872 μg m^{-3} for Treatment B. One-hour average concentrations were 632.16, 60.56, and 292.85 μg m^{-3} for the control, Treatment A, and Treatment B, respectively (fig. 4). The estimated emission flux for the

Table 2. Number of valid, 1-min average data after filtering with weather data, separated by treatment block.

	J Pens	J+K Pens
Control	98	80
Treatment A	114	79
Treatment B	186	138

Table 3. Number of one-hour averaged data used in the dispersion model for each treatment block.

	J Pens		J+K Pens	
	No. of 1-h Data	Standard Error	No. of 1-h Data	Standard Error
Control	34	1025.7	27	392.9
Treatment A	30	196.5	22	47.4
Treatment B	38	454.4	30	113.3

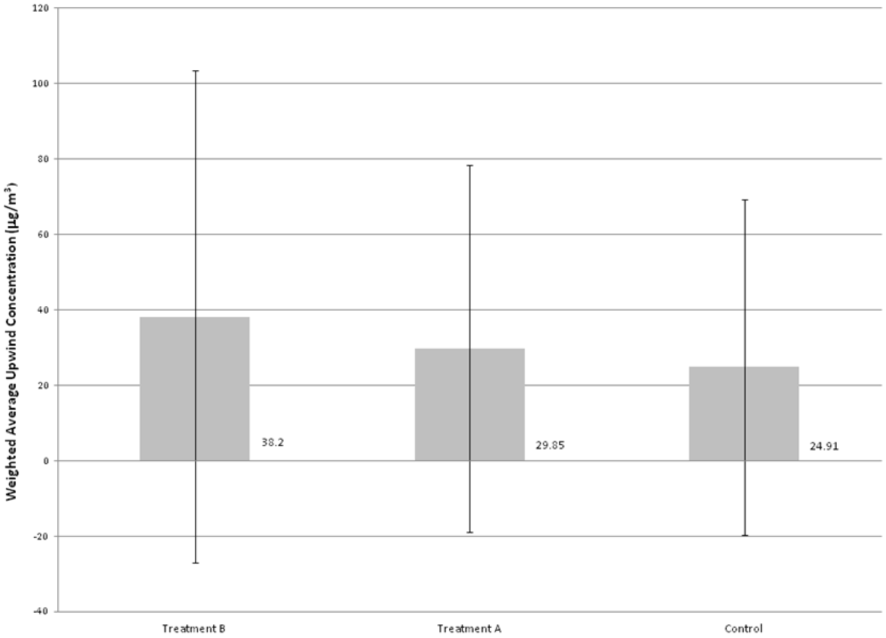

Figure 3. Weighted average upwind dust concentrations measured with the OPS, separated by treatment block.

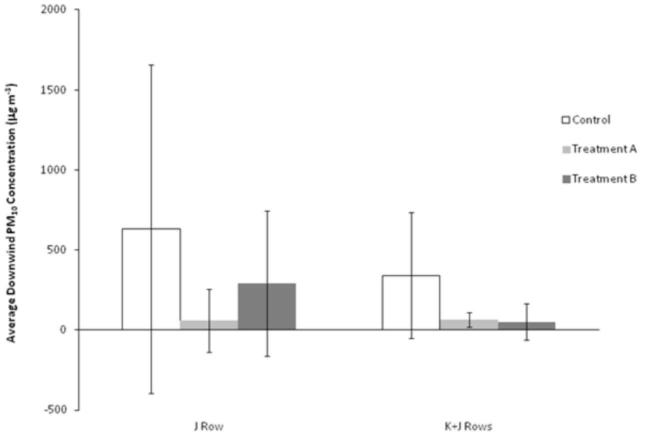

Figure 4. Mean hourly downwind dust concentrations.

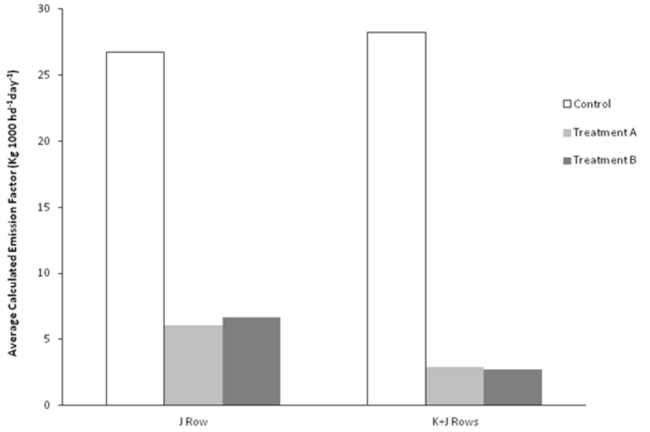

Figure 6. Average calculated dust emission factors.

control block (22.5 µg m^{-2} s^{-1}) was more than twice those of Treatments A and B (10.12 and 11.10 µg m^{-2} s^{-1}, respectively) (fig. 5). The calculated emission factors were 26.76, 6.09, and 6.68 kg $(1{,}000\ hd)^{-1}$ d^{-1} for the control, Treatment A, and Treatment B, respectively (fig. 6).

Dust concentrations measured downwind of the J and K pens using the DUSTTRAK II ranged from 19 to 1,720 µg m^{-3} for the control pens, 4 to 561 µg m^{-3} for Treatment A, and 4 to 403 µg m^{-3} for Treatment B. The average 1-h concentrations for the control block (339.8 µg m^{-3}) greatly exceeded those of Treatments A and B (64.99 and 51.87 µg m^{-3}, respectively) (fig. 4). The mean apparent emission fluxes were 4.82, 4.55, and 23.45 µg m^{-2} s^{-1} for Treatments A and B and the control pens, respectively (fig. 5). The computed emission factors were 2.90, 2.75, and 28.21 kg $(1000\ hd)^{-1}$ d^{-1} for Treatments A and B and the control pens, respectively (fig. 6).

Statistical Analysis

Results of the ANOVA showed a significant difference (α=0.05) among treatments for downwind concentration but not for emission flux using measurements taken immediately downwind of the J row. However, both concentration and emission fluxes among treatments downwind of the K row were statistically different among treatments. *Post hoc* tests revealed that, for the J row, Treatment A concentrations were significantly different than those associated with the control and Treatment B pens, but there was no difference between Treatment B and the control with regard to downwind concentrations. There were no differences in emission flux among treatments. In contrast, data from downwind of both J and K rows showed that the control was significantly different than both treatments with regard to both concentration and emission flux. Likewise, based on data from downwind of both rows of pens, there was no difference between treatments A and B for concentration or emission flux.

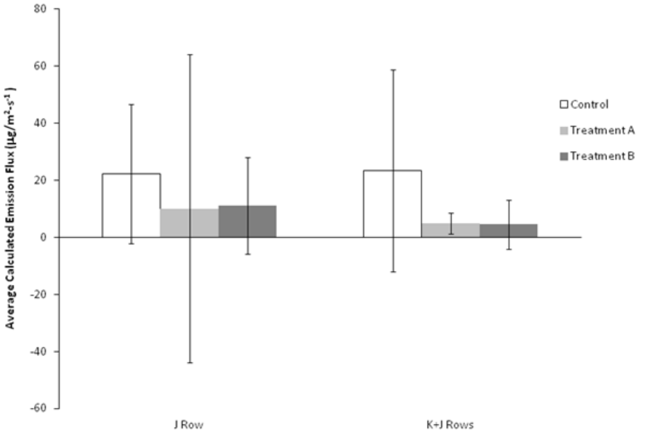

Figure 5. Average AERMOD-estimated emission fluxes.

Increasing stocking density appeared to reduce the downwind dust concentrations, emission fluxes, and emission factors of the feedyard pens. The flux reduction as estimated from the J-row data was not statistically significant. Using measurements taken downwind of the J and K rows, both flux and emission-factor reductions were statistically significant. The lack of statistical significance measuring only the J row may be, in part, due to the shape of the study area. Each treatment block in each row was a long rectangle with the long side running in an east-west direction. This shape and orientation allow for wider tolerances for wind directions that would isolate a particular measurement to only one treatment block. When sampling downwind of the K row, each source area was shaped more like a square since we were effectively monitoring emissions from both rows of pens. As such, the range of acceptable wind directions was smaller than the range of acceptable wind directions for J-row data. Acceptable wind directions for the J row were 180 ± 69°. Acceptable wind directions for the K row were 180 ± 47°. The differences in shape and acceptable wind directions result in a greater variation in fetch across the pen surface for the J-row-only data as compared to the J+K-row data. The minimum possible fetch, with a south wind of 180°, in the J row would be 70 m. The maximum fetch would be 170 m. This means that the variation in fetch across the J row was up to 100 m. When measuring downwind of the K row, the minimum fetch would be 140 m and the maximum 208 m. This results in a variation of only 68 m of fetch (fig. 7).

The increase in fetch between the J row and the J+K row measurements may explain the lack of statistical significance in the J-row fluxes. The longer fetch

Table 4. Analysis of variance (ANOVA) results.

ANOVA (α=0.05)			
J Row (OPS)		K+J Row (DUSTTRAK II)	
Concentration	Emission Flux	Concentration	Emission Flux
* p= 0.003	p= 0.425	* p= 0.001	* p= 0.002

Post Hoc Tukey Test (α=0.05)								
	J Row (OPS) (n=102)				K+J Row (DUSTTRAK II) (n=79)			
	Concentration	Std Error	Emission Flux	Std Error	Concentration	Std Error	Emission Flux	Std Error
Control - TA	* p = 0.002	165.55	0.398	9.32	* p=0.001	69.84	* p=0.010	9.00
Control- TB	p=0.063	155.07	0.693	8.73	* p=0.001	65.03	*p=0.004	8.53
TA-TB	* p = 0.002	165.56	0.845	9.04	0.981	68.75	0.821	9.00

associated with the J+K row measurements required a narrower envelope of acceptable wind direction, reducing the number of sampling events that met the wind direction criteria but doubling the source area associated with each measurement. In addition, for the J+K row measurements, the relationship between upwind and downwind of a single treatment is more clearly defined, reducing the probability of interference between plumes from adjacent treatments. Consequently, we have greater confidence in J+K row measurements.

The empty section of pens in Treatment A may also have contributed to error in J-row flux calculations. The feed bunk for the J row ran along the southern edge of the pens, while the feed bunk in the K row ran along the northern edge. This made it necessary to fence off the northern half of the J row and the southern half of the K row to ensure the animals had access to feed. During J-row monitoring, the ATV was driven down the working alley located between the two rows. Monitoring took place directly downwind of the control and Treatment B blocks but approximately 30 m downwind of the Treatment A pens (figs. 1 and 2). While monitoring downwind of the K row, the ATV was driven down the feed alley and was the same distance downwind of the nearest emitting area within each treatment block.

Pen Surface Assessments

Eleven people performed a total of 36 pen-surface assessments of the 38 pens throughout the study. This resulted in 1368 individual pen scores. Results from the pen-surface assessments showed that both Treatment A and Treatment B pens were more likely to receive a low dust-potential rating than control pens. All 63 "W" ratings were given to high-stocking-density pens. They were evenly split between treatments, with 33 pen ratings of "W" in Treatment B and 30 in Treatment A. All pens that exhibited the highest dust emitting potential were rated an "F." Control pens, which had the lowest stocking density, received all 19 "F" ratings. A rating of "C" was given most often (n=581), 386 from the treatment pens and 195 from the control pens. Treatment pens were most often rated a "B", while control pens were most often rated a "D" (fig. 8).

The corral-surface assessment appears to resolve adequately the relative intrinsic dust susceptibility of a feedyard pen surface. Although it is subjective and difficult to make any quantitative comparisons to actual dust measurements, the corral surface assessment does seem to depict a relationship between apparent pen-surface characteristics and its dust susceptibility. These assessments could be used as a resource-allocation tool by feedyard managers to determine which pens need the most urgent attention when implementing dust-control practices.

In this study, because we did not have access to close-out data from the cattle in our study area, we were unable to ascertain any effects that doubling the stocking density may have had on cattle performance. Increased stocking density could affect cattle performance by reducing both pen space (Treatments A and B) and linear bunk space (Treatment B only) per animal. Limited bunk space causes animals to eat more per feeding and eat less often. This reduces

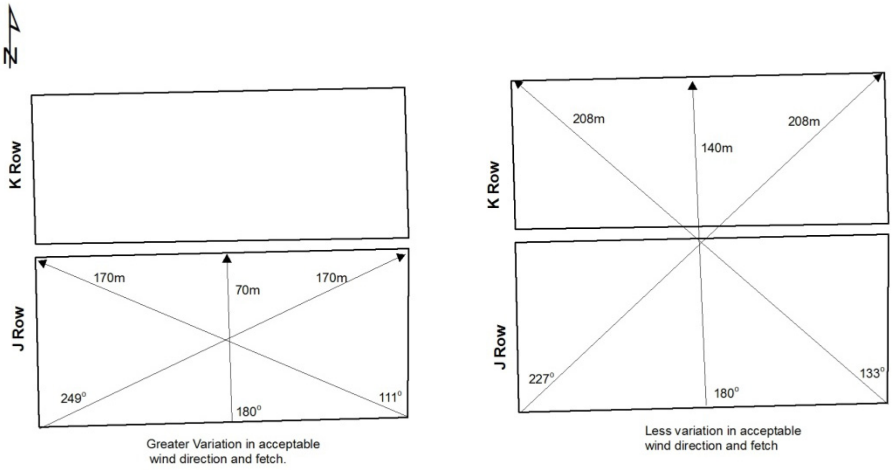

Figure 7. After filtering the data by wind direction, measurements downwind of K row resulted in fewer but less variable data points than measuring downwind of J row because the variation in fetch with changes in wind direction was lower.

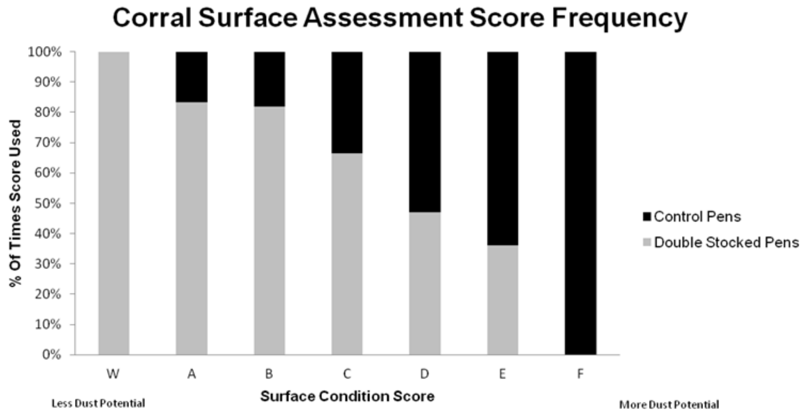

Figure 8. Histogram of corral-surface assessment scores.

performance by inhibiting the digestive system and rendering it less efficient (Wagner and Stanton, 2013). In dairy cattle, competition at the feed bunk causes less aggressive individuals to feed less and eat faster. Lower ranked individuals are displaced from the feed bunk more often than higher ranked individuals, and the displacements increase with feed bunk crowding (Huzzey et al., 2006). Proudfoot et al. (2008) also found that competitively fed cattle ate less overall than cattle with no feed bunk competition. Physical displacements also have a negative association with physiological response to insulin and glucose (Huzzey et al., 2012). Bunk space recommendations vary throughout the country. Wagner and Stanton (2013) recommend a minimum of 203.3 mm (8 in.) of bunk space per head, but prefer 254-305 mm (10-12 in.) for Colorado feedyards. In Kansas, feed bunk space should be around 229-305 mm (9-12 in.) Harner III and Murphy, 1998). The University of Minnesota recommends 152-229 mm (6-9 in.) of bunk space (DiCostanzo and Crawford, 2008). In this study, cattle in the control group and Treatment A had access to 203.2 mm (8 in.) of bunk space. However, in Treatment B, there were only 101.6 mm (4 in.) of bunk space available per animal. This is well below most recommendations and may have resulted in a reduction in cattle performance. By doubling the number of cattle, both pen space and bunk space were reduced. In Treatment A, bunk space remained the same, and only pen space was reduced.

There are few published data on the effect pen space reduction has on cattle performance. Mader and Colgan (2007) found that increasing pen space resulted in improved cattle performance in Nebraska. The cattle spacings in that study, 23.33 m^2 hd^{-1} (250 ft^2 hd^{-1}) and 46.45 m^2 hd^{-1} (500 ft^2 hd^{-1}), were much higher than the corresponding cattle spacings in this study. Gaughan et al. (1994) determined that reducing cattle spacing from 15.98 m^2 hd^{-1} (172 ft^2 hd^{-1}) to 3.99 m^2 hd^{-1} (43 ft^2 hd^{-1}) had no effect on stress levels as measured by heart rate, feed intake, or growth rate. Because of its oft-documented influence on feeding behavior, dry-matter intake, and feed conversion, bunk space appears to be more important than pen space when considering an increase in stocking density. Increasing stocking density should be accomplished in such a way as to maintain adequate bunk space.

CONCLUSION

Under the conditions observed in this study, doubling the stocking density successfully reduced dust emissions from a cattle feedlot surface. Mean downwind dust concentrations were between 53% and 90% lower downwind of treatment blocks as compared to the control. Mean emission fluxes inferred from AERMOD dispersion modeling were 50% to 80% lower downwind of treatment blocks as compared to the control; mathematical considerations suggest that those abatement-effectiveness figures are conservative (underestimated). Increasing stocking density reduced dust emissions through three indirect mechanisms, each of which would reduce the dust susceptibility or intrinsic dustiness of the feedyard surface: (A) increasing the effective moisture flux onto the corral surface through urine and feces excretion, (B) increasing the spatial intensity of vertical (i.e., compactive) hoof action, and (C) decreasing the effective solar radiation load by increased shading of the occupied pen area. Corral surface assessments can be an effective tool for managers to quickly assess the condition of a pen with regards to dust potential.

Further research is needed to determine whether or not stocking density should be expressed in terms of cattle liveweight or metabolic body weight rather than simply animal numbers. Additional research should also identify and characterize any seasonal differences in fugitive dust emissions. It may be important to increase the stocking density during hot, dry periods and decrease the stocking density during cold, wet periods to mitigate feed-to-gain performance losses associated with wet, muddy conditions.

We conclude that, under the conditions in which this research was conducted, increasing the stocking density in a cattle feedyard alters the moisture dynamics of the feedyard surface and thereby reduces its dust-emissions potential. Although our experimental design explicitly preserved the average linear bunk space per head for one of the two double-stocked treatments, cattle-feeding operations interested in adopting the cross-fencing technique should be alert to the possibility of reduced cattle growth rate and efficiency even where linear bunk space per head is preserved.

ACKNOWLEDGEMENTS

The authors acknowledge the direct funding and in-kind contributions from JBS Five Rivers Cattle Feeding, the United States Department of Agriculture-National Institute for Food and Agriculture (contract no. 2010-34466-20739), and Texas A&M AgriLife Research. JBS Five Rivers Cattle Feeding also provided significant logistical and personnel support for field operations. The authors also thank Tom McDonald, Brad Wilhite, and Brad Lubbers for their assistance with this project.

REFERENCES

Auvermann, B. W., & Casey, K. D. (2011). *Feedyard dust control in an epic panhandle drought, 2010-2011.* College Station, Tex: Texas A&M AgriLife Extension Service.

Auvermann, B. W., Parker, D. B., & Sweeten, J. M. (2000). *Manure harvesting frequency: The key to feedyard dust control in a summer drought.* College Station, Tex: Texas A&M AgriLife Extension.

Auvermann, B. W., & Romanillos, A. (2000). Effect of stocking density manipulation of fugitive PM_{10} emissions from cattle feedyards. *Proc. Air & Waste Mgmt. Assoc.* Salt Lake City, Utah.

Bonifacio, H. R., Razote, E. B., Auvermann, B. W., Harner III, J. P., Murphy, J. P., Guo, L., Sweeten, J. M. , & Hargrove, W. L. (2011). Particulate control efficiency of a water sprinkler system at a beef cattle feedlot in Kansas. *Trans. ASABE 54*(1), 295-304. doi:http://dx.doi.org/10.13031/2013.36257.

Bonifacio, H. F., Maghirang, R. G., Razote, E. B., Murphy, J. P., & Harner III, J. (2012). Particulate matter emission rates from beef cattle feedlots in Kansas—Reverse dispersion modeling. *J. Air & Waste Mgmt. Assoc. 62*(3), 350-361. doi:http://dx.doi.org/10.1080/10473289.2011.651557.

CFR. (2005). Code of Federal Regulations, 40CFR, Part 51: Revision to the Guideline of Air Quality Models: Adoption of a Preferred Genera Purpose (flat and complex terrain) Dispersion Model and Other revisions.

Cimorelli, A. J., Perry, S. G., Venkatram, A., Weil, J.C., Paine, R. J.,Wilson, R. B., Lee, R. F., Peters, W. D., Brode, R. W., & Paumier, J. O. (2004). *AERMOD: Description of Model Formulation; EPA-454/R-03-004.* Research Triangle Park, N.C.: U.S. EPA.

Dai, W., Otto, C. , & Reeves, D. 2003. Performing CALPUFF analyses with pseudo-station data derived from MM5 data. Paper No. 71052. Palatine, Ill.: Air & Waste Mgmt. Assoc.

DiCostanzo, A., & Crawford, G. (2008). Planning for a feedlot expansion.St. Paul, Minn.: University of Minnesota Extension.

Gaughan, J., Keenan, D., & Rowan, K. (1994). Effect of stocking rate on heart rate and performance of feedlot cattle. *Proc. Australian Soc. Animal Prod. 20*, 401.

Harner III, J. P., & Murphy, J. P. (1998, August). Planning cattle feedlots. Manhattan, Kans.: Kansas State University.

Harner, J., Maghirang, R., & Razote, E. (2008). Water requirements for controlling dust from open feedlots. *Mitigating Air Emissions from Animal Feeding Operations Conf.* Des Moines, Iowa: Iowa State University Extension.

Huzzey, J. M., DeVries, T. J., Vlois, P., & von Keyserlingk, M. A. G. (2006). Stocking density and feed barrier design affect the feeding and social behavior of dairy cattle. *J. Dairy Sci.*, 89(1), 126-133. doi:http://dx.doi.org/10.3168/jds.S0022-0302(06)72075-6.

Huzzey, J. M., Grant, R. J., & Overton, T. R. (2012). Relationship between competitive success during displacements at an overstocked feed bunk and measures of physiology and behavior in holstien dairy cattle. *J. Dairy Sci.*, *95*(8), 4434-4441. doi:http://dx.doi.org/10.3168/jds.2011-5038.

Loneragan, G. H., Gould, D. H., Mason, G. L., Garry, F. B., Yost, G. S., Miles, D. G., Hoffman, B. W., & Mills, L. J. (2001). Involvement of microbial respiratory pathogens in acute interstitial pneumonia in feedlot cattle. *American J. Veterinary Res.*, 62(10), 1519-1524. doi:http://dx.doi.org/10.2460/ajvr.2001.62.1519.

MacVean, D. M., Frazen, D. K., Keefe, T. J., & Bennett, B. W. (1986). Airborne particle concentration and meteorologic conditions associated with pneumonia incidence in feedlot cattle. *American J. Veterinary Res.*, *47*(12), 2676-2681.

Mader, T. L., & Colgan, S. L. (2007). Pen density and straw bedding during feedlot finishing. Nebraska Beef Cattle Reports. Paper 70.

Proudfoot, K. L., Veira, D. M., Weary, D. M., & Von Keyserlingk, M. A. G. (2008). Competition at the feed bunk changes the feeding, standing, and social behavior of transition dairy cows. *J. Dairy Sci., 92*(7), 3116-3123. doi:http://dx.doi.org/10.3168/jds.2008-1718.

Purdy, C. W., Straus, D. C., Parker, D. B., Wilson, S. C., & Clark, N. R. (2004). Comparison of the type and number of microorganisms and concentration of endotoxin in the air of feedyards in the Southern High Plains. *American J. Veterinary Res.*, *65*(1), 45-52. doi:http://dx.doi.org/10.2460/ajvr.2004.65.45.

Rahman, S., Mukhtar, S., & Wiederholt, R. (2008). Managing odor nuisance and dust from cattle feedlots. NM-1391. Fargo, N.D.: North Dakota State University Extension Service.

Sweeten, J. (1982). Feedlot dust control. L-1340. College Station, Tex.: Texas Agricultural Extension Service.

Sweeten, J., & Lott, S. (1995). Dust management. In P. Watts & R. Tucker (Ed.), *Designing Better Feedlots* (pp. 23-30). Toowoomba, Queensland, Australia: Department of Primary Industries.

US EPA. (2008). AERSURFACE User's Guide; EPA-454/B-08-001. Research Triangle Park, N.C.: US EPA.

Von Essen, S. G., & Auvermann, B. W. (2005). Health effects from breathing air near CAFOs for feeder cattle or hogs. *J. Agromedicine*, *10*(4), 55-64. doi:http://dx.doi.org/10.1300/J096v10n04_08

Wagner, J., & Stanton, T. (2013). *High Grain Rations for Cattle.* Ft. Collins, Colo.: Colorado State University Extension. Retrieved from http://www.ext.colostate.edu/pubs/livestk/01614.html.

Wilson, S. C., Morrow-Tesch, J., Straus, D. C., Cooley, J. D., Wong, W. C., Mitlohner, F. M., & McGlone, J. J. (2002). Airborne microbial flora in a cattle feedlot. *Appl. Environ.Microbiol.68*(7), 3238-3242. doi:http://dx.doi.org/10.1128/AEM.68.7.3238-3242.2002.

Wyatt, T. A., Slager, R. E., DeVasure, J., Auvermann, B. W., Mulhern, M. L., Von Essen, S., Mathiesen, T., Floreani, A. A., & Romberger, D. J. (2007). Feedlot dust stimulation of interleukin-6 and -8 requires protien kinase Cε in human bronchial epithelial cells. *American J. Physiolog. Lung Cellular and Molecular Physiol., 293*(5), L1163-L1170. doi:http://dx.doi.org/10.1152/ajplung.00103.2007.