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Improvement of PM10 Emission Factors for Almond Harvesting
Almond Board of California (#03-RF-01)
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Executive Summary

The focus of this project was to provide a PM10 emission factor to update that used by the San Joaquin Valley Air Pollution Control District currently. The work evaluates whether current measurement methods are sensitive enough to provide quantitative results from alternate almond harvesting management practices. This information will be necessary to determine the effectiveness of the District's PM10 control regulations. This report provides assessment of progress and updates for the almond pick up portion of the current PM10 emission factor. Three sites and a total of eight implements were monitored for PM10 emissions during the 2004 almond harvest season. Each site included two orchard blocks that were identical with respect to all controllable variables (tree age and variety, irrigation, etc.) and located side-by-side. The implements tested at Site 1 and Site 3 were identical, while those at Site 2 were unique.

Aerosol monitors developed by Texas A&M University (TAMU) and those traditionally used by the air quality group at UC Davis (UCD) were used to measure both upwind and downwind total suspended particulate (TSP) and PM10 concentrations during various almond harvesting operations. The harvesting equipment used during the studies included sweepers, conditioners and harvesters using both conventional and newest technologies from two different manufacturers. Conditioners are harvesters modified to leave the nuts in the orchard and were operated without carts or associated product transport machinery.

The current PM10 emission factor for almond harvesting was developed using a protocol incorporating PM10 concentration measurements and a dispersion model referred to as the Vertical Profiling Method (VPM). During this harvest season, the EPA approved dispersion model ISCST3 was also used to develop PM10 emission factors from measured concentrations. Comparisons between the emission factors generated from the two modeling methods using identical input parameters (measured concentrations, met data, etc.) are provided in this report. The recommendation for using ISCST3 in preference to the VPM as the modeling component of the suggested methodology for quantifying PM10 emission factors for almond harvesting is discussed. Representative PM10 emission factors presented in this report have been generated exclusively by use of the ISCST3 model and other specific guidelines detailed in this report. One of the main advantages observed with the use of ISCST3 was the independence of the location of the sampler in relation to the source (orchard). This is to say that the measured concentrations at sampler locations both near and far from the edge of the orchard could be modeled fairly precisely with ISCST3.

Though the use of the ISCST3 model greatly enhances data recovery by enabling the computation of PM10 emission factors in proximity and meteorological conditions prohibitive to the VPM, the quality of emission factors derived from measurements made under less than ideal conditions is not comparable to those made during better conditions. For purposes of providing a PM10 emission factor average for comparison with the current harvest emission factor, data from some tests was eliminated and tests using similar equipment were grouped as follows:

- Sweeping tests were determined to be non-representative based on grower report (see Appendix C) of non-typical pass numbers for conventional sweeping.
- Tests conducted on August 19 (Site 1, one each of type 1 and 2 harvesters, see Table 1) were disregarded due to large deviations from optimal wind direction.
- Tests conducted on September 13 and 14 (Site 3, all conditioning tests) were disregarded due to high PM10 concentrations measured upwind (background)

Based on equipment descriptions provided by collaborating growers (see Appendices B and C), all of the Manufacturer A harvesters (those used as conditioners and those used for nut pick up) can be classified as

“conventional”. However, since conventional harvesters are not typically used for nut pick up following windrow conditioning, tests of pick up operations on sites 1 and 3 are not considered conventional. The Manufacturer B Harvesting System equipment is considered separately as operationally unique. A summary of the PM10 emission factors grouped in this manner is presented below:

Description of equipment group	PM_{10} emission factor (kg/km^2)				Number of tests
	average	St. Dev	minimum	maximum	
Conventional harvest	484	155	288	640	6
B conditioner	200	19	187	213	2
B harvester	432	183	305	642	3

The values reported for conventional harvest represent several types of equipment, orchard ages and configurations, and harvest operations and, thus, provide the most comprehensive evaluation of PM10 emission factors for almond harvest to date. However, because experiments conducted in 2004 were intensively controlled to eliminate multiple harvesters operating simultaneously and the influence of carts and other equipment associated with product transport from the field, these emission factors for almond pick up are lower than those reported earlier.

The procedure for measuring and computing PM10 emission factors for almond harvesting presented in this report was capable of detecting differences in the PM10 emission rates of compared equipment and of identical equipment on compared orchards. The tables below provide PM10 emission factor averages (n=2, except where noted) for each equipment type and orchard tested in 2004 for which data were not eliminated for reasons stated above:

Operation	*Site	*Type	Avg. Emission factor (kg/km^2)	Reduction (%)
Conditioning	1	1	481	
		2	200	59
Pick up	2	3	605	
		4	365	40

*Please see Introduction (Table 1) for description of sites and equipment types.

In most cases where replicate data are available for evaluation (4 of 6), the difference in PM10 emission factors under identical conditions (two halves of same orchard) was less than 15%. Thus, the method is considered to be sufficiently sensitive to quantify the approximately 50% differences in PM10 emission factors attributed here to equipment.

A consistent difference can also be seen between the same harvest implements (types 1 and 2) conducting nut pick up operations, of conditioned windrows, on two different orchards (sites 1 and 3). Although it is not possible to completely isolate the variables that may have caused this 50% difference, it may be at least partially attributed to differences in soil type and structure (see Report Table 3). Additionally, particle size distribution (PSD) analysis of TSP filters from Sites 1 and 3 showed that PM generated on Site 1 was 18.1 % PM10 and that at Site 3 was 37.6% PM10 (see Appendix Table A9). These data indicate that the soil type and structure effect the nature of PM generated during harvest, as well as the amount of PM generated, and this could have a site-dependant variable effect on the relationship between FRM-measured and “true” PM10 concentrations.

Operation	*Type	*Site	Avg. Emission factor (kg/km^2)	Difference (%)
Pick up	1	1	⊥1807	
		3	815	57
	2	1	⊥642	
		3	327	52

*Please see Introduction (Table 1) for description of sites and equipment types.
⊥Emission factors resulting from single test for each implement type (n+1).

All of the PM10 emission factors reported were derived from the PM10 concentrations measured from by the FRM PM10 samplers rather than the true PM10 concentrations determined from the concentrations and particle size distributions from the TSP samples. The PSD analysis of samples collected at Site 1 showed that, at that location, 63% of the FRM PM10 sampler measured concentration can be considered true PM10.

Introduction

Background

The San Joaquin Valley Air Basin is classified as a non-attainment area for PM10 emissions. The San Joaquin Valley Air Pollution Control District (the District) is faced with a mandate to reduce PM emissions and attain a 5% reduction in PM10 concentrations each year. The District will impose controls on all significant sources. The current PM10 emission inventory shows almond harvesting to be one of the largest agricultural sources of PM10. The accuracy of this inventory depends on accurate estimates of emission rates from all observed operations during almond harvesting. This project was aimed at providing more accurate PM10 emission factor to update those used by the District in the past. Ongoing research addresses the difficulties and uncertainties in the measurements of PM10 emissions generated during almond harvesting operations. In addition, the work evaluates whether current measurement methods are sensitive enough to provide quantitative results from alternate almond harvesting management practices. This information will be necessary to determine the effectiveness of the District's PM10 control regulations.

The PM10 emission factor currently used by the District for almond harvesting is based on measurements made of almond pick-up operations by Dr. Flocchini's lab at University of California, Davis (UCD). The measured emission factors for almond pick-up were used to estimate PM10 emission factors for the other two operations associated with almond harvesting; shaking and sweeping. Based on visual observation, a factor 10% of the pickup was suggested for sweeping and 10% of sweeping for shaking by Gene Beach and the Agricultural Technical committee chaired by the District. Taken together, these three emission factors comprise the current almond harvest PM10 emission factor.

Improvement of the current PM10 emission factor for almond harvesting was initially focused on evaluating the one element of that emission factor based on measurement: that of the pick up operation. This effort required progress in several different areas:

- The method for PM10 concentration measurement on which the current emission factor is based were tested against an independent method,
- Improvements to the method for computing emission factors from PM10 concentration measurements were evaluated, and
- More current, well documented, and representative examples of base-line harvest operations were tested.

This report provides assessment of progress on these fronts and updates the almond pick up portion of the current PM10 emission factor.

Approach

Context of previous studies

A critical element to establishing a base-line PM10 emission factor for almond harvesting is the identification of a representative operation. Ideally, a finite number of orchard and equipment combinations would be acceptable to all stakeholders as representing the "conventional" almond harvest operation. Measured emission factors from each of these sources could then be combined to produce a universal base-line. In practice, the strategy pursued by the UCD team has historically been to opportunistically capture an operation in process. Research upon which the current PM10 emission factors for on-field agriculture were based was guided by evaluation of the regional distribution of crop acreage and dominance of equipment markets. Once a geographic region and grower were identified as likely representatives of the industry, individual orchards were selected based on compatibility with measurement requirements and sampled to the limits of measurement capabilities. In returning with the current project the same approach was attempted (please see results of 2002 and 2003 sampling seasons, 2004 final report to ABC).

Because it is not possible to identify and test all possible variations of "conventional", quantification of the inherent variability in the measurements was needed to estimate how many measurements of "typical" conditions were necessary to represent the base-line. Opportunistic sampling was quickly found to be inadequate to this task because it requires an estimation of the accuracy and precision of the method and this, in turn, requires replication of testing under identical conditions. Ironically, the need to define the quality of the base-line PM10 emission factor precluded the use of opportunistic sampling to capture "typical" conditions. Thus, all measurements performed in the 2004 season were under tightly controlled conditions that may not be judged sufficiently representative to contribute to the development of a base-line PM10 emission factor for almond pick up operations.

Description of field experiments

Three sites and a total of eight implements were monitored for PM10 emission during the 2004 field season. Each site included two orchard blocks that were identical with respect to all controllable variables (tree age and variety, irrigation, etc.) and located side-byside. Implements tested at Site 1 and Site 3 were identical, while those at Site 2 were unique**. Table 1** summarizes the experiments conducted.

Aerosol monitors developed by Texas A&M University (TAMU) and those traditionally used by UCD were used to measure PM10 during actual almond harvesting operation within the District area, both upwind and downwind of the orchard for the 2004 season. Both groups also employed Total Suspended Particle (TSP) samplers. Extensive particle size distribution (PSD) analyses of the dust collected from the TSP sampler filters were conducted to define the particles less then 10 microns using the Coulter Counter Multisizer III. The result of this procedure will be called the "PM10 from PSD" analysis and also referred to as "true" PM10.

Meteorological parameters were recorded simultaneously with aerosol collection and the LIDAR instrument was employed at all sites to detect and provide information about vertical and horizontal extent of the plumes. Soil samples were collected for evaluation of moisture and soil texture including the description of the cultural and management practices done for particular orchards sampled.

Table 1: Summary of tests conducted in 2004 harvest season. Code numbers are referenced in the text for data evaluation purposes.

Site/row orientation	Operation	Implement				
		Make	Model	Year	Code	# tests
1/N-S	Sweeping	A	3	2003	1	1
		B	1	2004	2	3
	Conditioning	A	4	2002	1	2
		B	2	2004	2	2
	Pick up	A	1	2002 (1990)	1	2
		B	3	2004	2	2
2/ E-W	Pick up	A	1	2004 (1990)	3	2
		A	2	2004 (2002)	4	2
3 / N-S	Condition	A	4	2002	1	2
		B	2	2004	2	2
	Pick Up	A	1	2002 (1990)	1	2
		B	3	2004	2	2

Site 1. The first orchard sampled was in Kern County. The orchard was located off Kimberlina road, north of Bakersfield and west of highway 99. The rows were oriented north-south (N-S) with 64 rows of 29 trees. The

first 8 rows were not used because they were not of full length. Detailed descriptions of the orchard and equipment used on Sites 1 and 3 can be found in **Appendix C**.

The first four tests conducted on Site 1 used sweeping machines. Descriptions of sweeping tests are provided in **Appendix Table A1**. These tests were conducted using UCD sampling towers only.

Tests using conditioning and harvesting equipment were also performed at site 1. Details are shown in **Appendix Table A2**. The LIDAR instrument was operational for these tests. For tests 73 to 80, UCD and TAMU samplers were used simultaneously, and both sets included both PM10 and TSP samplers. Two UCD sampling towers were used at different locations downwind of the orchard during these tests.

Site 2. This orchard was situated south of Arbuckle. The trees were about 4 years old. The rows were oriented east to west, were 210 meters long, and were split into two plots along the N-S axis. UCD samplers for both PM10 and TSP were placed at 4 different heights on a 10-meter tower. PM10 and TSP samplers from TAMU were used 20 meters further downwind than the UCD tower. The lidar was also employed at this site. **Appendix Table A3** shows the details of tests. Detailed descriptions of the orchard and equipment used at Site 2 can be found in **Appendix B**.

Site 3. The third site sampled was in Kern County. The orchard is situated south of Highway 46, west of Brown Material road just outside of Lost Hills. The rows were oriented east-west. The orchard had 109 rows and only the southern sections were used for testing. The width of each half was about 190 meters. Similar sampler placement strategies were employed at this site to those used at Site 2, with the UCD tower used approximately 10 meters downwind of the orchard edge and one pair of PM10 and TSP samplers from TAMU were used 20 meters further downwind than the UCD tower. The lidar was also employed at this site. Details of tests are shown in **Appendix Table A4**.

Description of Models

There is no known method for direct measurement of PM10 emission rates from open area sources such as on-field agricultural operations. Almond harvesting is considered to be an area source because of the contributions to PM10 emission, both positive and negative, of interaction of the primary source (e.g. the exhaust from the implement fan) with orchard elements such as the soil surface at the tree row and the tree canopy. Thus, measurements of the PM10 enrichment in the air leaving the orchard are the only data attainable for estimation through computation of a PM10 emission rate. This emission rate can then be used to compute an emission factor by converting the time variable in the rate to an operation-specific variable, usually the orchard area covered by the operation.

The current PM10 emission factor for almond harvesting was derived from PM10 concentration measurements using a model called Vertical Profiling Method (VPM). This technique uses the PM10 concentrations measured at several heights on a tower downwind of the source to estimate the size and strength of the plume it generated. Wind speed data are incorporated to account for the movement of the plume from the source to the PM10 samplers. Together with lidar data to verify that a representative portion of the plume was sampled (e.g. the tower is tall enough that the PM doesn't pass over it), this technique has been demonstrated to adequately quantify PM10 fluxes when a source is close (within 50 meters) to the samplers. The principle shortcoming of the VPM is the requirement of sampling a representative portion of the plume. As a source moves away from the sampler the plume disperses and rapidly becomes too large to be adequately sampled using ground-based instruments.

It is this ability to account for plume dispersion that is the principle strength of the EPA-approved dispersion model, Industrial Source Complex Short Term Version 3 (ISCST3). The ISCST3 model uses additional meteorological data as well as detailed information about the juxtaposition of the source and the samplers to estimate the impact (change in size and strength) of dispersion on the portion of the plume that is sampled. Thus, it does not require measurement of PM10 concentrations at multiple heights and can utilize data collected a relatively long distance (hundreds of meters) from the source. As long as the enrichment in PM10 concentrations measured downwind of the source is quantifiable relative to background concentrations, the emission rate can be estimated using ISCST3. The less stringent data gathering requirements of the ISCST3 model relative to the VPM directly enhance the data recovery rate of almond harvest experiments, where it is not always possible to place samplers close to the source. While wind speed and direction must be adequate to carry the plume from the source to the sampler, the ISCST3 model is less demanding in functional requirement than the VPM in this aspect as well. Finally, the ability of the ISCST3 model to estimate plume dispersion characteristics eliminates errors due to horizontal diffusion (i.e. in the cross-wind directions) of the plume which cannot be accounted for by the VPM.

Comparisons between emission factors generated from identical measured data using the two modeling methods are provided in section IV of this report. Here the recommendation for using the ISCST3 model in preference to the VPM as the modeling component of the suggested methodology for quantifying PM10 emission factors for almond harvesting will be fully justified. In all other parts of this report and in the presentation of representative emission factors therein, PM10 emission factors have been generated exclusively by use of the ISCST3 model.

Pre-2004 PM10 Emission Factors

As the only component of the current PM10 emission factor for almond harvesting based on actual measurement of PM10 emission rates is the nut pick-up operation, subsequent measurements of pick-up are our first step to improving the emission factor. In order to assess the utility of recently reported emission factors to replacement of the current emission factor, both experimental and mechanical parameters must be comparable. To this end, specifications of harvesters used during monitoring that produced previously reported PM10 emission factors are presented in Table 2. In addition to the manufacturing specifics of the harvesters used, many other variables exist in attempting to make comparisons between data collected on different orchards with different growers in different years. These include, but are not limited to:

- After-market modifications and set-up of harvesters,
- Harvester speed,
- Orchard age, tree density, and size,
- Crop size and windrow condition,
- Soil characteristics, irrigation methods, and orchard floor maintenance.

With the exception of basic soil texture and moisture analysis, quantification of these variables is not included in the methodology used to derive the reported PM10 emission factors. The intent of this work has been to randomly select “typical” harvesting operations to represent standard industry conditions for development of base-line PM10 emission factors for almond harvesting.

Table 2: Previously reported PM10 Emission factors based on monitoring specific almond pick-up machines.

Experiment description			Machine description			Emission Factor (kg/km^2)	
Year	Analysis	# Test	Make	Model	Year(s)	Average	StdDev
1995	VPM	5	A; C	1; 1		4117	3210
2002	VPM	1	D	1	1984	2107	
2003	VPM	1	A	4	1993,95,96	2595	

Particle Size Distributions

Statement of Problem and Methodology

This section evaluates the impact of PM-10 concentration measurement methods on PM10 emission factors for almond harvesting. Sampling procedures utilized complimentary sampler types to enable comparisons between the two dominant mechanisms for PM-10 concentration quantification. Equipment used by the UCD team, including both the Federal Reference Method (FRM) PM10 samplers and the TAMU-designed low volume (LV) Total Suspended Particulate matter (TSP) samplers mounted at four heights on towers, are herein referred to as UCD towers. The TAMU designation refers to use of LV TSP and FRM PM10 samplers from Texas A&M. PM concentrations reported in this report are in units of micrograms per actual cubic meter ($\mu g/m^3$).

After the gravimetric weighing of all filters for concentration calculations, all filters collected using TAMU samplers (both PM10 and TSP) and TSP samples collected on the UCD tower were sent to TAMU for particle size distribution (PSD) analysis using the Coulter Counter Multisizer III. PSD analyses were made on all filters, both the TSP and PM10 filters, to evaluate sampler bias. The PSD follows a lognormal distribution with the defining characteristics being the mass median diameter (MMD) and geometric standard deviation (GSD). From this information, the particle size fraction less than 10 microns is computed as the PM10 from PSD analysis (or the "true" PM10).

Samples collected using PM-10 samplers which use the FRM particle sizing mechanism (both TAMU and UCD) were gravimetrically analyzed and these masses were used to compute “measured” PM10. Comparisons between PM-10 concentrations measured by the two theoretically identical FRM-type samplers will indicate the precision of these measurements and the possibilities for comparable measurements by independent parties. The “measured” PM-10 concentrations are also used to provide backward compatibility to previous measurements and to evaluate measurement bias through comparison with the “true” PM-10.

Results and Discussions

Measured (FRM) PM10 Concentrations

In order to make useful comparisons between the two methods for measuring PM10 concentrations (FRM vs. TSP with PSD) it is important to establish that samplers designated by each group to measured the same parameter are, in fact, producing comparable data. Collocated FRM samplers independently designed by the UCD and TAMU groups, using the same commercially available FRM-designated inlet, were used to make this comparison. For tests 74 through 80 (Site 1 conditioning and pick-up experiments) one FRM PM10 sampler from each group was placed side-by-side with the other and each group collected and analyzed the resulting samples independently. Results of this comparison are shown graphically in **Figure 1**. Given the relatively small number of samples, inherent spatial variability in the plume with the N-S rows of this orchard, and the inability to place the samplers closer than 10 m from one another, the agreement between measured PM10 concentrations is quite good. There appears to be a slight positive bias in the data collected by the UCD team, but this may be due to the tower being placed consistently closer to the source, though only by a small distance.

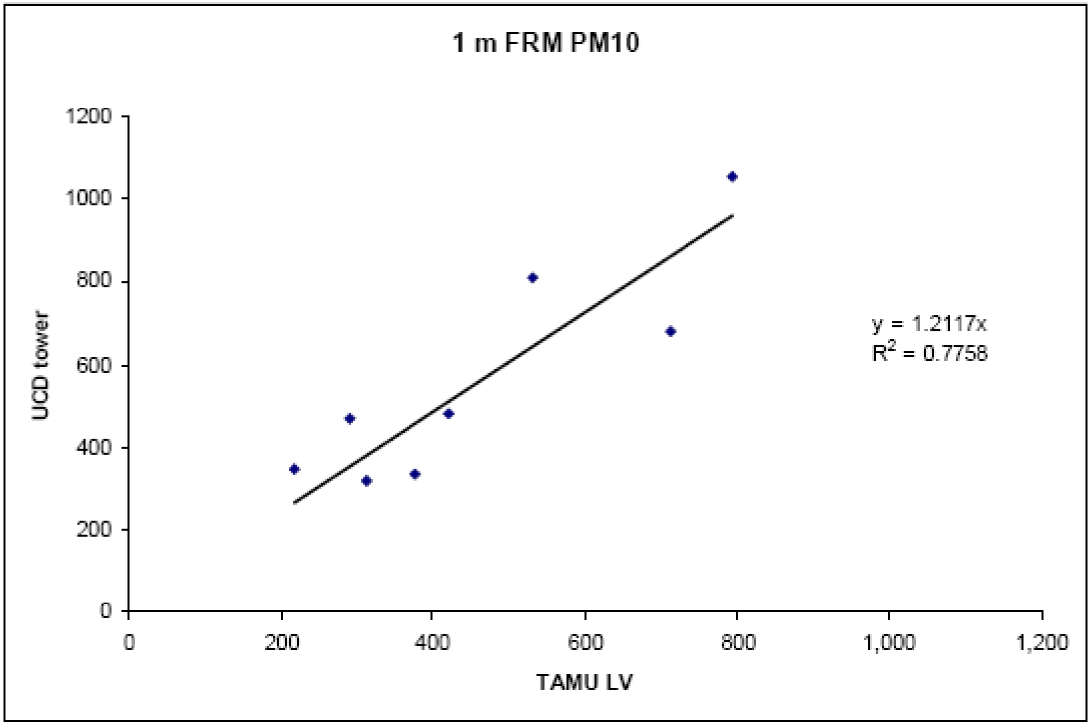


Figure 1: PM10 concentrations measured at 1 meter using collocated FRM samples designed and operated by the TAMU and UCD groups, independently.

Soil Texture and Moisture

Differences in soil texture from orchard to orchard might contribute to differences in PSD of particulate matter suspended in the air during harvest activities. This hypothesis is based on the fact that soil texture is an analysis of the size distribution of soil particles. If an orchard is planted on soil with more larger particles, will the dust plume generated on it also have more large particles than a plume generated on an orchard where the soil has a larger proportion of smaller particles? Another aspect of PM emission that might be affected by soil properties is the relative amount of PM and/or PM10 generated on different orchards using the same equipment. It has been shown in previous work that soil moisture is inversely correlated to PM10 emission factors, all other variables being held the same. It has also been shown in laboratory experiments that soils with larger proportions of silt (very small particles) have higher PM10 generation potentials.

In this project, soil samples were collected for moisture analysis for every test performed. These data are provided with the PM10 emission factors in Section IV of this report (**Table 11**). Soil texture was measured for each portion of each orchard defined as a separate site for purposes of replication (where each implement type was tested repeatedly). For sites 1 and 2 all measurements gave the same soil texture, so the percent found in each size fraction is presented as an average (**Table 3**). For site 3, analysis showed the two halves to have slightly different soil textures, so those are presented separately.

Table 3: Soil texture on each orchard surveyed.

Site	1 - All	2 - All	3 - East	3 - West
% sand	76.3	61.6	43.4	49.7
% silt	10.3	20.7	26.1	24.1
% clay	13.4	17.7	30.4	26.2
Soil texture	Sandy loam	Sandy loam	Clay loam	Sandy clay loam

Particle Size Distributions

A particle size distribution analysis was performed on each of the filters from all of the low volume TSP samplers (TAMU and UCD tower) and the TAMU-collected PM10 samplers. The percent mass versus particle diameter distribution of dust particles follows a lognormal distribution defined by its mass median diameter (MMD) and geometric standard deviation (GSD).

Table 4: PSD of dust collected from TSP filters collected by TAMU downwind of operations at Site 1.

Range	Conditioner # 1		Conditioner # 2		Harvester # 1		Harvester # 2	
	MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD
High	21.99	2.37	25.56	2.52	27.87	2.36	30.85	2.74
Low	8.11	1.85	12.33	1.9	11.49	1.26	13.65	1.95
Average	15.45	2.0	17.17	2.15	16.89	2.0	20.36	2.31
StdDev	4.16	0.14	3.35	0.21	4.37	0.26	4.61	0.27

When the MMD and GSD of a TSP sample are known, the percent of particles less than any given size particle can be calculated using the lognormal distribution. **Table 4** shows the MMDs and GSDs of the dust collected at downwind locations using the TSP samplers. The MMD of the dust collected on the TSP filters at Site 1 had an overall average MMD of 17.6 and GSD of 2.1. The PSD analyses of TSP filters from previous years of sampling are shown in **Table 5**. The variability in PSD of TSP collected downwind of the same operation on the same orchard is generally greater than that in the average from year to year. Thus, the average PSD and PM10 fraction of TSP has been shown to be consistent over time and space for the monitored almond harvest operations.

Table 5: Summary of PSD analysis over the tree almond harvesting seasons

2002 Season		2003 Season		2004 Season	
MMD	GSD	MMD	GSD	MMD	GSD
19.0	2.0	18.8	2.1	17.6	2.1
Particle Density	2.7565	Particle Density	2.5621	Particle Density	2.3855

Representative samples of TSP collected upwind of the operations on Site 1 were also analyzed for PSD characteristics and the data are shown in **Table 6**. The average MMD measured upwind of the sources, 22.4, was higher than the average PSD measured downwind at the same site. The average percent PM10 that is computed from this TSP is 18.9%. Compared to the average PM10 fraction of the TSP concentrations measured downwind, which is about 22.6%, these data suggest that the ambient air at Site 1 has a higher proportion of larger particles than ambient air at EPA monitoring sites throughout the SJV. This would imply that truly ambient air, unaffected by local upwind sources, was not sampled during these experiments. Concentrations of PM (whether TSP or PM10) measured upwind were, however, consistently much lower than concentrations measured downwind and consistent with ambient concentrations measured at EPA monitoring sites. It is also possible that the TSP sample mass and/or the number of TSP samples analyzed were insufficient for definite determination of PSD of the air monitored upwind of the sources. Either way, at the very least these data demonstrate that there was no quantifiable difference between the PSD of TSP collected upwind and downwind of the sources and the same average percent PM10 can be applied to all samples equally to determine "true" PM10 concentrations.

Table 6: Upwind PSD Analysis Data

Conditioner # 2		Conditioner # 2		Harvester # 1		Harvester # 2	
MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD
25.56	2.52	18.69	2.20	17.48	2.54	27.87	2.36

Analysis of PSD was also preformed on the PM10 samples collected by TAMU using their FRM samplers. **Table 7** summarizes the PSD analysis results of all the PM10 sampler filters collected at Site 1. These results indicate that the average MMD (of the PM10 filters) is greater than 10 µm. This result is a consequence of the PM10 samplers collecting particles larger than what they were designed to collect. The overall average MMD was 12.97 µm (aerodynamic equivalent diameter) with a GSD of 1.94. It has been hypothesized that the operating characteristics of the FRM PM10 samplers (cut-point and slope) may have shifted from what they were designed to be as a consequence of an interaction with the PSD of the dust being sampled. A shift in the cut-point and slope of the FRM PM10 samplers can further confound the measurement errors encountered when FRM PM10 samplers are used to sample dusts with MMDs over 10 µm. The theoretical basis for the measurement error associated with the FRM PM10 samplers as a consequence of an interaction with the PSD of the dust is discussed by Buser et al. (2001). At this time, no analysis has been conducted to identify a shift in the cut-point and slope of the PM10 samplers during the orchard sampling tests. **Tables A5, A6 and A7** in the Appendix show the PSD results of the PM10 filters from the TAMU samplers.

Table 7: Average PSD of dust collected from PM10 filters collected by TAMU downwind of operations at Site 1.

Sweeping Operations				Conditioning Operations				Pickup Operations			
Conventional		Modified		Conventional		Modified		Conventional		Modified	
MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD
12.83	1.85	12.98	1.94	11.94	1.85	12.73	1.94	12.51	1.94	15.46	2.14

PSD Analysis of Filters from Site 1 and 3

The particle size distribution of all TSP filters from Sites 1 and 3 (**Table 1**) were compared to evaluate the differences in the MMD and GSD of the dust particles at these sites where identical harvest equipment was used. In this study, Site 1 has higher sand and lower clay content than Site 3 (**Table 3**). **Table 8** shows the dust generated at Site 1 had higher MMD than that generated at Site 3, even though only 3 filter samples provided PSD data from this site. Following the lognormal distribution, the filter dust PSD analysis showed that Site 1 dust samples on the average had 18.1% PM10 while those collected at Site 3 had 37.6% PM10. These data indicate that soil characteristics may affect quantification of PM10 concentrations and, thus, emission factors.

Qualitatively, the greater proportion of particles larger than 10 µm in the PM collected at Site 1 would tend to increase the difference between FRM measured PM10 concentration and "true" PM10, relative to FRM sampler performance on Site 3. Thus, some portion of the larger PM10 emission factors measured on Site 1 relative to Site 3 may be due to an increased artifact in PM10 concentration measurement as well as an actual increase in emission rates. Coincidentally, both phenomena can be attributed to the presence of more larger particles in the soil.

Table 8: PSD Analysis of TSP filters for Sites 1 & 3.

Test Site	Test No.	Operation	MMD	Std. Dev	GSD	Std. Dev.	No. of samples
1	77-80	Pick-up	19.90	4.57	2.13	0.18	20
3	88-92	Pick-up	13.33	1.71	2.48	0.32	3

"True" PM10 concentrations

The LV PM10 and TSP samplers were collocated at downwind locations for most of the tests conducted on Site 1 for the purpose of evaluating PM10 sampler measurement errors. The particle size distribution and mass concentration obtained from the TSP samples was used to determine the "true" PM10 concentrations for comparison with the PM10 concentrations measured with the collocated PM10 samplers. Plotting the paired PM10 from PSD/Sampler PM10 concentration values (see **appendix Table 8**) from all of the tests (**Figure 2**), a linear relationship is observed. There was an excellent linear correlation with an R2 of 0.9371. Similar results have been observed for other agricultural dust such as those from cotton gins (Capareda, et.al. 2005). With this relationship, sampler PM10 concentration could easily be corrected by simply noting that 63% of the reported sampler PM10 concentration can be considered "true" PM10. The dashed line in Figure 1 would result if the PM10 samplers were actually measuring the true concentration of PM10. The PM10 sampler has minimal over sampling error at low PM10 concentrations. At higher ambient concentrations, the over sampling error is greatly increased. There were few instances where the PM10 from PSD analysis were the same as the sampler PM10 concentrations. The errors in the measured PM10 concentrations have a direct impact on the resulting emission factors as emission flux is estimated by the model to match measured downwind concentrations. If the ratio of the true to measured PM10 concentrations is known, it can be applied directly to the measured PM10 concentrations producing an estimate of true PM10 concentration from which to model corrected emission factors that would reflect the true PM10 concentrations (these being more accurate, assuming the TSP sampling and PSD analysis to be accurate).

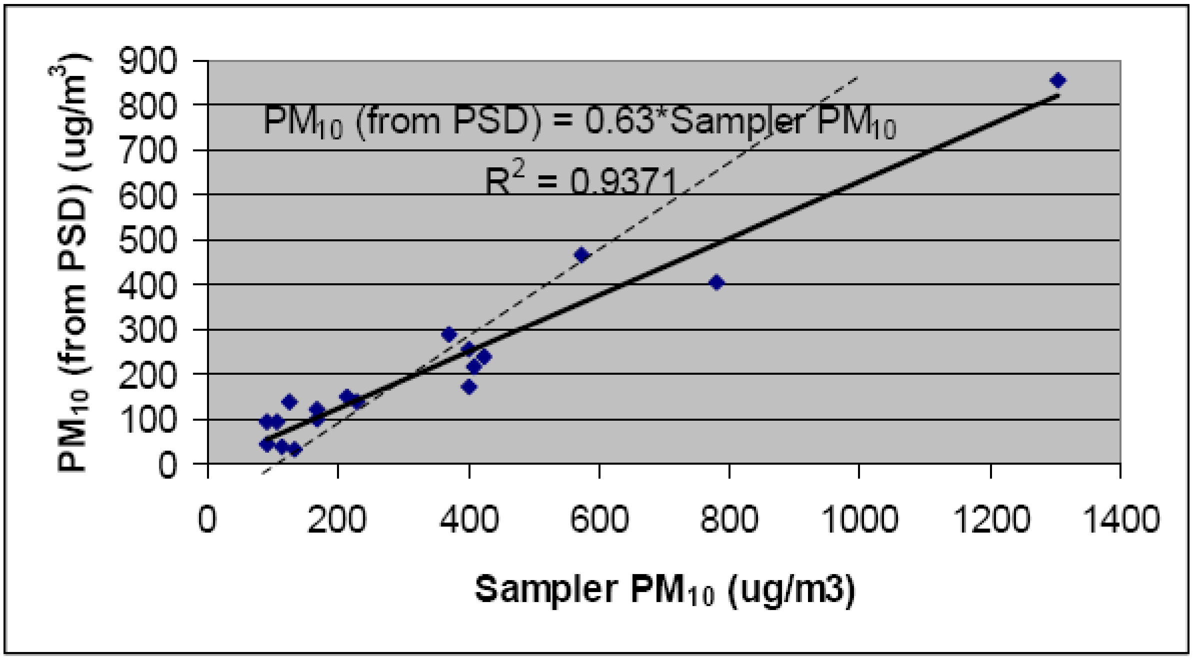


Figure 2. Relationship between PM10 concentrations calculated from TSP sampler using PSD analysis and those from FRM PM10 samplers used downwind at 1 meter height on Site 1. Dotted line represents the ideal (1:1) correlation that the data would describe if the two PM10 concentration measurement methods obtained identical results.

Similar analysis of PM10 concentrations measured by the FRM and computed from PSD of TSP samples collected side-by-side at 3 heights downwind of Sites 2 and 3 produced the same ratio of "true" PM10 to measured PM10 concentrations (**Figure 3**). Data collected at 9 meters is excluded due to sampler malfunctions.

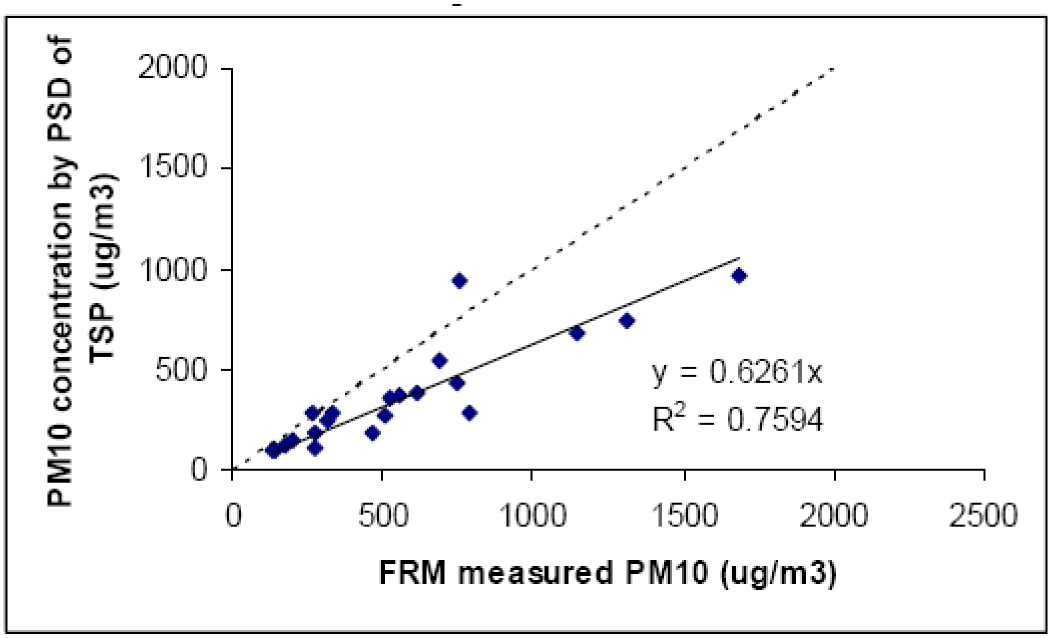


Figure 3. Relationship between PM10 concentrations calculated from TSP sampler using PSD analysis and those from FRM PM10 samplers used downwind at Sites 2 and 3 at 1, 3, and 5 meters. Dotted line represents the ideal (1:1) correlation that the data would describe if the two PM10 concentration measurement methods obtained identical results.

Based on all available data comparing the two methods for measuring PM10 concentrations surrounding almond harvesting operations, the following observations can be made:

- The PSD and MMD of TSP samples are dependent on the orchard selected as affected by soil texture and characteristics.

- The correction to FRM-collected PM10 concentrations indicated by PSD analysis is consistently about 63%.

- PM10 emission factors are likely also overestimated when computed from FRM-collected PM10 concentrations, assuming the PSD analysis to be the accurate measure of "true" PM10.

References

1. Capareda, S.C., M. D. Buser, D.Whitelock, J.K. Green, C.B. Parnell, Jr., B.W. Shaw and J.D. Wanjura. 2005. Particle Size Distribution Analysis of Cotton Gin Dust and Its Impact on PM10 Concentration Measurements. Paper presented at the 2005 Beltwide Cotton Conferences held from January 4-7, 2005 at New Orleans organized by the National Cotton Council, Memphis, TN.

2. Buser, M. D., C.B. Parnell, R. E. Lacey, B.W. Shaw, and B.W. Auvermann. 2001. Inherent biases of PM10 and PM2.5 samplers based on the interaction of particle size and sampler performance characteristics. ASAE Paper No. 011167. St. Joseph, MI: ASAE.

Model Evaluation

Evaluation of Measured PM10 Emission Factors

Two goals were defined for the research described in this report. First, a need was identified to develop, test, and describe a method by which precise, accurate PM10 emission factors could be produced for almond harvesting operations. Then, there is the requirement for accurate measurements of PM10 emission factors for each and all the processes and variations which define almond harvesting in California. These two goals are compatible to the extent that development of method requires the actual measurement of PM10 emission factors. Evaluation of the PM10 emission factors computed from the measurements of PM concentrations and meteorological data collected during the 2004 harvest season was an iterative process. Comparisons of data collected under varying conditions of sampler type, sampler placement, meteorological conditions, and harvester location within the orchard provide one type of assessment of the data. Comparison between measurements made under similar conditions varying only the type of harvester gives another type of evaluation. Ultimately, a specific representation of the data was indicated as the most likely to provide accurate emission factors. Generally, PM10 emission factors herein presented to define the best estimate for each measurement opportunity, or test, were derived through the following guidelines:

- Measured PM10 concentrations, using the FRM samplers, were used in preference to “true” PM10 derived from PSD analysis of TSP samples.

- Measured PM10 concentrations upwind of the sources were generalized as equal to ambient and, thus, not incorporated into ISCST3 model runs.

- With multiple measurements of PM10 concentrations, as was the case with all tests, the ISCST3 model requires a choice of concentrations upon which to base predictions of emission rate. This choice was made with consideration of which samplers were actually in the wind-shadow and, from among those that were, based on consistency with the others.

- Where used, the two UCD towers and the body of TAMU samplers each contributed a PM10 concentration to the ISCST3 model prediction of emission rate. Thus, as many as three separate emission rates are incorporated in a single test average emission factor.

- PM10 emission factors were computed via ISCST3 model runs for data collected by all samplers found to be in the wind-shadow and averaged to produce the final test emission factor.

Evaluation of the total measurement and modeling method presented in the following section (IV) describes the data sets that established the ISCST3 model as the preferred method for computing PM10 emission factors. The standardization of how to apply the ISCST3 model to the wide variety of measurement data collected was based on the experience that the average emission factor for a test was found to be relatively insensitive to the choice of measured concentration used to predict emission rates, as long as the location was in the wind-shadow.

Changing a single variable to define method precision

One objective of the current project is to evaluate the validity of the current PM10 emission factor for almond harvest operations. Many approaches are useful in this endeavor, but one question that becomes unavoidable is: “How reliable is the method used to obtain the PM10 emission factor?” This, in turn, can be paraphrased in many ways and there are many related questions such as: “Was the correct thing (PM10) measured?” and “Were the harvest conditions monitored really representative of the industry?” But in order to address any of these questions one must first quantify whether the method can measure the same thing twice under identical conditions. At first glance, this might appear simple. It seems strait forward to qualitatively determine whether the same thing can be measured twice: just make it happen twice and measure it. The difficulty comes in quantifying that capability. It can be established to the satisfaction of most people that agricultural practices such as almond harvesting are never exactly the same; from day to day, orchard to orchard, grower to grower, something is always changing. Agriculture is a delicately manipulated natural system. In order to quantify the difference between the effects of the natural differences from one harvest to another on measured PM10 emission factors and the difference that can be detected by the method we chose to deliberately change a single variable in the system. To provide the largest expected differences (and best chance at success), and given the interest of collaborating equipment manufacturers, the variable we chose was implement type.

As detailed in Section I (**Table 1**), two types of implement were used for each harvesting operation (sweeping, conditioning, and pick up) monitored. Orchards were selected primarily for the fact that they would be harvested in two sections. These sections were identical in every aspect controllable by the grower. Trees were of identical plantings, orchard floors were maintained the same, and they were geographically side-by-side. However, many uncontrollable factors could have differed. Certainly, the time of day and meteorology varied from test to test, as it was impossible to sample both halves of the orchards simultaneously due primarily to equipment and personnel limitations.

In evaluating PM10 emission factors derived from measurements in these paired experiments one implement of the pair is always expected to produce a higher emission rate than the other. This forgone knowledge is used to test the "reasonableness" of some of the data collected to aid investigation of the limitations of the method (times when it doesn't work). Generally, however, all that was necessary was that some tests were expected to produce the same results and others were to give different results. Since no two measured emission factors (indeed, harvests) are truly identical, we use these data to determine whether differences in measured PM10 emission factors can be attributable to known differences (in equipment) or indistinguishable from natural variation.

Relationship between downwind concentrations and Emission Factors

Measurements of PM10 concentrations downwind of a source are not representative of emission rates or emission factors. Many variables can affect downwind PM10 concentration other than the PM10 emission rate, the dominant ones being meteorological. To examine the affects of variables other than emission rate on PM10 concentrations we can look at the relative differences between concentrations and emission rates in paired experiments where a single controlled factor is changed. In **Table 9**, two types of harvesters are compared on the basis of PM10 concentration measured downwind and the modeled PM10 emission factors derived from those concentrations. By comparing the ratios (data for one harvester divided by that for the other) of PM10 concentrations to ratios of PM10 emission factors, the possibilities for misinterpretation of emission rate based on PM10 concentrations alone can be seen. In some cases, as illustrated by data from tests 04-075/04-076, the ratios between paired PM10 concentrations are similar to the ratios between paired PM10 emission factors. This indicates that similar meteorological conditions existed from one testing period to another. In paired tests 04-073/04-074, 04-077/04-078, and 04-079/04-080, however, some factor influencing measured PM10 concentrations other than the emission rate were found to differ. This is an indication of the effects, such as meteorology, that the model brings into account in computing emission factors and the danger in using concentration data alone to evaluate variables thought to control emission rates.

Table 9: Comparison of single variable (implement) effects on downwind PM10 concentrations vs. computed PM10 Emission Factors.

Test #	Implement	Rep.	Avg. PM10 conc. (ug/m3)	Avg. PM10 EF (kg/km)	PM10 conc. Ratio	PM10 EF ratio
04-073	Condition1	1	302	323		
04-074	Condition2	1	338	213	0.9	1.5
04-076	Condition1	2	865	640		
04-075	Condition2	2	245	187	3.5	3.4
04-078	Pickup1	1	342	904		
04-077	Pickup2	1	190	1237	1.8	0.7
04-079	Pickup1	2	795	1807		
04-080	Pickup2	2	431	642	1.8	2.8

Choosing the Industrial Source Complex (ISC) Model

While it is clear that it is necessary to compute PM10 emission rates to assess either the base-line emission factors used in emission inventories or the impact of dust reduction efforts on PM10 emission, emission rates cannot be measured directly for area sources. This project used two different mechanisms to make the computations of PM10 emission rates from the PM10 concentrations measured. The current emission factor is based on the use of a Vertical Profiling Model (VPM) to estimate the emission flux required to produce measured PM10 downwind concentrations. In the current project, two additional methods were used for comparison: 1) PM10 derived from TSP measurements applied to ISCST3 dispersion model and 2) FRM PM10 concentrations applied to the ISCST3 dispersion model. Detailed discussion of the advantages of the ISCST3 model in producing reliable estimates of PM10 emission rates can be found in section IV of this report. In brief, data in **Table 10** contrast the overall data recovery attained in the current study using each modeling method, illustrating at the most basic requirement that the more versatile ISCST3 model produces data which can fulfill the project objectives while the VPM is less capable of doing so. In the 2004 harvest season, a total of 51 separate sets of measurements were taken to quantify PM10 emission factors for almond harvest operations. The VPM produced 22 emission factors and the ISCST3 produced 48.

Table 10: Summary of attempted tests of almond harvest operations using a combination of UCD tower mounted samplers and TAMU LV samplers at 1 m only and the number of those tests that yielded quantifiable PM10 emissions factors using the VPM vs. ISCST3 models.

Success rate (%)	UCD tower		TAMU (1 m only)
Operation	Vertical Profile	ISCST3	ISCST3
Sweeping	75	75	
Conditioning	82	91	100
Pick up	63	94	100

One of the most important advantages of the ISCST3 model is the acceptability of particulate matter concentrations collected at only one height as inputs to the model. Unlike the Vertical Profile method, concentrations need not be measured at multiple heights. This disparity is clear in examination of the two right hand columns of **Table 10**, where the VPM is not represented because it cannot be applied to those data. This means exclusive use of the ISCST3 model can eliminate a significant equipment cost as it has no need for the tower or the time, space, and expertise needed to erect the tower. It also reduces the requirement for PM mass measurement sensitivity as only the lowest height, where concentrations will be highest for a ground level source, need be monitored. These points are further illustrated with examples from the data in section IV of this report.

Vertical Profiles of PM10 concentrations and lidar images as supporting data

In order to use the PM10 emission factors developed from the 2004 season field data for comparison with and verification of previously reported PM10 emission factors for almond harvesting it is critical that:

- Sample collection and analysis techniques used previously are included in the current work and

- New techniques developed in the current work are used to determine the quality of data gathered previously, under the specific circumstances of those efforts. To this end, vertical profiles of PM10 concentrations and vertical and/or horizontal lidar scans of dust plumes were collected downwind of all operations monitored in the 2004harvest season.

While the principle determinations of average measured PM10 emission factors for each operation monitored are based on the results of ISCST3 modeling, VPM modeling was also conducted for all tests for which that method was valid. The results of the two methods were compared to indicate under which field conditions the VPM can be validated (please see section IV). Previously reported PM10 emission factors for almond harvesting based on the VPM are reexamined to determine whether the field conditions in those studies are consistent with current findings regarding the limitations of the VPM.

Lidar scans contribute to the interpretation of the value of both the ISCST3 and VPM models in application to PM10 concentrations measured downwind of a source. In the case of the ISCST3, the almond orchard represents a unique source configuration wherein the tree canopy and local topography (e.g. irrigation canals) have possible implications to the dispersion assumptions integral to the model. Comparisons between dust plume dispersion characteristics visualized via the lidar images and model results contribute to investigation of the adequacy of the ISCST3 dispersion algorithms in cross-wind and height axes. In the case of the VPM, vertical lidar scans are invaluable in determining whether the sampling tower was within the plume and whether the plume height estimated from the measured PM concentrations is consistent with the height of the plumes observed by the lidar. Additionally, data derived from lidar scans recording plumes in areas of the orchard not monitored by PM samplers can be used to indicate whether the plumes that were sampled were representative of PM generated throughout the orchard and the general homogeneity of the orchard as a source.

These uses of PM concentration measurement at multiple heights (vertical profiles) and the lidar instrumentation are considered supplementary in the current project to measurements of PM10 concentration as input to the ISCST3 model. The supportive role of these data to assessment of the ISCST3 model and the PM10 emission factor measurement method in general was critical to attaining the project objectives. However, these supplemental measurements can be reduced or, for the most part, eliminated in routine monitoring provided the guidelines of the recommended method are carefully followed.

Method Evaluation

Summary of Measured PM10 Emission Factors

Table 11: Summary of individual PM10 emission factors with soil moisture data.

Operation	Site (orientation)	Implement	Soil Moisture (%)	Emission Factor (kg/km2)
Sweeping	1 (N-S)	1	1.98	759
		2	2.45	593
Conditioning	1 (N-S)	1	2.00	323
		2	2.70	213
		1	2.10	640
		2	2.38	187
Pickup	1 (N-S)	1	2.51	904
		2	1.68	1237
		1	2.52	1807
		2	1.65	642
Pickup	2 (E-W)	3	1.87	584
		4	1.87	288
		3	1.91	626
		4	2.23	442
Conditioning	3 (E-W)	1	2.63	585
		2	2.91	240
		1	3.07	929
		2	2.53	935
Pickup	3 (E-W)	1	2.76	783
		2	2.76	305
		1	2.41	847
		2	2.41	349

Final computation of PM10 emission factors for each almond harvest event monitored in 2004 was conducted following the guidelines presented above. The extensive duplicity of measurements, especially at Site 1 when the TAMU team was in attendance, allowed for a choice of which data were included in each final computation and provided information regarding optimization of sampling strategies. Additional monitoring at Sites 2 and 3 provided opportunities for refining the optimization through the use of east to west planted rows, the monitoring of which present inherent differences from that in north to south planted rows (as Site 1 has). Evaluation of the PM10 emission factor quantification method was not the only objective of the research and the PM10 emission factors derived in this project are also of some inherent value.

A summary of the PM10 emission factors derived from the individual monitoring efforts (tests) conducted in the 2004 almond harvest is presented in **Table 11**. Evaluation of the quality of these individual emission factors follows. In some cases (e.g. Conditioning at Site 3) one pair of tests was conducted under conditions closer to optimal than the other, so there remains room for judgment as to which data provides the most accurate measure of PM10 emission factor of each operation. Thus, it is not advisable in every case to simply average results for "identical" operations to obtain a single PM10 emission factor. Further, differences in harvest equipment and practices from site to site have implications to comparing and interpreting the PM10 emission factors presented in **Table 11** as outlined in Section I of this report. Additional details provided by our collaborators familiar with the specific equipment and orchards can be found in the appendix and should be reviewed carefully before such interpretation is attempted.

Development of method recommendations

Research conducted in this project indicates that the ISCST3 model is the best tool for calculating PM10 emission factors from PM10 concentrations measured downwind of almond harvest operations. The primary advantage of the ISCST3 model over the previously used VPM is the representation of aerosol dispersion that it uses. This has the effect of producing emission factors under a wider range of meteorological conditions than the VPM and extending the distance between the source (harvest implement) and samplers. However, even the ISCST3 model has limitations in these areas. In this section we

- provide evidence for the superiority of the ISCST3 model over the VPM,
- describe the optimal monitoring conditions for the use of the ISCST3 model, and
- assess the limitations of the ISCST3 model as applied to calculating PM10 emission factors from almond harvesting operations.

These evaluations are presented primarily in terms of the axes of dispersion, preceded by a discussion of the measurement of meteorology as the vehicle for dispersion.

Measurement of meteorology

Because the PM10 emission rate of an open area source (such as an almond orchard) cannot be contained and directly sampled, they must be estimated (modeled) from the increase in PM10 concentrations downwind of the source (relative to background). The relationship between the PM10 concentrations measured downwind of the source and the actual emission rate is dominated by the effects of local meteorology. Wind is required to move the PM10 generated by the source to the samplers where concentrations can be measured. The wind speed is thus critical to computing emission rate. Wind direction is also an important variable as it defines which monitors are actually downwind of the source and what proportion of the source each monitor is downwind of. Finally, meteorological variables such as temperature, radiant energy, and relative humidity describe the atmospheric stability at the time of monitoring which in turn defines such aspects of dispersion as plume height. Taken all together, accurate measurement of the meteorological conditions that actually control the plume generated by the source are absolutely critical to calculation of accurate PM10 emission rates.

While the type, number, precision, and height of meteorological measurements are well established (see Section V for recommendations), the placement of the meteorological monitoring station relative to the orchard and the PM10 monitoring equipment was a topic of this research. Placement of the meteorological equipment downwind of the orchard, near the PM10 monitors, is a logical choice because in this way the wind field measured is the same as the one being sampled. However, the wind that is actually moving the PM10 from the source (the orchard) to the monitors downwind is generally over the orchard itself. Since the monitors are placed within very close proximity to the orchard (10-50 meters), the wind field downwind of the orchard is actually a small part of the wind field affecting the PM10 plume. It is not feasible to set up meteorological equipment within the orchard itself, since these are ground-based instruments and wind within the orchard canopy is negligible while measuring above the canopy is not possible. So the alternative is to measure the wind field upwind of the orchard to represent the wind over the orchard. The data in **Table 12** compares PM10 emission factors estimated using the ISCST3 model from identical measurements of PM10 concentrations and meteorological data collected upwind of the orchard vs. that collected downwind.

Table 12: Comparison of PM_{10} emission factors for almond conditions events on Site 1 derived from identical measurements of PM_{10} concentration using the ISCST3 model with each source split into two areas. Meteorological data collected upwind (UCD met) or downwind (TAMU met) of the orchard were used.

*Implement	PM10 EF by ISCST3 using UCD met (kg/km2)	PM10 EF by ISCST3 using TAMU met (kg/km2)	Percent difference (%)
1	404	740	-83
2	203	249	-23
2	287	283	1
1	1413	617	56

*Implement numbers are crossreferenced in Introduction, Table 1.

As expected, the effect of the meteorological data on calculated PM10 emission factors is considerable. There is not a consistent bias in the data; the downwind measurements produce greater PM10 emission factors than the upwind measurements in some cases and smaller emission factors in other cases. So the difference is not attributable to a simple scalar variance (e.g. wind speeds measured to be lower downwind). The chronological series of test periods presented in Table 12, performed on two successive days, indicate a progressive pattern to the effect of meteorological measurement on PM10 emission factors (percent difference increasing with time). This may be due to a temporal shift in the local weather pattern that effects wind speed and direction as well as atmospheric stability, all of which are variables in the ISCST3 model.

These data clearly demonstrate that a consistent choice of meteorological measurement location is needed to produce comparable PM10 emission factors using the ISCST3 model. It is suggested that upwind measured data is more consistent and reliable while the upwind fetch (area upwind of the orchard) is uniform.

Evaluation of Downwind Distance

There are two mechanisms for examining the effects of the distance between the source and the monitors on the accuracy of PM10 emission factors. In one case, monitors placed at different distances downwind of the source are used to evaluate the ISCST3 model's treatment of the dispersion that occurs after the plume leaves the orchard.

Complementarily, the modeling of dispersion that occurs within the orchard can be evaluated by comparing PM10 emission factors calculated from monitoring an operation conducted in the rows closest to the downwind edge of the orchard to those measured when the operation is conducted in a portion of the orchard further away from the monitors at the downwind edge.

An important limitation noted in the VPM when used to compute PM10 emission rates for row crop operations is in the proximity required between the monitors and the source. As an implement works the field (or orchard) further from the downwind edge, where the PM10 monitors are placed, the VPM model becomes less reliable. Data collected in this experiment provides ample evidence that similar limitations exist in applying the VPM to almond harvesting operations. The same data demonstrates the absence of such a limit in the ISCST3 model and, in fact, shows that the ISCST3 accounts quite well for the type of dispersion that occurs over the orchard. These data also give a good example of how lidar data can be used to confirm interpretation of the PM10 concentrations visually. The intentional replications incorporated in this experiment make this comparison possible (see Sect. I).

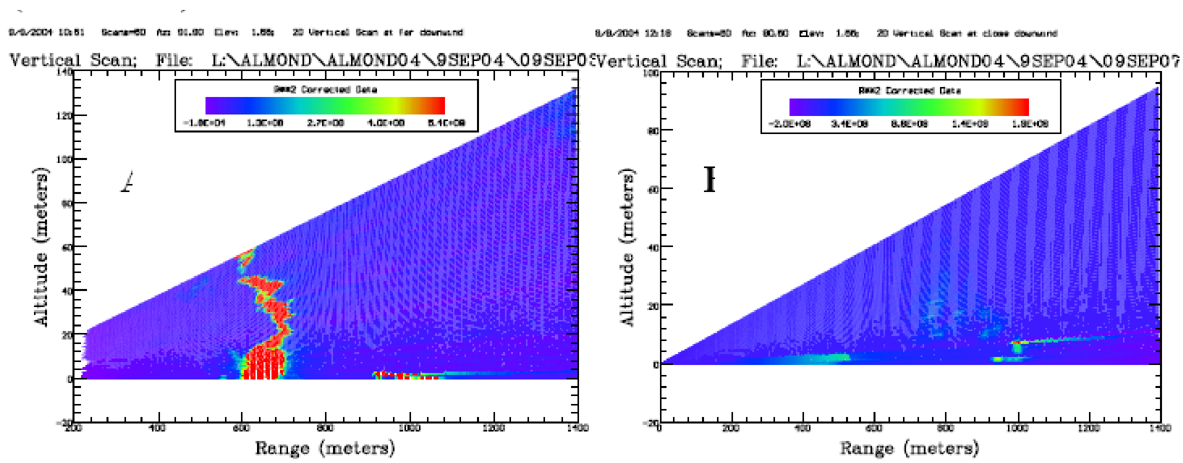


Figure 4: Vertical Lidar scans at south (downwind) edge of orchard at Site 2 during harvest of rows near the south edge (A) and near the center (B) of the orchard.

Figure 4 presents the lidar data collected at Site 2 (with east-west planted rows) during a test when the rows near the south (downwind) edge were harvested (**Fig. 4A**) and during the immediately following test while rows near the center of the orchard were harvested **(Fig. 4B)**. A much more intense plume (represented by color) is recorded during the nearer test with the bulk of the image very low to the ground (as quantified on the Y-axis) when the harvest is taking place close to the orchard edge. Plumes recorded when the harvest is well within the orchard are less intense and higher (**Fig. 4B**).

These observations can be quantified, in arbitrary units, to describe the maximal height and the range of intensities recorded by the lidar. An example of such data derived from the scans in Fig. 4 are presented in **Figure 5**. The lidar data show clearly that the intensityof plumes generated near and far from the orchard edge differ greatly in intensity, particularly in the lowest 15 meters (Y-axis) where PM10 concentrations are measured for use in the VPM.

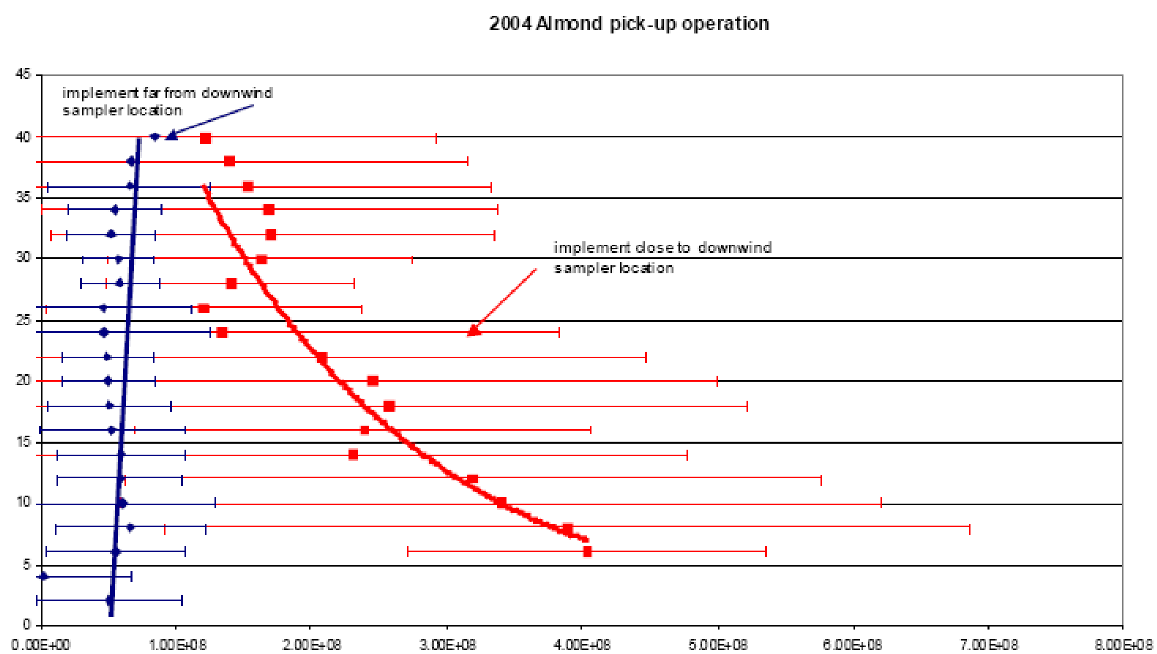


Figure 5: Vertical profiles of lidar data obtained by averaging the lidar signal at 2 m height intervals over a range interval corresponding to the sampling location. Points represent averages for all scans collected during each test and bars represent the standard deviation of the averages. Lines are best fit logarithmic interpolations.

Visually recognizing that the differences in density of the plumes measured in the two cases depicted in Figs. 4 and 5 it is perhaps more remarkable that the ISCST3 produces similar emission rates, when provided the appropriate spatial information. Herein lies the superiority of the ISCST3 model over the VPM in terms of downwind distance. There is no mechanism in the VPM to account for distance between the source and monitor, all dispersion characteristics must be derived empirically. This is very difficult when plume intensities are so low at ground level, as seen here. When both the ISCST3 and VPM models are applied to identical data collected in repeated measurements of harvest operations near and far from the orchard edge, the precision of the models can be judged by the agreement between estimated PM10 emission factors in the two cases.

Table 13 shows that, for three pair of tests conducted using pick up machines numbered 3, 1, and 4 as referenced in **Table 1**, PM10 emission factors estimated by ISCST3 are consistently in better agreement than those derived using the VPM. Though differences in uncontrollable variables from test to test do create differences in PM10 emission factors computed by the ISCST3, even in the experimentally designated duplicate tests, those differences are not attributable to the proximity of the monitors to the source. While PM10 emission factors estimated by the VPM are always greater when the harvester is close to the orchard edge, PM10 emission factors computed via the ISCST3 model are sometimes greater when the harvest is closer (implement 4, Table 13) and sometimes greater when the harvester is in the orchard center (implements 3 and 1, Table 13).

Table 13: PM10 emission factors estimated by VPM and ISCST3 using identical data for replicate tests conducted in series, one while rows near the orchard edge were harvested and the second while rows near the center of the orchard were harvested.

Almond Pickup test description by implement* and proximity		VPM Emission Factor (kg/km2)	ISCST3 Emission Factor (kg/km2)
3	Close to orchard edge	383	758
	Near orchard center	101	766
4	Close to orchard edge	155	392
	Near orchard center	54	519
1	Close to orchard edge	1450	1209
	Near orchard center	420	1086

* Implement numbers are cross referenced in Introduction, Table 1.

The other way in which PM10 emission factors could be biased by proximity of the monitors to the source is through the way the ISCST3 model handles dispersion and/or deposition of the PM10 as the plume proceeds downwind of the orchard.

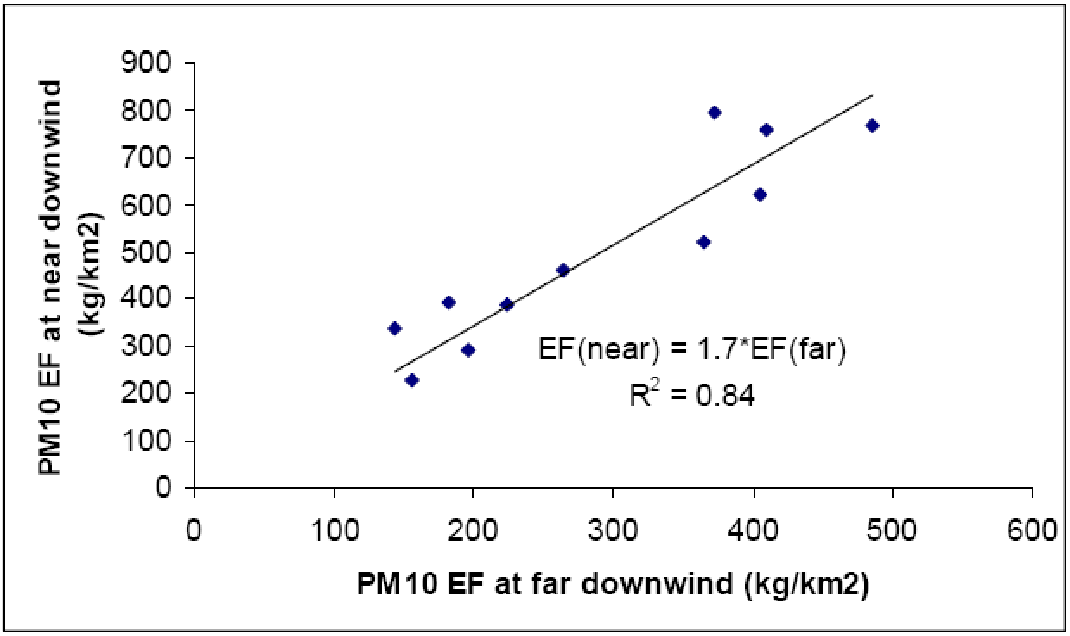


Figure 6: Comparison of PM10 emission factors computed using ISCST3 from PM10 concentration measurements made simultaneously near (within 30 meters) and far (35 to 70 meters) from the orchard during harvest.

By monitoring PM10 concentrations at varying distances from the south (downwind) edge of orchards planted east to west (Sites 2 and 3) we can evaluate the effect of sampler placement on PM10 emission factor estimations. In this experiment, there was a consistent negative bias of about 1.5 fold in PM10 emission factors estimated from measurements made 20 to 40 meters farther downwind from the orchard than the primary monitoring locations, which were 15 to 30 meters downwind of the orchard edge (**Figure 6**). This observation indicates that, if the PM10 emission factors based on the concentrations measured at the primary monitoring locations (near the orchard edge) are correct, the ISCST3 model is underestimating the dispersion and/or deposition occurring between the two monitoring locations (over the open ground downwind of the orchard). This may be due to differences in the wind field upwind of and over the orchard, which are measured by the meteorological instruments and incorporated in the model, and the wind field downwind of the orchard. Since such differences have been measured and documented (see above discussion), this is likely at least part of the reason for the observed bias. Other factors may also contribute.

Evaluation of Crosswind Sampler Placement

Identification of the optimal location(s) for monitoring equipment to measure PM10 concentrations downwind of an area source like an almond orchard during harvesting requires consideration of two variables; the wind direction and the configuration of the source. In this context, we define the source as the area of the orchard that the harvest implement will cover during the test period over which the average PM10 concentration will be monitored. It is generally difficult to anticipate the exact dimensions of either of these variables before the test starts. Wind direction can be forecast based on previous data and current weather patterns to the extent that the downwind edge of the orchard is readily identifiable. Slight variations in wind direction from the direct trajectory from source to monitor can greatly impact the performance of the ISCST3 model, however, so that the larger the variation in wind direction that will continuously put the monitor(s) downwind of the source – in the wind shadow – the greater the likelihood of a successful test.

The range of acceptable wind direction can be increased by the choice of source configuration. When the area covered by the harvest implement during the test is longer in the dimension perpendicular to the wind direction than in the parallel dimension, a wider range of wind direction variation is acceptable than when the source has the opposite configuration. Planning the test to produce the desired source configuration involves several interrelated considerations such as;

- length of the planted tree rows and placement of orchard alleys where equipment can turn around,
- harvesting rate,
- desired duration of the test (see following section),

and is usually easier for orchards with rows planted perpendicular to the wind direction than those planted parallel.

The range of acceptable wind direction is also influenced by the placement of the monitor(s) in the cross-wind axis (or along the edge of the orchard). If tree rows are planted parallel or perpendicular to the average wind direction for the region in the season of interest, then the ideal monitor placement to capture the greatest wind direction variability from average is directly in the center of the downwind orchard edge. Generally, however, this is not the case. The dominant wind direction for a region is often off-axis with the orchard row direction. In these cases it is possible that the optimal placement for monitor(s) is to one side or the other of the center.

The ISCST3 model offers useful mechanisms for quantifying and visualizing the effects of sampler placement in the crosswind axis on PM10 emission factors. First, the model produces wind roses, as shown in **Figure 7**, for each hour of meteorological data supplied. In this two hour test, there was a shift in wind direction from the start (northwesterly) to the end (northeasterly) of the test.

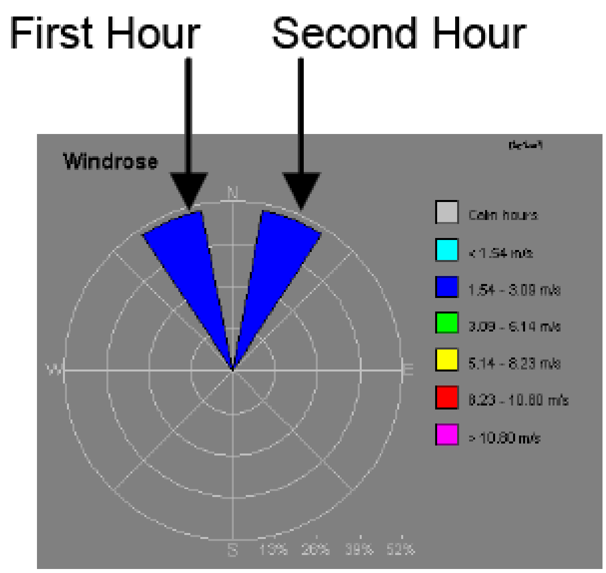


Figure 7: Wind rose for a two hour test of a pic up machine at Site 1.

In this test, monitors were placed in anticipation of the northwesterly wind, which is typical for this region and season, as shown by the labels A and B in Figure 8. The contour maps produced by the ISCST3 model of the estimated PM10 concentrations at all points on the downwind edge of the orchard (Figure 8) show the combined influence of a harvest operation progressing from east to west (right side of the image to left side) as the wind direction shifted from west to east (Fig. 7). Although the sampler designated A was in the wind shadow for the entire two hour test, the sampler B was not within the sphere of elevated PM10 concentrations predicted by the model during the second hour (Fig. 8 – II).

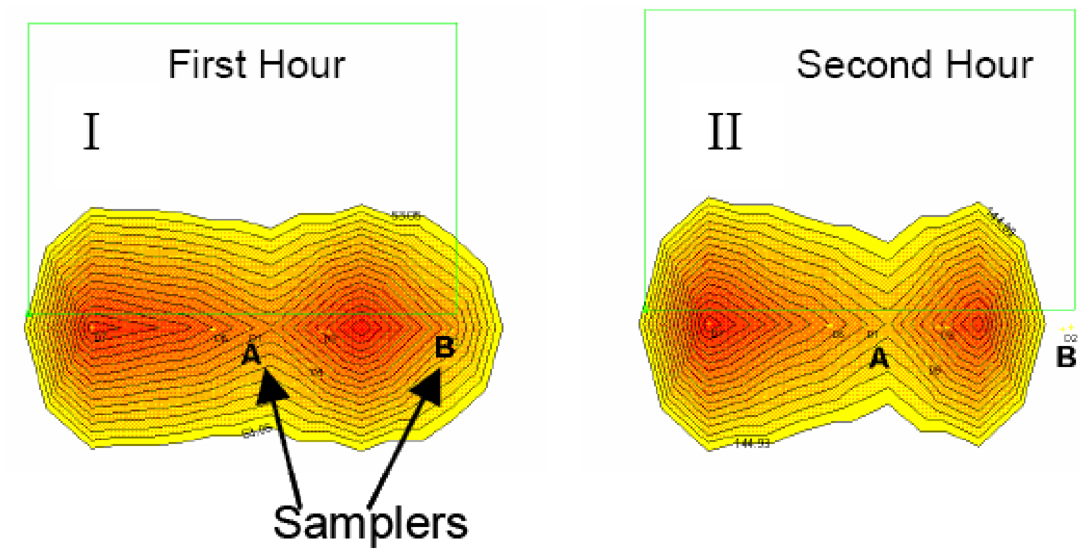


Figure 8: PM10 concentrations along the downwind edge of an orchard forecast by the ISCST3 model using the measured wind direction depicted in Fig. 7 and source proximity data during each of the two hours of the test (I and II).

Even though sampler B was not in the wind shadow of the area source during the second hour, the ISCST3 model calculated a similar emission factor from concentrations measured at that location to the emission factor derived for sampler A (Table 14). One of the advantages of the ISCST3 model over the VPM is its ability to incorporate accurate wind direction influences from source to sampler. This capability is related to the advantages of the ISCST3 model in accommodating a large range of distances in the downwind dimension between the source and the samplers (as evaluated above). The ability of the ISCST3 model to use proximity data relating the source to the sampler allows for a much wider range of monitoring locations in both axes. This is an important capability especially when sampling periods of more than 1 hour in duration are used to calculate the emission factor. In longer tests changes in both wind direction and the proximity relationship between source and sampler from the beginning to the end of a test are more significant.

Table 14: Predicted PM10 concentrations at sampler locations A and B as indicated in Fig. 8 by ISCST3 model runs including wind direction data depicted in Fig. 7. PM10 emission factors are estimated using both the VPM and ISCST3 models from PM10 concentrations measured at both sampler locations.

	Predicted Mass Conc. (ug/m3)	VPM EF (kg/km2)	ISCST3 EF (kg/km2)
Sampler A		170	256
Hour 1	231		
Hour 2	446		
Sampler B		136	285
Hour 1	355		
Hour 2	1		

Changes in these two very important variables over the test duration can be incorporated into the estimate of PM10 emission factor by the ISCST3 model if provided with the distinct wind direction and proximity data for each hour. In the case of the meteorological data, it is essential for operation of the ISCST3 model that each hour of data is provided separately. For the proximity data, however, it is possible to run the model with temporally indistinct data (assuming the harvest activity was distributed throughout the harvested area equally over the entire time of the test) or with a source area description that places the harvest in one location on the orchard during the first hour of a test period and in another location during the second hour. The latter is logically the more rigorous application of the model, as the harvester movement is unidirectional from one area of the orchard to another. It is also well supported by complementary data collected using the vertical profile of PM10 concentrations and lidar, as described in the following section.

Evaluation of Plume Height

The two models assessed to estimate PM10 emission factors from downwind measurements of PM10 concentrations, the VPM and the ISCST3, use fundamentally different mechanisms for characterizing the dispersion of the PM10 plume. For the VPM, dispersion in the vertical axis is determined directly from comparison between PM10 concentrations measured at different heights. The height of the PM10 plume and the change in intensity of the plume with height are used in the VPM to extrapolate to the entire mass flux of PM10 leaving the orchard at the downwind edge. This strategy makes it critical that the vertical profiles of PM10 concentration samplers are placed well within the plume to produce an accurate estimate of plume height. Conversely, the ISCST3 model uses algorithms to estimate dispersion given the meteorological conditions and forecasts the PM10 concentration at any location downwind of the source given an estimated emission rate and the relevant proximity data.

Lidar images are particularly valuable in assessing the accuracy of the plume height generated by the VPM which is, in turn, critical to the success of that method. Using a select test as an example, lidar data for a conditioning test conducted on Site 1 were processed as the images in Fig. 4 to produce the quantification graph in Figure 9 (similar to Fig. 5). The point where the functional fit to the data collected downwind of the orchard during harvest (line connecting closed symbols – Fig. 9) intersects the background (line connecting open symbols – Fig. 9) is the height of the plume. These data indicate a plume height for this test of 34 meters.

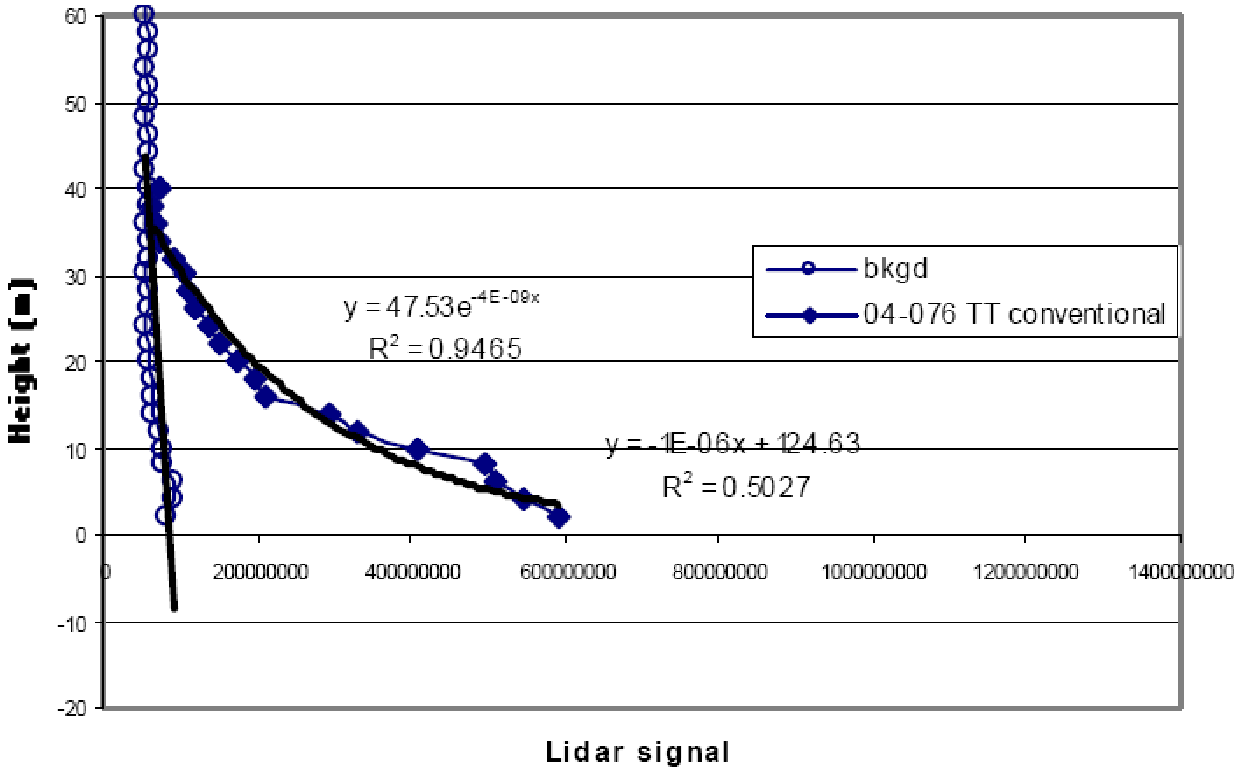


Figure 9: Averaged vertical profiles from 2D vertical scans at UCD tower location; closed symbols correspond to scans collected during test 76 (activity) and open symbols correspond to background.

As can be seen in **Table 15**, the plume height estimated by the VPM from the vertical profile of PM10 concentration measured at the same location as the lidar data was collected was 95 meters, when the same function is applied (logarithmic). When the dispersion implied by that plume height is used by the VPM, the estimated PM10 emission factor is 2490 kg/km2. As would be expected, this exceeds the PM10 emission factor computed by the same VPM using the lidar-generated plume height (**Table 15**). This type of assessment helps to confirm that the VPM is relatively insensitive to the large overestimate of plume height, since the plume height difference is 2.8 fold while the emission factor difference is only 1.3 fold. Of greater interest in this experiment is the comparison with PM10 emission factors computed by ISCST3. In this instance, using the most specific proximity data (two area sources for this two hour test, as described in the above section) produced the same PM10 emission factor as the use of the lidar – generated plume height in the VPM. This provides additional evidence for the rigorousness of the two area source approach in application of the ISCST3 model as well as confirming the general agreement between the ISCST3 and VPM, when both are used optimally with all possible supporting data available.

Table 15: PM10 plume heights estimated from PM10 concentration measurements (Vertical Profile) and lidar scans and emission factors generated from those plume heights in comparison with those derived by ISCST3.

Plume height (meters)		Emission Factor by VPM (kg/km2)		Emission Factor by ISCST3 (kg/km2)	
Vertical Profile	lidar	Vertical Profile	Lidar	1 area	2 areas
95	34	2490	1858	611	1858

Evaluation of Test Duration

The length of time for which each sampling effort to measure PM10 emission rates from almond harvest operations is run depends on many variables. Ultimately, however, test duration is optimized for the gravimetric analysis of the PM10 samples. The sensitivity of the analysis is determined by experimental artifacts (mass accumulated on filters that are not used to collect samples, called field blanks). Blanks acquire significant mass due to contamination (unclean handling conditions) and due to changes in the balance used to weigh the filters before and after sampling. So, tests must be run long enough that the PM10 accumulated on the sample filters exceeds these background sources. The capacity of the analytical method is defined by the mass of PM10 that will remain on a filter through the post-sampling handling and analysis procedures. Because PM10, especially from agricultural (geologic) sources, is dry and often electrostatic, it can fall off the filter if the filter becomes overloaded. Recommendations for PM10 mass ranges that have been found to be reliable in this project are presented as part of the protocol documented in the following section (V).

The mass loading on the filters used to collect the downwind PM10 samples for emission factor estimation depends on the combination of sampling duration and PM10 concentration of the air sampled (assuming sampling flow rate to be invariant, which it must be – at 16.7 liters per minute, if the FRM PM10 inlet is used). Therefore, sampling duration depends on the proximity of the sampler to the source and the strength of the source. An operation that is very dusty and very close requires a shorter test duration than one that is less dusty and/or further from the sampler. After consideration of PM10 sample loading, many other variables affect the sampling duration including:

- rate of harvest operation and source configuration,
- stability of meteorological conditions,
- availability of harvest implements (e.g. avoiding lunch breaks for operators), and
- interfering sources (e.g. uncontrolled traffic, upwind sources).

Finally, test duration is an important variable in the ISCST3 model. Since normal operation of the model uses representations of meteorological conditions and PM10 concentrations for the nearest whole hour actually monitored, it decreases the uncertainty in the model to use test durations of increments of as close to 60 minutes as possible.

Comparison between VPM and ISCST3 PM10 emission factors

The preceding discussion demonstrates the point-by-point superiority of the ISCST3 model for estimating PM10 emission factors for almond harvest operations in terms of flexibility and precision. One of the goals of the current project was the seamless integration of PM10 emission factors generated in this work with those presented previously. This requires establishing that methods used previously, if duplicated in the current work, would yield comparable data. There are indications that this is the case in the examples chosen for the preceding discussion. Here we present the entire available data set comparing PM10 emission factors generated using the previous standard (VPM) and the suggested model (ISCST3).

Due to the sensitivity of the VPM to wind direction deviations from optimal, as discussed above, PM10 emission factors are presented only for those vertical profiles of samplers (UCD towers) determined to be in the wind shadow during the entire test period. To provide the most appropriate comparison, PM10 emission factors generated using the ISCST3 model for each specific tower are provided. Thus, the ISCST3 model generated PM10 emission factors in these comparisons are not the same as the average (over all monitoring locations) PM10 emission factors provided in the summary tables (as **Table 11**).

Experimental conditions and objectives were slightly different at progressive phases of the field research carried out in the 2004 harvest season. On Site 1, with the presence of the TAMU team and the north to south planted orchard, multiple UCD towers were used when possible and all source areas were the same distance from the monitors. On Sites 2 and 3, with east to west planted orchards, investigation of the effects of variability in distance from source to sampler was emphasized. To better interpret the data, these two phases of the experiment are separated.

Table 16: PM10 emission factors generated using VPM and ISCST3 for multiple towers used on Site 1 during wind row conditioning operations.

Conditioner Type*	Tower 1		Tower 2	
	PM10 EF by VPM (kg/km2)	PM10 EF by ISCST3 (kg/km2)	PM10 EF by VPM (kg/km2)	PM10 EF by ISCST3 (kg/km2)
1	185	182	123	215
2	170	256	136	285
2			714	611

*Implement type is cross referenced from Table 1.

Meteorological conditions for the more restrictive VPM were valid for only three of the tests conducted on Site 1, all of them of the conditioning operation. Data in **Table 16** provide comparisons of PM10 emission factors generated by the VPM with those produced by the ISCST3 model from PM10 concentrations measured at five independent UCD tower locations. Agreement between the two models is generally good. In three cases, the PM10 emission factors estimated by the ISCST3 model exceeded those computed using the VPM and in two cases ISCST3 estimates were less than VPM, so there is no apparent bias. As seen in the preceding analysis, the ISCST3 generated results are more consistent from location to location within a test. They also produce a more consistent comparison from one type of implement to another (the PM10 emission factor for implement 2 is always higher than that for implement 1 for ISCST3 generated data only).

A larger number of vertical profile measurements were made under valid meteorological conditions during testing done on orchards planted east to west (Sites 2 and 3) due in part to the preferable source configuration (see discussion of crosswind sampler placement).

Table 17: PM10 emission factors generated by the VPM and ISCST3 models for UCD tower measurements of PM10 made during harvest of rows at the downwind edge of the orchard and near the center of the orchard.

Implement	Type*	PM10 EF at Orchard Edge		PM10 EF near Orchard Center	
		VPM (kg/km2)	ISCST3 (kg/km2)	VPM (kg/km2)	ISCST3 (kg/km2)
condition	1	661	796	66	291
	2	287	336	129	621
Pick up	1	1450	1209	420	462
	2			634	230
	3			101	766
	4	155	392	54	519

*Implement type is crossreferenced from Table 1.

Due to the effect of source to sampler proximity on results of the VPM noted above, data in Table 17 is presented to distinguish between PM10 concentration profiles measured when the operation was at the orchard edge and when it was at the center of the orchard. When the operation is near the edge of the orchard, agreement between the two modeling methods is good (Table 17). As was seen in the data collected at Site 1 (Table 16, the ISCST3 model produces slightly higher PM10 emission factors than the VPM in most cases, but not always. When the operation is near the center of the orchard, however, the PM10 emission factors generated using the ISCST3 model are generally higher than those produced by the VPM. As described above, this is due to a deficiency in the ability of the VPM to correctly model dispersion of the plume with large distances between source and sampler. Understanding of this limitation in the VPM provided by the current project should be projected to previously reported data to eliminate PM10 emission factors generated under similar conditions from comparison with current data.

Recommended method for measurement of almond harvest PM_{10} emission factors

In the course of this project many variants of the upwind to downwind measurement method that produced PM10 emission factors for on-field agricultural sources were employed and evaluated. The generous participation of our grower-collaborators provided the opportunity for experimental replication that greatly enhanced the interpretability of data for this purpose. The product of the duplicity and replication performed in this project is the ability to identify those components of the work that provide the most precise measure of PM10 emission factor with the least effort and cost. In this section, a minimalist method will be outlined which would be capable of reproducing the PM10 emission factor presented herein, given identical testing conditions. This method will be tested in fieldwork planned for the 2005 harvest season (please see previous section) and further detailed in the final report to be submitted in 2006.

Site selection

The selection of an appropriate orchard is critical to the success of PM10 emission factor measurement. This is due to the interplay of several site-specific factors;

- regional effects of meteorology,
- local effects of topography, and
- operational effects of specific farming practices.

The region of interest must first be evaluated in terms of seasonally typical meteorological conditions. Data from the nearest evapotranspiration monitoring station or airfield can be useful if personal experience is not available. The predominant wind direction must be identified and the time of day during which it is most reliable and constant (i.e. occurs repeatedly and is consistent in speed and direction) should be determined. Ideally, the predominant wind direction will be within 45 degrees of a direction perpendicular to one axis of the orchard and occur reliably during the time of day work is likely to occur (daylight hours).

Selection of a specific orchard is based on the configuration of the orchard and the orchard surroundings. Rectangular shaped orchards, with the longer axis perpendicular to the predominant wind direction, are most desirable. Often, an irregularly shaped orchard can provide a useful source area by simply limiting the harvest operation to a rectangular portion of the orchard. However, features such as access roads for equipment turn-around space and a downwind orchard edge that is strait (relative to compass direction) make a truly rectangular orchard much easier to describe numerically (see Data collection). The orchard should be planted on land that is relatively flat. There will be some slope on most irrigated agricultural plots, but substantial slope can affect the wind field and should be avoided. Similarly, the land surrounding the orchard should be as flat as possible. The presence of irrigation canals, levees, and natural drainage courses near the orchard can limit options for the placement of sampling equipment.

Ideally, PM10 monitors and meteorological instruments should be sited on open ground with a flat fetch for at least 100 meters upwind of the monitor. Since this is a procedure for measuring PM10 concentrations upwind and downwind of an orchard (which presents an obstruction of the wind field), this aspect of site selection must be compromised. An open field, either fallow or planted with a low profile row crop (e.g. not corn), upwind of the orchard under consideration is ideal for the placement of upwind PM10 monitors and the meteorological instruments. It is also important to control local sources of PM10 upwind of the orchard during testing, so the environs of the orchard should also be considered with respect to control over such possible sources. The downwind edge of the orchard should also be free of wind field obstructions, to the extent possible. Monitors will be placed 20 to 50 meters from the edge of the orchard, so flat, accessible space of at least those dimensions is required. The area downwind of the orchard beyond that needed for the placement of the samplers should also be open. As with the area upwind of the orchard, a fallow or small row crop field is the preferable configuration of areas downwind of source orchards.

Finally, the farming practices that will be followed during PM10 emission factor measurement are important to planning a successful test. As described in the above section regarding test duration, the rate at which the harvest operation progresses over the orchard test area influences the placement of downwind PM10 monitors to keep them in the wind shadow. This is particularly true when orchards are planted with row direction parallel to the predominant wind direction. Additionally, the dynamics of the expected harvest operation influence the personnel and type of data collection that will be required to adequately document the source. For example, the presence of multiple harvesters on an orchard simultaneously requires additional people on the ground to track the movement of each implement relative to the monitors (downwind orchard edge).

Samplers and sample handling

The minimum hardware required to monitor upwind and downwind PM10 concentrations for development of PM10 emission factors is two identical PM10 samplers and an array of meteorological sensors, including:

- wind speed sensors, at least two mounted at least one meter apart in height
- wind direction sensor
- temperature sensor
- photosynthetically active radiation (PAR) sensor
- barometric pressure sensor.

A tripod with a mast at least 3 meters tall is needed for mounting the meteorological equipment. PM10 monitors require support to place the inlets at a consistent and measurable height above ground.
The array of meteorological sensors should be placed upwind of the orchard, on level ground, with no significant obstructions within 100 meters upwind. It is critical that sensors be installed in a manner consistent with manufacturers' recommendations to produce accurate measurements, particularly of PAR and wind direction. Data collected by the sensors should be logged (integrated) over a time period equal to or less than 5 minutes, assuming a minimum test duration of one hour. More frequent data logging is needed for shorter test periods. Raw meteorological data should be preserved even after data averaging for the test period is performed for use in the ISCST3 model. Most commercially available meteorological sensors with data logging capabilities are adequately sensitive for use in this method. One exception may be wind speed monitors, which must be capable of at least a half meter per second threshold.

One PM10 monitor should be located upwind of the orchard, with similar site considerations at the meteorological instrumentation. Generally, it is practical to collocate the two, but since the PM10 monitor will require power and that is usually supplied by a gasoline generator, the juxtaposition of upwind equipment to one another can be important. Above all, the wind field presented to the meteorological array should be as unobstructed as possible, so it should be placed furthest upwind. The upwind PM10 sampler should be protected from local sources of PM10 to the extent possible, so it should be placed upwind of it's own generator and upwind of any road or access path around the orchard. The access the field crew will use to approach the upwind PM10 monitor during sampling should be considered when planning the location of the upwind monitor.

The PM10 monitor used to measure the downwind PM10 concentrations must be located in the wind shadow of the source during the operation. Exactly where this is depends on the specific wind direction at the time of sampling and the source configuration that results from the specific activity of the implement over some portion of the orchard during the duration of the test. The closer the monitor is placed to the center of the downwind edge of the orchard area covered the larger the range of wind direction variations that will provide data useful to the calculation of PM10 emission factors. However, the monitor must be placed far enough downwind of the orchard edge to prevent interference of the canopy with dispersion. Generally, 10 to 15 meters (about twice the tree height) is sufficient. When monitoring orchards planted parallel to the wind direction, turn around space for the harvest implements must also be considered in determining the location of the downwind PM10 monitor. Finally, access to the monitor by the field crew during the sampling should also be considered. Often, it is prudent to expect to access the downwind monitor only on foot during the test.

Requirements for sampling to determine PM10 concentrations upwind and downwind of almond harvest operations are similar to those for ambient sampling or other source testing. Filters used to collect the samples should be compatible with sensitive gravimetric mass measurement (i.e. stretched Teflon) and the balances used to weigh them sensitive to one one hundredth of a milligram. Pre- and post-weighing should be done in batches and field blanks (filters subject to all sample handling steps except sample collection) collected to equal at least 10 percent the number of actual samples. The detection threshold for PM10 concentrations can then be described by the precision of the field blank measurements. Samplers used to collect the PM10 samples should use Federal Reference Method (FRM) PM10 inlets in good repair. Due to the elevated concentrations of PM10 in the proximity of agricultural sources, equipment used for this type of sampling must be maintained much more frequently than would be necessary in ambient sampling studies. We recommend cleaning inlets every week, assuming about 20 hours of sampling per week, whereas the ambient recommendation is annually, or every 250 hours of sampling. The sampled air must flow directly to the face of the filter with no constriction in the internal diameter of the tubing leading from the FRM inlet to the filter and no turn in that tubing. The PM10 monitor must be able to maintain the necessary 16.7 liter per minute flow rate with deviation of less than 2% over the duration of the test. Sampling protocol should include reliable mechanisms for measurement and documentation of both flow rate and elapsed time of sampler operation.

Data collection and modeling

In addition to the measurement of meteorological parameters and PM10 concentrations, considerable site and process descriptive data are necessary for the formulation of PM10 emission factors. The ISCST3 model uses a site map to specify the proximity between the source and the monitors. The accuracy of this map is critical to the function of the model. Following the guidelines below should produce adequate data to build a functional map, but individual orchards and operations present distinct challenges and everything that happens on a site during a test should be documented along with the place and time it occurred, to the extent possible. Care must be taken to define the source as the portion of the orchard over which the operation takes place during the test. This distinction makes documentation much easier if the orchard selected can be harvested in entirety during the test. Assuming a fairly standard situation, the following data are required to build the site map for each test:

- Measurement of the source orchard perimeter; the distance from the south-west corner to each of the remaining three corners of the site on axes east to west and north to south. This produces a two dimensional grid in which each corner can be described by a distance in each of two directions.
- Measurement of the distance from any corner of the orchard to the PM10 samplers, again in strait lines east to west and north to south.
- Coordination of the “north” established in installation of the wind direction monitor and the grid describing the site. In the simplest case, this requirement could be satisfied by using a magnetic declination in wind vane installation, rather than using “true” north. The critical point is in matching the wind direction data and the site map; compass directions are simply a tool to this end.

Depending on the intended use of the measurements of PM10 emission factors, some documentation of the harvest practice measured is required. Ideally, all relevant parameters defining the agronomic practices on the orchard since planting as well as a description of the crop and the harvest for the measurement year would be documented. But it is not known exactly which parameters effect PM10 emission factors, so at the time of this writing the following list is expected to cover the basics:

- Age and variety of trees
- Row direction and spacing
- Irrigation type
- Presence or absence of cover crop or vegetation on orchard floor
- Make, model, and manufacture year of harvest implements used
- Number of passes; together with test duration and source area data this provides harvest rate (implement speed) information as well as process description.

It is also recommended that soil samples be taken on the day of testing within the source area for measurement of soil moisture and texture. Composite samples of the soil surface over which the implement wheels will run are most useful for interpretation back to PM10 emission factors.

During the actual testing period, while the harvest is underway, all activity on the orchard and in the surrounding area must be observed and noted. Some observations, like unintended sources (e.g. traffic on dirt roads surrounding the orchard), will be important in quality assurance and quality control when data are compiled. Other information are critical to defining the actual source area (when the entire orchard is not used) and other parameters used directly in the generation of PM10 emission factors. The following list itemizes some of the observations that must be documented during the actual test period:

- Occurrence of any local source other than the harvest practice. Some examples are vehicular traffic near the PM10 monitors or fires upwind of the monitors.
- Progression of the harvest implement. In addition to counting the number of passes made during the test and documenting the total orchard area covered, it is important to note which side of the orchard the harvest started on, any breaks the operator took during the test, and any other change in the rhythm of the harvest. Ideally, the time and location of the beginning and/or end of each pass will be logged. This is absolutely necessary if more than one implement is working the orchard simultaneously.
- The start and end time of the test. In many cases it is simple to begin the harvest operation and start the PM10 monitor simultaneously, then stop the monitor as soon as the harvest is complete. In some cases, however, this is not possible. Generally, upwind samplers can be started before the operation and stopped well after it is finished. The start and end times of the downwind sample should define the time of the test and the area of the orchard over which the harvest took place between those time points should be defined as the area of the test.

Prior to use in the ISCST3 model, measured PM10 concentrations and meteorological data will require some processing. Wind speed and solar radiation data are used to define the Pasquill-Gifford atmospheric stability classification via the Turner modification. If wind speed is not measured at 10 m (above the canopy height), the two wind speed measurements are used to extrapolate to 10 m assuming a logarithmic relationship between wind speed and height. Then all meteorological parameters are averaged by the hour.

Measured PM10 concentrations should be background corrected for the average field blank mass and upwind concentrations examined for possible local source interferences. Only those tests during which PM10 concentrations measured upwind of the orchard are consistent with expected ambient PM10 concentration will provide high quality estimates of PM10 emission factors. If test durations are not in exactly 60 minute increments, a 60 minute concentration must be estimated from the measured PM10 concentrations for use in the ISCST3 model.

Cost estimates for the recommended method

All successful measurements of PM10 emission factors for on-field agricultural operations, including almond harvesting, have been produced in research projects. The costs of doing research and development are generally higher than the costs of subsequent work, after the needed technologies are in place. Given the relative infancy of this particular type of area source emission monitoring, cost estimates can only be forecast by tempering research costs with the application of existing technologies to the novel method. Generally, the costs of producing a measure of the PM10 emission factor for a specific operation or implement can only be determined after considering the uncontrollable variability in the emission factor, thereby the number of samples or tests necessary, and requesting quotes for exactly the work needed. In absence of such detailed information, this overview of measurement costs will make some assumptions of the number of samples and field work time needed to perform an example characterization of PM10 emission factor for a generic operation that has an inherent variability similar to that seen in the equipment comparisons documented in the 2004 project.

In the 2004 field work two pickup implements were compared on two orchards (see **Table 1**, Pick up implements # 1 and 2). With these eight separate tests, two replications on each of two orchards with two implements, it is possible to delineate implement differences from orchard differences and all other uncontrollable variability. With an overall recovery rate of 75-100% for the method (Table 10), a safety factor of about 20% is advisable to be sure of the minimal number of valid tests. So, for the quantification of the PM10 emission factors of two implements using this method, a total of 10 tests would be advised. To put the following cost estimates on a per-variable basis, this would equate to 5 tests needed per variable examined.

Table 18 provides the line items expected in a general budget for PM10 emission factor measurement. For one-time equipment costs, the expense is expanded over 10 such projects. Though the capital equipment in all cases will outlast this amount of work (total 50 tests) by at least another 10 fold (10 year old research equipment is currently still in use), repair and replacement cost will begin to enter into calculations after the end point assumed in this budget. Labor costs assume a crew of two people each on $2500/mo. salary with $100/d per diem in the field. One day for travel and two days for sampling are allowed for each 5 tests. Two days for sample processing and shipping to the contract lab, five days for data reduction and modeling, and five days for QA/QC and reporting are allowed for the same two technicians to produce PM10 emission factors from the field data.

Table 18: Cost estimates for applying the recommended method.

Budget Item	Cost basis	Cost per variable
Meteorological Instruments (Onset package)	Capital ($1870)	$187
PM10 samplers (2 BGI PQ167R)	Capital ($11,700)	$1170
Gravimetric analysis (Chester LabNet)	$19/filter	$190
Field work (labor)	$225/person/d	$1350
Field work (vehicles)	$125/truck/d	$375
Data reduction (labor)	$125/person/d	$3000
Data reduction (Modeling software)	Capital ($2495)	$250
Total		$6522

Appendix A: Details of Air Sampling Parameters

Table A1. Test descriptions for modified and conventional sweeping operations at Site 1.

					Test area dimensions	
Test No.	Date	Operation	Implement	Duration(min)	E-W	N-S
04-069	8-12-04	Sweeping	Modified	86	120	190
04-070	8-12-04	Sweeping	Conventional	114	105	190
04-071	8-13-04	Sweeping	Modified	71	106	190
04-072	8-13-04	Sweeping	Modified	79	113	190

Table A2. Details of tests to compare modified and conventional conditioning and pick-up operations at Site 1.

					Test area dimensions	
Test No.	E-W	E-W	Implement	Duration (min)	E-W	N-S
04-073	8-17-04	Conditioning	Conventional	118	298	190
04-074	8-17-04	Conditioning	Modified	143	270	190
04-075	8-18-04	Conditioning	Conventional	122	285	190
04-076	8-18-04	Conditioning	Modified	129	286	190
04-077	8-19-04	Pick-up	Modified	124	154	190
04-078	8-19-04	Pick-up	Conventional	95	139	190
04-079	8-20-04	Pick-up	Conventional	106	139	190
04-080	8-20-04	Pick-up	Modified	87	138	190

Table A3. Tests descriptions for comparing conventional pick-up operations at Site 2.

					Test area dimensions	
Test No.	E-W	E-W	Implement	Duration (min)	E-W	N-S
04-081	9-9-04	Pick-up	Conventional	73	203	198
04-082	9-9-04	Pick-up	Conventional	78	203	190
04-083	9-10-04	Pick-up	New	71	203	205
04-084	9-10-04	Pick-up	New	74	203	184

Table A4. Tests descriptions for comparing conventional and modified conditioning and pick-up operations at Site 3.

					Test area dimensions	
Test No.	Date	Operation	Implement	Duration (min)	E-W	N-S

04-085	9-13-04	Conditioning	Conventional	59	192	137
04-086	9-13-04	Conditioning	Conventional	124	192	252
04-087	9-14-04	Conditioning	Modified	60	191	130
04-088	9-14-04	Conditioning	Modified	120	191	243
04-089	9-15-04	Pickup	Modified	60	191	65
04-090	9-15-04	Pickup	Modified	120	191	144
04-091	9-15-04	Pickup	Conventional	61	192	101
04-092	9-15-04	Pickup	Conventional	115	192	158

Table A5. PSD of dust collected from PM_{10} sampler filters for Tests 69-80.

Test Number	Operation	MMD	GSD
04-070	Conventional Sweeping	11.34	1.8
04-070	Conventional Sweeping	14.58	1.94
04-070	Conventional Sweeping	12.58	1.82
04-071	Modified Sweeping	15.65	1.90
04-071	Modified Sweeping	13.82	1.88
04-074	Modified conditioning	16.02	1.80
04-076	Modified conditioning	13.37	1.81
04-076	Modified Conditioning	13.18	1.82
04-079	Conventional Pickup	12.86	1.83
04-079	Conventional Pickup	11.57	1.80
04-079	Conventional Pickup	14.88	1.91
04-080	Modified Pickup	14.30	1.54
	Average	13.66	1.90

Table A6. PSD of dust collected from PM_{10} sampler filters for Tests 81-92.

Test Number	Operation	MMD	GSD
04-081	Conventional pick-up	12.48	1.90
04-081	Conventional pick-up	13.21	1.98
04-081	Conventional pick-up	18.21	1.91
04-081	Conventional pick-up	14.41	2.04
04-091	Conventional pick-up	11.72	1.95
04-091	Conventional pick-up	9.77	2.01

04-091	Conventional pick-up	11.94	2.07
04-092	Conventional pick-up	11.80	2.40
04-092	Conventional pick-up	11.05	2.05
04-092	Conventional pick-up	12.90	2.60
04-081	Conventional Pickup	13.26	2.3
04-089	Modified pickup	12.84	2.11
04-090	Modified pickup	12.41	1.85
04-083	New/Modified pickup	19.49	1.92
04-085	Conventional conditioner	11.31	1.91
04-085	Conventional conditioner	14.27	1.08
04-085	Conventional conditioner	11.36	2.00
04-086	Conventional conditioner	11.73	1.99
04-086	Conventional conditioner	13.77	2.43
04-085	Conventional Conditioner	9.56	2.07
04-087	Modified conditioner	11.80	2.19
04-087	Modified conditioner	12.83	2.27
04-087	Modified conditioner	11.69	1.99
04-088	Modified conditioner	12.63	2.18
04-088	Modified conditioner	15.17	2.30
	Average	12.86	2.06

Table A7. PSD of all PM_{10} filters from TAMU co-located samplers.

Conventional Conditioning		Modified Conditioning		Conventional Pickup		Modified Pickup	
MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD
11.11	1.76	11.72	1.94	14.50	1.14	23.34	2.52
12.56	1.83	12.83	2.11	10.91	1.81	19.45	2.07
12.01	2.08	11.51	1.94	12.16	1.91	13.55	2.52
12.81	1.94	11.58	1.81	11.73	1.89	12.89	1.93
12.37	1.79	10.50	1.70	15.89	2.00	12.74	1.92
11.06	1.76	9.93	1.70	12.37	1.79	13.63	2.01
10.67	1.73	13.53	1.91	10.24	1.94		

10.17	1.70	14.85	1.65	10.83	1.83		
		13.50	1.78	10.04	1.81		
		12.48	2.02				
Average	Average	Average	Average	Average	Average	Average	Average
MMD	GSD	MMD	GSD	MMD	GSD	MMD	GSD
11.60	1.82	12.24	1.86	12.07	1.79	15.93	2.16

Table A8. PM_{10} concentrations from all PM_{10} sampler and those derived from PSD analysis of TSP filters.

Test Number	Test date	Operation	TAMU Sampler PM_{10} (ug/m^3)	PM_{10} from PSD (ug/m^3)
073	17-August 2004	Conventional Conditioning	371	291
076	18-August 2004	Conventional Conditioning	1303	856
085	13-September 2004	Conventional Conditioning	575	466
086	13-September 2004	Conventional Conditioning	91	47
086	13-September 2004	Conventional Conditioning	126	138
074	17-August 2004	Modified Conditioning	410	215
075	18-August 2004	Modified Conditioning	228	137
087	14-September 2004	Modified Conditioning	167	99
088	14-September 2004	Modified Conditioning	109	96
081	9-September 2004	Conventional Pickup	402	255
092	15-September 2004	Conventional Pickup	168	120
078	19-August 2004	Conventional Pickup	426	240
079	20-August 2004	Conventional Pickup	781	403
080	20-August 2004	Modified Pickup	401	170
077	19-August 2004	Modified Pickup	135	34
089	15-September 2004	Modified Pickup	214	152
090	15-September 2004	Modified Pickup	90	92
084	10-September 2004	Modified Pickup	116	37

Table A9. PSD Analysis of TSP Filters on Test Site 1 and 3 (Tests 77-80 and Tests 88-92)

Test No.	Test Site	Operation	MMD	GSD
04-077	1	Modified Pick-up	30.85	2.44
04-077	1	Modified Pick-up	25	2.12
04-077	1	Modified Pick-up	24.83	2.07

04-077	1	Modified Pick-up	19.75	2.38
04-077	1	Modified Pick-up	24.41	2.40
04-077	1	Modified Pick-up	17.48	2.54
04-078	1	Conventional Pick-up	21.74	1.96
04-078	1	Conventional Pick-up	15.77	2.02
04-078	1	Conventional Pick-up	14.61	1.98
04-078	1	Conventional Pick-up	15.77	1.98
04-079	1	Conventional Pick-up	18.67	2.03
04-079	1	Conventional Pick-up	17.93	1.99
04-079	1	Conventional Pick-up	13.9	1.99
04-079	1	Conventional Pick-up	16.1	2.14
04-079	1	Conventional Pick-up	27.87	2.36
04-080	1	Modified Pick-up	19.34	2.08
04-080	1	Modified Pick	18.61	1.95
04-080	1	Modified Pick	16.29	2.04
04-080	1	Modified Pick	19.41	2.08
04-080	1	Modified Pick	19.69	2.11
		Mean	19.90	2.13
		Standard deviation	4.57	0.18
		n	20	20
		% PM10 fractions	18.1%	
04-089	2	Modified Pick-up	14.86	2.69
04-090	2	Modified Pick-up	13.65	2.63
04-092	2	Conventional Pick-up	11.49	2.11
		Mean	13.33	2.48
		Standard deviation	1.71	0.32
		n	3	3
		% PM10 fractions	37.58%	

Appendix B: Description of Orchard and Equipment used on Site 2
Author: Mike Flora

Summary:
The purpose of this testing was to quantify the difference in dust emissions from current and older conventional nut harvesters. A secondary goal was to give another data set for conventional harvesters in a different location of the San Joaquin valley. The older harvester used was the same model as was used on numerous tests in Kern County during this testing season.

Test Site:
A long-time almond grower in Arbuckle, CA offered a block of young trees for testing of dust emissions in harvest. This orchard was representative of orchards at the northern end of the San Joaquin Valley of California. The orchard floor was well maintained, with a firm soil surface. The soil in this area is heavy and somewhat rocky. The irrigation system is a single line drip hose. The row middles were mostly bare with some sparse, dry vegetation. This block of trees has three varieties. However, the first variety, Non-Pareil, had already been harvested prior to this testing. The last two varieties, Butte and Carmel, were harvested simultaneously for testing purposes.

Equipment:
This test was intended to be a comparison of current conventional harvester technology and older conventional harvester technology. The machines tested were the Manufacturer A, Model 1 harvester and the Manufacturer A, Model 2 harvester. Both of these machines were manufactured in 2004. However, the Model 1 has been in production since 1990 and the Model 2 was introduced to the market recently, in 2002. Hence, the model 1 represents ten to fifteen year old technology while model 2 is representative of current technology available on the market today.

Both harvesters were equipped with standard almond components, and all machine settings were typical for a standard almond configuration. The model 1 fan is a 28-1/2” diameter centrifugal fan which operates at 1610 rpm. The model 2 fan is larger, 34” diameter, but it runs slower at 1080 rpm. Orientation of the cleaning fan discharge is quite different. The air blast from the model 1’s fan strikes the ground about ten feet away from the harvester. By design, the model 2 fan discharges parallel to the ground so as to eliminate the problem of secondary dust, from the orchard floor, being entrained into the air. While the gravity separation systems of both machines are similar in concept, the system on the model 2 is greatly improved in terms of dust reduction. The model 2 has 70% more gravity separation before the fan when compared to the model 1. This allows for much more dirt and debris to be removed from the product before the fan does the final cleaning.

Both models are tractor drawn and tractor powered. They are designed for an input speed from the Power Take-Off (PTO) of the tractor of 540 rpm. The same tractor was used for testing of both machines.

Procedure:
Both varieties of almonds were removed from the trees with traditional tree shakers. A conventional sweeper was then used to sweep the material into a windrow on each side of the tree row. These windrows were then ready for pick up. For testing purposes, both varieties were

harvested together to insure that there were enough windrows available to give needed test time. The harvesters were pulled through the field at 3 mph. This ground speed was chosen for two reasons. First, this was the speed that the researchers had used for most other tests; and secondly, this speed resulted in the desired test run time for the air monitoring equipment.

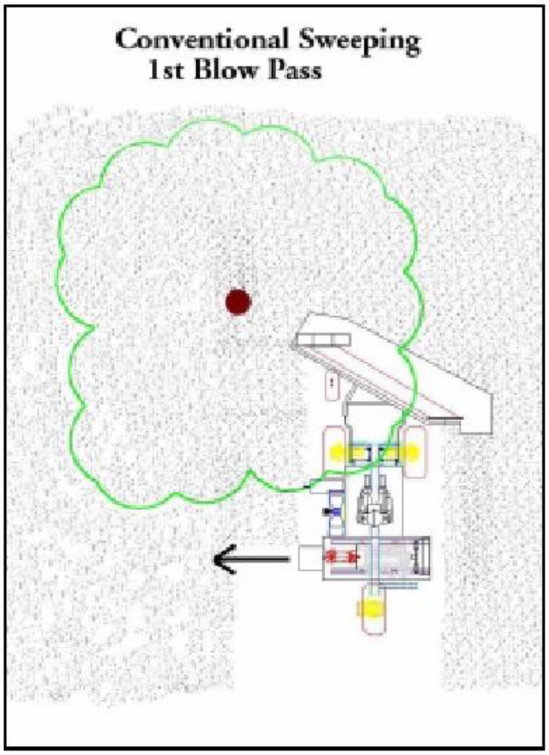
A standard crop cart was pulled behind the harvester to collect the nuts. However, the nuts were not taken out of the field but instead were placed right back on the ground. This was accomplished by leaving the bottom door on the cart open to distribute the nuts in a windrow again. The reason for this was solely convenience to the grower. He was not ready to take the crop to the hulling plant, and yet he was willing to allow the use of his orchard for testing. By this method, there was no additional dust emission impact of shuttle equipment in the harvest operation. The only dust being generated was from the harvester.

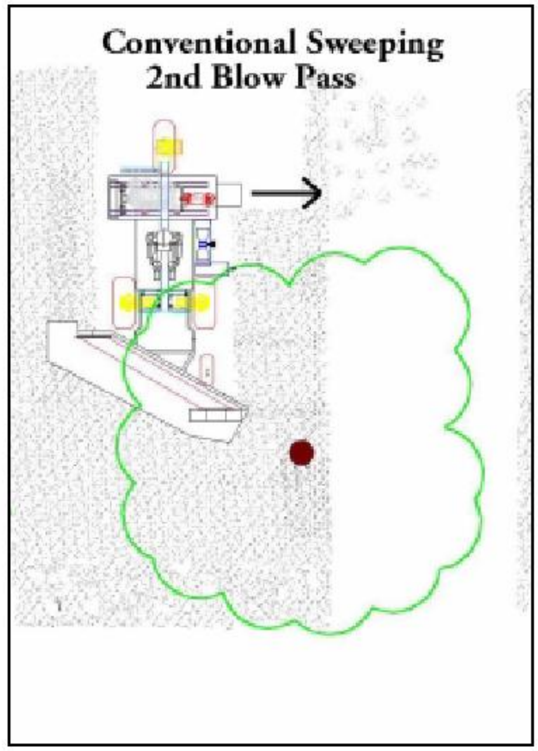
Appendix C: Description of Orchard and Equipment used on Sites 1 and 3
Author: Doug Flora

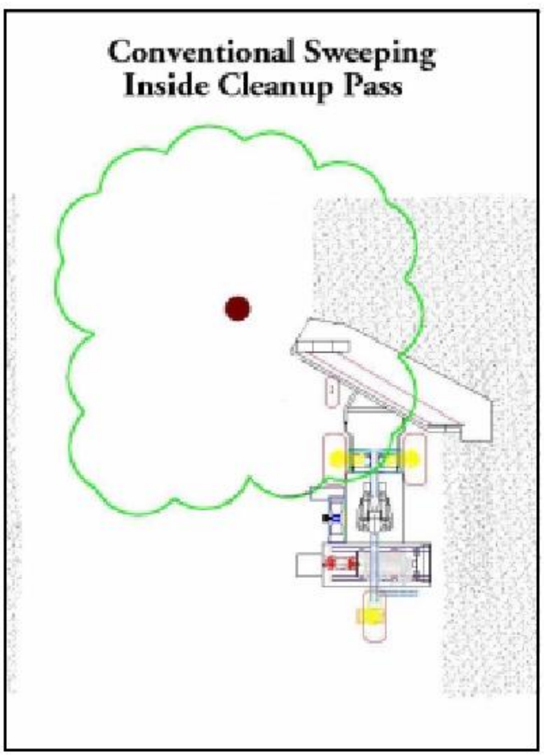
Sweeping Test at Site #1

The trees in this test plot are 7 years old. Crop yield for 2004 season was approximately 2,602 pounds per acre. This test compared sweeping blow passes done with a conventional sweeper to blow passes done with a sweeper utilizing wafer brush technology, allowing for a substantial reduction of air from the blower. The conventional sweeper was a 2003 Manufacturer A model 3 which uses a blower to move the product out of the tree row area. The other sweeper was a 2004 Manufacturer B model 1 which uses a wafer brush to remove most of the product from the tree row area.

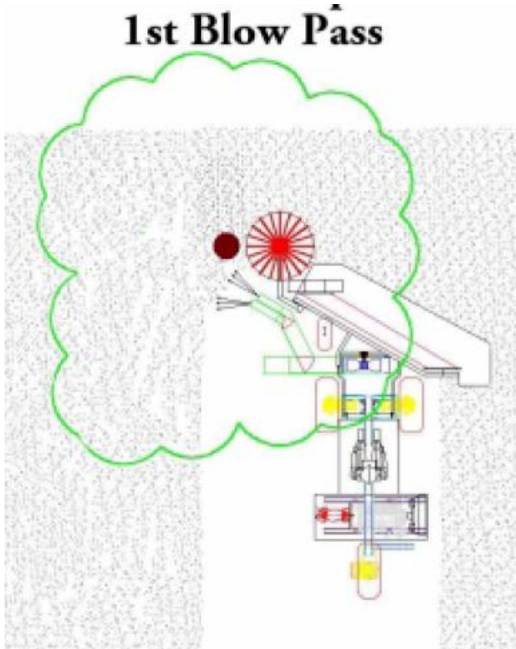
Each harvested row received two blow passes and one inside cleanup pass. Outside cleanup passes were not done on this test plot.

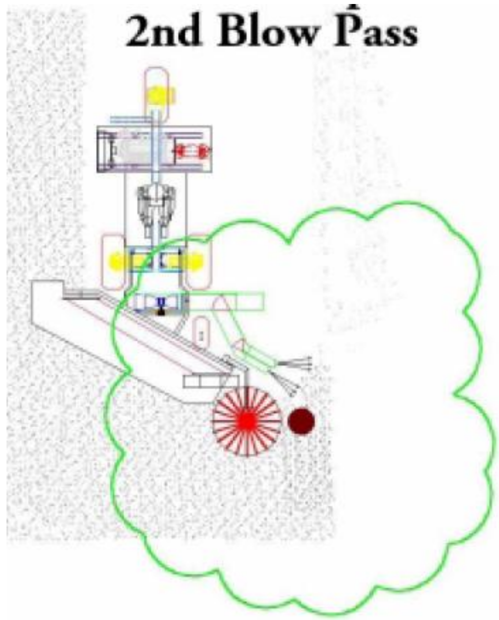

Conventional Sweeping
1st Blow Pass

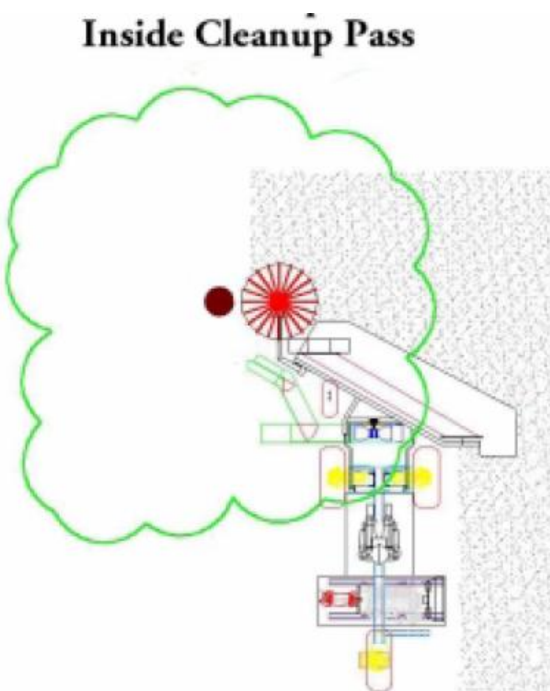

Conventional Sweeping
2nd Blow Pass


Conventional Sweeping
Inside Cleanup Pass

Sweeper Manufacturer B, Model 1







Conditioning & Pickup at Site #1

This is the same test plot referred to in table A1, so the trees are 7 years old and yield for 2004 season was approximately 2,602 pounds per acre.

This test compared the conventional cleaning systems which utilize high velocity air discharges to a new cleaning system that utilizes a “regenerative” air system that recycles the air within the machine, eliminating the high velocity discharges.

A conditioner is simply a harvester that drops the almonds back on the ground after cleaning them rather than placing them in a cart. This process is done to equalize and accelerate the drying process. The configuration of the cleaning systems on both conditioning machines used in this test could also be used as a harvester if the grower is not interested in the benefits of conditioning.

Data collected on the “conditioning” process in this trial would be an exact representation of the “harvesting” or “pickup” process of a traditional harvesting operation. Again, the only difference in this “conditioning” process compared to the traditional “pick up” process is that the product was put back on the ground after it was cleaned, rather than placed into a cart.

The conventional conditioner that was used in this test was a 2002 Manufacturer A Model 4. This machine was purchased from Manufacturer A with some modifications made to the back conveyor to allow the product to be placed back to the ground rather than conveyed into a cart.

The other conditioner that was used for comparison in this test was a 2004 Manufacturer B Model 2 which utilizes the regenerative air cleaning system, eliminating the high velocity air discharge.

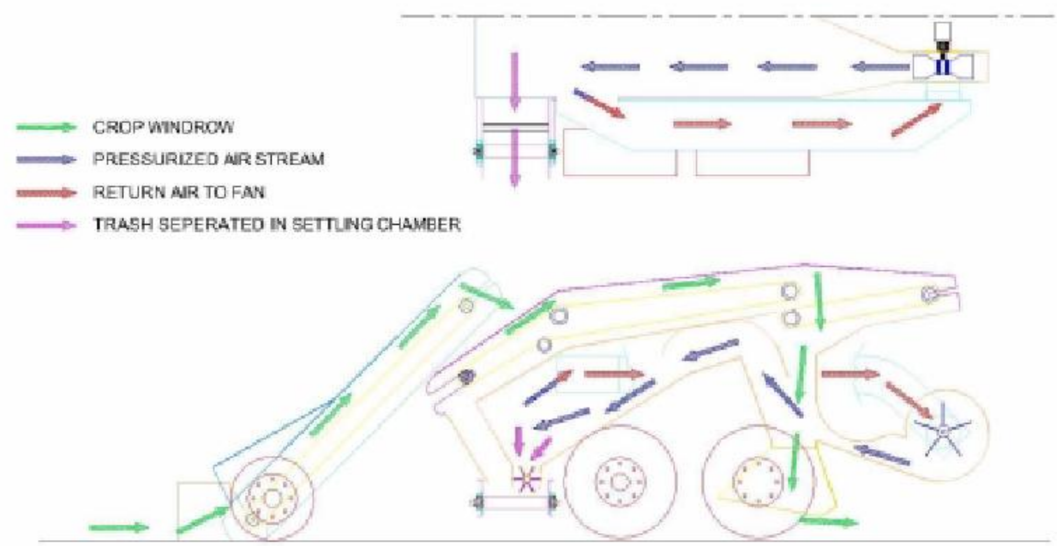
Each windrow in these test plots received one pass with the conditioner, providing data representative of the traditional “pick up” process.

What’s referred to as the “pick up” process in this test is the actual picking up of the previously “conditioned” or “cleaned” windrows.

The conventional harvester used in this test was a 2002 Manufacturer A, model 1 which utilizes a standard cleaning system.

The other harvester used for comparison was a 2004 Manufacture B, model 3 Pick-Up Cart which uses a smaller version of the regenerative air system to remove any foreign material that may have settled on the product during the drying process.

Each windrow in this test plot was picked up during the test. The product was transferred using a bank out system and loaded into semi trailers to send to the processor. Every effort was made to prevent the bank out and loading operation from interfering with the data collection process.



Basic schematic of the Regenerative Air System

The discharge on the Regenerative Air System

Manufacturer B Pick Up Cart

Conditioning & Pickup at Site #3

The trees in this test plot were 7 years old with approximate yield for 2004 of 1746 pounds per acre. The equipment and procedure for this test were the same as previously described in table #2 on test site #1.