2007 Beltwide Cotton Conferences, New Orleans, Louisiana, January 9-12, 2007

A PRELIMINARY PARTICULATE MATTER EMISSION FACTOR FROM COTTON HARVESTING

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Abstract

Particulate matter (PM) sampling of cotton harvesting operations at three locations in Texas was conducted during the summer of 2006. PM emissions generated by a two-row (John Deere model 9910) and six-row (John Deere model 9996) cotton picker were measured at each sampling location. The PM emissions from the two-row and six-row machines were measured using a protocol employing collocated low volume total suspended particulate (TSP) and PM_{10} samplers upwind and downwind of the operation. The concentrations measured by the collocated samplers were used in the Industrial Source Complex Short Term version 3 (ISCST3) dispersion model to back calculate the emission fluxes from the source (harvesting operation). The resulting TSP emission fluxes were converted to PM_{10} and $PM_{2.5}$ emission factors using the results of particle size distribution (PSD) analyses. The mean PM_{10} emission factors for the two-row and six-row harvesters resulting from this protocol are 0.89 ± 0.20 and 0.66 ± 0.27 kg/ha, respectively (0.79 ± 0.18 and 0.59 ± 0.24 lb/ac, respectively). Similarly, the mean $PM_{2.5}$ emission factors for the two-row and six-row harvesters resulting from this protocol are 0.014 ± 0.011 and 0.005 ± 0.043 kg/ha, respectively (0.012 ± 0.01 and 0.004 ± 0.04 lb/ac, respectively). Large uncertainty in the emission factors developed using the upwind/downwind sampler protocol was observed. Thus, the differences in the PM_{10} and $PM_{2.5}$ emission factors for the two-row and six-row harvesters are not statistically significant ($\alpha = 0.05$). However, the PM emission factors from the six-row harvester trend lower than the emission factors from the two-row machine. In addition, a novel source sampling system was developed to measure the PM emission concentration from the six-row harvester. The resulting emission concentrations were converted to emission factors and compared to the emission factors resulting from the collocated sampler/ISCST3 protocol. Emission factor data for the six-row harvester from the source sampling system was collected at the first two sampling locations. The PM_{10} and $PM_{2.5}$ emission factors resulting from the source sampling system on the six-row harvester are 45 and 0.15 g/ha, respectively. An analysis of the emission factor data from the source sampling system indicates that it is more appropriate to report PM emission factors on a mass of PM per unit area basis than on a mass of PM per bale harvested basis.

Introduction

Air pollution regulation across the US is implemented and enforced by state air pollution regulatory agencies (SAPRA). This authority is granted to the SAPRA by the federal EPA upon approval of the state implementation plan (SIP). The SIP outlines the steps that a state will take to ensure that the air quality within the state meets federal air quality standards (CFR, 1996). The National Ambient Air Quality Standards (NAAQS) are established for six criteria pollutants including SO_x, NO_x, CO, ozone, PM_{10}, and $PM_{2.5}$. An area within a state may be classified as a non-attainment area if the ambient concentration of a criteria pollutant is shown to exceed the NAAQS by measurement or through dispersion modeling.

On September 21, 2006 EPA finished the five year cyclical review of the PM NAAQS and published "the most protective suite of national air quality standards for particle pollution ever" (EPA, 2006). Included in these revisions to the PM NAAQS were the removal of the annual PM_{10} standard of 50 $\mu g/m^3$ and the lowering of the 24 hour average $PM_{2.5}$ standard from 65 to 35 $\mu g/m^3$. The EPA based the decision to implement these NAAQS revisions on an in depth review of the most current and up-to-date scientific studies which investigated the health related impacts of PM pollution on certain sensitive populations.

The primary criteria pollutant of interest to the cotton industry is PM_{10}. PM_{10} refers to the fraction of particulate matter (PM) with aerodynamic equivalent diameter (AED) less than or equal to 10 micrometers (μm). The 24-hour average NAAQS concentration limit for PM_{10} is 150 $\mu g/m^3$ (Federal Register, 2006). $PM_{2.5}$ refers to particles (liquid or solid) that have an AED less than or equal to 2.5 μm. The NAAQS limits the 24 hour average concentration of $PM_{2.5}$ to 35 $\mu g/m^3$. The annual average NAAQS concentration limit for $PM_{2.5}$ is 15 $\mu g/m^3$ (Federal Register, 2006). Historically, the $PM_{2.5}$ NAAQS has been of little concern to agricultural producers. Agricultural operations (including cotton production and processing) typically emit PM with larger particle sizes than urban sources (Wanjura, 2005) and which contain very few particles smaller than 2.5 μm

Cotton producers in some states across the cotton belt are facing increased regulatory pressure from SAPRAs due to poor air quality (PM_{10} and $PM_{2.5}$ NAAQS non-attainment status) and inaccurate emission factors. Cotton producers in California have been identified as a significant source of PM_{10} due to the use of a flawed emission factor. As a result, agricultural producers are required to obtain operating permits from the SAPRA (CARB, 2003) and submit Conservation Management Practice (CMP) plans detailing the actions to be taken by the producer to reduce fugitive PM emissions (SJVAPCD, 2004 a and b). Further, the reduction of the $PM_{2.5}$ NAAQS accomplished during the five year review of the NAAQS by EPA in 2006 will present cotton producers with new air quality regulation challenges due to the lack of accurate emission factors.

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). Emission factors are used by air pollution regulators to determine annual emissions inventories and in dispersion models to predict downwind concentrations resulting from the pollutant emissions from a source.

A limited amount of research has been conducted to quantify the PM_{10} 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. It was reported by Snyder and Blackwood (1977) that particulate matter samplers followed the harvesting machine at a fixed distance within the plume to collect particulate matter concentrations. The authors stated further that particulate matter concentrations downwind of trailer loading operations were taken by placing samplers at a fixed downwind distance. It is stated in AP-42 (EPA, 1995) that the emission factors reported are based on the following assumptions:

1. the average speed of the picking machine was 1.34 m/s (3.0 mph),
2. the basket capacity of the picking machine was 109 kg (240 lbs),
3. the capacity of the transport trailers were 6 baskets each, and
4. the average cotton lint yield was 1.17 bales/acre for pickers.

The information given in AP-42 (EPA, 1995) is based on antiquated harvesting technology and a flawed protocol. No detail is given as to how the researchers used measured concentrations to determine the emissions from the harvesting machine. The same is true for the method used to determine the emission rate from the trailer loading operation. Did the researchers use a dispersion model to back-calculate the emission rates from these operations, and if so, which one? Further, the emission factors reported are based on concentrations of particulate matter less than 7 μm mean aerodynamic diameter. This size range of particulate matter represents only part of the regulated size fraction of dust in the US. PM_{10} concentrations include the mass of all particles less than 10 μm in aerodynamic diameter.

The harvesting machinery used to develop the emission factors in AP-42 (EPA, 1995) does not represent the technology that is used today. Today's machinery can harvest up to six rows of cotton per pass with basket capacities in the range of 4086 kg (9000 lbs) (basket volume: 40 m^3 or 1400 ft^3) . Clearly, the machines used to harvest the US cotton crop today are significantly different from the machines used in the 1970's, when the Snyder and Blackwood study was conducted.

Farming practices have also changed resulting in increased yields and field efficiencies since the 1970's. In particular, US cotton production has increased from approximately 10 million bales to around 20 million bales over the last 30 years while the total production area has remained the same (USDA, 2005). This is due primarily to improved plant varieties producing higher yields and farming practices that optimize the use of input resources to produce maximum yields. Average annual yields have increased from around 0.85 bales per acre to around 1.5 bales per acre in 2004 (USDA, 2005).

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 protocol used by Flocchini et al. (2001) is summarized as follows:

1. Ambient PM_{10} samplers (Sierra Anderson Model 246b) were used to measure PM_{10} concentrations both upwind and downwind of the harvesting operation.
2. The vertical concentration profile of the dust plume downwind of the operation was quantified using a series of three mobile towers with PM_{10} samplers and anemometers mounted at several heights.
3. A LIDAR instrument was also used to help describe the shape of the plume downwind of the harvesting operation. The results of the LIDAR instrument give insight as to the shape of the plume as it travels downwind, but it does not give any reliable indication of the concentration or size of the particulate matter within the plume.
4. A mass balance box model was used with the concentration data to determine the area source emission rate from the operation. Several different methods to describe the shape of the plume were used within the box model to assess the influence of the plume shape on the estimated emission factors.

The work by Flocchini et al. (2001) represents the most up-to-date information regarding PM_{10} emissions from cotton harvesting operations. However, the sampling protocol used by Flocchini et al. (2001) contained several components that introduced significant levels of uncertainty, including:

1. The federal reference method PM_{10} samplers have been shown to exhibit substantial over-sampling errors when sampling agricultural dusts. Buser et al. (2001) indicated that the Federal Reference Method (FRM) PM_{10} sampler could theoretically overstate PM_{10} concentrations by as much as 340% when sampling a dust with mass median diameter (MMD) and geometric standard deviation (GSD) of 20μm and 2.0, respectively. The over-sampling errors reported by Buser et al. (2001) have been observed in field work conducted by several sources including Wanjura et al. (2005a) and Capareda et al. (2005).
2. The box model used to estimate the area source emission rate from the harvesting operation relies on several assumptions pertaining to the height of the plume and depth of the emitting area. In addition, the emission rates determined using the box model are specific to the box model and may not be appropriate to use with another dispersion model. In other words, an emission rate developed with the box model and subsequently used in the box model will return the same measured concentrations initially used to develop the emission rate. However, if the same emission rate is used in another dispersion model, such as those utilized by SAPRAs, it is likely that the model will not return the measured concentration values. This is important from a regulatory standpoint.

In order for agricultural sources to be equitably regulated, accurate emissions inventories must be calculated by air pollution regulators using accurate, science-based emission factors. Along with facilitating the equitable regulation of agricultural sources, accurate emissions inventories will help regulators and agricultural producers focus their emissions reduction efforts on the operations or processes that produce the highest level of emissions.

The objective of this manuscript is to report the first year findings of a two year study to develop a science-based PM emission factor for modern picker type cotton harvesting machines. The results of this study indicate that the overall emission factor of cotton harvesting operations is lower than the current emission factor used by air pollution regulators in California. The PM_{10} and $PM_{2.5}$ emission factors developed for the six-row harvester from the work of this study are on the order of 0.66 kg/ha and 5 g/ha , respectively. Differences in the level of PM emissions between two-row and six-row harvesting equipment were observed. The PM_{10} and $PM_{2.5}$ emission factors developed for the two-row harvester are on the order of 0.89 kg/ha and 14 g/ha, respectively.

Methods

Sampling Locations

Farm #1 is located approximately 8 km south of El Campo, TX. The dark, clay soil was fairly wet at the beginning of the four day sampling event but dried out by the end. The 28.3 ha (70 ac) rectangular field was planted with a 96.5 cm (38 in) row spacing oriented in a north – south pattern. The field was divided into two sections (16.2 ha to the south and 12.1 ha to the north) by a house and grazing area (see figure 1). The southern section of the field was subdivided into 8, 1.6 ha (4 acre approximate size) test plots (450 m row length). The northern section was subdivided into 4, 2.4 ha (6 acre approximate size) test plots (245 m row length). A conventional picker variety of cotton was planted and defoliated with one application of Ginstar® (Bayer Crop Science, Research Triangle Park, NC).

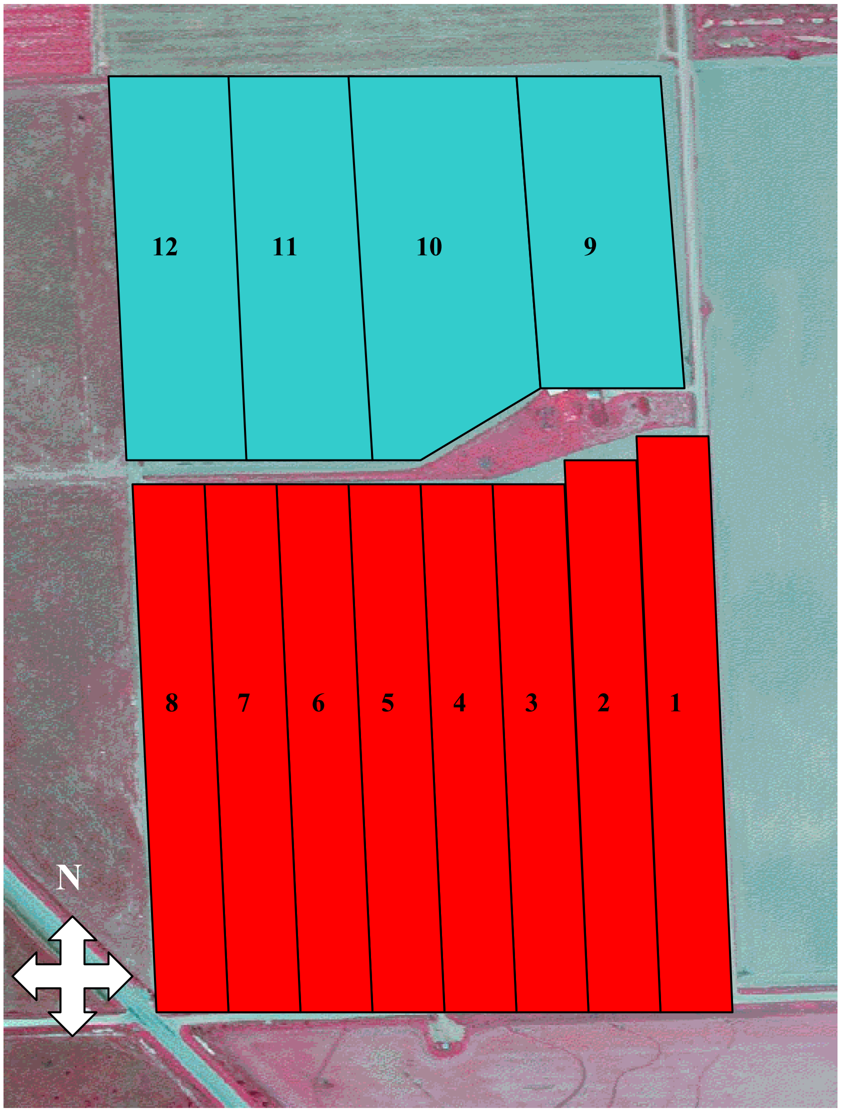

Figure 1. Layout of the test plots used in the testing at farm #1.

Ten of the original twelve planned sampling tests were conducted at farm #1 due to unexpected delays caused by equipment failures and the labor intensive nature of the sampling work. Approximately 6 man hours of labor were required to install and remove the source sampling system between tests. Moving and resetting the collocated TSP and PM_{10} samplers between tests required approximately three to four man hours. Ten to fourteen hour working days became common place over the duration of the sampling work conducted at farm #1.

Three treatments were tested in a randomized complete block design (blocked by day/replication). The three treatments included 1) upwind/downwind sampling of the PM emissions from the two-row harvester ("2 row"), 2) upwind/downwind sampling of the PM emissions from the six-row harvester without the source sampling system ("6 row"), and 3) source sampling in conjunction with upwind/downwind sampling of the six-row harvester emissions ("6 row w/SS"). The experimental design for the tests conducted at farm #1 is shown in table 1.

Table 1. Experimental design of the sampling tests conducted at farm #1.

Test Order	Day 1	Day 2	Day 3	Day 4
1	2 Row	6 row w/SS	2 Row	6 Row
2	6 Row	6 Row	6 Row	2 Row
3			6 row w/SS	6 row w/SS

Farm #2 is located approximately 21 km south-southwest of College Station, TX. The soils varied across the farm from clay to sandy clay loam. The soil was dry during the four day sampling event. The rectangular 32.4 ha (80 ac) field is oriented in a northeast-southwest manner with rows oriented northwest-southeast (96.5 cm row spacing). The field was subdivided into 9, 1.9 ha (4.7 ac) test plots, each with 366 m row length (figure 2). DP555 BG/RR was grown on farm #2 and Def® and Prep® (Bayer Crop Science, Research Triangle Park, NC) were used to defoliate the crop and open the bolls.

Figure 2. Layout of the test plots used in the tests conducted on farm #2.

Nine total tests were planned for farm 2. Equipment malfunctions and the labor intensive nature of the work again caused a reduction in the number of tests conducted to eight. The experimental design was modified from that used at farm #1 to a randomized complete block design with blocks on location within the field. This change in the experimental design was made to account for differences in soil type within the field and to reduce the labor involved with installing and removing the source sampling equipment between tests. The test plots were ordered sequentially from northeast to southwest and three groups of adjacent test plots were formed (area 1 = plots 1-3, area 2 = plots 4-6, area 3 = plots 7-9). The treatments were randomly assigned to one plot within each area of the field and all of the plots for one treatment were harvested before proceeding to the next treatment. The design of the experiments conducted at farm #2 is shown in table 2.

Table 2. Design of the experiments conducted at farm #2.

Test No.	Treatment	Plot No.	Area No. (Experimental Block)	Day of Test
1	6 Row	1	1	1
2	6 Row	5	2	1
3	6 Row	7	3	2
4	2 Row	2	1	2
5	2 Row	4	2	2
6	2 Row	8	3	3
7	6 Row w/SS	3	1	3
8	6 Row w/SS	6	2	3

Farm #3 is located approximately 12.5 km southwest of College Station, TX. The northeastern edge of the field is bordered by the Brazos River. The soil varies across the field from clay to sand and remained dry during the sampling event. The rows are spaced 101.6 cm (40 in) apart and are oriented northeast to southwest. The 13.8 ha (35 ac) field was subdivided into six test plots with areas ranging from 2 to 2.6 ha (4.9 to 6.9 ac) (see figure 3). The row lengths of the test plots ranged from 184 to 300 m. FM988 LL/B2 was grown and defoliated with one treatment of Ginstar ® and Dropp ® (Bayer Crop Science, Research Triangle Park, NC).

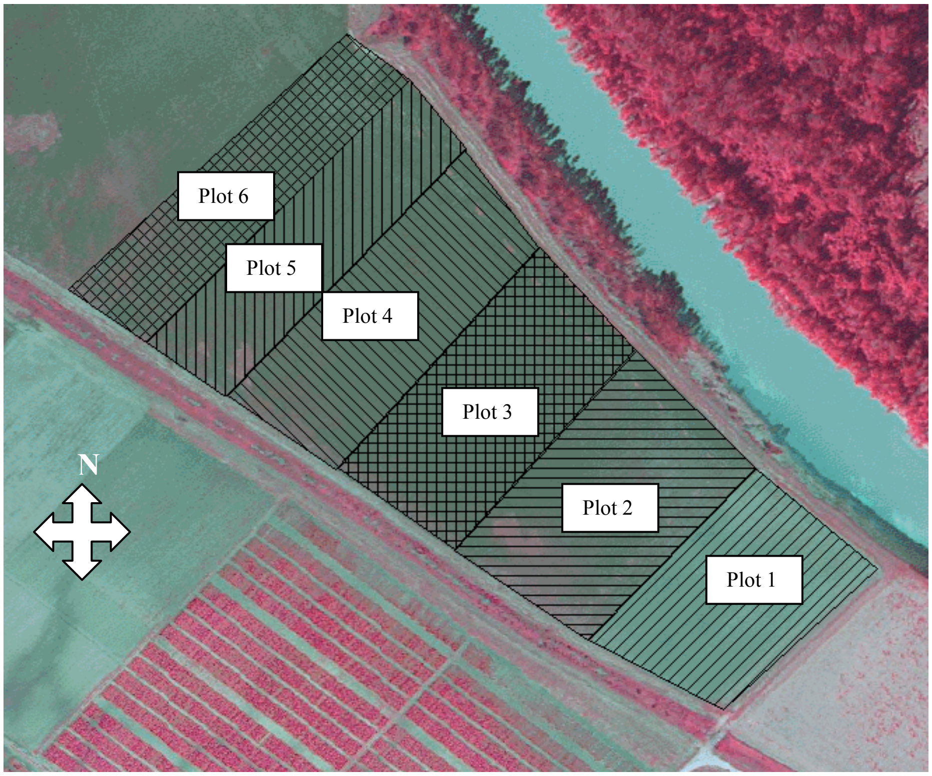

Figure 3. Layout of test plots on farm #3.

Since only six test plots were available for use on farm #3, the decision was made to reduce the number of treatments tested to two. Source sampling of the six-row harvester was not conducted at farm #3. The experiments were designed as a randomized complete block design with a block on replication (similar to that used at farm #1). The soil texture varied consistently across the field from well drained sand (plot #1) to a clay soil (plot #6). Thus the plots were harvested in sequential order (2 plots per day) with the order of the treatments randomized. A problem in the right side picking unit on the two-row machine caused a fire during test 3. Only 84 of 108 rows were harvested during test 3 prior to the fire and the others were not harvested that day to avoid the further risk of fire. Due to the fire, the test on plot four was not conducted. Thus, five of six tests were conducted at farm #3. The design of the experiments conducted at farm #3 is shown in table 3.

Table 3. Order of the experiments conducted at farm #3.

Test No.	Treatment	Day
1	2 Row	1
2	6 Row	1
3*	2 Row	2
4	6 Row	3
5	2 Row	3

*Fire during test

Soil samples, 3 kg bulk seed cotton samples from the harvester, and hand harvested seed cotton samples for moisture analysis were taken from each test plot on each farm. Size distribution data from each soil sample were obtained by sieve analysis. The designation of the sieves used are 22.4 mm (7/8 in), 16 mm (5/8 in), 9.5 mm (3/8 in), 8 mm (5/16 in), 2 mm (#10), 1.4 mm (#14), 710 µm (#25), 180 µm (#80), 106 µm (#140), and 75 µm (#200). The sieves were divided into two stacks and the soil samples were processed for 20 min in each stack. The net material mass remaining in each sieve was used to determine the mass percent of the original soil sample mass within each size range.

The bulk seed cotton samples were air washed to remove the PM smaller than 100 µm. The PM removed in the air wash process was used in later particle density and particle size distribution analyses.

The hand harvested seed cotton samples were stored in air tight containers for transport back to the laboratory for moisture content analysis by the 10 hr oven method (USDA, 1972). The net change in the mass of the samples was measured and divided by the original sample mass to determine the percent moisture for each sample.

Upwind/Downwind PM Concentration Measurements

Six sets of collocated low volume TSP and PM_{10} samplers were used to measure the PM concentrations upwind and down wind of the harvesting operation during each test. Five sets of the collocated samplers were arranged around the test plots to measure the PM concentrations downwind of the harvesting operation. One set of collocated samplers was placed at a distance (100 – 200 m approximately) away from the test plot to measure the background PM concentrations in the area. The common sampler arrangement around the test plots is shown in figure 4. This arrangement was modified during tests 1 – 5 of farm #2 where the downwind samplers were all placed inline along the downwind side of the test plot (figure 5). This modification was made to increase the number of samplers measuring the highest downwind concentrations from the operation. The arrangement shown in figure 4 was used to ensure that a reliable downwind concentration would be measured from the harvesting operation in times of meandering wind direction.

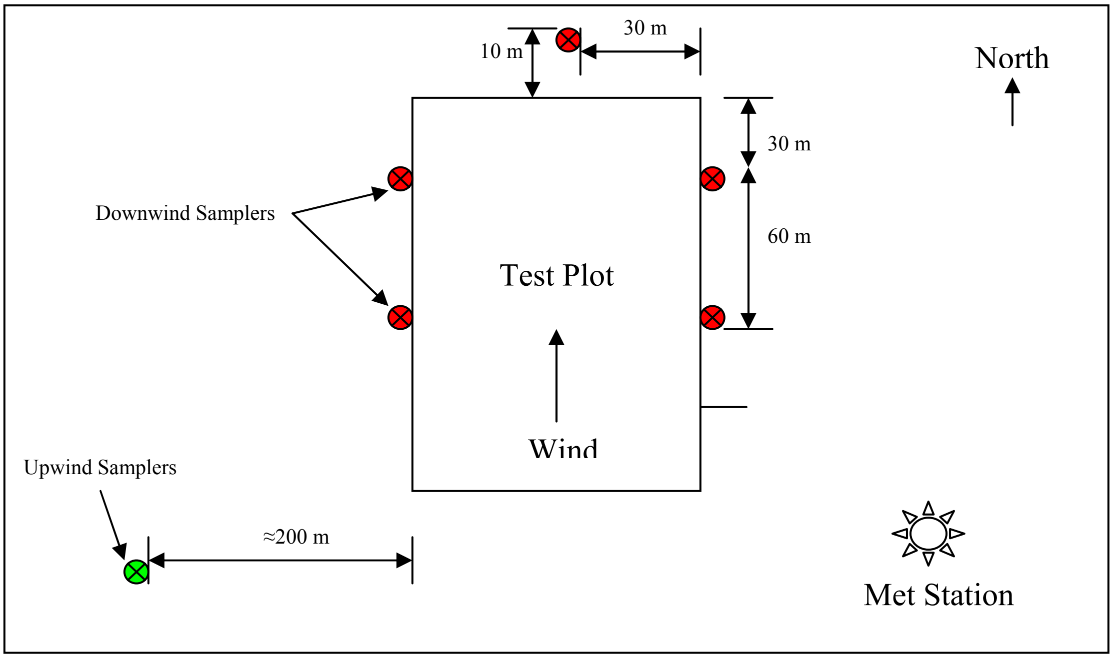

Figure 4. Typical arrangement of collocated TSP/PM_{10} samplers around the test plots.

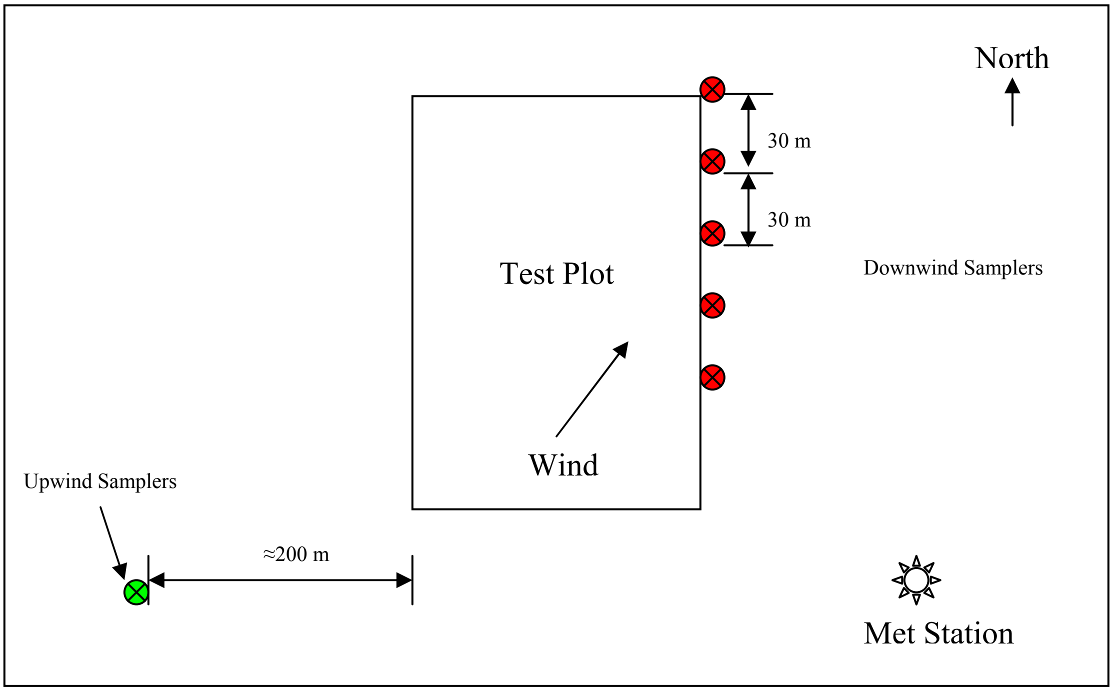

Figure 5. Modified sampler arrangement used during tests 1 – 5 at farm #2.

The TSP and PM_{10} samplers used to measure the PM concentrations upwind and downwind of the harvesting operations both operated with an air flow rate of 16.7 l/min (Wanjura et. al., 2005b). The flow rate of the samplers used in this study is approximately 85 times less than the flow rate of a comparable "high volume" federal reference method (FRM) TSP or PM_{10} sampler (1.42 m^3/min). Thus the term low volume is used to describe the sampler air flow rate of the samplers used in this study.

The TSP inlet head used in this study was designed and evaluated by Wanjura et. al. (2005b). TSP concentration measurements represent the concentration of a broad range of inhaleable particles. The cutpoint of the TSP sampler was reported to be around 45 µm with a slope of 1.5 by McFarland and Ortiz (1983). Thus the TSP sampler concentration represents the concentration of airborne particles with diameters up to 100 µm. The results of subsequent PSD analysis of the PM captured on the TSP sampler filter was used to determine the true concentration of PM less than a given particle diameter (i.e. true PM_{10} or $PM_{2.5}$ concentrations) (Buser, 2004).

The PM_{10} samplers used the Graseby-Andersen FRM PM_{10} inlet. The concentrations measured by the PM_{10} samplers are intended to represent the concentration of PM less than 10 µm. However, the concentrations measured by the FRM PM_{10} samplers do not accurately represent true PM_{10} concentrations when sampling PM from agricultural operations due to the interaction between the sampler performance characteristics and the PSD of the sampled PM (Buser, 2005). PM_{10} concentration measurements were made in this study using FRM PM_{10} samplers to investigate this sampling error phenomenon in the presence of dust emitted from cotton harvesting operations.

The systems used to establish and control the flow rate of the TSP and PM_{10} samplers were identical. The flow system used a 0.09 kW (1/8 hp) diaphragm pump to draw the 16.7 l/min sample flow rate through the sampler 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, Mass). 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.

$$Q = 3.478 * K * D_o^{\ 2} * \sqrt{\frac{\Delta P}{\rho_a}} \qquad (1)$$

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 was 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. The density of air used in (1) was calculated using the air properties recorded by the weather station in equation 2.

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

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 (AG245, Mettler-Toledo, Greifensee Switzerland). The pre and post processing of the filters is described 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 (μg/m^3),
ΔM = change in mass of the filter due to PM loading (μg),
Q_i = average air flow rate over the ith time interval, and
t_i = ith time interval duration (s).

The logging intervals (t_i) used by the data loggers was 12 seconds. However, 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 duration of the test.

Source Sampling

A novel source sampling system was designed to directly measure the PM emissions from the seed cotton transport ducts on the six-row harvester. The source sampling system was designed to collect all of the air, seed cotton, and foreign material (plant material, soil, etc.) from one of the ducts on the six-row harvester, separate the seed cotton from the air stream, and exhaust the particulate laden air stream after collecting an isokinetic emission concentration sample. Although an in depth discussion of the source sampling system is outside the scope of this manuscript, a brief description of the design of the source sampler is given.

Pitot tube traverses were performed on the six ducts which transport the seed cotton from the picking units to the basket to determine the average air velocity in each duct. The average air velocities ranged from 1070 to 1525 m/min (3500 – 5000 ft/min) across the six ducts. The maximum average velocity was observed in Duct #3 (numbering the ducts from left to right sitting in the operator seat). Thus, the source sampling system was designed for use on duct #3 so that any increase in static pressure loss caused by the source sampler would lower the average duct velocity (in duct #3) to a value closer to that observed for the other ducts. The average air velocity measured at the exit of the source sampler was approximately 914 m/min (3000 ft/min) after the source sampler was installed on duct #3. The air flow rate of each duct was calculated by multiplying the average velocities determined by the pitot tube traverse by the cross sectional area of each duct (duct area = 0.093 m^2 = 1 ft^2).

The transition inlet duct to the source sampler (from the exit of duct #3) maintained the cross sectional area of the harvester duct so that the velocity of the seed cotton and air would be approximately the same entering the source sampler as it was exiting duct #3. Separation of the seed cotton from the air stream was accomplished in the separator section by means of a baffle type separator (see figure 6). The critical air velocity, as described by Mihalski (1996), used for the design of the baffle separation section was 305 m/min (1000 ft/min). The critical air velocity was provided by increasing the flow area at the edge of the baffle to four times that of the inlet area. It is expected that the actual air velocity at the edge of the baffle was less than the designed critical velocity due to a decrease of the inlet air velocity caused by static pressure loss in the inlet duct. Once the seed cotton was separated from the air stream, the seed cotton was dropped into the basket of the harvester via a 38 cm (15 in) diameter brush wheel revolving at approximately 85 rpm.

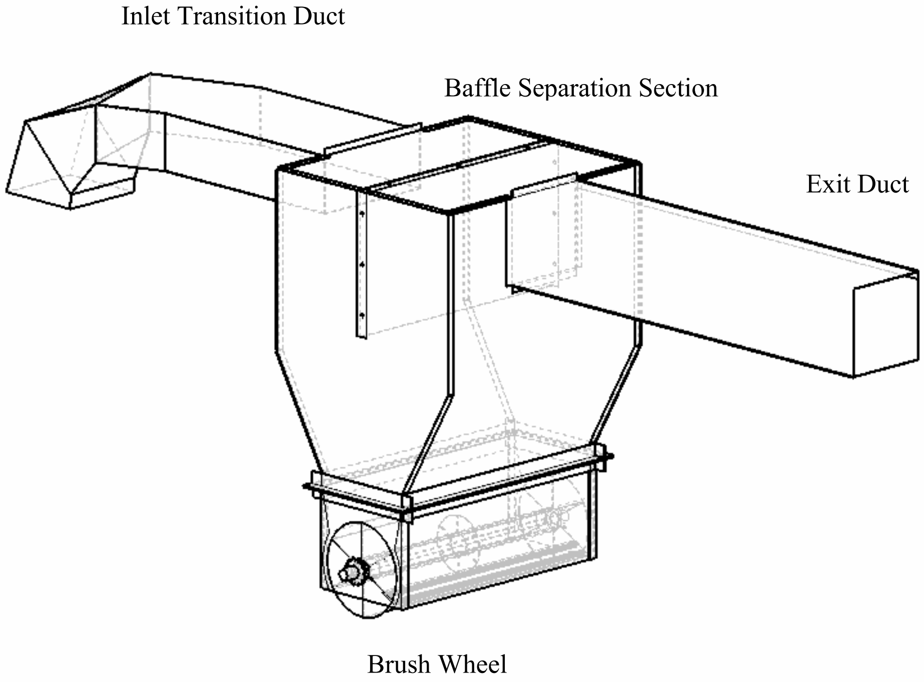

Figure 6. Schematic diagram of the source sampler system designed to collect the air, seed cotton, and foreign material from duct #3 of the six-row harvester.

The particulate laden air was exhausted through the 1.6 m (64 in) exit duct. The cross sectional area of the exit duct was 0.093 m^2 (1 ft^2). The air velocity in the exit duct was measured by a pitot tube located in the center of the duct approximately 40 cm (16 in) from the exit. An isokinetic emission concentration measurement was taken by a sampler probe located at the center of the duct approximately 20 cm (8 in) from the exit. The PM laden air captured by the isokinetic sampler nozzle was passed though a 15 cm (6 in) diameter barrel type cyclone (Tullis et.al., 1997) to separate the large PM from the air stream. The PM which penetrated the cyclone was captured on a bank of 4, 20.3 by 25.4 cm borosilicate glass microfiber filters (Pall Corp., Pallflex Emfab filter material, East Hills, NY).

The air velocity in the exit duct was calculated according to the relationship shown in (4).

$$V = 14.01\sqrt{\frac{P_v}{\rho_a}} \tag{4}$$

where:

V = air velocity (m/s), and
P_v = velocity pressure measured by pitot tube (cm H_2O).

The design air flow rate of the isokinetic sampler was 2.12 m^3/min (75 ft^3/min). The sampler air flow was provided by two fans (Model HP-33, Clements National Company, Chicago, IL) installed in series mounted on top of the harvester. In order for the velocity of the air passing the sampler probe to equal the velocity of the air entering the isokinetic nozzle, the diameter of the nozzle was designed to be 47 mm (1.85 in). The air flow rate through the isokinetic sampling system was measured by an orifice meter. The orifice diameter was specified such that the pressure drop across the orifice plate would be equal to the velocity pressure of the pitot tube when the velocity of the air entering the sampler nozzle was equal to the velocity of the air in the exit duct (thus producing an isokinetic sample of the air exiting the harvester). This was done to simplify the operation of the sampler control system. Pressure transducers (PX274, Omega Engineering, Inc., Stamford, Conn.) were used to measure the velocity pressure from the pitot tube in the exit duct, the pressure drop across the orifice plate, and the pressure drop across the filter housings (to give a measure of the filter loading). Data loggers (HOBO H8 RH/Temp/2x External, Onset Computer Corp, Pocasset, Mass) were used to record the differential pressure readings from the pressure transducers over the duration of the test. The system operator (sitting inside the cab of the harvester) maintained the isokinetic sampling condition by matching the pitot tube velocity pressure to the pressure drop across the orifice plate. This was accomplished by controlling the speed of the fans using a variable transformer (Dayton E165942, Dayton Electric Manufacturing Co., Niles, IL).

The emission concentration measured by the source sampler was calculated according to (5).

$$EC = \frac{M_F + M_B}{\sum_i Q_i t_i} \tag{5}$$

where:

EC = emission concentration (g/m^3),
M$_F$ = PM mass on the four filters used in the source sampler (g), and
M$_B$ = PM mass < 100μm captured in the cyclone bucket (g).

The logging interval (t$_i$) used for the source sampling system data loggers was 6 sec.

The cyclone bucket contained all of the material separated from the sampled air stream by the cyclone. This material was primarily plant and soil material with small amounts of lint fiber and PM. The material taken from the cyclone bucket was air washed for 15 minutes (1.1 m^3/min, tumbler rotation speed = 60 rpm) to remove the PM <100 μm. The air wash tumbler was covered with 100 μm stainless steel mesh and the extracted PM was collected on a 20.3 by 25.4 cm borosilicate glass microfiber filter (Pall Corp., Pallflex Emfab filter material, East Hills, NY). All of the filters used in the source sampler and in the air washing process of the cyclone bucket material were pre and post weighed according to the same procedure used for the collocated low volume TSP and PM$_{10}$ sampler filters.

The total mass of PM emitted from duct #3 during the test was calculated by multiplying the emission concentration from (5) by the total volume of air passing through the duct. The total mass of PM emitted from the harvester was estimated by multiplying the total PM mass emission from duct #3 by 6 (the number of ducts). It was assumed that the total mass of PM emitted from one duct was constant across all of the ducts. TSP emission factors were calculated by dividing the total mass of PM emitted by the harvester by either the area harvested or the number of 218 kg (480 lb) bales harvested to obtain emission factors in units of mass of TSP per area harvested or per bale harvested, respectively. The total mass of lint harvested (bales) was estimated by multiplying the weight of seed cotton harvested per test by an estimated 34% lint turnout and dividing by 218 kg/bale (480 lb/bale). Seed cotton weights were obtained from a boll buggy equipped with load cells.

PM$_{10}$ and PM$_{2.5}$ emission factors were obtained by multiplying the TSP emission factors by the respective mass fractions from the results of PSD analyses on the filters.

PSD Analysis

PSD analyses were performed on the dust captured on the 47 mm diameter filters from the TSP samplers, the source sampler filters, the material less than 100 μm captured in the source sampler cyclone bucket after air washing, soil material less than 75 μm (#200 Sieve), and the PM less than 100 μm collected from the bulk seed cotton samples after air washing. A Coulter Counter Multisizer III (Beckman – Coulter, Coulter Multisizer III, Miami, FL) was used to determine an estimate of the PSD for the different materials in terms of percent volume versus equivalent spherical particle diameter (ESD) according to the procedure described by Buser (2004). The PSD based on percent volume is equivalent to the distribution relating percent mass to ESD under the assumption that the particle density of the PM is constant. The PSDs measured by the Coulter were converted from ESD to aerodynamic equivalent diameter (AED) by equation 6.

$$AED = ESD\sqrt{\rho_p} \tag{6}$$

where:

AED = aerodynamic equivalent diameter (μm),
ESD = equivalent spherical diameter (μm), and
ρ_p = particle density (g/cm^3).

The particle density of the soil material less than 75 μm was measured using a pycnometer (Micromeritics, AccuPyc 1330 Pycnometer, Norcross, GA) according to the procedure described by Wanjura (2005). This analysis was easily carried out as the mass of the soil material available for analysis was approximately 10 g (approximately 1 g of material is required to carry out the particle density analysis). However, the mass of PM available for particle density analysis from the TSP sampler filters, source sampler filters, and cyclone bucket material <100 μm was much less than the required amount. Thus, in an effort to further characterize the PM collected on the TSP sampler filters, source sampler filters, and the PM <100 μm from the source sampler cyclone bucket, the bulk seed cotton samples taken during each test were air washed to remove the PM less than 100 μm. Two sub-samples (approximately 600 g each) of each bulk seed cotton sample taken from the harvester during each test were processed in the air wash machine. The air wash procedure used with the cyclone bucket material was used with the bulk seed cotton samples with the following modifications:

- The PM from all of the seed cotton samples taken from one testing location was collected on one 20.3 by 25.4 cm borosilicate glass microfiber filter (Pall Corp., Pallflex Emfab filter material, East Hills, NY).
- A 47 mm diameter polytetrafluoroethylene (PTFE) (2 μm pore size Zefluor Membrane Filters, Pall Corp., East Hills, NY) filter was placed on top of the larger filter to collect a sample of the PM deposited on the filter from each bulk seed cotton sample for PSD analysis. A new 47 mm diameter filter was used for each bulk seed cotton sample processed.

Once all of the samples (from one location) were processed through the air wash machine, the PM collected on the 20.3 by 25.4 cm filter was removed by placing the filter upside down on a clean sheet of paper and lightly tapping the back side of the filter to help remove as much of the accumulated PM as possible. Care was taken to prevent tearing the filter material causing particles of the filter media to be incorporated in the PM from the seed cotton samples. Approximately 3 g of PM was collected from each sampling location using the air wash procedure. Particle density analyses were performed on the PM material collected from the air washing procedure for each location according to the procedure described by Wanjura (2005).

Dispersion Modeling

ISCST3 is a Gaussian dispersion model that uses the normal (Gaussian) distribution to describe the horizontal and vertical dispersion of a pollutant downwind from the source (Wanjura et. al., 2005c). The pollutant concentration estimated by ISCST3 at a downwind receptor is influenced by meteorological factors (wind direction, wind speed, temperature, etc.), source emission characteristics (emission height, emission temperature, emission velocity, etc.), and receptor characteristics (receptor height and distance from source to receptor). ISCST3 is an EPA approved dispersion model for evaluating the impact of emissions from a source on downwind concentrations. SAPRAs have used ISCST3 in New Source Review permitting processes to determine off property concentrations resulting from emissions from the facility seeking the permit.

When used for regulatory purposes, one hour average meteorological data is used in ISCST3 to estimate downwind concentrations (EPA, 2000). Beychok (1994) indicates that using one hour average meteorological data in ISCST3 can result in the over-estimation of downwind concentrations by as much as 250%. Variations in wind direction within a one hour period are not adequately accounted for in the use of hourly average meteorological data (Fritz, 2002). Thus, the meteorological data collected during each test was averaged using 15 – 20 minute intervals for use in ISCST3.

ISCST3 was used with the TSP concentrations and meteorological data measured during each test to back calculate area source PM emission fluxes (g/m^2-s) according to the following procedure.

- The test plots and sampler locations were input to ISCST3 using the graphical user interface BreezeISC (Trinity Consultants, 2006).
- The meteorological data collected onsite during the tests was processed according to the guidelines given by EPA (EPA, 2000).
    - The meteorological data were processed using 15-20 minute averaging times. 15 minute average meteorological data were used for the short averaging period from farm #1 due to a weather station malfunction whereas 20 minute average data were used for farms #2 and #3. It was assumed that differences in the emission factors developed using the short time average meteorological data (15 – 20 minute averages) would not be a consequence of the 5 minute discrepancy in the averaging periods.
    - The wind direction was processed using the unit vector averaging procedure described by EPA (2000).
    - The wind speed data were scalar averaged over the two time periods according to EPA recommendations.
    - The Solar Radiation Delta-T method was used to define the atmospheric stability classes during the tests.
- The processed meteorological data was input to ISCST3 along with an initial PM emission flux (Q_1) of 2.57E-3 g/m^2-s. This initial flux is used to develop the relationship between the source emissions and the estimated downwind concentration as influenced by the test specific meteorological data. Thus the initial flux may be assigned an arbitrary value not necessarily representative of a typical emission flux. The initial flux value used is equivalent to the PM_{10} emission factor used in California of 1.9 kg/ha (1.7 lb/ac) under the following assumptions: 1) 101.6 cm (40 in) row spacing, 2) 6.4 km/hr (4 mph) harvester speed, 3) harvester width of six rows, and 4) the mass fraction of TSP that is PM_{10} is 20%.
- The model was run to produce the estimated concentrations (C_1) at each of the receptors located at each sampler position.
- The Gaussian dispersion equation 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 (7) 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, μg/m^3), and the measured TSP concentrations (C_2, μg/m^3). The background concentration measured upwind of the harvesting operation was not subtracted from the measured TSP concentrations. The designated upwind sampler failed to yield a reliable upwind concentration on a consistent basis due to changes in wind direction during the test period and because of the unforeseen influence from outside sources (i.e. unpaved road traffic and activity in neighboring fields).

$$\frac{C_1}{C_2} = \frac{Q_1}{Q_2} \tag{7}$$

Emission flux values were calculated for each downwind sampler location for each test. However, not all of the downwind sampler locations yielded reliable emission flux values due to the orientation of the receptor to the source. For example, if the wind direction were to shift such that the wind is blowing toward the northeast in figure 4, the northern and eastern samplers would become the downwind samplers. ISCST3 would estimate the highest concentrations at the receptors located on the east side of the plot. This is a consequence of the area within the source that is available to contribute to the receptor concentration. If the concentrations measured during the test at the samplers located along the north and eastern sides of the plot were approximately equal (which this was the situation in most cases), the resulting emission flux calculated for the sampler located along the north side of the plot would be substantially larger than the fluxes calculated for the samplers locates on the east side of the plot. Said differently, the emission flux from the small area contributing to the concentration at the sampler located on the north side of the plot would have to be much larger than the flux from the larger areas contributing to the concentrations measured by the samplers on the east side of the plot in order to calculate the same concentration at all three receptor locations. In this situation, only two of the fluxes calculated from the downwind sampler concentrations (the two located on the east side of the plot) would be used to determine the average test flux.

TSP emission factors were calculated from the average test fluxes according to the relationship shown in (8).

$$EF_{TSP} = Q_{avg} * D_t * C \tag{8}$$

where:

EF_{TSP} = emission factor, kg/ha (lb/ac),
Q_{avg} = test average flux, g/m^2-s,
D_t = test duration, min, and
C = unit conversion constant, 600 for EF in kg/ha (535 for EF in lb/ac).

The TSP emission factors were also calculated on a mass of cotton harvested basis by multiplying the emission factors resulting from (8) by the area harvested and dividing by the estimated number of 218 kg (480 lb) bales harvested. The lint yield was estimated by multiplying the weight of seed cotton harvested per test by an estimated 34% lint turnout. Seed cotton weights were obtained from a boll buggy equipped with load cells.

PM_{10} and $PM_{2.5}$ emission factors were calculated by multiplying the TSP emission factors by the respective mass fractions from the results of the PSD analyses.

Results and Discussion

Soil Sieve Analysis

The results of the sieve analysis on the soil samples taken from the three farms are shown in table 4.

Table 4. Sieve analysis results on the soil samples taken from farm #1, #2, and #3. The values in the table represent the percent of the original sample mass within the size range.

	Farm #1		Farm #2		Farm #3	
Test No.	**#200 Sieve 106µm >%> 75 µm**	**< #200 Sieve %<75 µm**	**#200 Sieve 106µm >%> 75 µm**	**< #200 Sieve %<75 µm**	**#200 Sieve 106µm >%> 75 µm**	**< #200 Sieve %<75 µm**
1	10.9	20.2	1.3	5.1	11.4	31.1
2	11.0	21.0	1.5	2.4	16.2	28.2
3	6.0	12.7	0.7	1.3	2.2	8.6
4	9.1	18.3	n/a	n/a	6.0	23.0
5	10.7	26.2	n/a	n/a	3.3	12.0
6	5.9	16.1	0.9	1.5		
7	7.6	19.7	0.6	1.5		
8	7.0	21.8	0.6	1.3		
9	7.9	22.5				
10	8.0	23.3				
Mean*	**8.4^a**	**20.2^c**	**0.9^b**	**2.2^d**	**7.8^a**	**20.6^c**

*Means with the same letter are not significantly different at the 0.05 level of significance using Tukey's HSD post-hoc procedure.

The sieve analysis results indicate that the soils from farm #1 and farm #3 are not significantly different at the 0.05 level of significance (p value = 0.99, Tukey's HSD test) when comparing the means of the 106 to 75 µm and <75µm size ranges. However, the means of the same size ranges for the soil samples taken from farm #2 are different from those of farm #1 and #3 at the 0.05 level of significance. This may indicate differences in the PM emission factors from these locations.

Seed Cotton Moisture Content Analysis

The moisture content analysis results of the hand harvested seed cotton samples taken during the tests conducted at farms #1, #2, and #3 are shown in table 5. The mean moisture content for farm #1 is significantly different from that of farm #2 (p value = 0.001) and farm #3 (p value = 0.007) at the 0.05 level of significance (Tukey's HSD test). This difference is likely due to the higher relative humidity of the air during the harvest at farm #1. The mean moisture content of the seed cotton samples from farm #2 and farm #3 are not significantly different (p value = 0.788).

Table #5. Moisture content analysis results of the hand harvested seed cotton samples taken during the tests at farms #1, #2, and #3.

	Seed Cotton Moisture Content (%)		
Test No.	**Farm #1**	**Farm #2**	**Farm #3**
1	8.1	5.5	5.0
2	10.6	5.1	4.6
3	8.7	6.0	6.0
4	10.3	n/a	8.7
5	8.1	n/a	6.5
6	7.6	5.6	
7	8.3	5.1	
8	9.5	5.7	
9	8.2		
10	14.6		
Mean	**9.39^{a}**	**5.50^{b}**	**6.17^{b}**

*Means with the same letter are not significantly different at the 0.05 level of significance.

Particle Density Analysis

The results of the particle density analysis on the soil material less than 75µm are shown in table 6. The mean particle densities of the soil samples taken from each sampling location were different at the 0.05 level of significance (Tukey's HSD test using the harmonic mean sample size adjustment for unequal sample sizes). This difference was expected due to observed differences in soil structure and texture between sampling locations.

Table 6. Particle density measurements on soil material less than 75 µm taken from three sampling locations in Texas.

	Soil Particle Densities by Harvesting Location (g/cm^3)		
Harvesting Test No.	Farm #1	Farm #2	Farm #3
Test 1	2.59	2.53	2.62
Test 2	2.58	2.54	2.61
Test 3	2.55	2.51	2.61
Test 4	2.61	n/a	2.61
Test 5	2.62	n/a	2.60
Test 6	2.56	2.52	
Test 7	2.56	2.50	
Test 8	2.57	2.57	
Test 9	2.58		
Test 10	2.58		
Average (g/cm^3)	2.58^{a}	2.53^{b}	2.61^{c}
St. Dev. (g/cm^3)	0.02	0.03	0.01

*Particle density means with the same letter are not significantly different at the 0.05 level of significance.

The results of the particle density analysis on the PM from the air wash procedure are shown in table 7. The air wash PM was mixed thoroughly before performing the analysis to help decrease the bias in the particle density measurements due to sampling.

Table 7. Air wash PM (less than 100 µm) particle density analysis results.

Air Wash PM Particle Density (g/cm^3)	
Farm #1	1.86
Farm #2	1.79
Farm #3	1.97

The air wash PM particle densities are ranked in order from most dense to least dense by the following: Farm #3, Farm #1, Farm #2. The particle density results of the air wash PM from the three locations follows the same trend as the soil material particle density results. This trend is likely a consequence of the influence of soil particles in the air wash material. The other primary constituent of the air wash PM is organic matter from the crop biomass. The presence of organic matter particles in the air wash material results in the decrease in particle density between the soil material and air wash PM.

PSD Analysis

PSD analyses were conducted on the PM from 10, 9, and 10 TSP filters from farms 1, 2, and 3, respectively. Light PM loading resulted in the exclusion of the other TSP filters. Typically, more than 200 µg of PM must be collected on a 47 mm diameter filter in order to conduct a PSD analysis. PSD analyses were conducted on all of the source sampler filters (16 total filters, four per source sampling test) and the four filters containing the PM less than 100 µm from the material captured in the source sampler cyclone bucket (a separate filter was used to capture the PM less than 100 µm from each source sampling test). The results of the PSD analyses from test 7 of farm #1, test 7 of farm #2, and test 1 of farm #3 are shown in figures 7, 8, and 9, respectively. The ESD MMD and GSD of the best fit lognormal curves for the data shown in figures 7, 8, and 9 are shown in table 8.

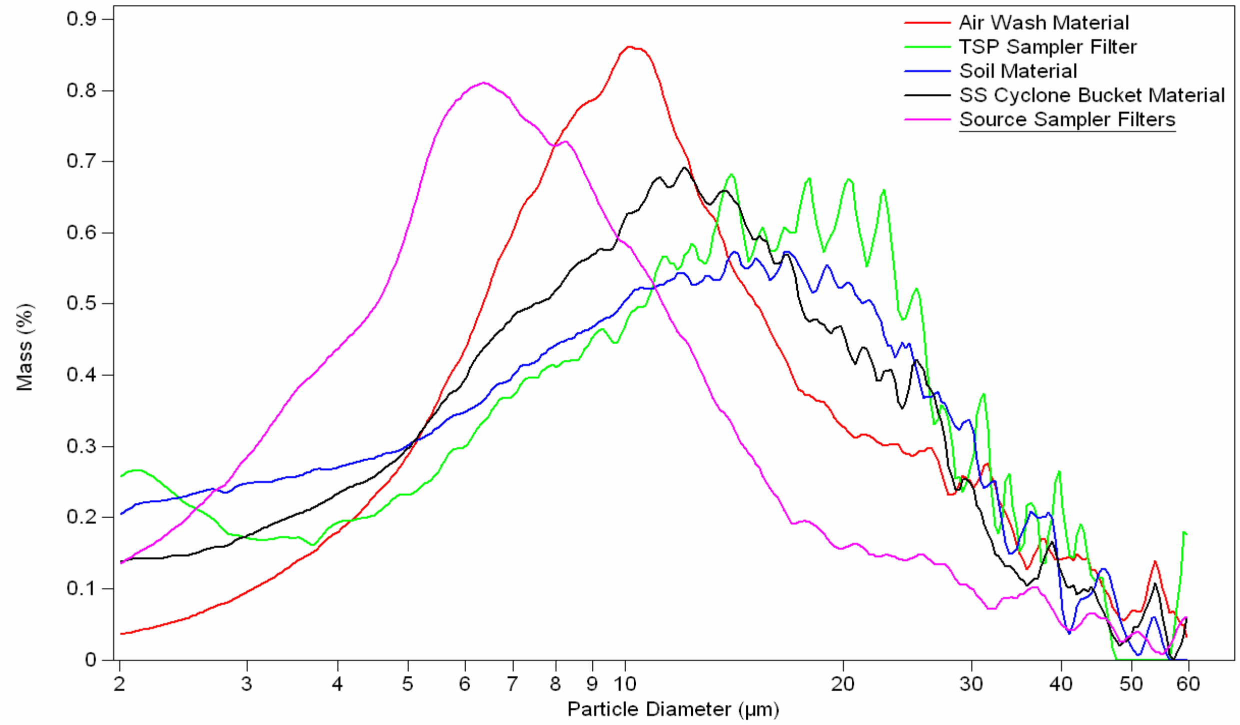

Figure 7. Percent volume vs. ESD particle diameter PSDs for the air wash PM <100 µm (Air Wash Material), PM on the TSP sampler filter (Ambient TSP Sampler Filter), soil material < 75 µm (Soil Material), source sampler cyclone bucket material <100 µm (SS Cyclone Bucket Material), and PM on the source sampler filters (Source Sampler Filter) from test #7 from farm #1.

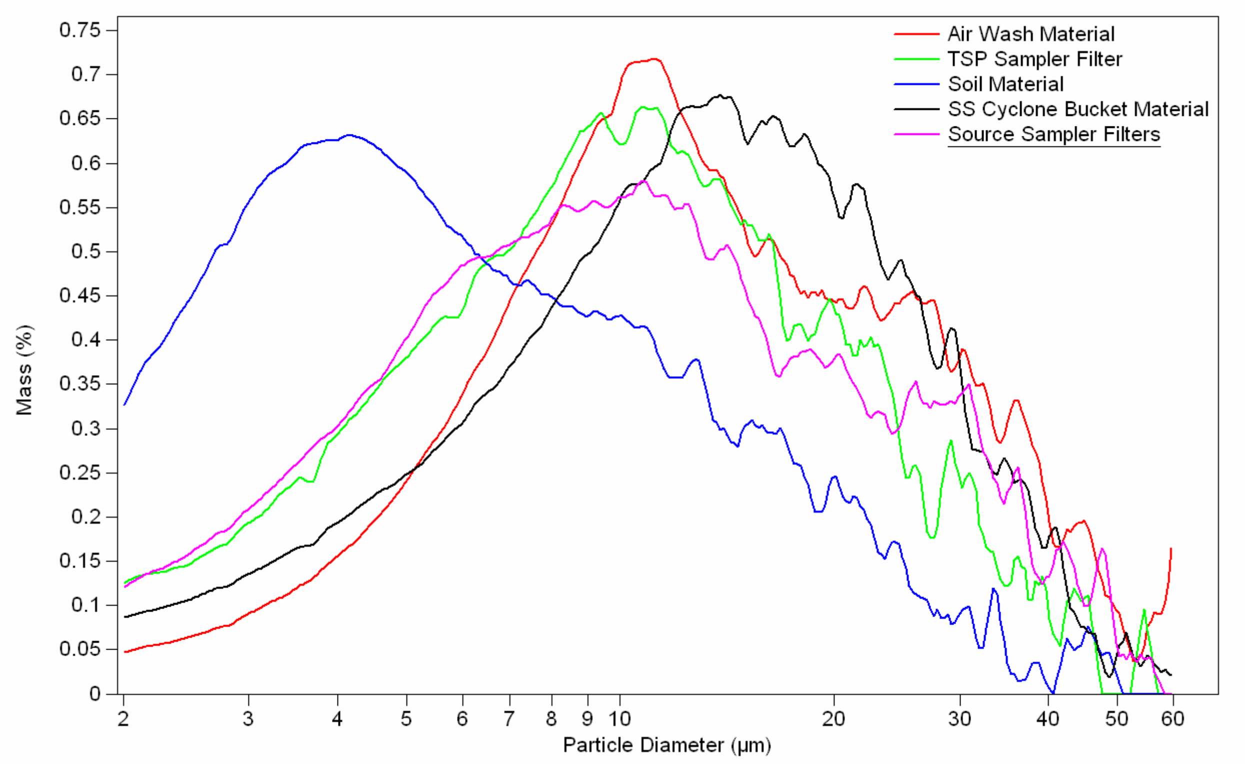

Figure 8. Percent volume vs. ESD particle diameter PSDs for the air wash PM <100 µm (Air Wash Material), PM on the TSP sampler filter (Ambient TSP Sampler Filter), soil material < 75 µm (Soil Material), source sampler cyclone bucket material <100 µm (SS Cyclone Bucket Material), and PM on the source sampler filters (Source Sampler Filter) from test #7 from farm #2.

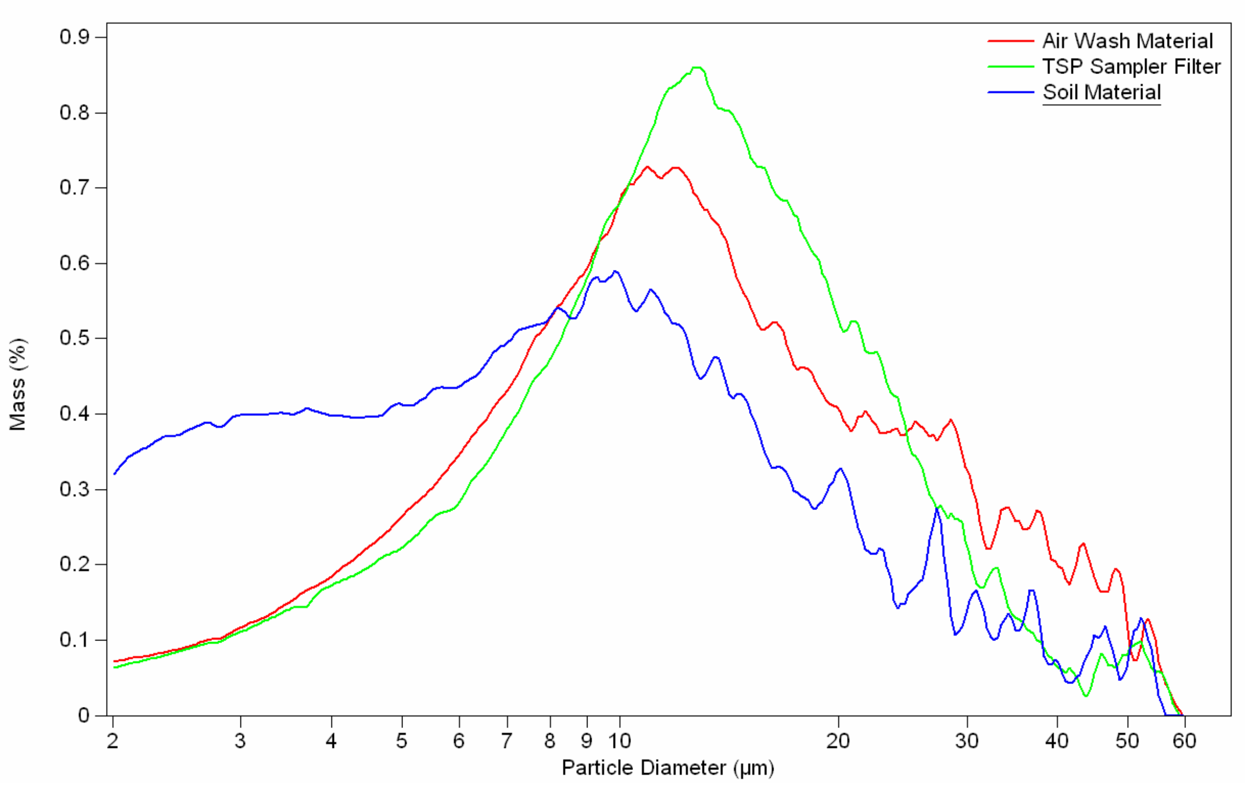

Figure 9. Percent volume vs. ESD particle diameter PSDs for the air wash PM <100 µm (Air Wash Material), PM on the TSP sampler filter (Ambient TSP Sampler Filter), soil material < 75 µm (Soil Material), source sampler cyclone bucket material <100 µm (SS Cyclone Bucket Material), and PM on the source sampler filters (Source Sampler Filter) from test #1 from farm #3.

Table 8. MMD (ESD) and GSD of the best fit lognormal curves for the data shown in figures 7, 8, and 9.

	Farm #1		Farm #2		Farm #3	
Sample	MMD (µm)	GSD	MMD (µm)	GSD	MMD (µm)	GSD
Air Wash Material	10.5	1.92	12.4	2.06	11.9	2.18
Ambient TSP Sampler Filter	12.7	2.25	10.0	2.19	12.4	1.85
Soil Material	11.2	2.36	5.7	2.1	7.9	2.34
SS Cyclone Bucket Material	11.1	2.08	13.0	2.07	n/a	n/a
Source Sampler Filter	7.4	1.73	10.0	2.28	n/a	n/a

The PSDs shown in figures 7, 8, and 9 represent the distribution of % volume to ESD particle diameter. Particle densities for the air wash and soil material were measured and subsequently used to convert the ESD PSDs of the respective materials to an AED basis using the relationship shown in (6). The average PSD of the soil material and air wash material from each location are shown in figures 10 and 11. The MMD and GSD of the best fit lognormal distributions for the average air wash PSDs are shown in table 9. The average soil PSDs (shown in figure 10) for all three farms do not follow the lognormal distribution. Consistently, the left tail of the observed average soil PSDs indicates the presence of a substantial amount of PM with particle diameters less than 10 µm. One possible explanation for this is that the PSD of the soil material <75 µm is best represented by a multi-mode distribution. This explanation is further substantiated by the observation of two peaks in the average soil PSD shown for farm #2.

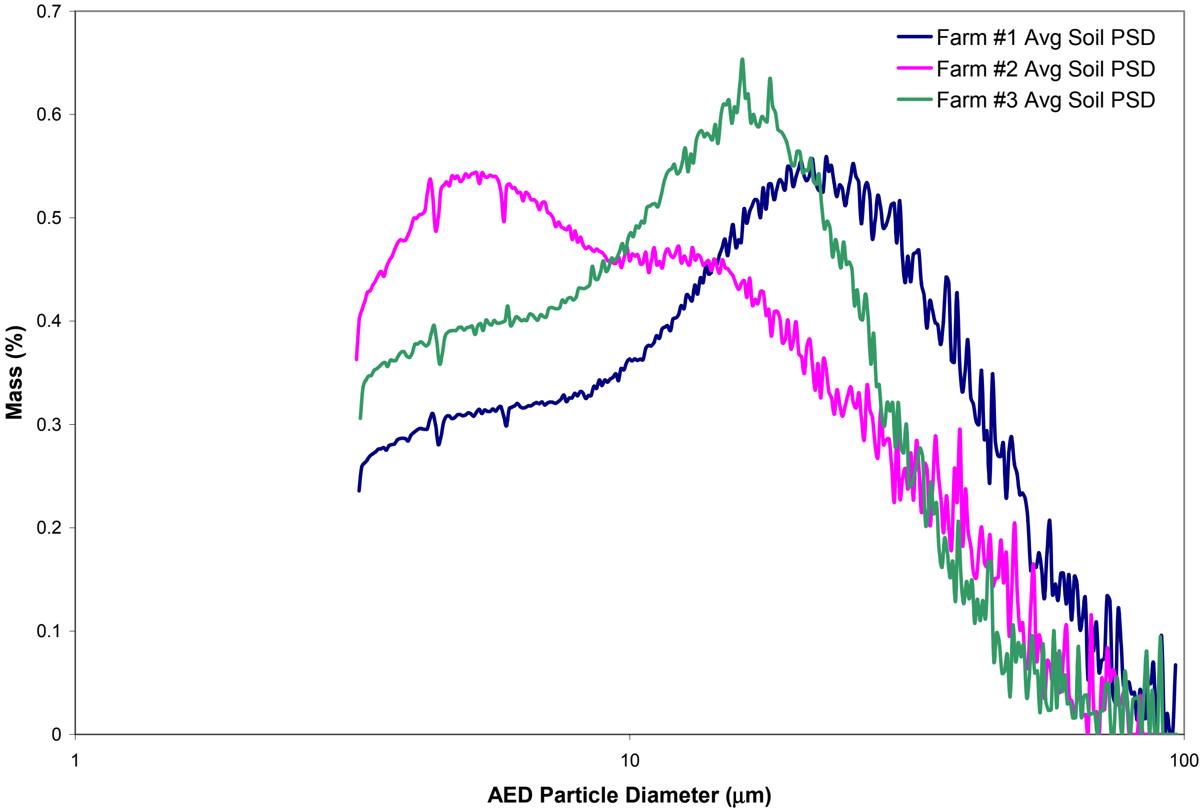

Figure 10. Average PSD results for the soil material <75 µm from farm #1, #2, and #3.

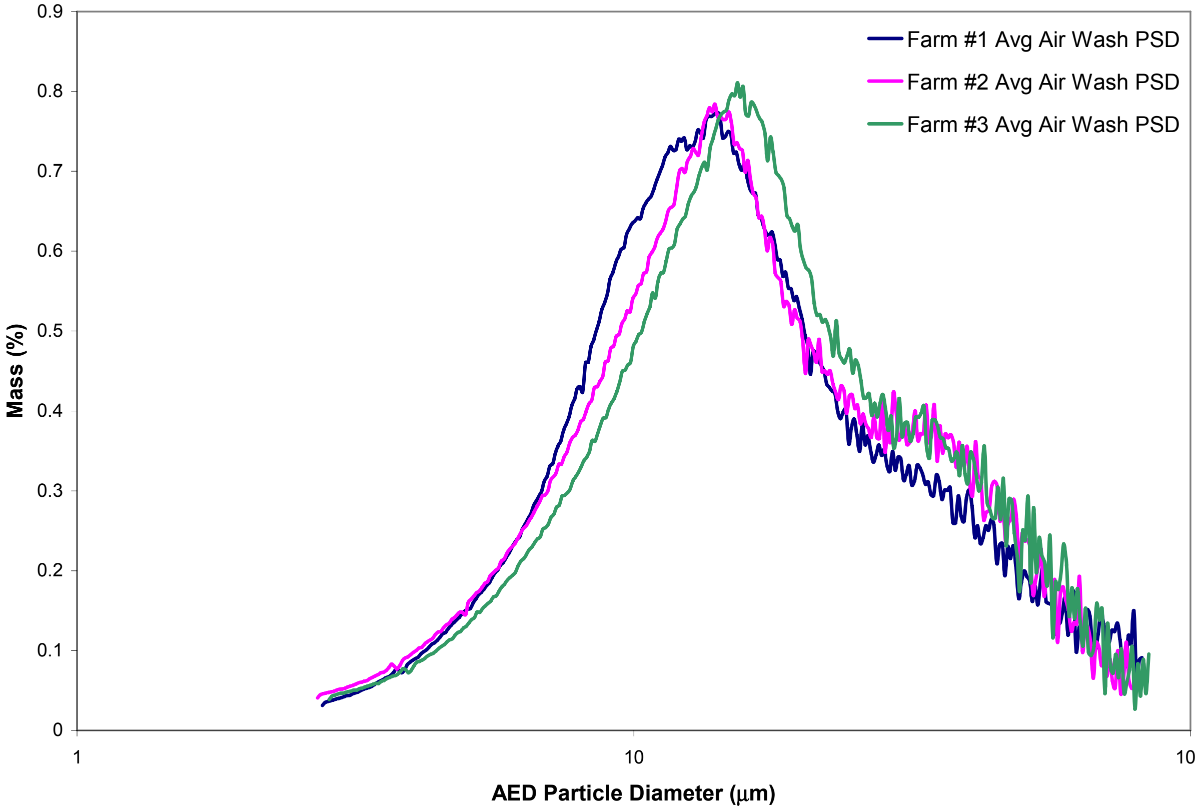

Figure 11. Average PSD results of the air wash material from farm #1, #2, and #3.

Table 9. MMD and GSD values for the best fit lognormal distributions for the average air wash PSDs from farm #1, #2, #3.

	Farm #1	Farm #2	Farm #3
MMD	14.6	15.3	16.4
GSD	2.00	2.05	2.00

The PSD of the air wash material from farm #1 and farm #2 falls between the PSDs of the PM on the source sampler filters and source sampler cyclone bucket material. This result is indicative of the separation of particles that takes place in the source sampling system. PM similar to the air wash material is collected by the source sampling probe and is fed into the barrel cyclone where larger particles are removed from the air stream and accumulated in the cyclone bucket. The PSD of the PM remaining in the sampler air stream (which is deposited on the filters) is then shifted to the left of the PSD of the inlet material.

In order to determine the total mass fraction of a certain size PM sampled by the source sampling system, the PSDs of the PM on the source sampler filters and the cyclone bucket must be considered. Thus, a composite PSD was created for each source sampling test by combining the filter and cyclone bucket PSDs on a mass weighted average basis. The composite PSD matched the PSD of the air wash material more closely than the soil material PSD. Thus, the composite PSD was converted from ESD to AED using the particle density of the air wash material measured for the location of the test. The composite PSDs of the source sampling tests are shown in figure 12.

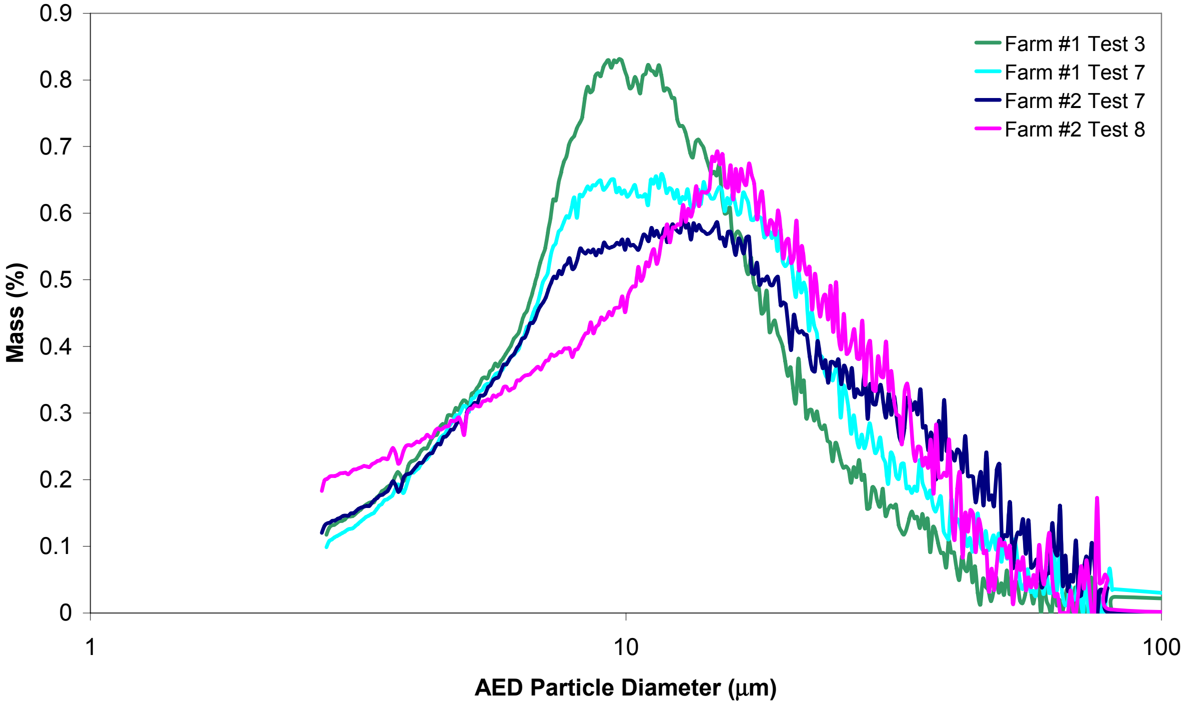

Figure 12. Composite source sampler PSDs for the four source sampling tests conducted at farm #1 and farm #2.

The MMD and GSD of the best fit lognormal distributions for the composite PSD data shown in figure 12 are presented in table 10 along with the mass percentage of PM_{10} and $PM_{2.5}$ derived from the respective cumulative lognormal functions. Also presented in table 10 are the mass percentages of PM_{10} and $PM_{2.5}$ of the composite source sampler PSDs developed from the Coulter Counter PSD data.

Table 10. MMD and GSD values for the best fit lognormal distributions for the composite source sampler PSDs. Also shown are the mass percentages of PM_{10} and $PM_{2.5}$ of the best fit lognormal distributions and PSD data measured by the Coulter Counter.

		MMD	GSD	Lognormal Distribution		Coulter Counter PSD Data	
Location	Test #	(μm)		% PM_{10}	% $PM_{2.5}$	% PM_{10}	% $PM_{2.5}$
Farm #1	3	10.5	1.8	46.6	0.7	46	0.1
	7	11.8	1.96	40.4	1.1	40.4	0.1
Farm #2	7	12.5	2.19	38.8	2	38.6	0.1
	8	13.2	2.19	36	1.7	36.3	0.2

Historically, the single mode lognormal distribution has been shown to best represent the distribution of particulate matter dispersed in air (Hinds, 1999). Further, the use of the lognormal distribution to describe the relationship between percent mass and particle size is a simple way to produce an accurate estimate of the percent mass of a regulated particle size range from a TSP sample. The data in table 10 from the Coulter Counter PSD data indicate that the mass fraction of $PM_{2.5}$ in the dust emitted from the harvester is in the range of 0.1 to 0.2% while the same mass fraction from the lognormal distribution is in the range of 0.7 to 2%. This result implies that the mass fraction of $PM_{2.5}$ in a TSP concentration sample from a cotton harvesting operation is likely overstated by the use of the lognormal distribution.

The PSDs of the PM on the TSP sampler filters were converted from an ESD basis to an AED basis using the particle density of the air wash material under the following logic:

- The PSD of the PM on the TSP filter shown in figure 7 seems to follow the PSD of the soil material from the test location. However, the MMD (ESD) of the TSP filter is larger than the MMD of the soil material and air wash material. This is likely caused by the settling out of dense soil particles leaving the larger, less dense organic material particles entrained in the air.
- The PSDs of the air wash material, PM on the TSP sampler filter, and soil material shown in figure 8 indicate that the primary influence on the TSP sampler filter PSD is from the air wash material. The soil material PSD seems to have very little influence on the PSD of the PM on the TSP sampler filter.
- The PSDs of the PM on the TSP sampler filter, air wash material, and soil material seen in figure 9 also indicate the same settling phenomena seen in figure 7. The MMD of the PM shifts to the right as the PM emitted by the harvester travels down wind.

The results of the PSD analyses on the PM on the TSP sampler filters from the three farms are shown in table 11.

Table 11. PSD analysis results of the PM on the TSP filters from farm #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

The mean, minimum, and maximum percentages of PM_{10} and $PM_{2.5}$ (of the PM on the TSP sampler filters) from the lognormal distribution and Coulter Counter PSD data are also shown in table 11. The mean percent $PM_{2.5}$ is in the range of 0.9 to 4% using the lognormal distribution and in the range of 0.1 to 0.2% for the Coulter Counter PSD data. This result is similar to that observed from the source sampler composite PSD analysis in that the lognormal distribution tends to overstate the percentage of $PM_{2.5}$.

Upwind – Downwind Sampling

The upwind and downwind TSP and PM_{10} concentration measurement results for farms #1, #2, and #3 are summarized in tables 12, 13, and 14, respectively.

Table 12. Concentration measurement results from the sampling conducted at farm #1.

		TSP Sampler Concentration (µg/m^3)			PM_{10} Sampler Concentration (µg/m^3)			Upwind Concentration (µg/m^3)	
Test No.	Treatment	Mean	Max	Min	Mean	Max	Min	TSP	PM_{10}
1	2 Row	83	109	71	47	56	22	65	52
2	6 Row	219	354	121	40	71	13	147	100
3	6 Row w/SS	80	118	45	26	42	12	86	88
4	6 Row	331	882	120	103	179	42	62	16
5	2 Row	118	307	37	37	117	7	69	n/a
6	6 Row	232	330	120	81	145	44	n/a	67
7	6 Row w/SS	123	171	16	34	57	12	21	n/a
8	6 Row	61	121	9	19	31	7	n/a	40
9	2 Row	52	107	7	15	18	10	39	9
10	6 Row w/SS	97	133	77	32	45	27	25	54

Table 13. Concentration measurement results from the sampling conducted at farm #2.

		TSP Sampler Concentration (µg/m^3)			PM_{10} Sampler Concentration (µg/m^3)			Upwind Concentration (µg/m^3)	
Test No.	Treatment	Mean	Max	Min	Mean	Max	Min	TSP	PM_{10}
1	6 Row	66	133	45	35	51	18	46	46
2	6 Row	57	70	45	59	123	10	n/a	n/a
3	6 Row	36	51	19	40	46	34	52	3
4	2 Row	58	66	49	34	49	7	44	12
5	2 Row	189	205	170	114	125	91	94	n/a
6	2 Row	48	59	42	29	40	9	54	n/a
7	6 Row w/SS	116	190	65	39	60	19	26	19
8	6 Row w/SS	104	154	34	46	49	44	146	42

Table 14. Concentration measurement results from the sampling conducted at farm #3.

		TSP Sampler Concentration (μg/m^3)			PM_{10} Sampler Concentration (μg/m^3)			Upwind Concentration (μg/m^3)	
Test No.	Treatment	Mean	Max	Min	Mean	Max	Min	TSP	PM_{10}
1	2 Row	242	297	170	75	102	60	33	36
2	6 Row	164	232	95	89	135	70	20	75
3	2 Row	76	90	57	28	41	16	112	29
4	6 Row	105	190	37	165	574	23	2	2
5	2 Row	237	704	50	37	57	22	49	18

The concentration results presented in tables 12 – 14 were developed from the average concentrations measured over the duration of each test. The test durations ranged from 3 – 5 hours (approximate) for the two-row harvester and from 1 – 2 hours for the six-row harvester.

The ratio of the true PM_{10} concentration to the concentration measured by the PM_{10} sampler (true/measured PM_{10} concentration ratio) was calculated for each TSP sampler filter used in the PSD analysis using the concentration from the corresponding collocated PM_{10} sampler. The true PM_{10} concentrations were calculated by multiplying the TSP concentration (of the filters used in the PSD analysis) by the PM mass % ≤ 10 μm from the Coulter Counter PSD analysis. The true/measured PM_{10} concentration ratio was in the following ranges for each farm:

- 44% to 122% for farm #1,
- 70% to 130% for farm #2, and
- 70% to 300% for farm #3.

A true/measured PM_{10} concentration ratio less than 100% indicates that the PM_{10} sampler measured a concentration less than the true PM_{10} concentration calculated from the TSP concentration. A possible explanation is that the loading on the PM_{10} sampler filters was too light to give an accurate PM_{10} concentration. However, these results also indicate that it is possible for an FRM PM_{10} sampler to measure a PM_{10} concentration three times greater than the true concentration of PM_{10} present. This result is similar to those found by Buser (2004).

The emission factors back-calculated with ISCST3 using the TSP concentrations and meteorological data from the tests conducted at farm #1 are shown in table 15. An analysis of the emission factor data from farm #1 using the GLM procedure in SAS (SAS Institute Inc., 2003, Cary, NC) indicated that there were no significant differences in the emission factors between replications or between treatments (treatments are the harvester configurations: 2 Row, 6 Row, or 6 Row w/SS). However, the mean of the six-row harvester PM_{10} and $PM_{2.5}$ emission factors is less than the mean of the two-row harvester emission factors when reported as either mass/area or mass/bale. Further, the mean of the six-row harvester treatments was larger than the mean of the six-row harvester with source sampler treatments.

Table 15. Emission factors developed from the upwind/downwind concentrations measured at farm #1 using ISCST3.

				PM_{10} Emission Factors		$PM_{2.5}$ Emission Factors		TSP Emission Factors	
Test	**Treatment**	**Area (ha)**	**Bales Harvested**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**
1	2 row	1.8	5.7	0.48	0.15	2.68E-03	8.56E-04	1.34	0.43
2	6 row	1.8	5.7	0.99	0.31	5.53E-03	1.71E-03	2.77	0.85
3	6 row w/SS	1.7	6.5	0.18	0.05	1.02E-03	2.67E-04	0.51	0.13
4	6 row	1.7	7.6	0.41	0.09	2.28E-03	5.10E-04	1.14	0.25
5	2 row	1.7	7.4	0.65	0.15	3.65E-03	8.38E-04	1.83	0.42
6	6 row	1.7	6.9	0.56	0.14	3.11E-03	7.61E-04	1.55	0.38
7	6 row w/SS	1.7	6.0	0.65	0.18	3.64E-03	1.03E-03	1.82	0.51
8	6 row	2.5	12.7	0.54	0.11	3.02E-03	6.04E-04	1.51	0.30
9	2 row	1.5	6.9	0.87	0.19	4.88E-03	1.07E-03	2.44	0.54
10	6 row w/SS	2.6	9.8	0.28	0.07	1.55E-03	4.13E-04	0.77	0.21
			Mean	**0.56**	**0.14**	**3.13E-03**	**8.06E-04**	**1.57**	**0.40**

The PM_{10}, $PM_{2.5}$, and TSP emission factors (back-calculated using ISCST3 from the data collected at farm #2) shown in table 16 were also analyzed in SAS using the GLM procedure (SAS Institute Inc., 2003, Cary, NC). The results of this analysis were similar to those from the farm #1 data in that no significant differences ($\alpha = 0.05$) were found between the treatments or the blocks (blocks based on location within the field). The six-row and two row treatment means (for PM_{10}, $PM_{2.5}$, or TSP) based on either mass/area or mass/bale were almost identical. However, the mean for the six-row w/SS treatment was lower than the means of the other treatments. It is likely that this difference was not found significant because there were only two observations for the six-row w/SS treatment.

Table 16. Emission factors developed from the upwind/downwind concentrations measured at farm #2 using ISCST3.

				PM_{10} Emission Factors		$PM_{2.5}$ Emission Factors		TSP Emission Factors	
Test	**Treatment**	**Area (ha)**	**Bales Harvested**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**
1	6 row	1.91	7.2	0.49	0.13	2.02E-03	5.35E-04	1.01	0.27
2	6 row	1.27	6.1	1.11	0.23	4.54E-03	9.47E-04	2.27	0.47
3	6 row	1.91	7.7	1.20	0.30	4.92E-03	1.21E-03	2.46	0.61
4	2 row	1.76	6.3	0.91	0.25	3.71E-03	1.04E-03	1.86	0.52
5	2 row	1.27	4.9	1.17	0.31	4.81E-03	1.26E-03	2.41	0.63
6	2 row	1.91	7.1	0.70	0.19	2.86E-03	7.69E-04	1.43	0.38
7	6 row w/SS	1.91	7.6	0.71	0.18	2.90E-03	7.24E-04	1.45	0.36
8	6 row w/ SS	1.91	7.5	0.38	0.10	1.56E-03	3.96E-04	0.78	0.20
			Mean	**0.83**	**0.21**	**3.42E-03**	**8.60E-04**	**1.71**	**0.43**

The PM_{10}, $PM_{2.5}$, and TSP emission factors developed from the sampling work conducted at farm #3 are shown in table 17. Again, the GLM procedure in SAS (SAS Institute Inc., 2003, Cary, NC) was used to test for differences between the means of the treatments and blocks (block on replication number). The results of this analysis indicated that there were no significant differences between the treatment or block means. However, the mean emission factors of the six-row treatment were substantially lower than the means of the two-row treatment (e.g. six-row mean = 0.33 kg PM_{10}/ha, two-row mean = 1.09 kg PM_{10}/ha). The insignificance of this difference is again likely due to the small number of observations.

Table 17. Emission factors developed from the upwind/downwind concentrations measured at farm #3 using ISCST3.

				PM_{10} Emission Factors		$PM_{2.5}$ Emission Factors		TSP Emission Factors	
Test	**Treatment**	**Area (ha)**	**Bales Harvested**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**	**(kg/ha)**	**(kg/bale)**
1	2 Row	2.14	4.6	1.07	0.50	3.24E-02	1.50E-02	3.60	1.67
2	6 Row	2.47	11.8	0.27	0.06	8.30E-03	1.73E-03	0.92	0.19
3	2 Row	1.97	7.0	1.30	0.37	3.93E-02	1.11E-02	4.37	1.23
4	6 Row	2.14	11.6	0.38	0.07	1.15E-02	2.14E-03	1.28	0.24
5	2 Row	1.98	8.2	0.90	0.22	2.73E-02	6.59E-03	3.04	0.73
			Mean	**0.78**	**0.24**	**2.38E-02**	**7.32E-03**	**2.64**	**0.81**

The results of the emission factors determined from the upwind/downwind sampling conducted at the three Texas farms are summarized by the following:

- The uncertainty of the emission factors developed from the upwind/downwind sampling protocol is high due to the influence of uncontrollable factors such as changes in wind direction, low mass of PM collected on the filters, orientation of samplers to the source, etc. Statistical analysis of the emission factors (TSP, PM10, and PM2.5) indicated that there were no significant differences between the mean emission factors developed for the two-row and six-row harvesters. However, the mean emission factors for the six-row harvester and the two-row harvester at farms 1 and 3 indicate that the six-row harvester tends to emit less PM_{10}, $PM_{2.5}$, and TSP on a per unit area basis and on a per bale harvested basis.
- The mean TSP emission factor (kg/ha) and 95% confidence interval for the three harvester treatments (combining the data from all three farms) is:
    - two-row: 2.48 ± 0.79 (kg/ha),
    - six-row: 1.66 ± 0.52 (kg/ha), and
    - six-row w/SS: 1.07 ± 0.68 (kg/ha).
- The mean PM_{10} emission factor (kg/ha) and 95% confidence interval for the three harvester treatments (combining the data from all three farms) is:
    - two-row: 0.89 ± 0.20 (kg/ha),
    - six-row: 0.66 ± 0.27 (kg/ha), and
    - six-row w/SS: 0.44 ± 0.29 (kg/ha).
- The mean $PM_{2.5}$ emission factor (kg/ha) and 95% confidence interval for the three harvester treatments (combining the data from all three farms) is:
    - two-row: 0.014 ± 0.011 (kg/ha),
    - six-row: 0.005 ± 0.043 (kg/ha), and
    - six-row w/SS: 0.002 ± 0.018 (kg/ha).

The emission factor data were further analyzed to determine if there are differences in the mean emission factors between the three farms for the two-row and six-row harvester treatments. The results of these analyses are:

- No significant differences ($\alpha = 0.05$) were found between the mean PM_{10} emission factors between the three farms for the two-row harvester treatments. However, significant differences ($\alpha = 0.05$) were found between the means of the TSP emission factors between the three farms. Tukey's HSD test ($\alpha = 0.05$) indicated that the mean TSP emission factors from farms 1 and 2 were not significantly different. However, the mean TSP emission factors between farms 1 and 3 were significantly different. The mean TSP emission factors between farms 2 and 3 are not significantly different. Similar results were observed for the $PM_{2.5}$ emission factor data between the three farms. The mean $PM_{2.5}$ emission factors from farms 1 and 2 are not significantly different ($\alpha = 0.05$). However, the mean $PM_{2.5}$ emission factor from farm 3 is significantly different from the mean $PM_{2.5}$ emission factors from farms 1 and 2.
- No significant differences were found between the mean TSP emission factors from the six-row harvester treatments between the three farms ($\alpha = 0.05$). Similarly, no significant differences were found between the mean PM_{10} emission factors from the six-row harvester treatments between the three

farms. However, significant differences were found between the mean $PM_{2.5}$ emission factors from the six-row harvester treatments between the three farms. Again, the mean $PM_{2.5}$ emission factors from farms 1 and 2 were not significantly different (Tukey's HSD test, $\alpha = 0.05$) but the mean $PM_{2.5}$ emission factor from farm 3 was found to be significantly different from the mean $PM_{2.5}$ emission factors from farms 1 and 2.

Since differences in the emission factors were detected between the farms for the two-row and six-row harvester treatments, a correlation analysis was conducted to determine if significant linear relationships exist between the emission factor data (TSP, PM_{10}, or $PM_{2.5}$) and the soil sieve analysis results for the mass percent between 106 and 75 µm and less than 75 µm. No significant correlations were found for the two-row or six-row harvester emission factor data when correlated with either size range of soil.

Source Sampling

The results of the source sampling tests on the six-row harvester emissions at farm #1 and farm #2 are shown in table 18. The results of only four source sampling tests are available due to equipment problems during test 10 at farm #1. Similarly, equipment malfunctions prevented the third replication of the source sampler tests at farm #2. The emission factors reported for the source sampler are substantially lower than the emission factors determined through upwind/downwind sampling. The overall average TSP, PM_{10}, and $PM_{2.5}$ source sampler emission factors are 114, 45, and 0.15 g/ha, respectively. Similarly, the overall average TSP, PM_{10}, and $PM_{2.5}$ source sampler emission factors are 10, 4, and 0.01 g/bale, respectively. The emission factors developed from the source sampler emission concentrations are more precise than the emission factors developed from the upwind/downwind sampler concentrations. For example, the source sampler TSP emission factor for tests 3 and 7 from farm #1 are 60 and 99 g/ha, respectively while the corresponding emission factors developed from the downwind sampler concentrations are 0.51 and 1.82 kg/ha. The difference between the TSP emission factors for these two tests are 39 and 1310 g/ha for the source sampler and downwind sampler emission factors, respectively. This result is also true for tests 7 and 8 from farm #2 as the difference in the two TSP emission factors developed from the source sampler emission concentrations is 27 g/ha whereas the difference in the TSP emission factors developed from the downwind sampler concentrations is 670 g/ha. More testing with the source sampling system is planned for the 2007 harvest season.

Table 18. Emission factor results from the source sampling tests conducted at farm #1 and farm #2.

		PM_{10} Emission Factors			$PM_{2.5}$ Emission Factors			TSP Emission Factors		
Farm	Test	(g/min)	(g/ha)	(g/bale)	(g/min)	(g/ha)	(g/bale)	(g/min)	(g/ha)	(g/bale)
1	3	2	27	3	4.8E-03	6.0E-02	5.7E-03	5	60	6
1	7	3	40	4	6.8E-03	9.9E-02	1.0E-02	7	99	10
2	7	2	63	5	6.3E-03	1.6E-01	1.4E-02	6	162	14
2	8	3	49	4	1.6E-02	2.7E-01	2.3E-02	8	135	12

Emission Factor Basis

A correlation analysis was performed on the source sampler and downwind sampler emission factor, area harvested, and number of bales harvested data to investigate the hypothesis that the total amount of PM emitted during harvesting was more closely correlated with the mass of cotton harvested. The total TSP emissions were calculated from the source sampler data by multiplying the total emission rate (kg TSP/min) by the duration of the test. Similarly, the total TSP emissions were calculated from the average emission flux values from the downwind sampler tests (g/m^2-s) by multiplying by the test duration and area harvested. High correlation coefficients were found between the source sampler total TSP emission and area harvested ($r = 0.93$) as well as between the source sampler total TSP emission and number of bales harvested ($r = 0.83$). However, the correlation coefficients for these relationships using the downwind sampler total TSP emission data were 0.08 for the former and -0.12 for the latter. The poor correlations observed with the downwind sampler emissions data is likely due to the high variability in the data. However, the good correlations observed using the source sampler data were developed from four observations measured over a fairly small range of area harvested (1.7 to 1.91 ha) and number of bales harvested (6 to 7.6 bales).

Conclusions

The major findings of the PM sampling work conducted during the cotton harvesting operations at the three Texas farms are:

- The PSD of the PM emitted from the harvester (as measured by the source sampling system) can be described by a log normal distribution with MMD ranging from 10.5 to 13 µm and GSD ranging from 1.8 to 2.2. However, downwind of the harvester, the PSD of the PM sampled by the TSP samplers shifted to the right of the PSD of the PM sampled by the source sampler. The PSD of the PM captured on the low volume TSP sampler filters can be described by a lognormal distribution with MMD ranging from 8 to 18 µm with GSD ranging from 1.8 to 2.5. The wide range in MMD for the PM collected on the TSP sampler filters is likely a consequence of the small mass of PM collected on the filters.
- The PSD of the PM emitted from the harvester shifts to the right as the plume travels downwind. This is likely caused by the settling out of soil particles.
- The mean PM_{10} emission factors (kg/ha) and 95% confidence intervals for the two-row and six-row harvesters from the protocol using ISCST3 (combining the data from all three farms) are:
    - two-row: 0.89 ± 0.20 kg/ha (0.79 ± 0.18 lb/ac), and
    - six-row: 0.66 ± 0.27 kg/ha (0.59 ± 0.24 lb/ac).
- The mean $PM_{2.5}$ emission factors (kg/ha) and 95% confidence intervals for the two-row and six-row harvesters from the protocol using ISCST3 (combining the data from all three farms) are:
    - two-row: 0.014 ± 0.011 kg/ha (0.012 ± 0.01 lb/ac), and
    - six-row: 0.005 ± 0.043 kg/ha (0.004 ± 0.04 lb/ac).
- The uncertainty of the emission factors developed using the upwind/downwind sampling protocol is large due to uncontrollable factors encountered during the tests. Thus, no significant difference was found between the emission factors (TSP, PM_{10}, or $PM_{2.5}$) developed for the two-row and six-row harvesters. However, PM emissions from the six-row harvester tend to be lower than the emissions from the two-row harvester.
- The mean PM_{10} and $PM_{2.5}$ emission factors developed from the source sampling measurements are 45 and 0.15 g/ha (4.01 E-2 and 1.34 E-4 lb/ac), respectively.
- The emission factors resulting from the source sampling work exhibit much less variability than the emission factors developed from the protocol employing upwind/downwind sampling and ISCST3. This indicates that the source sampler concentration measurements are much more precise. However, the difference in the magnitude of the emission factors developed by the two protocols will be further investigated.
- The emission factor analysis presented indicates that the appropriate basis on which to report the PM emission factor from cotton harvesting is: mass of PM emitted per unit area harvested. This finding was based on a small number of source sampling tests and further investigation is planned for the 2007 harvest season.

Disclaimer

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