UPDATE ON THE DEVELOPMENT OF PARTICULATE MATTER EMISSION FACTORS FOR COTTON HARVESTING

J. D. Wanjura
USDA-ARS Cotton Production and Processing Research Unit
TAMU 2117
College Station, TX
W. B. Faulkner
Texas A&M University
2117 TAMU
College Station, TX
C. B. Parnell
BAEN-TAMU
TAMU 2117
College Station, TX
B.W. Shaw
Department of Biological and Agricultural Engineering
College Station, TX
S.C. Capareda
College Station, TX
Michael D. Buser
USDA-ARS Cotton Production and Processing Research Unit
Lubbock, TX
Derek P. Whitelock
USDA-ARS, Southwestern Cotton Ginning Research Laboratory
Las Cruces, NM

Abstract

Accurate particulate matter emission factor data from modern cotton harvesting operations is not available for regulatory use. Thus, the objective of this work was to develop accurate dust emission factors for modern cotton harvesting operations in terms of PM_{10}, $PM_{2.5}$ and TSP. Particulate matter sampling of cotton harvesting operations was conducted on three farms in Texas during 2006 and 2007. Two protocols were used to develop emission factors in terms of TSP, PM_{10}, and $PM_{2.5}$ from the operations. The first protocol used the regulatory dispersion models ISCST3 and AERMOD to back calculate emission flux values for a two-row John Deere model 9910 cotton picker and six-row John Deere model 9996 cotton picker from measured downwind concentrations and meteorological data collected onsite. The second protocol employed a novel source sampling system onboard the six-row cotton picker to measure emission concentrations emitted from the basket as the machine operated in the field. The results from the first protocol indicated that the two-row harvester emission factors were higher than the six row machine and the mean difference in the PM_{10} emission factors developed in ISCST3 and AERMOD were 1.08 and 3.61 kg/ha, respectively (0.96 and 3.22 lb/ac, respectively). These differences were found to be insignificant for ISCST3 but significant for AERMOD. The emission factors developed under the source sampling protocol exhibited much higher precision and lower uncertainty than those developed under the first protocol. The TSP, PM_{10}, and $PM_{2.5}$ emission factors developed using the source measurement protocol are 1.64 ± 0.37, 0.55 ± 0.12, and 1.58E-03 ± 4.5E-04 kg/ha, respectively (1.46 ± 0.33, 0.49 ± 0.11, and 1.41E-03 ± 4.01E-04 lb/ac, respectively). Further analysis of the emission factors developed with the source sampling protocol indicate that it is appropriate to report cotton harvesting particulate matter emission factors in terms of mass per bale harvested. In terms of kg/bale, the TSP, PM_{10}, and $PM_{2.5}$ emission factors from the source measurements of PM emissions from the six row machine were 0.22 ± 0.019, 0.07 ± 0.007, and 2.15E-4 ± 1.49E-5 kg/bale, respectively (0.48 ± 0.04, 0.15 ± 0.015, and 4.74E-4 ± 3.3E-5 lb/bale, respectively). Particle size distribution (PSD) analyses on the PM collected by the downwind TSP samplers and by the source sampling system indicates that the PSD of the dust emitted from cotton harvesting operations is closely approximated by a lognormal density function characterized by MMD and GSD values of 14 μm and 2.2 respectively.

Introduction

Air pollution regulation in the US continues to intensify with growing national and global concern for the conservation of environmental resources. Emissions from agricultural operations are not exempt from such regulation. In fact, agricultural operations are facing new regulatory challenges with regard to particulate matter (PM) emissions. The cotton producing regions of CA and AZ are in non-attainment status with federal PM_{10} standards (NAAQS). PM_{10} refers to all PM with aerodynamic diameter equal to or smaller than 10 micrometers (µm). As a result, air pollution regulators were forced to identify (in the state implementation plan) and implement methods by which ambient air quality levels will be brought back into attainment with federal standards. Through this process, agricultural field operations (including cotton harvesting) were identified as a significant source of PM_{10}. Farmers in California and Arizona are now required to obtain air quality permits which estimate the amount of PM_{10} and $PM_{2.5}$ emitted annually from all field operations (e.g. tillage, planting, harvesting, etc.) (CARB, 2003; SJVAPCD, 2004 a and b; AAC, 2000). Farmers in CA and AZ are also required to submit conservation management plans which detail (for a particular operation) the steps a producer will implement to help reduce fugitive PM emissions from the operation.

The emission factors used in the air pollution regulatory process play a critical role in the appropriate regulation of agricultural and industrial operations. Emission factors are estimates of the amount of a pollutant emitted by an operation per unit of production (i.e. lbs. PM_{10} per acre of cotton harvested). Air pollution regulators use emission factors to determine annual emission inventories and in dispersion models (as input emission rates) to predict downwind concentrations resulting from the pollutant emissions from a source. For example, an overly conservative emission factor (i.e. an emission factor which grossly overstates true emission rates) will accomplish the goal of air pollution regulators to protect public health, but will have a detrimental effect on the emitting operation through the additional (and likely unnecessary) cost of abatement devices used to reduce pollutant emissions. Some states grant air quality permits based on the results of dispersion modeling. An overly conservative emission factor used in a dispersion model will result in the prediction of downwind concentrations in excess of true levels and likely the denial of the air permit.

A limited amount of research has been conducted to quantify PM emissions from cotton harvesting. A study conducted under contract with the USEPA by Snyder and Blackwood (1977) reported emissions of particulate matter less than 7 µm (mean aerodynamic diameter) on the order of 0.96 kg/km^2 ($8.4*10^{-3}$ lbs/acre) for harvesting operations using cotton pickers. This emission factor represented the total emission factor from harvesting operations including emissions from the harvesting machine, trailer loading operations, and trailer transporting operations. In an effort to quantify the PM_{10} emissions from modern cotton harvesting operations, Flocchini et al. (2001) conducted a study to measure the emissions from cotton harvesting operations using two to five row equipment. The results of the study by Flocchini et al. (2001) indicate that the PM_{10} emissions from cotton picking machines in the San Joaquin valley of California are on the order of 1.7 lbs/acre. The emission factor development protocols used by Snyder and Blackwood (1977) and Flocchini et al. (2001) introduced substantial amounts of uncertainty in the resulting emission factor estimates. Additionally, the size fraction of PM for which the emission factor was developed by Snyder and Blackwood (1977) is not a regulated size indicator used today.

The purpose of this study was to develop accurate emission factors for modern cotton harvesting operations in terms of PM_{10}, $PM_{2.5}$ and TSP. Emission factors were developed under two protocols employing indirect and direct measurement techniques. Emission factors for a two-row (John Deere model 9910) and six-row (John Deere model 9996) cotton picker were developed with a protocol employing two dispersion models to back calculate emission flux values from downwind concentrations and meteorological data measured onsite (indirect technique). The dispersion models used are Industrial Source Complex Short Term version 3 (ISCST3) and American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD). The second protocol (direct technique) employed a novel source sampling system designed for use onboard the six-row machine. Particle size distribution (PSD) analyses were conducted on the PM collected under both protocols and used to determine PM_{10} and $PM_{2.5}$ emission factors from TSP measurements. The emission factor data from the source measurement protocol was also used to determine the most appropriate basis on which to report PM emission factors from cotton harvesting (i.e. kg/ha vs. kg/bale).

Methods

Sampling of PM emissions from cotton harvesting operations on three farms in Texas during 2006 and 2007 was conducted. Measurements were taken at all three farms during 2006 while only at farm 3 during 2007. Brief descriptions of the three farms used during 2006 follow.

- Farm 1 is located approximately 8 km (5 mi) south of El Campo, TX. The farm was divided into twelve test plots with areas ranging from 1.6 – 2.4 ha (4 – 6 ac). The dark clay soil was wet at the beginning of the sampling event but dried out by the end. Ten of twelve planned tests were conducted due to equipment failures and the labor intensive nature of the sampling work.
- Farm 2 is located approximately 5 km (3 mi) north of Clay, TX. The farm was divided into nine, 1.9 ha (4.7 ac) test plots and the soil varied across the farm from clay to sandy clay loam. The soil remained dry during the testing period. Eight of nine planned tests were conducted on farm 2 due to equipment malfunctions and the labor intensive nature of the sampling work.
- Farm 3 is located approximately 13 km (8 mi) southwest of College Station, TX and the northeastern edge of the farm is bordered by the Brazos River. The field was divided into six test plots ranging in area from 2 – 2.6 ha (4.9 – 6.4 ac) and the soil ranged in texture from sand to clay. The soil remained dry over the testing period. Five of six planned tests were conducted due to equipment failures on farm 3.

In 2007, the area planted to cotton on farm 3 was over double that of 2006. Thus, the field was divided into 21 test plots with areas ranging from 1 – 2.6 ha (2.5 – 6.4 ac). The test period duration was substantially lengthened in 2007 due to the increased number of test plots. The sampling events with the six-row machine were conducted over a five day period and were separated from the tests conducted with the two-row machine by a rain event. A one week period was allowed to adequately dry the soil surface prior to the start of the tests with the two-row machine. Soil surface moisture readings were taken during all the tests in 2007 to investigate differences in emission factors resulting from different soil moisture conditions.

Emission Factor Development Protocol I: Concentration Sampling with Dispersion Modeling

Collocated TSP and PM_{10} samplers were placed at several locations around the test plots (see figure 1) to measure upwind and downwind concentrations. The TSP sampler inlets were designed and evaluated by Wanjura et al. (2005). The PM_{10} samplers used the Graseby-Andersen FRM PM_{10} inlet. PM_{10} concentrations were measured using FRM PM_{10} samplers to investigate the sampling error phenomenon identified by Buser (2004) in the presence of dust emitted from cotton harvesting operations. The results of the sampling error analysis are given by Wanjura (2008).

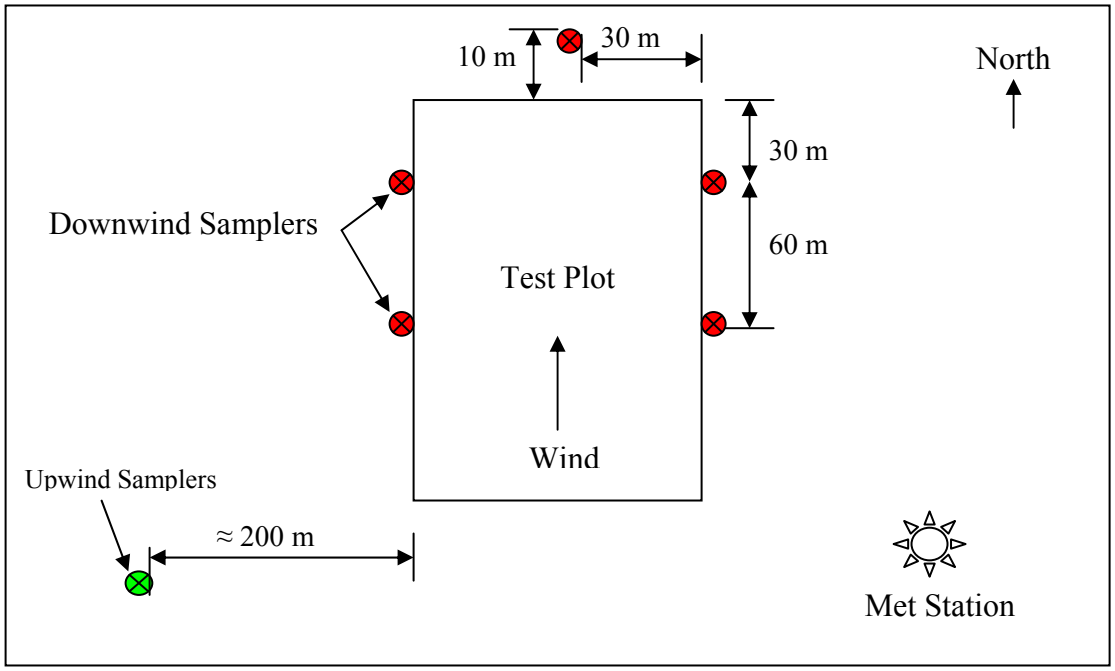

Figure 1. Test plot sampler arrangement.

The systems used to establish and control the flow rate of the TSP and PM_{10} samplers were identical. The air flow systems used a 0.09 kW (1/8 hp) diaphragm pump (917CA18-59, Thomas Industries, Sheboygan, WI) to draw 16.7 l/min (sampler flow rate) through the inlet head. Electrical power for the samplers was supplied by gasoline powered generators located between the samplers. The air flow rate was measured using a sharp edge orifice meter. The diameter of the orifice was 4.76 mm (3/16 inch). The pressure drop across the orifice plate was measured by a Magnehelic gauge (as a visual check) and also by a differential pressure transducer (PX274, Omega Engineering, Inc., Stamford, Conn.). The differential pressure transducer converted the differential pressure readings into a current (mA) signal that was recorded by a data logger (HOBO H8 RH/Temp/2x External, Onset Computer Corp, Pocasset, MA). Pressure drop readings were recorded for each sampler at the beginning and end of each test. The relationship shown in equation 1 was used to calculate the sampler flow rate using the pressure drop across the orifice plate recorded on the log sheets (from the Magnehelic gauge) and recorded by the data loggers.

$$Q = 3.478 * K * D_o^{\,2} * \sqrt{\frac{\Delta P}{\rho_a}} \tag{1}$$

where,

Q = air flow rate through the orifice meter (m^3/s),
K = flow coefficient (dimensionless),
D_o = orifice diameter (m),
ΔP = pressure drop cross the orifice (mm H_2O), and
ρ_a = air density (kg/m^3).

Meteorological data were collected during each test by an onsite weather station. The weather station recorded air temperature, relative humidity, barometric pressure, wind direction, wind speed, and solar radiation (Temp/RH Sensor: Model S-THB-M002; Barometric Pressure Sensor: Model S-BPA-CM10; Wind Direction/Speed Sensor: S-WCA-M003; Silicon Pyranometer: S-LIB-M003, Onset Computer Corporation, Pocasset, MA). The density of air used in (1) was calculated using the air properties recorded by the weather station in equation 2.

$$\rho_a = \frac{P_b - \phi P_s}{0.0028 * (t_{db} + 273)} + \frac{\phi P_s}{0.0046 * (t_{db} + 273)} \tag{2}$$

where:

P_b = Barometric pressure (atm),
ϕ = relative humidity (decimal),
P_s = Saturation vapor pressure (atm), and
t_{db} = Dry bulb temperature, (ºC).

The PM collected by the TSP and PM_{10} samplers was deposited on 47 mm diameter polytetrafluoroethylene (PTFE) filters (2 µm pore size Zefluor Membrane Filters, Pall Corp., East Hills, NY). These filters were pre and post weighed using a high precision analytical balance (XS205, Mettler-Toledo, Greifensee Switzerland). The pre and post processing of the filters is described in detail by Wanjura (2005). The PM concentrations were determined using the relationship shown in (3).

$$C = \frac{\Delta M}{\sum_i Q_i t_i} \tag{3}$$

where:

C = average concentration of PM measured over the test duration ($\mu g/m^3$),
ΔM = change in mass of the filter due to PM loading (µg),
Q_i = average air flow rate over the i^{th} time interval, and
t_i = i^{th} time interval duration (s).

The logging intervals (t_i) used by the data loggers was 12 s during 2006 and 1 min during 2007. When determining the total flow volume measured during the test period using the beginning and ending pressure drop readings from the log sheets, the time interval duration (t_i) was the total duration of the test.

The average total uncertainty due to systematic effects of the low volume sampling systems was determined to be 11.85% by Price (2004) using the method described by Kline and McClintock (1953).

The TSP concentrations measured downwind of the harvesting operations were used along with the meteorological data measured onsite in ISCST3 and AERMOD to back-calculate emission flux values. These emission flux values (g/m^2-s) were converted to emission factors (kg/ha) by multiplying by the test duration and appropriate unit conversion constants. The process of back-calculating emission flux values with ISCST3 and AERMOD described by Wanjura (2008) is briefly described here.

1. The receptor locations and source configuration data were input to the graphical user interface BREEZE (Trinity Consultants, 2006) along with processed meteorological data collected during the test period. The meteorological data used in ISCST3 were processed using EPA guidelines (EPA, 2000). The meteorological data used in AERMOD was developed using the procedures described by Wanjura (2008).
2. An initial source emission flux (Q_1) of 2.57E-3 g/m^2-s was used to model the concentrations measured at each receptor (sampler) location. The Gaussian dispersion equation used by both ISCST3 and AERMOD defines the relationship between downwind concentration and source emission rate (flux) to be direct such that an increase in emission flux will produce a proportional increase in estimated concentration. Thus, the relationship shown in equation 4 was used to determine the TSP flux (g/m^2-s) from the harvesting operation (Q_2) using the initial flux (Q_1), estimated concentrations (C_1, $\mu g/m^3$), and the measured TSP concentrations (C_2, $\mu g/m^3$).

$$\frac{C_1}{C_2} = \frac{Q_1}{Q_2} \tag{4}$$

The TSP emission factors resulting from the dispersion modeling process were converted to PM_{10} and $PM_{2.5}$ emission factors using the results of particle size distribution (PSD) analyses on the downwind TSP sampler filters. All PSD analyses were conducted with a Coulter Counter Multisizer 3 (Beckman – Coulter, Coulter Multisizer III, Miami, FL) according to the procedure described by Buser (2004), Faulkner and Shaw (2006), and Wanjura (2008). The PSD results reported by the Coulter instrument are in terms of equivalent spherical diameter (ESD). In the US, PM regulations are based on aerodynamic equivalent diameter (AED). Thus, equation 5 was used to convert the PSD results from an ESD to AED basis.

$$AED = ESD\sqrt{\rho_p} \tag{5}$$

where ρ_p is the particle density of the PM (g/cm^3). The lognormal density function was used to describe the percent mass vs. AED distribution of the PM samples. The lognormal distribution, characterized by the mass median diameter (MMD) and geometric standard deviation (GSD), provides a convenient form from which to estimate the percent of total mass within a particular size range and is commonly used to describe the distribution of single source polydisperse dusts in the atmosphere (Hinds, 1999).

Emission Factor Development Protocol II: Source Measurement of Harvester Emissions

A novel source sampling system was designed and tested on the six-row cotton picker used in the study during 2006. The initial system design captured all of the air, seed cotton, and foreign material transported to the basket from the number 3 row unit, separated the seed cotton from the air stream, and exhausted the particulate laden air through a duct with cross section area of 0.093 m^2 ($1ft^2$). Isokinetic emission concentration measurements were collected inside the exit duct of the separation system located in the basket of the harvester. Four field tests were conducted with the source sampling system during 2006 and are described by Wanjura et al. (2007).

The source sampling system was improved during 2007 to include an automated control system, improved duct work in the isokinetic sampling train, and substantially increased seed cotton separation through an optimized baffle/separator box configuration. The isokinetic nozzle (diameter = 59.6 mm) mounted inside the exit duct was designed for a sampling velocity of 732 ± 122 m/min (2400 ± 400 ft/min) based on onboard duct measurements from 2006. The sampling flow rate (passing through the nozzle), based on the design inlet velocity of the 15.2 cm (6 in) barrel cyclone (Tullis, 1997), was specified at 2.124 m^3/min (75 ft^3/min). The airflow through the system was provided by two fans mounted in series (Model HP-33, Clements National Company, Chicago, IL) and controlled by an automated ball valve (PBVPV1206, Dwyer Instruments Inc., Michigan City, IN). The pressure drop across the orifice meter (used to measure the sampling flow rate) and the duct velocity pressure measured by a pitot tube (Model 160-8, Dwyer Instruments Inc., Michigan City, IN) were measured by pressure transducers (Series 677, Dwyer Instruments Inc., Michigan City, IN). Air temperature and relative humidity as well as barometric pressure were measured inside the duct using a T/RH probe (HX94A, Omega Engineering Inc., Stamford, CT) and barometric pressure transmitter (Model 278, Setra Systems Inc., Boxborough, MA). The measurement and control system (cFP-AI-110 input module, cFP-AO-200 output module, National Instruments, Austin, TX) used with the source sampling system was operated by a laptop

computer running LabView 8.0 (LabView v. 8.0, National Instruments, Austin, TX). The measurement and control system monitored and recorded readings from the pressure transducers, T/RH probe, and barometric pressure transmitter and performed calculations for controlling the airflow rate on a 1 Hz frequency.

Ten field tests were conducted with the source sampling system in conjunction with upwind/downwind sampling at farm 3 during 2007. Each test plot was setup so that the harvester made a total of eight passes in the field covering 48 rows per test. The test plots ranged in size from 2.3 to 1.01 ha (5.7 – 2.5 ac) and the test durations ranged from 128 to 49 min. The 20.3 x 25.4 cm filters used in the source sampler (Pall Corp., Pallflex Emfab filter material 7224, East Hills, NY) were pre and post weighed using a high precision analytical balance (XS205, Mettler-Toledo, Greifensee Switzerland). A total of four filters were used during each test. The two filters initially installed in the source sampling filter bank were replaced half way through each test to prevent overloading. The cyclone bucket was weighed prior to and after each test using a laboratory balance (PB1502, Mettler-Toledo, Greifensee Switzerland) and the captured material was collected in a plastic bag for later air wash analysis. Air washing was used to quantify the mass of PM <100 μm from the cyclone bucket material and provide a PM sample for PSD analysis.

Prior to entering the field, the system operator would start the cotton conveying fan on the harvester and run the picker engine at full throttle to allow the system to stabilize before entering the field. Once the harvester fan was running at full speed, the operator switched on the source sampler fans through the laptop computer and allowed the source sampling system to equilibrate with the harvester air system before entering the field. Typically this warm-up process lasted approximately 10-15 s. The harvester speed was held approximately constant in the field at 6.44 km/h (4 mi/hr). Thus the load on the harvester would vary by yield and plant density resulting in fluctuations in the harvester fan speed. Typically, these fluctuations were brief in nature only lasting a few seconds. Therefore, the control algorithm used in the source sampler control system was configured to modulate the valve position based on a 7 s running average for both the exit duct velocity (measured by the pitot tube) and source sampler nozzle velocity (calculated by dividing the sampling flow rate measured by the orifice meter by the nozzle velocity).

TSP emission concentrations measured by the source sampling system were calculated according to equation 6.

$$EC = \frac{M_F + M_B}{\sum_i Q_i t_i} \tag{6}$$

where EC = emission concentration (g/m^3), M_F = PM mass on the four filters used in the source sampler (g), M_B = PM mass < 100μm captured in the cyclone bucket (g), Q_i = air flow rate during the ith logging interval (m^3/s), and t_i = ith logging interval (1 s). Test average total harvester TSP emission rates were calculated by multiplying the emission concentrations by the average duct flow rate (m^3/s) and then by 6 to account for the total number of seed cotton transport ducts on the harvester. Emission factors were calculated by multiplying the total harvester emission rates by the respective test durations, then normalizing the total mass of PM emitted by the test plot area or the number of lint bales harvested. PSD analyses were conducted on the PM captured on the source sampler filters and on the PM air washed from the material collected in the cyclone bucket. A mass weighted average composite PSD was calculated from the resulting PSDs and used to convert the TSP emission factors to emission factors in terms of PM_{10} and $PM_{2.5}$.

Results

Emission Factor Development Protocol I

A summary of the emission factors developed in ISCST3 and AERMOD from the sampling work conducted in 2006 and 2007 are presented in tables 1 and 2. An in depth analysis of the emission factors developed with the two models by farm/year is given by Wanjura (2007). Emission factors are reported for three harvesting treatments including 1) emission factors for the two-row harvester (2-Row), 2) emission factors for the six-row harvester with the source sampling equipment installed (6-Row w/SS), and 3) emission factors for the six-row harvester without the source sampling system installed (6-Row). The emission factors reported in tables 1 and 2 and in this section for the "6-Row w/SS" treatment were developed from the methods described in *Emission Factor Development Protocol I* and not by the measurements taken with the source sampling system. All statistical analyses were conducted in SPSS (SPSS 12.0.1, SPSS Inc., Chicago, IL) using the General Linear Model with a 0.05 level of significance.

Analysis of variance (ANOVA) tests on the ISCST3 emission factor data for each size indicator reported in terms of kg/ha indicated significant differences by farm (table 1) (p values < 0.008). Significant differences were observed in

the kg/ha emission factor data by harvesting treatment for the TSP and PM_{10} size indicators (TSP p value = 0.023, PM_{10} p value = 0.024). Significant differences in the $PM_{2.5}$ emission factor data by harvesting treatment, reported in terms of kg/ha, were not observed (p value = 0.080).

For the ISCST3 data, significant differences by farm were observed within the TSP and $PM_{2.5}$ emission factors reported in terms of kg/bale (TSP p value = 0.043, $PM_{2.5}$ p value < 0.001). Significant differences were observed in the TSP emission factor data (kg/bale) by harvester treatment (p value = 0.020) and again in the $PM_{2.5}$ emission factor data (p value = 0.01). The PM_{10} emission factor data, in terms of kg/bale, indicated no significant differences by farm (p value = 0.121) but significant differences were observed by harvesting treatment (p value = 0.019).

Table 1. Summary of ISCST3 emission factor results combining the data from farms 1, 2, and 3 (2006) and farm 3 (2007).

		PM_{10} Emission Factors		$PM_{2.5}$ Emission Factors		TSP Emission Factors	
Year	**Means For**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**
2006	Farm 1*	0.61[a]	0.15[d]	3.41E-03[g]	8.62E-04[i]	1.70[k]	0.43[n]
2006	Farm 2*	0.83[a]	0.21[d]	3.42E-03 [g]	8.60E-04[i]	1.71[k]	0.43[n]
2006	Farm 3*	0.82[a]	0.25[d]	2.48E-02	7.52E-03	2.76[k]	0.84[no]
2007	Farm 3*	2.77	0.35[d]	7.67E-03	9.63E-04[i]	7.97	1.00[o]
	2 Row*	1.79[bc] ± 0.92	0.26[e] ± 0.08	1.16E-02[h] ± 6.18E-3	4.28E-03 ± 3.52E-3	5.09[LM] ± 2.68	0.73[pq] ± 0.29
	6 Row*	0.71[b] ± 0.16	0.15[e] ± 0.04	4.45E-03[h] ± 2.08E-3	9.38E-04[J] ± 4.18E-4	1.88[L] ± 0.36	0.39[p] ± 0.1
	6 Row w/ss*[+]	2.55[c] ± 1.18	0.35[f] ± 0.13	7.38E-03[h] ± 3.14E-3	1.06E-03[J] ±3.42E-4	7.28[M] ± 3.44	0.99[q] ± 0.39

Treatment means are shown with 95% confidence intervals.
* Means with the same letter are not significantly different at the 0.05 level of significance (Fisher's LSD).
[+]Emission factors reported for the 6 row w/ss treatment were developed from the methods described in protocol I using the upwind/downwind measured concentrations and not by the source sampling protocol.

AERMOD requires substantially more meteorological input data to characterize the modeling domain. This data was not available from the instrument used in 2006 to collect meteorological data. As a result, emission factors were developed in AERMOD using the PM concentration results from the tests conducted on farm 3 during 2007 only. Wanjura (2007) defines the parameters and describes a method for calculating the required meteorological input parameters for use in AERMOD from measured data.

The emission factors developed in AERMOD for the harvesting tests conducted at farm 3 during 2007 are shown in table 2. ANOVA tests indicate significant differences in the mean emission factors by harvesting treatment for the emission factors reported in terms of kg/ha (p value = 0.046). Fisher's LSD test indicates that the 2-row and 6-row treatment means for PM_{10}, $PM_{2.5}$, and TSP are significantly different (p value = 0.014) with the 2-row treatment mean larger than the 6-row harvesting treatment. ANOVA tests on the emission factor data in terms of kg/bale indicate a significant difference (p value = 0.018) between the 6-row and 6-row w/ss treatment means for PM_{10}, $PM_{2.5}$, and TSP. Inspection of the data shows the treatment means for the 6-row w/ss to be higher than the 6-row treatment means. Yield data was not available for the 2-row tests during 2007.

Table 2. Emission factor results from the dispersion modeling procedure using AERMOD for farm 3 during 2007.

		PM_{10} Emission Factors		$PM_{2.5}$ Emission Factors		TSP Emission Factors	
Test	**Treatment**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**
1	6 Row	0.87	0.18	2.42E-03	5.10E-04	2.52	0.53
2	6 Row	1.32	0.29	3.67E-03	8.04E-01	3.81	0.84
3	6 Row	1.65	0.19	4.57E-03	5.31E-01	4.75	0.55
4	6 Row	1.39	0.16	3.85E-03	4.37E-01	4.00	0.45
5	6 Row	0.30	0.04	8.43E-04	1.14E-01	0.88	0.12
6	6 Row w/ss[+]	1.69	0.27	4.67E-03	7.39E-01	4.86	0.77
7	6 Row w/ss	1.28	0.21	3.54E-03	5.95E-01	3.68	0.62
8	6 Row w/ss	2.93	0.49	8.11E-03	1.37E+00	8.43	1.42
9	6 Row w/ss	1.62	0.24	4.50E-03	6.55E-01	4.68	0.68
10	6 Row w/ss	3.93	0.43	1.09E-02	1.20E+00	11.31	1.25
11	6 Row w/ss	4.98	0.54	1.38E-02	1.49E+00	14.34	1.55
12	6 Row w/ss	2.77	0.33	7.68E-03	9.18E-01	7.98	0.95
13	6 Row w/ss	5.22	0.64	1.45E-02	1.76E+00	15.02	1.83
14	6 Row w/ss	3.83	0.57	1.06E-02	1.58E+00	11.03	1.65
15	6 Row w/ss	1.35	0.18	3.73E-03	4.95E-01	3.88	0.51
16	2 Row	5.64	n/a	1.56E-02	n/a	16.23	n/a
17	2 Row	1.16	n/a	3.22E-03	n/a	3.35	n/a
18	2 Row	0.81	n/a	2.25E-03	n/a	2.34	n/a
19	2 Row	9.22	n/a	2.55E-02	n/a	26.55	n/a
20	2 Row	8.50	n/a	2.35E-02	n/a	24.46	n/a
21	2 Row	2.97	n/a	8.22E-03	n/a	8.54	n/a
Overall Means		3.02	0.32	8.37E-03	8.46E-01	8.70	0.92
2 Row Means*§		4.72^{a} ± 2.92	n/a	$1.31E-02^{c}$ ± 0.0081	n/a	13.58^{e} ± 8.39	n/a
6 Row Means*		1.11^{b} ± 0.47	0.17^{g} ± 0.08	$3.07E-03^{d}$ ± 0.0013	$4.78E-4^{i}$ ± 2.17E-4	3.19^{f} ± 1.33	0.50^{k} ± 0.22
6 Row w/ss Means*		2.96^{ab} ± 0.92	0.39^{h} ± 0.10	$8.20E-03^{cd}$ ± 0.0026	$1.08E-3^{J}$ ± 2.84E-4	8.52^{ef} ± 2.64	1.12^{L} ± 0.29

[+]Emission factors reported for the 6 row w/ss treatment were developed from the methods described in protocol I using the upwind/downwind measured concentrations and not by the source sampling protocol.
[*] Means with the same letter are not significantly different at the 0.05 level of significance.
[§] Yield data was not available for the 2 row harvesting treatment from 2007.
Treatment means are displayed with 95% confidence intervals.

Emission Factor Development Protocol II

The emission factors developed from the source measurement system used onboard the six-row harvester during 2007 are shown in table 3. These emission factors represent the emission factors for the PM emitted from the basket of the harvester. The mean PM_{10}, $PM_{2.5}$, and TSP emission factors developed with the source sampling system were 0.47 ± 0.085, 8.53E-04 ± 1.18E-04, and 1.40 ± 0.261 kg/ha, respectively. Wanjura (2007) states that the uncertainty due to systematic effects in the emission factors determined with the source sampling system is approximately 3%.

Table 3. Six-row harvester emission factors from ten tests performed with the source sampling system on farm 3 during 2007.

	Emission Factors (kg/ha)			Emission Factors (kg/bale)		
Rep	**TSP**	**PM_{10}**	**$PM_{2.5}$**	**TSP**	**PM_{10}**	**$PM_{2.5}$**
1	0.96	0.34	5.88E-04	0.15	0.05	9.30E-05
2	0.89	0.33	5.60E-04	0.15	0.05	9.40E-05
3	0.97	0.35	7.21E-04	0.16	0.06	1.22E-04
4	1.35	0.48	9.06E-04	0.20	0.07	1.32E-04
5	1.97	0.69	1.13E-03	0.22	0.08	1.25E-04
6	1.90	0.66	1.14E-03	0.20	0.07	1.23E-04
7	1.94	0.57	9.39E-04	0.23	0.07	1.12E-04
8	1.36	0.44	7.64E-04	0.17	0.05	9.31E-05
9	1.52	0.54	1.00E-03	0.23	0.08	1.50E-04
10	1.12	0.33	7.79E-04	0.15	0.04	1.03E-04
Mean*	1.40 ± 0.261	0.47 ± 0.085	8.53E-04 ± 1.18E-04	0.19 ± 0.021	0.06 ± 0.009	1.15E-04 ± 1.2E-05
St. Dev.	0.42	0.14	2.05E-04	0.03	0.01	1.90E-05

*Means displayed with 95% confidence intervals.

Wanjura (2007) describes the results of a study conducted to quantify the PM emissions generated by the interaction of the harvester wheels and the soil surface. The TSP, PM_{10}, and $PM_{2.5}$ emission factors (with 95% confidence intervals) reported by Wanjura (2007) for the PM generated by the wheel/soil surface interaction are 0.24 ± 0.11, 0.08 ± 0.036, and 7.27E-04 ± 3.32E-04 kg/ha respectively. Combining the basket and wheel/soil surface PM emission factors, the total TSP, PM_{10}, and $PM_{2.5}$ emission factors were 1.64 ± 0.37, 0.55 ± 0.12, and 1.58E-03 ± 4.5E-04 kg/ha, respectively (1.46 ± 0.33, 0.49 ± 0.11, and 1.41E-03 ± 4.01E-04 lb/ac, respectively). In terms of kg/bale, the TSP, PM_{10}, and $PM_{2.5}$ emission factors from the source measurements of PM emissions from the six row machine were 0.22 ± 0.019, 0.07 ± 0.007, and 2.15E-4 ± 1.49E-5 kg/bale, respectively (0.48 ± 0.04, 0.15 ± 0.015, and 4.74E-4 ± 3.3E-5 lb/bale, respectively). These emission factors are inclusive of the PM emissions generated by the harvester wheel/soil surface interaction and represent the average mass per bale emission factors measured over a crop yield range from 5.9 to 9.3 bales/ha (2.4 to 3.8 bales/ac).

In an effort to further investigate the trends in the emission rate data, correlation analyses were conducted on the emission rate variables (i.e. PM_{10}, $PM_{2.5}$, and TSP emission rates in terms of kg/min). The emission rate variables were correlated with crop yield (lint bales/ha), test plot area (ha), test duration (min), soil mass % < 75 µm, soil mass % < 106 µm, seed cotton moisture content (%), and soil surface moisture content (%). Wanjura (2007) describes the collection and processing of the soil and seed cotton samples used in the correlation analysis. The results of the correlation analysis using the source sampler emission rate data are shown in Table 4.

Table 4. Correlation results of the source sampler emission rate data with area, yield, test duration, soil mass % < 75 µm, soil mass % < 106 µm, seed cotton moisture content, and soil surface moisture content.

		Emission Rate (g/min)		
		TSP	PM_{10}	PM2.5
Area (ha)	**R**	-0.503	-0.379	-0.611
	p value	0.1382	0.2795	0.0605
Yield (bales/ha)*	**R**	0.850*	0.775*	0.718
	p value	0.0018	0.0085	0.0194
Duration (min)	**R**	-0.539	-0.425	-0.682
	p value	0.1080	0.2203	0.0298
Soil Mass % < 75 µm	**R**	-0.460	-0.377	-0.086
	p value	0.1815	0.2832	0.8129
Soil Mass % < 106 µm	**R**	-0.334	-0.272	0.070
	p value	0.3458	0.4471	0.8473
Seed Cotton Moisture Content (%)	**R**	-0.005	-0.168	-0.028
	p value	0.9885	0.6427	0.9384
Soil Surface Moisture Content (%)	**R**	0.018	-0.071	-0.153
	p value	0.9610	0.8448	0.6725

*Correlation coefficients are statistically significant at the 0.01 level of significance.

Significant correlations at the 0.01 level were observed in the relationships between TSP and PM_{10} emission rates with yield. The $PM_{2.5}$ emission rate correlation with yield is significant at the 0.05 level. Poor correlations with test plot area were observed for the emission rate data for any size indicator. These results indicate that PM emission rates are more closely related with the mass of material processed through the harvester on a unit area basis (i.e. yield) than with land area. Therefore it is appropriate to list PM emission factors for cotton harvesting on a mass of PM emitted per lint bale harvested basis.

Particle Size Distribution Results

The PSD analysis results on the TSP sampler filters from the field tests conducted during 2006 and 2007 are shown in tables 5 and 6, respectively. The composite PSD results from the analyses on the PM collected by the source sampling system are shown in table 7. The MMD and GSD values reported in tables 5, 6, and 7 define the best fit lognormal distributions which describe the measured PSDs.

Table 5. PSD analysis results of the PM on the TSP sampler filters from the tests conducted in 2006 on farms 1, 2, and 3. The particle densities used to convert ESD to AED for farm 1, 2, and 3 are 1.86, 1.79, and 1.97 g/cm^3, respectively.

	Farm 1 (n = 10)			Farm 2 (n = 9)			Farm 3 (n = 11)		
	Mean	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
MMD (µm)	13.2	17.3	9.9	10.4	13.5	7.9	14.9	18.0	12.2
GSD	2.1	2.3	1.9	2.2	2.5	1.9	2.1	2.3	1.8
Lognormal Distribution									
% PM_{10}	36.0	50.3	22.6	49.3	64.2	34.2	29.7	39.6	18.3
% $PM_{2.5}$	1.6	4.0	0.1	4.0	7.2	1.1	0.9	2.0	0.1
Coulter Counter PSD									
% PM_{10}	35.8	49.6	23.5	48.8	63.3	33.5	30.3	39.5	19.2
% $PM_{2.5}$	0.2	0.4	0.1	0.2	0.3	0.1	0.1	0.2	0.1

Table 6. TSP sampler filter PSD analysis result statistics for samples taken on farm 3 during 2007. The particle density used to convert ESD to AED was 1.59 g/cm^3.

	TSP Sampler PSD Statistics		
	Mean	**Max**	**Min**
MMD (µm)	14.7	21.1	9.7
GSD	2.2	2.5	2.0
Lognormal Distribution			
% PM_{10}	33.6	52.0	16.0
% $PM_{2.5}$	1.7	4.3	0.2
Coulter Counter PSD			
% PM_{10}	34.7	50.9	21.7
% $PM_{2.5}$	0.1	0.2	0.01

The mean MMD and GSD values of the TSP sampler filter PSDs measured in 2007 fall within the ranges measured during 2006. The mean MMD and GSD values measured in 2007 were 14.7 µm and 2.2, respectively. Similarly, the mass percent PM_{10} and $PM_{2.5}$ for the 2007 TSP sampler filters measured by the Coulter Counter also fall within the ranges measured during 2006. The mean percent PM_{10} and $PM_{2.5}$ measured on the TSP sampler filters in 2007 were 34.7 and 0.1%, respectively.

The mean MMD and GSD values for the source sampler composite PSDs were 14.3 µm and 2.2, respectively (table 7). The mean measured percent PM_{10} and $PM_{2.5}$ values were 34.0 and 0.06% respectively. The ranges for MMD and GSD as well as %PM_{10} and %$PM_{2.5}$ were substantially smaller than those observed for the TSP sampler filter PSD analyses from 2006 and 2007. TSP sampler filter PSDs are subject to wider variation due to the changes in wind direction during a test. The wind direction at the beginning a particular test may be directly from the source to the sampler but may shift away from the sampler by the end of the test.

Table 7. Result statistics for the mass weighted average composite PSDs developed from the PSDs of the source sampler filters and PM < 100 µm captured in the source sampler cyclone bucket during 2007.

	Source Sampler Composite PSD Statistics		
	Mean	**Max**	**Min**
MMD (µm)	14.3	16.6	13.4
GSD	2.2	2.4	2.1
Lognormal Distribution			
% PM_{10}	32.7	35.5	27.3
% $PM_{2.5}$	1.40	2.44	0.84
Coulter Counter PSD			
% PM_{10}	34.0	36.6	29.5
% $PM_{2.5}$	0.06	0.07	0.05

Conclusions

PM emissions from cotton harvesting operations in Texas during 2006 and 2007 were measured using both indirect and direct techniques. The first protocol (indirect technique) used TSP concentration measurements collected downwind of the source, meteorological data collected onsite, and a dispersion model to back calculate emission flux estimates from harvesting operations. The resulting TSP emission flux values were converted to emission factors in terms of kg/ha and kg/bale harvested. Mass fraction measurements for PM_{10} and $PM_{2.5}$ from PSD analyses on the TSP filters were used to calculate PM_{10} and $PM_{2.5}$ emission factors from the TSP emission factors.

The second protocol (direct technique) measured emission concentrations onboard a six-row cotton picker as it harvested cotton. Air flow measurements were used with measured emission concentrations to determine TSP emission rates from the harvester on a mass per unit time basis. Production data on crop yield and area harvested were used to convert emission rates to emission factors in terms of kg/ha and kg/bale harvested. The results of PSD analyses on the PM collected by the source sampling system were used to calculate PM_{10} and $PM_{2.5}$ emission factors from TSP emission factors.

The major findings of this study are:

- Statistically significant differences between the two-row and six-row treatment emission factors developed in ISCST3 were not observed for the combined data set. However, the emission factors developed for the two-row and six-row treatments in AERMOD were significantly different. Both models indicated a substantial difference between the two-row and six-row emission factors. Additionally, both models showed the two-row treatment emission factors to be higher than those of the six-row treatment. The difference in the mean PM_{10} emission factors for the two-row and six-row treatments developed in ISCST3 and AERMOD were 1.08 and 3.61 kg/ha, respectively (0.96 and 3.22 lb/ac, respectively). The difference in the mean $PM_{2.5}$ emission factors for the two-row and six-row machines in ISCST3 and AERMOD were 0.007 and 0.01 kg/ha, respectively (0.006 and 0.009 lb/ac, respectively).
- The TSP, PM_{10}, and $PM_{2.5}$ emission factors developed using the source measurement protocol in 2007 were 1.64 ± 0.37, 0.55 ± 0.12, and 1.58E-03 ± 4.5E-04 kg/ha, respectively (1.46 ± 0.33, 0.49 ± 0.11, and 1.41E-03 ± 4.01E-04 lb/ac, respectively). These emission factors are inclusive of the PM emissions generated by the interaction of the harvester wheels and the soil surface as the machine moves through the field. The emission factors developed through the source sampling protocol exhibit much higher precision and much less uncertainty than those developed through the protocol employing upwind/downwind sampling with dispersion modeling.
- Additional analysis of the emission rates calculated from the source emission concentration measurements indicates that PM emissions from cotton harvesting operations are more closely correlated with crop yield than with land area harvested. Thus, the most appropriate basis on which to report emission factors from cotton harvesting is in terms of mass per lint bale harvested (e.g. kg/bale). In terms of kg/bale, the TSP, PM_{10}, and $PM_{2.5}$ emission factors from the source measurements of PM emissions from the six row machine were 0.22 ± 0.019, 0.07 ± 0.007, and 2.15E-4 ± 1.49E-5 kg/bale, respectively (0.48 ± 0.04, 0.15 ± 0.015, and 4.74E-4 ± 3.3E-5 lb/bale, respectively). These emission factors are inclusive of the PM emissions generated by the harvester wheel/soil surface interaction and represent the average mass per bale emission factors measured over a crop yield range from 5.9 to 9.3 bales/ha (2.4 to 3.8 bales/ac).
- Particle size distribution analysis of the TSP sampler filters indicates that the PSD of the dust measured downwind of the harvesting operation can be approximated by a lognormal density function characterized by MMD and GSD values of 14 μm and 2.2 respectively. The mass percent PM_{10} and $PM_{2.5}$ from PSD analysis of the TSP filters were on the order of 35 and 0.1%, respectively. These results are further corroborated by the PSD analysis on the PM captured on the source sampler filters and PM < 100 μm captured in the source sampler cyclone bucket.

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