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Determination of Particulate Matter Emissions from Cattle Feedlots Using WindTrax and the Flux-Gradient Technique

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Abstract

Large commercial cattle feedlots are significant sources of particulate matter (PM) emissions. This research compared WindTrax and the flux-gradient technique in estimating emissions of PM with aerodynamic diameter ≤ 10 µm (PM_{10}) from cattle feedlots. Meteorological conditions were measured and PM_{10} concentrations were profiled vertically (*i.e.*, 2.0 to 7.62 m) at a large commercial beef cattle feedlot in Kansas from May through September 2011. Results show that between the two methods evaluated, WindTrax was least sensitive to changes in heights and number of heights used in the emission estimation, with calculated PM_{10} emission rates varying by up to 18% only. On the other hand, PM_{10} emission rates produced by the flux-gradient technique varied by almost 56% when changing either heights and/or number of heights in emission calculation. Both methods were sensitive to height settings, with their respective PM_{10} emission rates higher when the lowest height setting (2.0 m) was included. Calculating PM_{10} emission rates with the 7.62-m height led to lower estimates for the flux-gradient technique but no significant change in estimates was observed for WindTrax. As demonstrated in this study, for the flux-gradient technique, settings for the lowest and highest heights were the most critical in emission estimation; exclusion of other heights in between showed only to 2% to 6% change in calculated PM_{10} emission rates. In general, the higher PM_{10} emission rates were obtained with the flux-gradient technique. However, eliminating the lowest height (2.0 m) in the calculation and, at the same time, using a specific set of formulations for the flux-gradient technique made its calculated PM_{10} emission rates slightly lower (but not significantly different) than those from WindTrax.

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Keywords

PM_{10} Emission Rates, Cattle Feedlots, Emission Rate Estimation, WindTrax, Flux-Gradient Technique

1. Introduction

Air pollutant emissions from concentrated animal feeding operations (CAFOs), such as large commercial cattle feedlots, are a major air quality concern because of their harmful effects on human health and the environment. Air pollutants emitted from cattle feedlots include ammonia (NH_3) [1] [2], hydrogen sulfide (H_2S) [3] [4], greenhouse gases (GHGs) such as nitrous oxide (N_2O) [5] and methane (CH_4) [6], volatile organic compounds (VOCs) [7], and particulate matter (PM) [8] [9]. Assessing the potential impact of these air pollutants, individually or in combination, on downwind locations remains challenging because of several factors, including lack of accurate emission rate estimates and reliable emission estimation methods [10] [11]. To address this, the US Environmental Protection Agency (EPA) initiated the National Air Emissions Monitoring Study (NAEMS) in 2005 as a 2-yr study to measure air pollutant emission rates at several participating CAFOs for development of new and improvement of existing emission estimation methods [12] [13]. Beef cattle feedlots were not part of the NAEMS; in 2011, however, the EPA requested quality-assured PM and gaseous emission rates from CAFOs, which now included cattle feedlots, to supplement those collected through NAEMS [14].

In large beef and dairy cattle feedlots, the animals are typically confined in open dirt lots. For these CAFOs, emission estimation is challenging because direct measurement of emission rates is often not feasible. Because the open dirt lots are exposed to and influenced by the outside environment, determining emission rates requires accounting for the temporal and spatial variability of emission rates, surface heterogeneity and local meteorology.

Several methods can be used to estimate pollutant emission rates from area sources, such as feedlots: these include micrometeorological techniques [15], box models [16], and inverse dispersion models [1]. The authors of the present study were involved in a large air quality project that included estimation of PM emission rates from a large commercial beef cattle feedlot in Kansas. The PM emission rates for the cattle feedlot studied were determined using several estimation methods, which included AERMOD, WindTrax and the flux-gradient technique, and estimates were already presented in published companion studies [8] [17] [18]. In Bonifacio *et al.* [18], emission rates for total suspended particulates (TSP), PM with aerodynamic diameter ≤ 10 µm (PM_{10}), and PM with aerodynamic diameter ≤ 2.5 µm ($PM_{2.5}$) determined using the flux-gradient technique were presented. Compared to other previously published values for California and Texas feedlots, these determined emission rates were significantly lower than those reported by EPA [19] and Auvermann *et al.* [20] but were within range of others [21] [22].

The method applied in emission rate estimation is a critical factor that can contribute to differences among reported PM emission rates—others include feedlot management practices, PM sampling methods, and measurement designs (e.g., length of measurement period). In a companion study [17], PM_{10} emission rates determined by AERMOD and WindTrax were already compared. Although it was found that AERMOD produced higher emission rates, a very high linearity ($R^2 \geq 0.93$) in calculated emission rates between AERMOD and WindTrax was observed, indicating the possibility of developing conversion factors [17]. In the present study, PM_{10} emission rates determined by WindTrax and the flux-gradient technique were compared using the same set of concentration and meteorological measurements employed in companion studies [8] [17]. Effect of measurement heights used on emission estimation with each method was also verified. Similar to the previous study, the possibility of development of conversion factors between these two methods was explored.

2. Materials and Methods

The PM_{10} concentrations and meteorological conditions were measured at a commercial cattle feedlot in Kansas. From these field measurements, PM_{10} emission rates were calculated with WindTrax via inverse dispersion analysis, and with the flux-gradient technique using estimated vertical PM_{10} concentration profiles and approximated PM_{10} eddy diffusivities.

2.1. Feedlot Description

The feedlot studied is generally rectangular in shape and has approximate dimensions of 0.5 and 1.7 km in east-west and north-south directions, respectively (**Figure 1(a)**). It has a total pen area of approximately 0.59 km^2 (59 ha) designed for 30,000-head capacity. The feedlot is relatively flat, with median surface roughness of 4.0 cm [8] [15]. Measurements used in comparing WindTrax and the flux-gradient technique were taken from May through September 2011. Information on feedlot management practices affecting pen conditions, such as manure scraping and water application, and meteorological conditions during this 5-month period were presented in Bonifacio *et al*. [8].

2.2. Field Instrumentation

A three-dimensional sonic anemometer (Campbell Scientific, Inc., Logan, UT) was installed at a 5.3-m tower for measurement of micrometeorological conditions at the feedlot. Eddy covariance measurement was recorded at 15-min intervals and included measured variances and covariances of the three wind velocity components (u_x, u_y, u_z) and air temperature (T). Using formulations presented by Flesch *et al*. [23], corresponding friction velocity (u_*), Monin-Obukhov length (L) and surface roughness (z_o) were first computed in 15-min intervals before being integrated into hourly values.

Measurements of PM_{10} concentrations were conducted at two locations simultaneously: 1) within the feedlot, approximately 400 and 200 m from the feedlot's north and west edges, respectively; and 2) at the sampling site north (5 m away from the fenceline) or south (800 m away from the fenceline) edge of the feedlot if the wind was coming from the north or south, respectively (**Figure 1(a)**). In computing net PM_{10} concentrations, measurement within the feedlot was used as downwind concentration and measurement at either north or south sampling site was used as upwind concentration, depending on wind direction. The PM_{10} concentrations within the feedlot were measured at four sampling heights: 2.0, 3.81, 5.34, and 7.62 m above the feedlot surface (**Figure 1(b)**). The PM_{10} concentration at the upwind sampling site was measured at the 2.0-m height only due to limited equipment availability. The PM_{10} concentrations were measured using tapered element oscillating microbalance (TEOM) samplers (series 1400a, Thermo Fisher Scientific, East Greenbush, NY), a US EPA federal equivalent method for determining PM_{10} concentrations (designation No. EQPM-1090-079). Monthly routine maintenance (*i.e.*, inlet cleaning, flow audit, and leak test) was performed on TEOM PM_{10} samplers to ensure quality of data collection. The TEOMs were operated to record PM_{10} concentrations at 20-min intervals. The 20-min downwind and upwind concentrations were integrated into hourly averages before computing net hourly PM_{10} concentrations. Calculation of PM_{10} emission rates were based on hourly data points that had measured downwind and upwind concentrations and positive calculated net concentrations.

2.3. WindTrax

WindTrax is based on a reduced transport equation given by:

$$\frac{\partial C}{\partial t}+u_x\frac{\partial C}{\partial x}+u_y\frac{\partial C}{\partial y}+u_z\frac{\partial C}{\partial z}=0 \quad (1)$$

where the overall mass transport for concentration, C, is defined by convective mass transport in all directions (x, y, z) with corresponding velocity components held constant, and an accumulation term ($\partial C/\partial t$) [24]. The method selected by the developers of WindTrax to solve Equation (2) is the backward Lagrangian stochastic (bLS) approach that describes the evolution of particle position and particle velocity in a backward time frame. The derivation of concentration equations using the bLS approach is explained in detail by Flesch *et al*. [25] and Flesch and Wilson [24].

WindTrax has an interface that enables mapping of the area source of interest and sampler locations using aerial image files [26]. The studied feedlot was mapped using available satellite imagery (MapQuest.com, Inc.). In this study, WindTrax simulation inputs included measured hourly net PM_{10} concentrations and meteorological parameters. From the meteorological inputs, WindTrax estimates other variables required in parameterization of the atmospheric surface layer based on formulations described in Crenna [27] and Flesch *et al*. [23]. In the simulation, the number of particle released was set to 50,000, which is the default value [26]. The PM_{10} emission rates calculated with WindTrax were also screened based on criteria described by Flesch *et al*. [28].

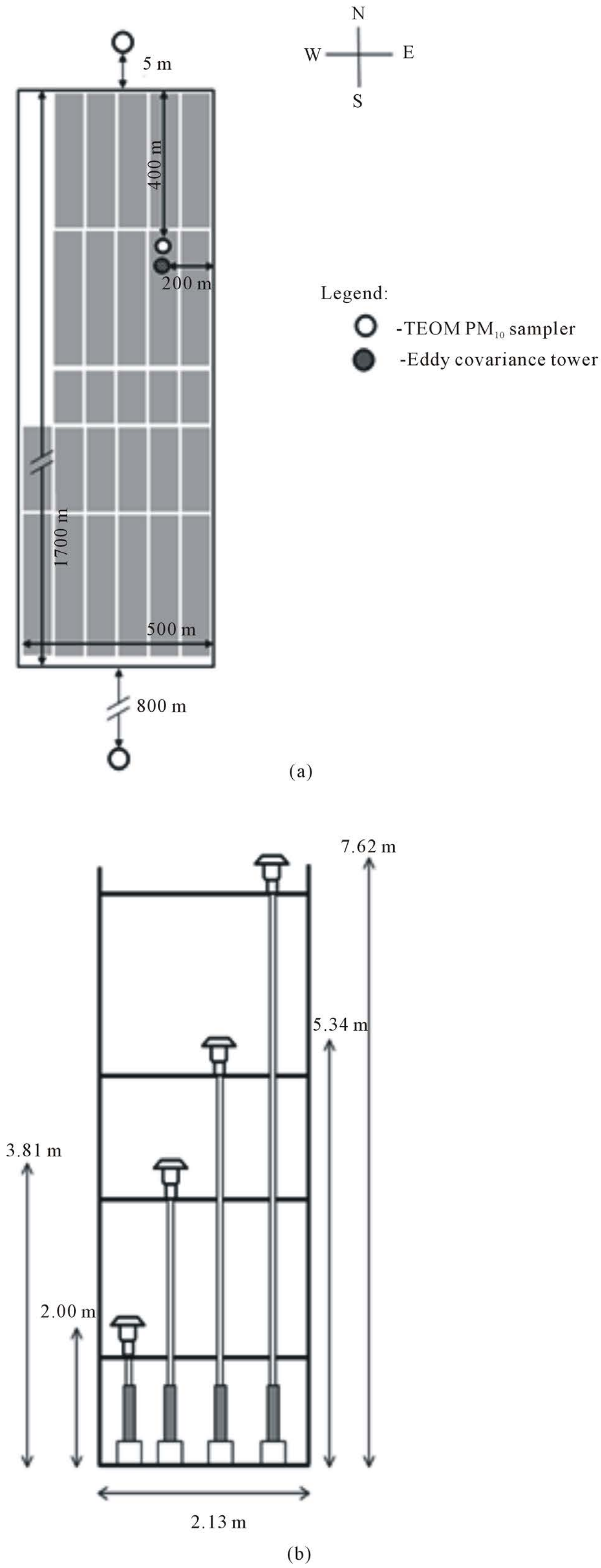

Figure 1. Field instrumentation: (a) location of sampling site within the feedlot, and (b) sampling heights for tapered element oscillating microbalance (TEOM) PM_{10} samplers.

Measurement periods with very strong atmospheric stability ($|L| < 10$ m), low wind speed ($u_* < 0.15$ m/s), or unrealistic wind profile ($z_o > 1$ m) were considered unreliable and therefore not included in the comparison.

WindTrax can calculate emission rates using one or more concentration measurements [26]. Use of concentration measurements from several heights and locations, referred to as "overdetermined" simulation, is described to reduce the influence of concentration measurement errors on emission estimation, with the calculated emission rate the best fit for the given set of concentrations [26] [29]. In the present study, PM_{10} emission rates determined by WindTrax using single-height and multiple-height measurements were examined. But in comparing WindTrax and the flux-gradient technique, only the multiple-height measurements were used.

In McGinn *et al*. [9], PM_{10} emissions from Australian cattle feedlots was determined using a version of WindTrax modified to account for effects of gravitational settling on particle motion; however, this modified version still has to be made public. In the present study, the latest WindTrax version available (2.0.8.8, www.thunderbeachscientific.com) was used. Based on a companion study that used AERMOD [17], neglecting gravitational settling underestimated PM_{10} emission rates by 4%.

2.4. Flux-Gradient Technique

For the flux-gradient technique, PM_{10} emission rate (Q, µg/m²·s) was calculated as:

$$Q = -K_{PM} \frac{\mathrm{d}C_m}{\mathrm{d}z} \tag{2}$$

where K_{PM} is PM_{10} eddy diffusivity (m²/s), C_m is measured net PM_{10} concentration (µg/m³), and $\mathrm{d}C_m/\mathrm{d}z$ is vertical PM_{10} concentration gradient (µg/m³-m) [30] [31]. The vertical concentration gradient, $\mathrm{d}C_m/\mathrm{d}z$, was the derivative of the regression equation derived for sampling heights with concentration measurements [18]. In Bonifacio *et al*. [8], suitability of the flux-gradient technique in determining PM_{10} emissions from cattle feedlots had been verified using the criterion presented by Lilly [32]. Based on ratios of particle relaxation times calculated for different PM sizes to Lagrangian time scales measured at the studied feedlot, feedlot PM with aerodynamic diameter < 35 µm is essentially governed by eddy diffusion [18], and thus, suggesting suitability of the flux-gradient technique for PM emissions within this size range.

The K_{PM} was determined from eddy diffusivity for momentum, K_m (m²/s), and Schmidt number, S_c (Equation (3)) [33] [34].

$$K_{PM} = \frac{K_m}{S_c} \tag{3}$$

The S_c was set to 0.63, which was the overall value determined for PM_{10} emissions at the studied feedlot that had hourly median S_c ranging from 0.40 to 1.23 [8]. The K_m was given by:

$$K_m = \frac{k u_* z_m}{\phi_m} \tag{4}$$

where z_m is mean geometric height based on heights with PM_{10} concentration measurements, and ϕ_m is a non-dimensional correction parameter that accounts for atmospheric stability effects [34]. Prueger and Kustas [31] provided a summary of different formulations that can be used in calculating ϕ_m. With a general expression given by:

$$\phi_m = \left(1 + a\frac{z_m}{L}\right)^b \tag{5},$$

four sets of formulations for ϕ_m were used in this study, with values for a and b summarized in **Table 1**. Selection of these formulations were based on its appropriateness for representing the feedlot surface: 1) Hogstrom [35] applies for multiple surface from oceans to forest and was the one used in the companion studies [8] [18]; 2) Flesch *et al*. [23] is the one implemented in WindTrax; 3) Dyer and Hicks [36] was derived for plowed field (*i.e.*, with a loose surface layer like that of the feedlot surface); and 4) Hogstrom [37] has been used in a previous cattle feedlot study [38].

For the flux-gradient technique, two screening criteria were implemented. The first criterion required that the corresponding fetch of the uppermost sampling height (7.62-m) fall within the feedlot boundary to ensure that

Table 1. Values of parameters *a* and *b* in calculating the nondimensional correction parameter ϕ_m for the flux-gradient technique.

ϕ_m	Stable atmospheric conditions		Unstable atmospheric conditions		Reference
	a	*b*	*a*	*b*	
1	5.3	1	−19.0	−0.25	Hogstrom [35]
2	5.0	1	−6.0	−0.25	Flesch *et al.* [23]
3	5.0	1	−16.0	−0.25	Dyer and Hicks [36] for unstable condition Dyer [39] for stable condition
4	4.8	1	−15.2	−0.25	Hogstrom [37]

calculated emission rates represented PM_{10} emitted at the feedlot only and not from outside sources. Calculation of fetch was based on Hsieh *et al.* [40] as previously implemented in companion studies [8] [18]. The second criterion described the vertical concentration profiles appropriate for the flux-gradient technique, such that PM_{10} concentration should be linear and decreasing with the logarithm of height. Linearity between PM_{10} concentration and logarithm of height was assessed in terms of Pearson correlation. Preliminary analyses showed that increasing the Pearson correlation criterion lowered the difference in calculated PM_{10} emission rates between WindTrax and the flux-gradient technique but greatly decreased the number of hourly data points for comparison. With the flux-gradient technique producing higher emission rates, Pearson correlation criteria of 0.75, 0.85, 0.95, and 0.975 resulted to differences of 31%, 28%, 20%, and 19%, respectively, in calculated PM_{10} emissions between the two methods based on 228, 184, 104, and 58 hourly data points, respectively. Based on these results, a Pearson correlation criterion of 0.95 was implemented for the flux-gradient technique.

2.5. Data Analyses

In this study, analyses include: 1) for each emission estimation method, comparison of PM_{10} emission rates derived using data sets that differed in heights and number of heights included (**Table 2**); and 2) comparison of PM_{10} emission rates calculated with WindTrax and the flux-gradient technique. For WindTrax, PM_{10} emission rates estimated using single-height measurements (*i.e.*, data sets 7 and 8) was also verified. Linear regression analyses were performed in comparing any two PM_{10} emission rate estimates. In addition, paired t-test was done when comparing PM_{10} emission rates of WindTrax and the flux-gradient technique. In the comparison, a 5%-significance level was applied. For hourly net PM_{10} concentrations, overall values were reported as averages. But due to its skewed and asymmetric distributions, PM_{10} emission rates were reported as medians.

3. Results and Discussion

A total of 74 hourly data points passed the screening criteria defined for both methods and was included in all data sets used in the comparisons (**Table 2**). Based on calculated *L*, 70 of these data points had unstable atmospheric conditions. In terms of time of the day, numbers of hourly data points were 7, 20, 27, and 20 for the 0100 h to 0600 h, 0700 h to 1200 h, 1300 h to 1800 h, and 1900 h to 2400 periods, respectively.

3.1. Net PM_{10} Concentrations

Hourly average net PM_{10} concentrations are shown in **Figure 2**. The PM_{10} concentrations at all four sampling heights exhibited diurnal trends, with the highest concentrations measured during the early evening period, which started to increase at 1900 h and ended at 2300 h, and the lowest during early morning period (0200 h to 0300 h) (note: no data point for 0400 h and 0500 h). From the 74 hourly data points, average net PM_{10} concentrations were 305 ± 351, 189 ± 194, 142 ± 145, 107 ± 117 μg/m³ for 2.0-, 3.81-, 5.34-, and 7.62-m heights. As shown in **Figure 3**, PM_{10} concentration had a very strong linear relationship (R^2 = 0.98) with the logarithm of sampling height (note: for illustration purposes, median concentrations and corresponding upper and lower standard deviations were used). On average, PM_{10} concentration decreased by 34 ± 41 μg/m³ for every 1 m increase in height. Within the day, the highest vertical PM_{10} concentration gradient was measured from 1900 h to 2000 h, in which the concentration decreased by 103 ± 100 μg/m³ for every 1 m increase in height, whereas the

Table 2. Description of data sets used in PM_{10} emission rate estimation using WindTrax and the flux-gradient technique.[a]

Data set	Number of heights	Heights (m)
1	4	2.0, 3.81, 5.34, 7.62
2	3	3.81, 5.34, 7.62
3	3	2.0, 3.81, 5.34
4	2	3.81, 7.62
5	2	2.0, 7.62
6	2	2.0, 5.34
7[a]	1	3.81
8[a]	1	2.0

a. For WindTrax only.

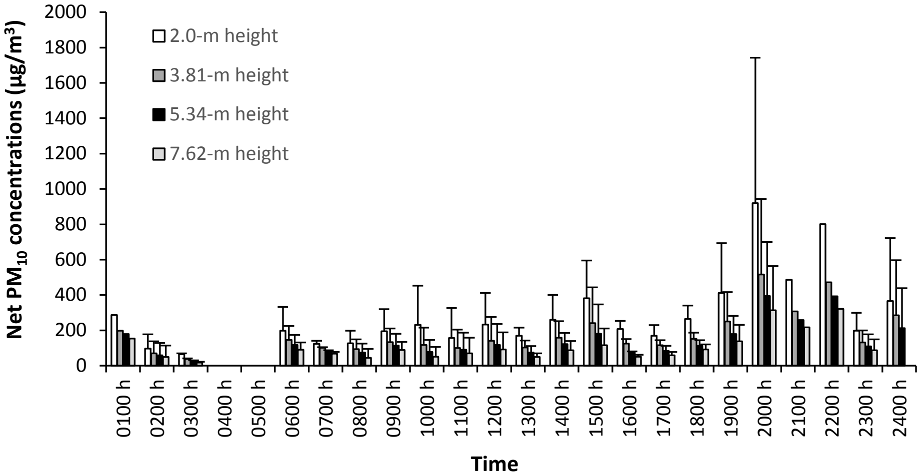

Figure 2. Hourly average net PM_{10} concentrations for the four measurement heights from May through September 2011 (n = 74). Error bars represent standard deviations.

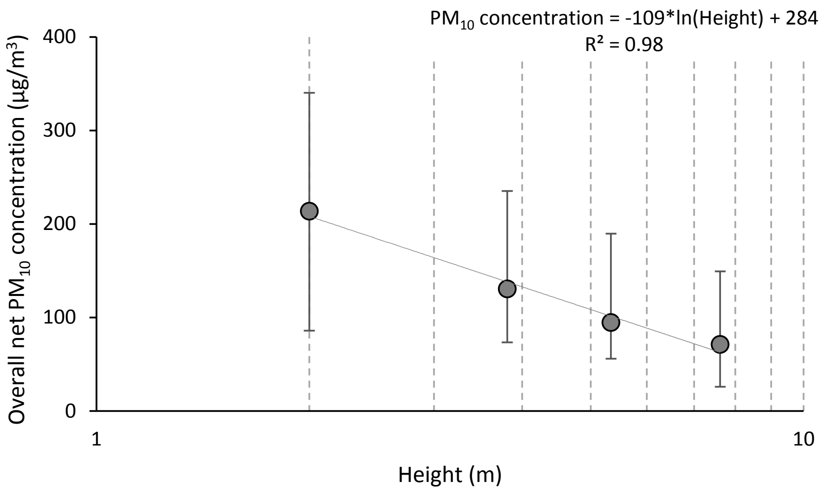

Figure 3. Plot of net PM_{10} concentrations against the logarithm of measurement heights (n = 74). Error bars represent upper and lower standard deviations.

lowest was measured from 0100 h to 0300 h (8 ± 1 μg/m³·m).

3.2. WindTrax-Based PM_{10} Emission Rates

Ranges of hourly PM_{10} emission rates for the eight data sets are plotted in **Figure 4**. Diurnal trend in calculated PM_{10} emission rates was observed for all data sets, with the highest PM_{10} emission rates calculated for the1900 h to 2200 h period (47 to 128 μg/m²·s), followed by the 1400 h to 1500 h period (50 to 80 μg/m²·s). Based on overall median hourly values, highest PM_{10} emission rates were obtained with data set 8 (*i.e.*, 2.0-m height only), with a value of 37 μg/m²·s, followed by data sets 5, 6, 3, and 1 with values of 34.8, 33.6, 32.8, and 32.6 μg/m²·s, respectively. On the other hand, the lowest PM_{10} emission rates were calculated using data sets 2, 4, and 7, with overall median values ranging from 29.1 to 30.5 μg/m²·s. These results indicate that use of the 2.0-m height, which was the lowest sampling height, in determining hourly PM_{10} emission rates with WindTrax led to emission estimates higher by almost 27%.

Slopes and R^2 values from regression analyses are summarized in **Table 3**. For WindTrax, high linearity was observed between any pair of data sets, with R^2 values ranging from 0.88 to 1.00. It was observed that the highest linearity was determined when comparing any two data sets as long as they had the same lowest measurement height—e.g., data sets 3 and 1 both with the lowest height at 2.0 m, data sets 4 and 2 both with the lowest

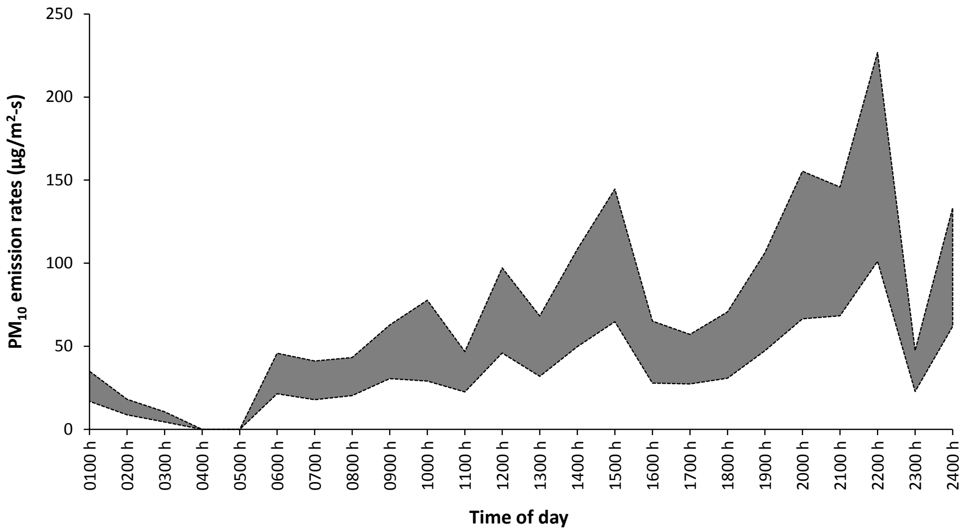

Figure 4. Hourly median PM_{10} emission rates calculated with WindTrax. Shaded area represents the range of emission estimates calculated using all the eight data sets.

Table 3. Linear regression between any two data sets (*x*, *y*) applied in WindTrax in terms of determined PM_{10} emission rates.[a,b]

Data set *y*\Data set *x*	1	2	3	4	5	6	7
2	0.91 (0.97)						
3	1.01 (1.00)	1.10 (0.95)					
4	0.92 (0.97)	1.00 (1.00)	0.90 (0.97)				
5	1.06 (0.99)	1.14 (0.92)	1.04 (0.99)	1.13 (0.93)			
6	1.05 (0.99)	1.13 (0.93)	1.03 (1.00)	1.12 (0.95)	0.99 (1.00)		
7	0.95 (0.98)	1.04 (0.98)	0.93 (0.98)	1.03 (0.99)	0.89 (0.94)	0.90 (0.96)	
8	1.10 (0.97)	1.18 (0.88)	1.08 (0.98)	1.18 (0.90)	1.05 (1.00)	1.05 (0.99)	1.15 (0.92)

[a]In performing regression, data set *x* was treated as the independent variable and data set *y* as the dependent variable. [b]Values presented are slopes from regression analyses; values in parentheses are corresponding R^2 values.

height at 3.81 m, etc. On the other hand, comparing any two data sets that differed in the lowest measurement height (*i.e.*, one at 2.0 m while the other at 3.81-m) resulted to the lowest linearity. The percentage difference between any two data sets ranged from 0% to 18%, with an average of 8%. Similarly, the difference in calculated PM_{10} emission rates lowered when comparing any two data sets that had the same lowest measurement height whereas increased when the lowest measurement heights differed. In addition, the difference was largest when comparing the single-height measurement at 2.0-m (data set 8) to multiple-height measurements with the lowest height at 3.81-m (data sets 2 and 4) (**Table 3**).

3.3. Flux-Gradient Technique-Based PM_{10} Emission Rates

Plotted in **Figure 5** are ranges of hourly PM_{10} emission rates calculated with the flux-gradient technique using the first six data sets (1 to 6, **Table 2**) and four ϕ_m formulations (*i.e.*, total of 24 data set-ϕ_m formulation combinations). Similarly, a diurnal trend in calculated PM_{10} emission rates was observed for all data set-ϕ_m formulation combinations, with the highest emission rates calculated for the 1900 h to 2200 h (44 to 154 μg/m^2·s) and 1400 h to 1500 h (43 to 102 μg/m^2·s) periods. Unlike with WindTrax, however, exclusion of the 2.0-m height measurement in emission estimation led to a slightly different profile – for combinations using data sets 2 and 4, the 1400 h to 1500 h period (43 to 96 μg/m^2·s) had higher PM_{10} emission rates than the 1900 to 2200 h period (44 to 81 μg/m^2·s). Comparing data sets 1 and 2, exclusion of the 2.0-m height slightly increased ϕ_m, and, equivalently, K_{PM} (average of 32%) but significantly lowered the calculated vertical PM_{10} concentration gradient (36%). Between 1400 h to 1500 h and 1900 to 2200 h periods, it was the latter that had the largest decrease (48%) in concentration gradient—this explained why the 1900 h to 2200 h period no longer had the highest PM_{10} emission rates calculated for the day.

Overall median hourly PM_{10} emission rates for all data set-ϕ_m formulation combinations ranged from 27 to 47 μg/m^2·s, with the highest values derived when using data set 3—*i.e.*, with the 2.0-m height (lowest) but without the 7.62-m height (highest). Among the four ϕ_m formulations, Hogstrom [35] produced the highest PM_{10} emissions rates whereas Flesch *et al*. [23] had the lowest. With respect to Hogstrom [35], Flesch *et al*. [23] resulted to emission rates lower by 10% to 12% while the other two differed by 1% to 3% only. This was not surprising as *a* (Equation (5)) from Flesch *et al*. [23] had a setting less than half of those from the other three for unstable conditions (**Table 1**).

For the flux-gradient technique, slopes and R^2 values from regression analyses are summarized in **Table 4**. Similar to WindTrax, the following applies for the flux-gradient technique: 1) high linearity ($R^2 > 0.74$) was observed between any pair of data sets; 2) the highest linearity was obtained when comparing data sets with the same lowest measurement height (e.g., data sets 2 and 4, 1 and 5, etc.); and 3) the lowest linearity was determined when the data sets differed in the lowest measurement height (e.g., data sets 2 and 3, 3 and 4, etc.). Un-

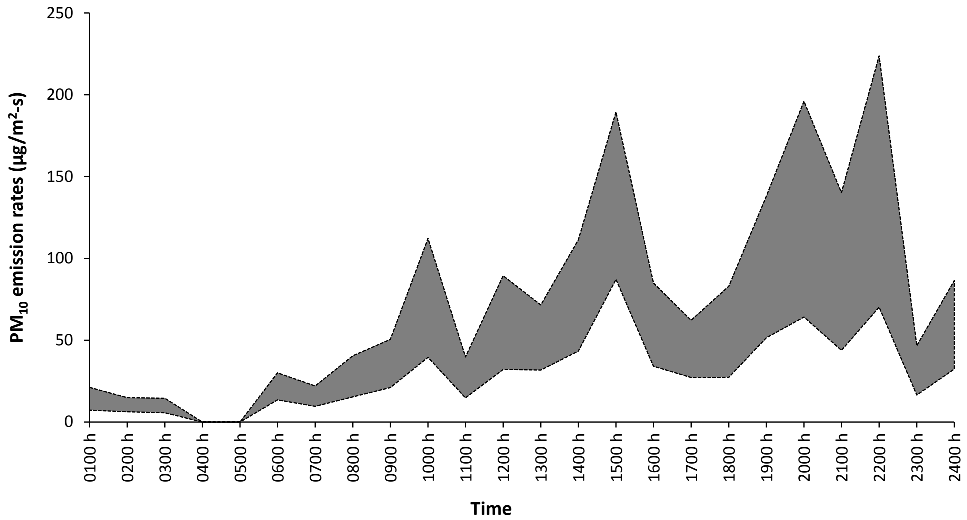

Figure 5. Hourly median PM_{10} emission rates calculated with the flux-gradient technique. Shaded area represents the range of emission estimates calculated using all the eight data sets.

Table 4. Linear regression between any two data sets (x, y) applied in the flux-gradient technique in terms of determined PM_{10} emission rates.[a,b]

Data set y/Data set x	1	2	3	4	5
2	0.77 (0.86)				
3	1.18 (0.97)	1.40 (0.74)			
4	0.79 (0.87)	1.02 (1.00)	0.64 (0.74)		
5	0.96 (1.00)	1.16 (0.85)	0.80 (0.98)	1.14 (0.85)	
6	1.10 (0.98)	1.31 (0.75)	0.94 (1.00)	1.28 (0.76)	1.16 (0.98)

[a]In performing regression, data set x was treated as the independent variable and data set y as the dependent variable; [b]Values presented are slopes from regression analyses; values in parentheses are corresponding R^2 values.

like with WindTrax, use of different data sets, which varied in heights and number of heights included, led to larger difference (<56%) in calculated emission rates (**Table 4**). The lowest differences were obtained when comparing data sets 2 and 4 (2%), data sets 1 and 5 (4%), and data sets 3 and 6 (6%) whereas the largest when comparing data sets 3 and 4 (56%) and data sets 2 and 3 (40%). In general, relatively higher PM_{10} emission rates were calculated when: 1) changing the lowest measurement height from 3.81 m to 2.0 m (e.g., data sets 4 and 5) or including the 2.0-m height (e.g., data sets 1 and 2), equivalent to what was observed with WindTrax; and 2) changing the highest measurement height from 7.62 m to 5.34 m (e.g., data sets 5 and 6) or excluding the 7.62-m height (e.g., data sets 1 and 3). Results also indicate that the most critical heights when implementing the flux-gradient technique would be the lowest and the highest measurement heights used in approximating the vertical concentration gradient and K_{PM}. As long as the lowest and the highest measurement heights remain the same, removal of heights in between would likely lead to very small change in estimated emission rate. Comparing data sets 2 and 4, 1 and 5, and 3 and 6, removal of other heights led only to 2%, 4%, and 6% change in calculated PM_{10} emission rates, respectively (**Table 4**).

3.4. Comparison of WindTrax and the Flux-Gradient Technique

Previous studies reported that between WindTrax (bLS model) and the flux-gradient technique, it was the latter that tended to have the lower emission estimates [33] [38] [41]. In the present study, however, the flux-gradient technique produced the higher PM_{10} emission rates in general. This difference in findings could be attributed to difference in measurement design when implementing the flux-gradient technique, including measurement heights (*i.e.*, 2.0 to 7.62 m range in this study, <2 m only in Wilson *et al.* [41] and Flesch *et al.* [33]), area source evaluated (*i.e.*, feedlot in this study, lagoon in Wilson *et al.* [41]), emissions measured (*i.e.*, PM_{10} in this study, gases/tracers in previous), comparison procedure (*i.e.*, hourly data points in this study, seasonal and annual means in Todd *et al.* [38]), and approximation of eddy diffusivity (*i.e.*, similar to companion studies [8] [18], the procedure implemented followed Prueger *et al.* [34]). As discussed below, the only time the flux-gradient technique gave the lower PM_{10} emission rates in this study was with the combination of data sets that excluded the 2.0-m height and ϕ_m formulations from Flesch *et al.* [23].

Slopes and R^2 values from performing regression analyses between WindTrax and the flux-gradient technique are summarized in **Table 5**. In terms of their calculated PM_{10} emission rates, WindTrax and the flux-gradient technique had relatively high linear relationship ($0.73 \le R^2 \le 0.89$). The highest linearity was observed between the two methods using data set 5—*i.e.*, with two measurement heights, the lowest (2.0 m) and the highest (7.62 m) in the measurement set-up. Based on slopes (**Table 5**), the percentage difference in estimated emission rate between WindTrax and the flux-gradient technique ranged up to 38%. The lowest differences (≤8%) were observed when using data sets 2 and 4, which did not include the 2.0-m height measurements in emission estimation. Meanwhile, the difference was largest when using data set 3 (29% to 38%) followed by data set 6 (19% to 27%), both of which included the 2.0-m height but excluded the 7.62-m height. These results suggest lower difference between WindTrax and the flux-gradient technique when estimating emission rates using the 7.62-m height and, in contrast, neglecting the 2.0-m height. Note that for both methods, use of the 2.0-m height measurements resulted to higher PM_{10} emission rate estimates—for the flux-gradient technique, this was due to lower ϕ_m and K_{PM}, and higher vertical concentration gradient calculated. And as mentioned above, use of the

Table 5. Linear regression between WindTrax and the flux-gradient technique for all data set-ϕ_m formulation combinations [24].[a,b]

Data set	ϕ_m formulations			
	Hogstrom [35]	Flesch *et al.* [23]	Dyer and Hicks [36] Dyer [39]	Hogstrom [37]
1	1.21 (0.84)	1.11 (0.82)	1.19 (0.84)	1.19 (0.83)
2	1.03 (0.76)	0.93 (0.73)	1.01 (0.75)	1.00 (0.75)
3	1.38 (0.78)	1.29 (0.76)	1.36 (0.78)	1.36 (0.78)
4	1.05 (0.77)	0.95 (0.75)	1.03 (0.77)	1.02 (0.77)
5	1.11 (0.89)	1.03 (0.87)	1.09 (0.89)	1.09 (0.89)
6	1.27 (0.81)	1.19 (0.80)	1.25 (0.81)	1.25 (0.81)

[a]For comparison purposes, WindTrax was treated as the independent variable and the flux-gradient technique as the dependent variable in the regression analyses; [b]Values presented are slopes from regression analyses; values in parentheses are corresponding R^2 values.

7.62-m height, which considerably reduced the estimated vertical concentration gradient, significantly lowered the emission rate calculated by the flux-gradient technique.

In terms of their calculated PM_{10} emission rates, WindTrax and the flux-gradient technique were not significantly different ($0.05 < P < 0.90$) from each other when using data sets 2, 4, and 5, the first two as the data sets that did not include the 2.0-m measurement height. For data set 1, in which all the four measurement heights were used, ϕ_m formulation from Flesch *et al.* [23], when used in the flux-gradient technique, was the only one in which the two methods did not significantly vary ($P = 0.09$) in estimated emission rates. To have closer estimates with WindTrax, the suggested ϕ_m formulation for data sets that included the 2.0-m height was the one from Flesch *et al.* [23] based on regression analyses and paired t-test. For data sets 2 and 4 (*i.e.*, no 2.0-m height), the suggested ϕ_m formulation was the one from Hogstrom [37], followed by Dyer [39] and Dyer and Hicks [36] in second, and Hogstrom [35] in third—still, these three formulations produced PM_{10} emission estimates that were not significantly different from each other ($P \geq 0.41$). Nevertheless, regardless of ϕ_m formulations for the flux-gradient technique, the high linearity observed indicates the possibility of developing conversion factors between the two emission estimation methods.

4. Conclusions

This study compared WindTrax and the flux-gradient technique as methods for estimating PM_{10} emissions from large commercial beef cattle feedlots. Using PM_{10} concentration measurements at several heights and measured meteorological conditions at a Kansas cattle feedlot, the two emission estimation methods were compared using different concentration data sets, which varied in terms of heights and number of heights included, and several formulations for the flux-gradient technique's nondimensional correction parameter ϕ_m. From the analyses, the following conclusions were made:

- Between the two methods, WindTrax was least sensitive to changes in heights and number of heights used in calculating emission rates. In this study, percent change in PM_{10} emission rates estimated by WindTrax ranged up to 18%, which was relatively small compared to the change observed for the flux-gradient technique (≤56%). Still, in each method, high linearity was observed among PM_{10} emission rates calculated using different concentration data sets.
- For both methods, higher PM_{10} emission rates were obtained when using the 2.0-m height, the lowest height in the measurement set-up, in emission estimation. On the other hand, PM_{10} emission rates calculated with the flux-gradient technique lowered when using the 7.62-m height, the highest height in the set-up.
- For the flux-gradient technique, the most critical heights were the lowest and the highest heights used in calculating the vertical concentration gradient. As demonstrated in this study, neglecting other heights in between resulted only in percent change of 2% to 6%.
- In general, the flux-gradient technique produced the higher PM_{10} emission rates. Only by excluding the 2.0-m height and using ϕ_m formulations from Flesch *et al.* [23] made the flux-gradient technique calculate

emission rates lower, but not significantly different, than those by WindTrax.

- For all ϕ_m formulations evaluated, the smallest difference in estimated PM_{10} emission rates was observed between WindTrax and the flux-gradient when using data sets without the 2.0-m height (≤8%). It should also be pointed out, however, that in this study, the flux-gradient technique was implemented with a very strict criterion for linearity (Pearson correlation = 0.95) between PM_{10} concentration and measurement height. Using a lower criterion would likely lead to higher difference in calculated PM_{10} emission rates between the two methods (e.g., Pearson correlation = 0.75 increased the difference by 50%).

Results from this study could serve as reference for and in developing conversion factors between WindTrax and the flux-gradient technique. The procedures presented for both methods can be used in determining PM emission rates from large commercial cattle feedlots. It must be emphasized, however, that the version of WindTrax implemented neglected gravitational settling effects; as noted, this might underestimate PM_{10} emissions by 4%. Based on meteorological conditions measured at the cattle feedlot studied, the flux-gradient technique was found to be applicable in estimating emission rates for PM with aerodynamic diameter ≤ 35 μm [8]; above this range, it is recommended to utilize a different emission estimation method that can account for gravitational settling effects.

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