COMPARISON OF AERMOD AND ISCST3 EMISSIONS FACTORS FOR PM FROM COTTON HARVESTING

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Abstract

In this study, the measured concentrations of regulated particulate matter (PM) including TSP, PM_{10} and $PM_{2.5}$ reported by Wanjura (2008) were the data source. Wanjura utilized the previous preferred model (ISCST3) to back-calculate PM EFs for cotton harvesting. These data were used to back-calculate emission factors (EFs) for cotton harvesting with the more recent preferred AERMOD dispersion model. The goal of this research was to document differences in emission factors as a consequence of the models used. The PM_{10} EFs developed for two-row and six-row pickers were 80 ± 11 kg/km^2 and 39 ± 11 kg/km^2, respectively.

In our research on EFs from cotton harvesting, we discovered that an alternative dispersion modeling protocol could be used to yield EFs. This new dispersion modeling approach was described and evaluated. The approach included modeling the harvesting operation as a moving area strip instead of a stationary area source. This approach resulted in EFs with a statistically higher correlation with process variables when compared to results using the previous modeling approach.

A comparison of downwind concentrations predicted by AERMOD and ISCST3 from a hypothetical cattle feedlot with varying meteorological conditions and emission rates were evaluated. It was observed that pollutant concentration results for the two models were dependent upon solar radiation. The impacts of solar radiation on downwind concentrations using AERMOD were different than those obtained using ISCST3. Results using the two models were compared under different meteorological conditions and solar radiation ranges. The results indicate that there is a linear relation between the models for all conditions. These results demonstrate that AERMOD predicted concentrations 55% higher than ISCST3 in the absence of solar radiation. This study also included an evaluation of both models with actual downwind concentration measurements taken at a feedlot in the Texas panhandle. It was observed that both models over-predict concentrations in a rural flat terrain. AERMOD's performance was within acceptable limits set forth by Kumar et al. (2006) for a convective and neutral atmosphere, but was not acceptable for a stable atmosphere. AERMOD predicted concentrations three times higher than the measured concentrations during night time conditions (zero solar radiation). The results indicate inconsistencies in the AERMOD model used to estimate concentrations in the absence of solar radiation. Using AERMOD predictions of pollutant concentrations off property for regulatory purposes will likely affect a source's ability to comply with limits set forth by SAPRAs and could lead to inappropriate regulation of the source.

Introduction

Cotton harvesting operations in states like California and Arizona are subjected to increased regulatory pressure from SAPRAs due to regional non-attainment status. Inaccurate emission factors have led to the identification of harvesting as a major contributor to PM_{10} emissions in non-attainment areas. Flocchini et al. (2001) reported EFs for PM_{10} of 191 kg/km^2 from cotton harvesting for two- to five-row equipment. The protocol used in the study included measuring PM_{10} concentrations using Federal Reference Method (FRM) PM_{10} samplers and using the concentration data in combination with a mass balance box model to estimate the EFs. The FRM PM_{10} samplers have been shown to exhibit significant over-sampling biases when used in the presence of dust with mass median diameter (MMD) greater than 10µm (Buser et al., 2007). The Buser study indicated that the FRM PM_{10} sampler could magnify PM_{10}

concentrations by as much as 340% when sampling a dust with an MMD of 20µm and geometric standard deviation (GSD) of 2.0. The average particle size distribution for emissions from cotton harvesting has an MMD of around 16µm (Wanjura et al., 2006). This induces significant uncertainty to the EFs developed by Flocchini.

Flocchini et al. (2001) used a box model in order to determine the EFs from cotton harvesting. The model (figure 1) consists of a theoretical box with a fixed height of 4 m, placed around the field being sampled. The width of the box was same as the width of the downwind edge of the field. Concentration measurements were made at the upwind and downwind edges of the field using FRM PM_{10} samplers. The researchers assumed that there was no reaction of PM inside the box. Therefore, the change in concentration between the upwind and downwind edge of the field was entirely attributed to the sources within the box. The net concentrations (difference between downwind and upwind concentrations) along with wind speeds were used to determine the net mass of PM_{10} emitted during the sampling period. The net mass was divided by the area harvested during the sampling period to determine flux. Emission flux was converted to an emission factor by suitable unit conversions (Goodrich, 2006).

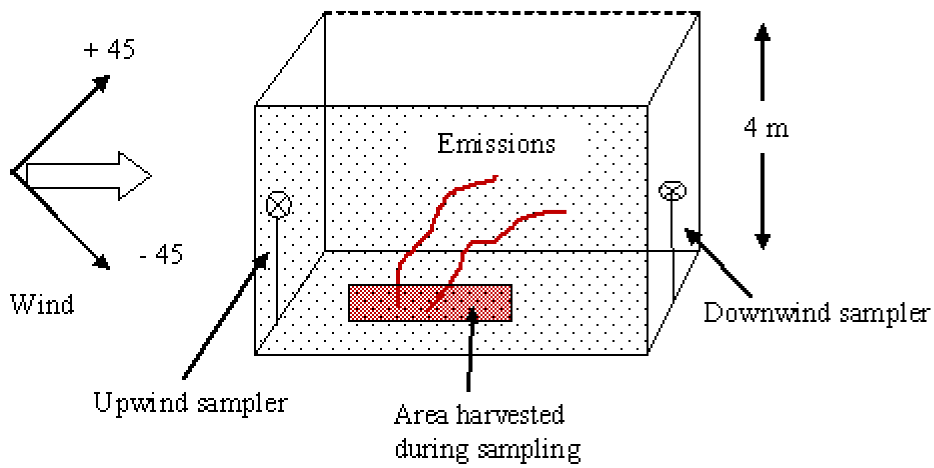

Figure 1. Schematic of the Flocchini box model

Goodrich, (2006) provided the following equation (equation 1) to represent the emission flux calculation from the box model.

$$Q = W_B \times H \times C \times U \cos(\theta) \times (1/A) \qquad (1)$$

where,
Q = Emission flux, µg/m^2-s;
W_B = width of the box, m;
H = height of the box, 4 m;
U = wind speed, m/s;
θ = deviation of wind direction;
C = net concentration, µg/m^3; and
A = area harvested during the sampling period, m^2.

Goodrich, (2006) analyzed the application of the box model for developing EFs for agricultural operations and identified the following limitations:

- The model is only valid when the wind direction is ±45 degrees from the sampling axis.
- The model is applicable to rectangular area sources only.
- The fixed box height may lead to underestimation of the total emissions, as the plume behavior of large sources cannot be adequately described by a constant mixing height.

Faulkner et al. (2007) and Lange, (2008) found that emission rates by back-calculated using a dispersion model are model specific. This means that if these box model emission rates were used with other dispersion models such as AERMOD or ISCST3, the results would be incorrect estimates of downwind concentrations. Most SAPRAs are using AERMOD to regulate industrial and agricultural sources of air pollution today. Wanjura, (2008) used measured concentrations of TSP and PM_{10} with inverse dispersion modeling to back-calculate EFs for two-row and six-row pickers. Wanjura reported PM_{10} EFs using ISCST3 at 66 kg/km^2 for six-row picker and 312 kg/km^2 for two-row pickers.

Methodology

Ambient Air Sampling for Cotton Harvesting

The concentration data and meteorological observations for this study were obtained from Wanjura, (2008). The researchers in the Wanjura study conducted collocated TSP and FRM PM_{10} concentration measurements for emissions from a two-row and a six-row picker. The sampling was conducted at a farm located 13 km southwest of college station, TX. Figure 2 shows the farm which was subdivided into 21 test plots. Test plots 1-6 had a six-row picker operating and test plots 15-21 had a two-row picker operating. Data for the particle size distribution analysis were also obtained from Wanjura, (2008).

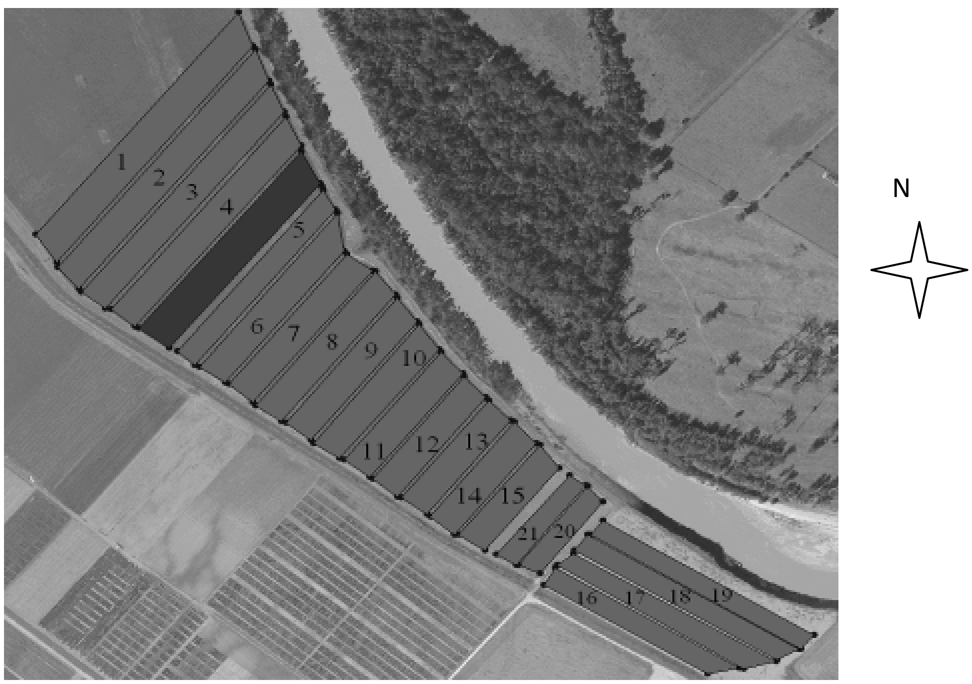

Figure 2. Layout of test plots

Emission factor development

The following methodology was used to calculate EFs:

1. Model setup parameters and processed meteorological data were used in the AERMOD dispersion model using a unit emission flux (1 μg/m^2-s). The model-user interface used for AERMOD was BREEZE AERMOD 6 (BREEZE AERMOD v. 6.2.2, Trinity Consultants, Dallas, TX). The interface used for ISCST3 was BREEZE ISC GIS Pro (BREEZE ISC GIS Pro v. 5.2.1, Trinity Consultants, Dallas, TX)

2. The output of dispersion modeling is a unit flux concentration (UFC) for each test at each sampling location. Dividing the concentration measured in the field at each location by the UFC at that location yields the actual flux at the location. The emission flux (μg/m^2-s) thus obtained was converted into an EFs by multiplying the sampling time as shown in equation 3.

$$Flux_{actual} = C_{measured} / UFC \quad (2)$$

$$EF = Flux_{actual} \times C \times ST \quad (3)$$

where,
UFC = Unit flux Concentration, μg/m^3;
$C_{measured}$ = Measured concentration, μg/m^3;
$Flux_{actual}$ = Pollutant flux from harvest operation, μg/m^2-s;
C = units conversion factor (0.06);
ST = Sampling time in minutes; and
EF = Emission factor, kg/km^2.

3. The TSP EFs were multiplied by percentage of PM less than 10 μm and 2.5 μm obtained from PSD analysis to get true PM_{10} and $PM_{2.5}$ EFs, respectively.

EFs for agricultural operations such as dairies, cattle feed yards etc. are typically developed through back-calculating emission fluxes using a dispersion model and simultaneously collected concentration and meteorological data (Goodrich, 2006; Wanjura et al., 2004). In this dispersion modeling approach, emissions were modeled as area sources. This is a reasonable estimate of the existing conditions in feedlots, dairies etc. The alternate hypothesis in this research was to treat harvesting as a mobile source instead of an area source. In such a case, concentrations recorded at the receptors vary with the position of the mobile source. When the harvester moves through the plot, the receptors start capturing PM. The PM collected varied with the position of the harvester. The EFs obtained by treating the harvesting as a mobile source were compared to the EFs obtained from the area source approximation. The EFs obtained from the area source approximation (Method 1) and the mobile source approximation (Method 2), were correlated with data taken during the Wanjura study (yield, soil moisture etc.) to investigate the trends observed in the EFs.

The protocol for measuring, modeling, and calculating emission factors for fugitive emissions has been established by researchers at Texas A&M (Wanjura et al., 2004). This protocol has been used for area sources with PM emissions. Samplers are deployed around the area to measure PM concentrations emitted from the area source. Samplers on the upwind side of the area source are used to measure the ambient (upwind) concentrations which are subtracted from the downwind concentrations to determine the net PM emitted from the area source. This protocol, referred to herein as “Method 1”, has been used to develop EFs for fugitive area sources. Method 1 was used to determine the emission factors for cotton harvesting. The procedure used consisted of dividing the cotton field into 21 individual strips, or plots (figure 2). Each plot was modeled separately as an area source using an emission flux of 1 μg/m^2-s for the duration of the harvest time (T). Receptors in the model corresponding to the actual samplers around the plot. (figure 3).

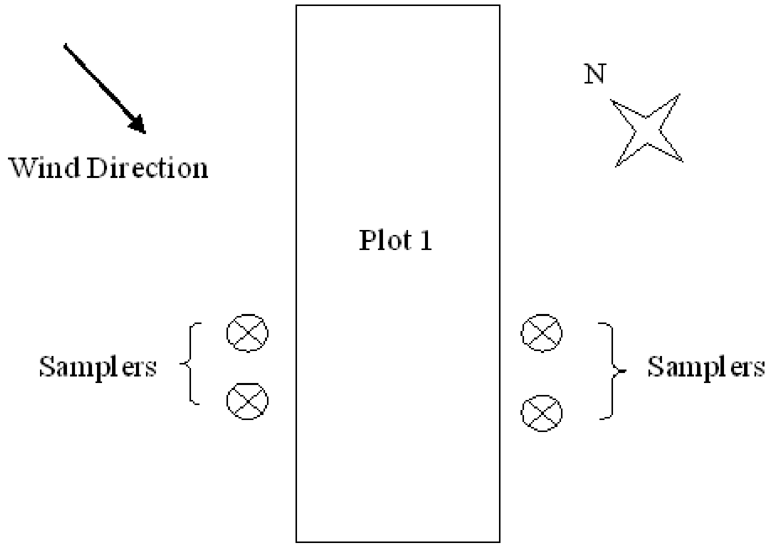

Figure 3. Method 1 setup in AERMOD

The meteorological data obtained from the Wanjura study were processed with a five minute averaging time for modeling. With an emission flux of 1 μg/m^2-s, each plot was modeled using AERMOD to calculate PM concentrations for the model receptors. The PM concentrations measured in the field were divided by the resulting model predicted concentrations as shown in equation 2 to determine the emission flux. Equation 3 was used to convert the emission flux into an emission factor. The same procedure was repeated for each of the plots to develop an EF for each plot. Standard deviations were calculated for the EFs obtained (equation 4). The EFs larger than three standard deviations were treated as outliers and deleted from the analysis.

$$\sigma = \{ \sum [(x_i - \mu)^2 / N] \}^{1/2} \qquad (4)$$

where,
σ is the standard deviation of the EFs;
x_i is the individual EF;
μ is the mean EF; and
N is the total number of EFs.

Method 1 has generally been used for area sources like feedlots and dairies. It is assumed that the cattle or dairy animals uniformly stir up PM by hoof action throughout the yard. Field harvesting operations present a different situation where the PM emissions vary during the harvest. The harvester moving through the field entrains PM in strips until the plot has been harvested. Method 2 was developed to address this difference.

Each plot within the field was divided into several line sources, each with a length equal to the total length of the plot and a width equal to the width of the harvester. The number of line sources in each plot was equal to the number of passes taken by the harvester in that plot (Wanjura, 2008). In the model, each line source was given a unit emission flux of 1 μg/m^2-s. In the field, when harvester is moving in a single pass PM is emitted only from that pass and the rest of field has zero emissions. To simulate this scenario the line sources were modeled sequentially. For example, consider figure 4 in which the plot contains 6 lines sources. When line 1 is given an input flux of 1 μg/m^2-s the remaining four lines 2,3,4,5 have zero emissions. Similarly when line 2 is given an input flux the remaining lines 1,3,4,5 have zero emissions.

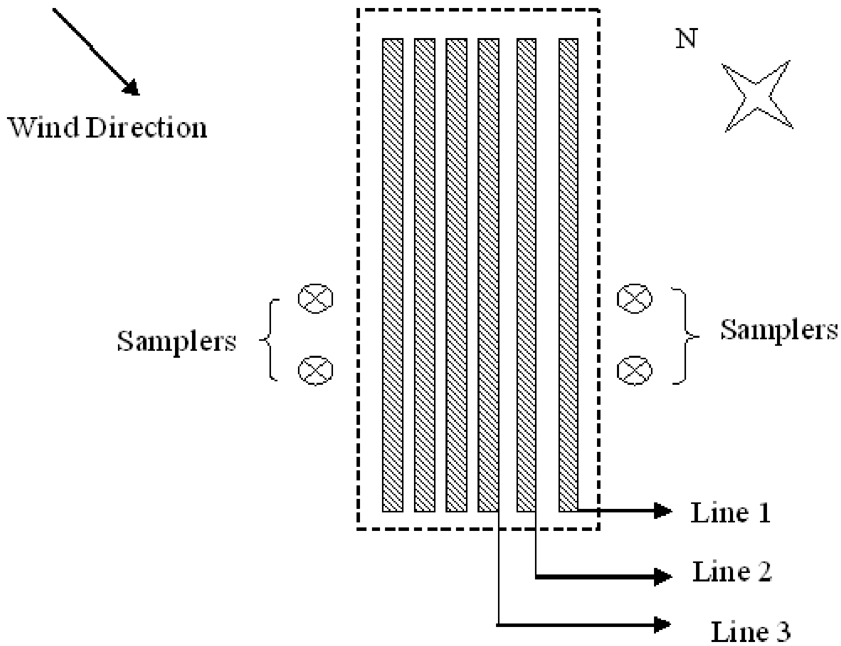

Figure 4. Method 2 setup in AERMOD

With Method 2, each successive line source was modeled and concentrations were predicted at all receptors. The modeled concentrations at the samplers were calculated by summing the predicted concentrations due to all the line sources (figure 4). Equation 2 was used to determine the emission flux by dividing the measured field PM concentrations by the corresponding modeled concentrations. Equation 3 was used to calculate the emission factor. The same procedure was repeated for each of the plots to develop an emission factor for the entire field.

The following are the key aspects of modeling common to both Methods 1 and 2:

- Meteorological (met.) data were recorded in the Wanjura study at every quarter of a second. These data were processed to obtain 5-minute average met. data corresponding to the 5 minute intervals during harvesting and the corresponding modeling runs for both Methods 1 and 2.

- The following input parameters were specified for each model run:

  a. Size and orientation of the emission source;
  b. A unit emission flux (1 μg/m^2-s)
  c. 5-minute met. data;
  d. Emission release height (4 m);
  e. Receptor locations and heights (2 m); and
  f. Terrain conditions (flat terrain).

- The outputs of each modeling run were estimated concentrations at the receptors using the unit flux. These are referred to as unit flux concentrations (UFC) in this paper.
- The TSP and FRM PM_{10} concentrations measured in the field were divided by the UFC to obtain the TSP and FRM PM_{10} emission fluxes, respectively. These emission fluxes were converted to EFs using equation 3.

The following are the key differences between Methods 1 and 2:

In Method 1, the UFC obtained from each 5-minute modeling run at receptors were a consequence of an average PM emission rate from the entire plot area. The met. data used for modeling runs were 5-minute averages of Wanjura's data. The number of modeling runs were determined by the number of five minute periods required to complete harvesting of the plot. The resulting flux was an average of all 5-minute modeling runs. For example, if the total time of harvesting an area was 2-hours, there would be 24 lines of met. data. Each data line would correspond to a 5-min average. Dispersion modeling runs were used to estimate concentrations at the receptors for each 5-min met. data line. The maximum UFC was the result used to calculate a flux for the plots as described above.

In Method 2, the total plot area was divided into sub-plots (line sources). The number of line sources corresponded to the number of harvester passes used to harvest the plot area. The GPS data taken during the Wanjura study gave a detailed estimate of the path followed by the harvester in the field. For example, if the harvester took 10 passes to cover an area, 10 line sources were laid out in the model. The GPS data also gave the time taken by the harvester to complete each pass. For example, if the harvester took 10 minutes to complete a pass, the met. data corresponding to that 10 were used in the model run. The UFCs in Method 2 were the results PM emissions by the harvester as it operated in each line source. The number of modeling runs for each line source was determined by the time required to harvest that particular line source. The 5-minute met. data used for modeling runs were a function of the location of the harvester in the plot and the time required to harvest the line sources. The modeling results consisted of UFCs for each line source. The resulting fluxes were averaged to yield fluxes and emission factors for the plot.

Results and Discussion

EFs for four species of PM (TSP, FRM PM_{10}, True PM_{10} and True $PM_{2.5}$) were developed for each treatment (six-row, two-row) and each modeling method. The results for six-row harvester are listed in Table 1. EFs developed using the two modeling methods were found not to be statistically different for all the four species at the 95% confidence level. No difference was observed even in the standard deviation values of the EFs developed using the two methods. The percentage differences in the mean EF were determined using equation 5.

$$\text{Percent difference} = [(EF_{Method\ 1} - EF_{Method\ 2}) / EF_{Method1}] *100 \qquad (5)$$

where,
$EF_{Method\ 1}$ is the EF developed using the Method 1; and
$EF_{Method\ 2}$ is the EF developed using Method 2.

FRM PM_{10} EFs were 60% higher than True PM_{10} EFs, indicating an over-sampling bias of the FRM PM_{10} samplers when sampling PM with large MMD dust. $PM_{2.5}$ EFs determined using both methods were less than 6 kg/km^2, indicating that cotton harvesting is not a major contributor of $PM_{2.5}$ emissions in the San Joaquin valley.

Table 1. EFs in kg/km^2 for six-row harvester using Method 1 and 2.

		TSP	FRM PM_{10}	True PM_{10}	True $PM_{2.5}$
Method 1	Mean	568	376	154	5.46
	Std error	76	69	21	0.68
Method 2	Mean	667	443	180	5.94
	Std error	85	79	23	0.76

The resulting emission factors for the two-row harvester are as listed in the table 2. Similar to the six-row EFs, the two-row EFs developed using methods 1 and 2 were not statistically different at the 95% confidence level. EFs for all the four species were higher for the two-row harvester than the six-row harvester. This indicated that the EFs for six-row harvesters were significantly lower than EFs for two-row harvesters. FRM PM_{10} EFs were 40% higher than True PM_{10} EFs. This indicated that the FRM PM_{10} samplers were subject to oversampling bias when used in the presence of PM with MMD greater than the cut-point of 10 µm.

Table 2. EFs in kg/km^2 for two-row harvester using Method 1 and 2.

		TSP	FRM PM_{10}	True PM_{10}	True $PM_{2.5}$
Method 1	Mean	1457	675	425	15.4
	Std error	286	85	83	3.03
Method 2	Mean	1380	626	403	14.6
	Std error	291	73	85	3.09

Spearman rank correlation analysis was carried out between the TSP EFs developed using the two methods and the process variable data obtained from Wanjura, (2008). The process variables considered were crop yield, plot area, soil & seed cotton moisture and percentage of soil mass less than 106 µm. The null hypothesis for this test was that there is no actual correlation between the TSP EFs developed and the process variables. The analysis yielded the results listed in Table 3. The table shows the correlation coefficient (R) and significance (p). The correlation coefficients represent the strength of the relationship between variables. R values closer to 1 indicate a strong correlation. Values of p less than 0.05 indicate that the null hypothesis can be rejected indicating that the correlation between the EFs and the process variable is significant at the 95% confidence level.

Table 3. Correlation analysis of TSP EFs with process variables.

		Yield[b] (bales/km^2)	Area (km^2)	% Soil mass < 75 µm	% Soil mass > 75 µm	Seed cotton moisture (%)	Soil moisture (%)
Method 1	R[a]	0.550*	-0.005	0.317*	0.098	-0.462*	-0.413*
	p	0.013	0.484	0.039	0.226	0.014	0.029
Method 2	R	0.620*	-0.093	0.382*	0.031	-0.343*	-0.333*
	p	0.022	0.247	0.024	0.410	0.015	0.017

[a] Yield correlations were performed for six-row harvester only.
[b] * Significant at 0.05 level.

TSP EFs showed significant correlation with yield, moisture contents of soil and seed cotton and % soil mass < 75 um. When the harvester processes more plant material per unit time, it is an indication that the yield is higher with a corresponding increase in PM emissions. Increased PM emissions were indicated by the EF correlation with yield. For both methods, the correlation is significant at the 95 percent confidence level. The EFs showed correlations with soil and seed cotton moisture. As the soil moisture increases the emissions due to entrainment of soil PM decreases and this relation is shown by a negative correlation coefficient. As expected, the EFs showed reasonable correlation with percentage of soil mass less than 75 µm. As the percentage of soil less than 75 µm increases, the concentrations of TSP and PM_{10} measured by the receptors increases. When EFs were expressed per unit area of harvest, there were no correlations with the area of the plot in all cases. No difference in trends was observed for EFs from Method 1 and Method 2.

The results for Spearman rank correlation analysis conducted for the FRM PM_{10} EFs developed using the two methods are listed in table 4.

Table 4. Correlation analysis of FRM PM_{10} EFs with process variables.

		Yield[b] (bales/km^2)	Area (km^2)	% Soil mass < 75 µm	% Soil mass < 106 µm	Seed cotton moisture (%)	Soil moisture (%)
Method 1	R[a]	0.510*	-0.008	0.320*	0.091	-0.426*	-0.323*
	p	0.014	0.412	0.036	0.203	0.018	0.027
Method 2	R	0.580*	-0.090	0.381*	0.027	-0.310*	-0.356*
	p	0.020	0.213	0.020	0.516	0.014	0.020

[a] * Significant at 0.05 level.
[b] Yield correlations were performed for six-row harvester only.

The null hypothesis for these tests was that there were no correlations between the FRM PM_{10} EFs developed and the process variables. Table 4 shows the correlation coefficients (R) and significances (p). The correlation coefficient represents the strength of the relationship between the two variables.. R values closer to 1 indicate a strong correlation. Values of p less than 0.05 indicate that the null hypothesis can be rejected. This means that the correlation between the EFs and the process variable is significant at the 95% confidence level. Values of p greater than 0.05 indicate that, the null hypothesis cannot be rejected. This means that there is no correlation between the EF and the process variable under consideration.

Similar to the TSP EFs the PM10 EFs showed significant correlation with crop yield and soil moisture. Similar to the TSP EFs, there were no differences observed between PM_{10} EFs from Method 1 and Method 2 in the correlation analysis.

Comparisons of AERMOD and ISCST3 EFs were carried out to identify the differences in EFs as a consequence of model used. The True PM_{10} EFs obtained from the methods 1 and 2 using AERMOD were compared to the EFs obtained for the same data with ISCST3 model. While modeling with ISCST3 model, only method 1 was used. It was observed that for the six-row harvester, the EFs for AERMOD and ISCST3 were statistically different. The mean AERMOD EFs were 50% higher than the ISCST3 EFs. For the two-row harvester, the AERMOD EFs were not statistically different from the ISCST3 EFs but the mean AERMOD EF was 25% higher than the ISCST3 EF (Table 5). The table contains the mean EF and 95% confidence limits. (Calculated as 1.96 x Std. error)

Table 5. Comparison of PM_{10} EFs in kg/km^2 from AERMOD and ISCST3.

	Six - Row	Two - Row
Method 1 (AERMOD)	154 $\pm$ 43	425 $\pm$ 178
Method 2 (AERMOD)	180 $\pm$ 48	403 $\pm$ 181
ISCST3	81 $\pm$ 16	322 $\pm$ 190

In the Wanjura study, EFs for the six-row picker were obtained from a direct measurement of PM concentrations from the harvester. The results obtained from this source-sampling method represent the most accurate estimates of EFs. However sampling studies like these are very expensive to carryout and also require considerable amount of time and labor. To overcome this trouble, dispersion models ISCST3 and AERMOD were used in this paper to develop EFs. Comparisons were made between the source-sampling EFs and the EFs developed by the dispersion models. It was observed that there was no statistically significant difference between the ISCST3 EFs and the source sampling EFs. However, AERMOD EFs were three times higher than the source-sampling EFs. Table 6 shows comparisons between the Wanjura EFs and the EFs developed in this paper.

Table 6. Comparison of source-sampling EFs and the EFs developed by dispersion models in kg PM_{10}/km^2.

Harvester type	Dispersion model	EFs from dispersion models	Source-sampling EFs from Wanjura study
six-row	ISCST3	81 $\pm$ 16	55 $\pm$ 12
six-row	AERMOD	154 $\pm$ 43	

Conclusions

EFs for TSP, PM_{10} and $PM_{2.5}$ from cotton harvesting were determined using AERMOD. Modeling results for two different methods were analyzed. Method 1, in which harvesting was modeled as an area source and Method 2, in which harvesting was modeled as a series of line sources. The Method 1 EFs for True PM_{10} were 154 $\pm$ 43, 425 $\pm$ 178 kg/km^2 for six-row and two-row harvesters, respectively. The Method 1 EFs for True $PM_{2.5}$ were 5.46 $\pm$ 1.42, 15.4 $\pm$ 6.46 kg/km^2 for six-row and two-row harvesters, respectively. The results of this study indicate that EFs developed using Method 1 and Method 2 were not statistically different. Contrary to our hypothesis, the results lead to the conclusion that modeling method (Method 1 or Method 2) would not cause difference in EFs. This is an important finding and it suggests that the protocol developed at Texas A&M for developing EFs for area sources (Method 1) can be used for harvesting operations. This would save valuable time in the modeling phase of projects aimed at developing EFs.

A comparison was made between AERMOD EFs and the ISCST3 EFs. This comparison observed that, for a six-row harvester, AERMOD EFs were 1.8 times higher than ISCST3 EFs. This leads to the conclusion that EFs developed with dispersion models are model specific. These EFs should be used in conjunction with the same model with which they were developed. If used with a different model, the results would lead to incorrect estimates of downwind concentrations.

FRM PM_{10} EFs were 50% higher than True PM_{10} EFs, indicating that the FRM PM_{10} samplers have an over-sampling bias when sampling larger MMD PM. For both two-row and six-row harvesters, the $PM_{2.5}$ EFs were less than 20 kg/km^2, indicating that the contribution of $PM_{2.5}$ from cotton harvesting towards emission inventories is very small.

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