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Improvement of PM_{10} Emission Factors for Almond Harvesting
Almond Board of California (#03-RF-01) Correct Project Number: 03-RF-00
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Background

Concentrations of PM_{10}, particulate matter of 10 micrometers or less in aerodynamic diameter, at receptor areas in the San Joaquin Valley have exceeded the national air quality standards for a number of years. Faced with a mandate to regulate PM_{10} sources to attain a 5% reduction in PM_{10} concentrations each year, the San Joaquin Valley Unified Air Pollution Control District (the District) will impose controls on all significant sources. The current PM_{10} emission inventory shows almond harvesting to be one of the largest agricultural sources of PM_{10}. The accuracy of this inventory depends on accurate estimates of emission rates from all sources. The PM_{10} 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 PM_{10} emission factors for the other two operations associated with almond harvesting; shaking and sweeping. Based on visual observation, a factor 10% of the pick-up 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 PM_{10} emission factor.

This project addresses the difficulties and uncertainties in the measurements of PM_{10} 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 PM_{10} control regulations.

Results of a pilot project conducted in 2002 directed hypotheses for the current work. Particle size distribution analysis obtained in 2002 indicated a positive bias in PM_{10} concentration measurements used to develop almond harvest emission factors. Thus, additional comparisons were planned to investigate the source of this bias. Also, emission factors for the conventional almond pick-up operation monitored in 2002 were consistent with those currently in use. So similar measurements of conventional operations were planned to confirm this assessment. Data obtained from LIDAR instrumentation in 2002 was very valuable in evaluating the quality of measured PM_{10} concentrations for calculation of PM_{10} emission factors and sites were selected for the current project to accommodate the LIDAR.

These measurement methods are not always technically and economically feasible and may disturb the process of harvesting itself. Therefore, the proposed project was expanded to include developing models to be used as an alternative tool for demonstrating the impact of emissions from almond harvesting on air quality. The application of a Gaussian dispersion model, Industrial Source Complex Short Term (ISCST3), to the quantification of PM_{10} emissions from almond harvesting indicated a potential of circumventing the more technically and economically demanding sampling procedures relied upon in the proposed part of this project.

Materials and Methods

Aerosol monitors developed by Texas A&M University and UCD were used to measure PM_{10} in the vicinity, both upwind and downwind, of the ongoing almond pick-up operations. Meteorological parameters were recorded simultaneously with aerosol collection and the LIDAR instrument was employed at some 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.

A summary of tests performed in 2003 is presented in Table 1, below. Sites are described by number, below, with details of the orchards and harvest practices. Equipment contributed by the UCD team is listed to the left of the slash (/) and those used by TAMU to the right, as described below. In all cases, TSP samplers were paired Hi Vol and Lo Vol. Full details of project sites and testing conditions are provided in Appendix A: Sites.

Table 1: PM_{10} emissions measurements made during almond pick-up operations in 2003.

Site	Harvest Practices	Equipment	Test #s
1	Conventional	FRM tower, LIDAR	1-3
2	Conventional	FRM tower/TSP, TAMU FRM	4-6
3	Conventional	FRM tower/TSP	7-9
4	Conventional vs. Catch Frame	FRM single ht./TSP	10-13
5	Windrow Conditioner followed by Conventional vs. Modified Pick-up	FRM tower, LIDAR/TSP	14-17

Site 1: A 761 x 805 m block planted east to west was the first orchard sampled. Row spacing of this orchard is 7.2 m with tree spacing of 5.5 m. The first pick-up (Non-Pariel) was monitored for which every other tree row was shaken conventionally and nuts were swept into wind rows on both sides of every row. A vertical profile of PM_{10} concentrations was measured using the FRM tower on the south edge of the orchard, to the east of center. This placed the tower at an optimal distance from the LIDAR, which was on a line-of-sight to the south edge of the orchard 870 m east of the tower. Upwind PM_{10} concentrations were measured on the north edge of the orchard in a fallow field. A single harvester was used to pick up the nuts in the 11 rows bordering the south edge of the orchard, traveling always from east to west with the blower facing north (away from the samplers). The three tests (numbers 1-3) were each conducted during the pick-up of three or four rows.

Site 2: A similar block, 710 x 518 m planted east to west with the same tree spacing as in site 1, was used for comparison of conventional harvest. Three sampling locations were established on the south edge of the orchard. The vertical profile of FRM samplers was placed east of the midpoint (as in site 1) and TSP samplers were collocated with it and placed near the midpoint and equally west of the midpoint. TAMU FRM samplers were also collocated with all TSP samplers. Upwind concentrations were measured in a fallow field north of the orchard using both FRM and TSP samplers. In this operation four pick-up machines were used simultaneously and operated more conventionally, traveling both east to west and west to east. While they worked generally from the north end of the orchard towards the south, rows in all parts of the orchard were pick-up during all three tests conducted on this orchard. Test 4 monitored the pick-up of 34 rows, test 5 was 22 rows, and test 6 was 16 rows.

Site 3: This site was also chosen for similarities to the first two sites. One notable difference is the age of this orchard. Planted in 1974 it has a larger percentage of Non-Pareil (67%) and wider tree spacing (7.4 m). Rows in this orchard run east to west and conventional harvest produced wind rows on both sides of every tree. The vertical profile of FRM samplers was placed at the midpoint on the south edge of the orchard along with TSP samplers. Both FRM and TSP samplers were used to measure upwind PM_{10} concentrations north of the orchard across a ravine from a fallow field which was being disked on the day of the tests. Four pick-up machines were used simultaneously in a similar manner to the operation on site 2. Test 7 included 15 rows, test 8 was 14 rows, and test 9 was 16 rows.

Site 4: This block, 845 x 1226 m, was planted north to south with a square corner to the southwest and a diagonal boundary on the north such that there is not the same number of trees in each row. The 33% Butte trees were divided into western and eastern halves and harvested by two different methods. The west half was conventionally shaken and swept, preparing wind rows on both sides of every third tree row. The east half was harvested with a modified catch-frame harvester leaving a wind row on only one side of every third tree row. The same conventional pick-up machine was used on both halves of the orchard. Six tree rows were identified in each half of the orchard for measurements, three rows were used for each test. No vertical profiles of PM_{10} concentrations were measured at this site. FRM and TSP samplers were operated side-by-side on the south edge of the orchard directly south of the middle tree row in each set of three and moved between tests. Both FRM and TSP samplers were used to measure PM_{10} concentrations north of the orchard, within a neighboring orchard where no operations were taking place.

Site 5: This orchard was geographically separated from the first 4 sites being near Bakersfield whereas the others were near Coalinga. It is a smaller block, 495 x 177 m, planted north to south. Row spacing is 9 m and tree spacing is 6.1 m. The pick-up of the Carmel variety (25%) was monitored. This entire orchard was shaken and swept in a conventional manner producing wind rows on both sides of every fourth tree row. All wind rows were conditioned with a novel implement that removes debris from the nuts. The orchard was split into a west and east half; rows on the east half were picked up using a conventional pick-up machine and rows on the west half were picked up using a modified machine. Six rows were again identified in each half for the monitoring and each test used three rows. Vertical profiles of PM_{10} concentrations were measured once on each half and FRM and TSP samplers were used at a single height in all four tests. Both FRM and TSP samplers were used to measure PM_{10} concentrations upwind of the operation in an orchard northwest of the site.

Samplers: The definition of PM_{10} as the mass of particulate matter less than 10 μm in aerodynamic diameter makes the method used for separating these small particles from the larger ones in the air stream critical to successful measurements. In a broad sense, the larger particles can either be eliminated at the time of collection or all particles can be collected and sized, measuring the proportion of smaller to larger ones. The Federal Reference Method (FRM) specifies the use of virtual impactors that remove the larger PM from the air stream prior to the collection of the PM_{10}. It is important to note that this method is tested and approved for ambient sampling and differences in the number and sizes of particles at ambient sites and sites near a source may make it unsuitable for source measurements. The FRM samplers developed by Dr. Flocchini's group at U.C. Davis (UCD) were used in this project at either 1 height (3 meters) or 4 heights (1, 3, 5, and 9 m). Measurements of PM_{10} concentration at multiple heights provides a vertical profile of PM_{10} which can be used to compute fluxes and emission rates.

Dr. Parnell's group at Texas A&M (TAMU) uses a method of collecting the Total Suspended Particulate matter (TSP) and measuring the sizes of the particles to determine a Particle Size Distribution (PSD). From these variables the PM_{10} concentration can be calculated. The original TSP samplers (Hi Vol) have very large flow rates, with high power requirements, and large, expensive filters. The TAMU group has developed a smaller TSP sampler (Lo Vol) that performs similarly and more economically. These two forms of TSP samplers were tested side-by-side in this study. Additionally, some Lo Vol samplers were fitted with FRM PM_{10} inlets, making them functionally identical to the UCD FRM samplers. Samplers provided by the TAMU group were always deployed at a single height of 1 m.

LIDAR: The single wavelength (1064 nm) backscatter lidar instrument was employed in this project. In elastic lidar, pulses of 1064 nm photons are emitted by lidar laser, scattered back from molecules and particles in the atmosphere towards the lidar instrument, collected by a telescope and focused onto the photodiode detector. The detector signal is digitized and analyzed by a computer to create a real-time detailed image of aerosol concentrations within the scanned region (Figure 1). Horizontal (azimuth) and vertical (elevation) scanning of the laser-telescope assembly allows to collect 2D images of aerosol distributions. The Lidar instrument was positioned along a line-of-sight with the downwind PM samplers. Lidar data were collected during the almond harvest operation (plume scans) and during breaks in harvest operation, usually after each test (background scans). Two-dimensional (2D) vertical scans were collected at the location of the downwind tower by making changes in the elevation angle of the lidar at constant azimuth. The majority of scans were collected at the downwind location (PM sampler location) to assure the ability to qualitatively assess PM concentrations at this location and consequently, assess emission factors from the operation.

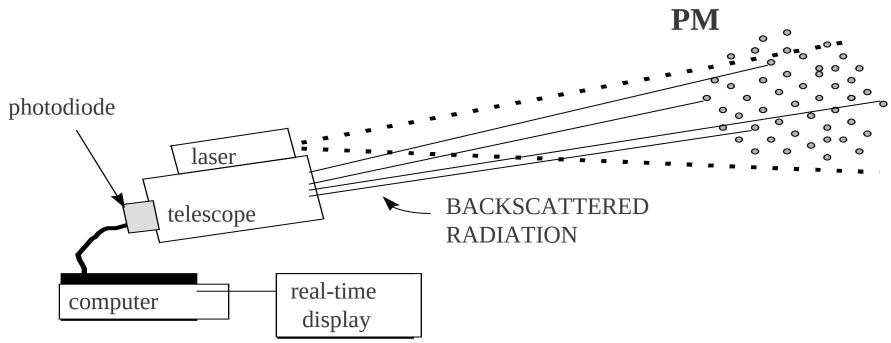

Figure 1: Lidar laser emission (dotted lines) is scattered back from molecules and particles in the air (grey spheres) and collected by a telescope (solid lines).

Soils: Samples of loose soil from the top inch of the soil profile were collected on each orchard sampled for the project. Samples were composites from a meter long stretch of the orchard floor adjacent to the wind rows, where harvester tracks were expected, that were picked up during the PM sampling tests. Duplicate steel cans were half filled and sealed on site for moisture determination. Approximately 1 pound of soil was collected to zip-closure bags for analysis of soil texture.

Results and Discussion

The objectives of this research project were:

- Assessing the quality of baseline PM_{10} emission factors from pick up operation of almonds for use in PM_{10} emissions inventories and
- Determining the ability of suggested methods to accurately measure the differences in PM_{10} emissions from the harvesting of almonds using different management practices.

Soils: The soils of the orchards used for this project were in a typical range of moistures and textures for San Joaquin Valley soils during almond harvest season (Table 2). Soil moisture and texture did not vary significantly enough from site to site to produce a measurable effect on PM_{10} emission factors for the almond harvest operations in these orchards.

Table 2: Soil properties of orchards used in PM_{10} emissions measurements.

Site #	Avg. Moisture (%)	St. dev. Moisture (%)	Sand (%)	Silt (%)	Clay (%)	Texture*	Silt content (%)**
1	3.21	0.53	65.40	13.18	21.42	SCL	1.58
2	2.95	0.42	63.76	17.43	18.81	SL	2.68
3	1.86	0.17	77.11	10.08	12.81	SL	2.93
4	1.30	0.10	79.47	8.58	11.95	SL	3.77
5	3.05	0.29	80.44	10.35	9.20	LS	2.02

*SCL = sandy clay loam, SL = sandy loam, LS = loamy sand on soil texture triangle.
**dry sieve silt content.

Federal Reference Method and Particle Size Distribution comparison: A pilot project conducted in 2002 at one orchard used a Hi Vol TSP sampler side-by-side with FRM PM_{10} samplers for three tests. The measured PSD downwind for that study had an average mass median diameter (MMD) of 19 and a geometric standard deviation (GSD) of 2.0. A comparison of downwind PM_{10} concentrations measured using the FRM to that derived from the PSD showed approximately a 100% to 400% increase in FRM measured PM_{10} over that measured by the PSD method. A trend in these data indicated a greater bias in

FRM measurements as the harvester moved away from the samplers and PM_{10} concentrations decreased. The average downwind PSD measured from Hi Vol TSP samplers used in 2003 had a MMD of 18.8 and a GSD of 2.1, very similar to that measured in 2002.

At Site 2, Lo Vol PM_{10} samplers were collocated with Lo Vol TSP samplers at the same height (1 m). The ratios of measured PM_{10} to TSP concentrations agree quite well with the percentage of PM_{10} taken from the PSD (Table 3), particularly from a location at the center of the downwind edge of the source (D2).

Table 3. Comparison of PM_{10} concentrations from PSD and collocated PM_{10} and TSP samplers.

Test No	Location	TSP (μg/m^3)	PM_{10} by FRM (μg/m^3)	Measured ratio (%) from FRM	Predicted ratio (%) from PSD
Test 5	D2 (middle)	1,122	359	32.0%	33.3%
Test 5	D1 (same as UCD)	695	453	65.2%	No PSD
Test 6	D2 (middle)	5,300	1,544	29.1%	32.5%
Test 6	D1 (same as UCD)	4,418	2,377	53.4	36.9%

For every test at Sites 2 through 5 FRM and Lo Vol TSP samplers were operated side-by-side, though not always at the same height. Concentrations of PM_{10} measured downwind of the source by the two methods were compared by matching FRM collected at 1 or 3 m to the TSP collected at 1 m. For those tests in which the tree rows ran East to West the PM_{10} concentrations measured by the two methods were comparable (Figure 2). Tests conducted on North to South tree rows showed far less correlation between results of the two methods (Figure 2).

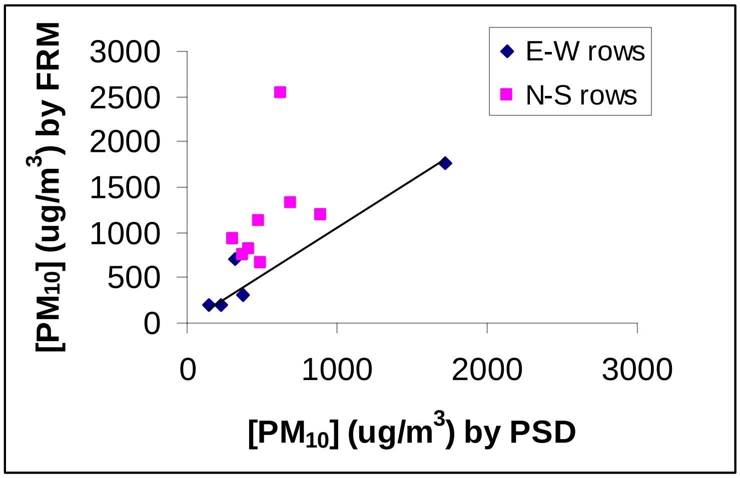

Figure 2: Comparison of PM_{10} concentrations measured by PSD of TSP samples to FRM measured PM_{10}.

More detailed analysis of PM_{10} concentrations measured by the two methods show some variability in the magnitude of the difference from test to test (Table 4). There are two cases (tests 5 and 8) when the FRM measured PM_{10} was less than that measured by the TSP with PSD method. On average, there appears to be a slight positive bias in PM_{10} concentration by the FRM (28%) relative to the TSP method under typical sampling conditions (rows running perpendicular to wind direction). This is substantially less than to 100-400% difference measured in 2002. A greater average bias (124%) was measured in tests conducted where the tree rows were parallel to the wind direction. There are several possible reasons for the observed bias.

Table 4: PM_{10} concentrations measured by TSP and FRM samplers and the difference between them expressed as percent (FRM-TSP/TSP).

Test #	PM_{10} concentrations (ug/m^3) by Lo Vol TSP and PSD	by FRM	difference (%)
rows E-W			28**
5	374	309	-17
6	1723	1764	2
7	316	704	123
8	233	206	-12
9	145	206	42
rows N-S			124**
10	891	1189*	33
11	312	932*	199
12	493	662*	34
13	408	806*	98
14	474	1120*	136
15	627	2538*	305
16	375	744*	98
17	698	1317*	89

* FRM sample collected at 3 m. ** Average difference for each row configuration.

The plume being sampled may not be homogenous such that side-by-side samplers, which are about 5 m apart and at different heights, are not actually sampling the same air. This explanation fits the observation of greater bias and variance in comparisons made in the North-South row orchards because this sampling scenario is much more vulnerable to shifts in wind direction carrying the plume to one side or the other of the sampling array. The air flow of the fans on the pick-up machines is equivalent to a very high wind. The inlets of the TSP samplers, placed at 2 m, may be impacted by this artificial wind which is greater than the wind speed those inlets are developed for. Again, the greater bias in the data collected at the orchards with N-S rows supports this hypothesis as the pick-up machine must turn at the end of the row and passes much closer to the samplers in that configuration than when traveling within the E-W oriented orchards. Finally, the FRM may be inappropriate for application to PM_{10} measurements downwind of almond orchards. These data support the hypothesis that the FRM is oversampling in some source sampling conditions, particularly when MMD is large (highest downwind MMD measured was 19 for test 7, which also has a high bias). Detailed descriptions of TSP samples and PSD analyses can be found in Appendix B – PSD and complete comparisons of PM_{10} concentrations are in Appendix C – PM10.

PM_{10} emission factors for conventional harvest operations: Sites 1, 2, and 3 (tests 1-9) were chosen for baseline measurements of PM_{10} emission factors for almond pick-up using conventional practices for comparison with data collected in 2002 and the emission factors currently in use by the District. Aspects of these orchards that suggest their comparability include: same variety (Non-Pariel) with similar percentage planting (50-67%), identical harvesters used (only one of the four was used on site 1), all drip irrigation, same geographical vicinity, similar block sizes and row spacing. These first three orchards were also chosen because the layout and surroundings are compatible with the established measurement methods. Evaluations of conditions under which reliable estimates of PM_{10} emission factors from on-field agricultural operations can be derived from vertical profiles of PM_{10} concentrations provide the following guidelines.

- No wind field obstructions, such as a neighboring orchard, shall exist downwind of the source area. This permits the assumption of uninterrupted PM_{10} dispersion from the point of emission to the samplers. It also provides the lidar with an unobstructed view of the downwind edge.
- Direction of implement progression must be perpendicular to the wind direction. In the case of predominantly North winds, rows must be planted from East to West. Thus, the plume created by the moving implement will be carried by the wind to the sampler for every pass upwind of the sampler that crosses the wind trajectory. Then, variations in wind direction from directly perpendicular (e.g. northwesterly) can be normalized as an increased distance between the source

and the sampler, assuming a constant source (that PM_{10} emission from the harvester is the same at all points along a pass).

- Open ground not impacted by other local sources (e.g. tractor activity or unpaved road traffic) shall exist upwind of the source area for measurement of meteorological instruments and upwind (background) PM_{10} concentrations.

These guidelines were used to select the data compiled for the PM_{10} emission factors currently in use by the District and were followed to establish sampling methods yielding comparable data.

In order to make a meaningful comparison between data collected in this project and the current emission factors the same Quality Assurance (QA) guidelines must be followed to determine whether a specific test is valid. The QA established in previous work requires:

- The upwind PM_{10} concentration shall not exceed the downwind concentration at any height except 9 m.
- The standard deviation of the average wind direction over the test period must be less than 25° and the average wind direction shall not deviate from perpendicular to the tree rows by more than 45°.

According to these criteria, three of the 9 tests collected at Sites 1-3 were invalid due to upwind concentrations that exceeded downwind concentrations (Table 5). In test 4, the likely cause unpaved road traffic at the upwind site. Those samplers were moved between tests 4 and 5. In tests 8 and 9, a disking operation upwind of the orchard contaminated the upwind measurements.

Table 5: Meteorological conditions, QA parameters, and PM_{10} emission factors for 2003 tests of conventional almond pick-up operations.

Test	Temp. (°C)	Relative humidity(%)	$[PM_{10}]_{DN}$ - $[PM_{10}]_{UP}$*	Wind Direction (°)	Wind Dir. St. dev. (°)	Model used**	PM_{10} Emission Factor (mg/m^2)
001	24.8	55.4	+	359	11	Box	98
002	28.9	46.7	+	346	11	Box	34
003	29.3	46.2	+	334	9	Box	302
004	28.2	49.9	-	41	6	--	--
005	32.0	24.7	+	22	10	V.P.	371
006	36.2	20.6	+	11	11	V.P.	2595
007	32.0	24.7	+	326	24	V.P.	150
008	33.6	21.1	-	321	23	--	--
009	33.3	25.3	-	321	20	--	--

*Difference in PM_{10} concentrations measured upwind and downwind of the harvest are described as (+) – Downwind > Upwind or (-) – Downwind < Upwind.

** Models used are (Box), as described in the text, and vertical profile (V.P.) which fits the measured PM_{10} concentrations to a logarithmic function with height.

Site 1: Computation of PM_{10} emission factors from vertical profiles of PM_{10} concentrations requires a profile of decreasing concentration with height. Vertical profiles collected in tests 1-3 (Site 1) did not measure any variation in PM_{10} concentration with height, though downwind concentrations were elevated with respect to upwind. In these cases, an alternate method for emission factor computation is employed called a box model, as indicated in Table 5 for tests 1-3. The box model can yield comparable results to the vertical profiling method, if the plume is small and the limitation of the profiling method is the precision of the PM_{10} concentration measurements. If, however, the reason for the constant measured PM_{10} concentration with height is that the plume traveled over the samplers at the highest height (9 m) the box model cannot produce meaningful emission factors. It should also be noted that operations during tests 1-3 were unusual in that the pick-up machines passed only from east to west, with blower fans facing away from the samplers. This may have caused the plume to leave the top of the orchard instead of the edge of the orchard, carrying it above the samplers. Or it may have been attenuated by the orchard canopy resulting in the lower than expected emission factors reported in Table 5. Lidar scans of the plumes during these tests may be used to verify the applicability of the box model to these data and address these hypotheses. A complete analysis of the lidar data is available in Appendix D – Lidar.

Lidar data were collected during the almond harvest and before (background scans) from a point approximately 650 meters east of the orchard and about 850 meters east of the downwind sampler location. Two-dimensional (2D) vertical scans were collected by making changes in the elevation angle of the lidar at constant azimuth location. The majority of scans was collected at the downwind location (PM sampler location) to assure the ability to qualitatively assess PM concentrations at this location and consequently, assess emission factors from this operation. The data collected with the lidar provide a qualitative assessment of PM concentrations (vertical profiles) at downwind and orchard locations. Background scans were collected before harvest operation started. All selected scans collected during the period of PM tests were averaged (lidar signal) and the results are shown in the Figure 1 below. To obtain the data, the vertical profiles of averaged lidar data were calculated for both background atmosphere and the plume, and selected files were averaged at the range corresponding to the location of the PM tower.

It is important to keep in mind, that lidar is capable of detecting dust from any source but can’t distinguish between plumes from different sources. Since there was almost constant traffic close by (trucks collecting almonds, etc.) and it was impossible to distinguish (separate) the dust generated by each source, for these series of experiments all dust sources related directly to the operation of interest (almond harvesting) were included. For example, if the trucks coming to pickup harvested almonds are considered, they were included because they are the part of the whole operation. Any other vehicles traveling near experimental setup during data collection however were excluded and the data collected during this period were excluded from further analyses.

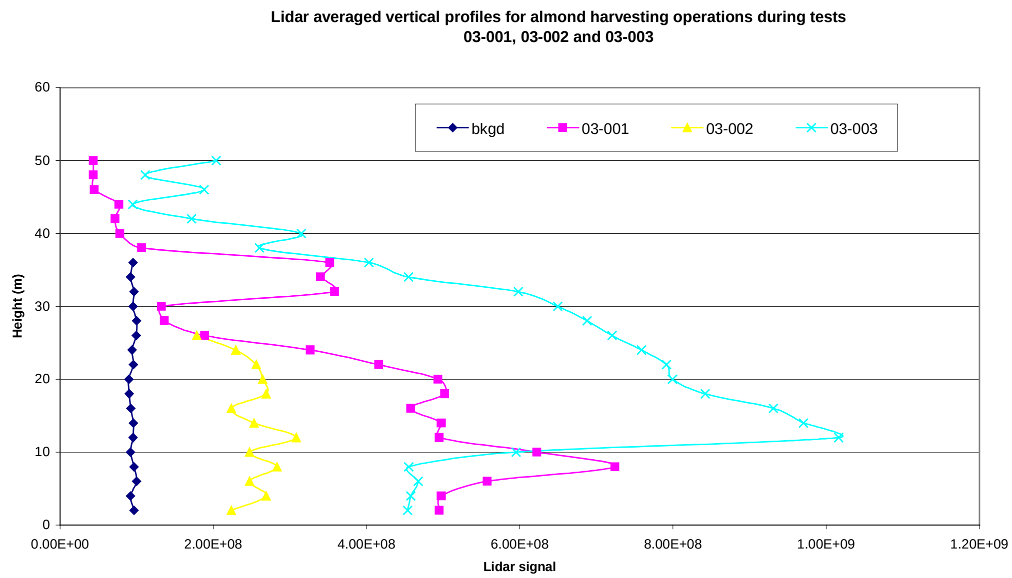

Figure 3: Background and downwind profiles of PM for conventional pick-up operations monitored at Site 1.

The background shown in Figure 1 is the result of data averaged from three 2D vertical scans collected before any activities related to harvesting operation took place. The lidar profiles collected during tests 03-001 and 03-003 have similar characteristics and are substantially different from the profile collected during test 03-002. During tests 03-001 and 03-003 noticeably higher plumes than in test 03-002, were generated. The plume heights exceeded 30 m for these tests. This suggests that, in tests 03-001 and 03-003, the bulk of the plumes missed the samplers placed on the tower, about 15 m from the edge of the orchard.   That maybe due to “filtering “ by the trees in the orchard, blocking the plume from exiting the orchard at the edge near the samplers and forcing it out through the tops of the trees. The lidar profiles for tests 03-001 and 03-003 have similar shapes, but the areas under the curves (after background subtraction) are different. These areas correspond (qualitatively) to the fluxes and consequently, emissions from the operation. The total lidar signal estimated for test 03-003 is about 2.5 times higher than the one calculated for test 03-001. These results seem to agree very well with ones based on PM_{10} sampler data for these tests. The emission factor for test 03-001 is about three times lower than the one for test 03-003 (Table 5).

The averaged lidar signal for test 03-002 is quite stable (only slight differences between heights), at least until 24 m (due to the computer graphics setup we can obtain data only until 24 m for tower location, about 850m from the lidar). The measured PM_{10} mass concentrations for test 03-002 are also lower than for other tests (good agreement with what the lidar sees).

Site 2: Of the valid tests taken on Site 2, the average and standard deviation of the wind direction was much more favorable for test 6 than test 5. While the wind direction QA parameters for test 5 did not exceed the acceptance levels, the average wind direction deviated from the ideal (perpendicular to the tree rows, measured as 0° or due North) enough to cause the centerline of the plume to miss the samplers on at least the furthest passes. This is because, anticipating a northwesterly wind, the samplers were place to the east of center (220 m from the SE corner) but the wind direction was actually northeasterly. Computing the angle of a wind trajectory from the east end of the farthest pass in test 5 (478 m from the samplers) using the arctangent of the rise over the run (opposite over adjacent) defines the actual wind direction limit for this test as 25°, which is only slightly more than the measured average wind direction for test 5 of 22°. With the wide deviation between the PM_{10} emission factors measured in tests 5 and 6 it is likely that the practical limits of the method were more restrictive than the theoretical limits and the wind direction was not adequate during test 5 for PM_{10} emission factor quantification by the vertical profiling method.

Site 3: The one valid test on Site 3, test 7, was also compromised by inadequate wind direction. In this case, the samplers were placed at the midpoint on the southern orchard edge (370 m from the SW corner) but the average wind direction was too far west of northwest to bring the plumes generated at the furthest passes to the samplers. Computing the angle of a wind trajectory from the west end of the farthest pass in test 7 (821 m from the samplers) using the arctangent of the rise over the run (opposite over adjacent) defines the actual wind direction limit for this test as 336°, which is greater (closer to the ideal of 360) than the measured average wind direction of 326°. Thus, although within the theoretical limits of the method, conditions for test 7 were not satisfactory for PM_{10} emission factor quantification in practice.

When sampling, modeling, and QA methods comparable to those on which the current PM_{10} emission factor is based were applied to conventional pick-up tests conducted in 2003 only one test yielded suitable data.   The PM_{10} emission factor measured in test 6 is similar to that measured in 2002 and the data from which the current emission factor is derived (Table 6).

Table 6: PM_{10} emission factors compiled for the current emission factor and measured in recent projects.

Source (Year)	PM_{10} emission factor (mg/m^2)
Current emission factor (1995)	1663
Current emission factor (1995)	1995
Current emission factor (1995)	2365
Current emission factor (1995)	5259
Current emission factor (1995)	9248
Pilot study (2002)	2107
Current study, test 6 (2003)	2595

In the current project, two additional methods were used for comparison: 1) FRM data applied to the ISCST3 dispersion model and 2) PM_{10} concentrations measured by the TAMU method applied to the ISCST3 dispersion model. The three methods concur for test 03-006, providing additional evidence for the validity of the vertical profiling method application under these testing conditions (Table 7). A full description of ISCST3 modeling results for the entire project can be found in Appendix E: Modeling.

Table 7: Comparison of PM_{10} emission factors for one almond pick-up event derived from three combinations of two measurement and two computational methods.

Test number	Harvest practice	Emission factor (calculated from UCD data)	Model - emission factor (based on UCD data)	Model – emission factor (based on TAMU data)
03-006	Conventional almond harvesting	2505 kg/m^2	2056 kg/m^2	2572 kg/m^2

Quantification of differences in PM10 emission rates using modified harvest practices: We conducted experiments on two orchards where non-conventional methods were compared to more conventional methods. Sites 4 and 5 were selected to provide test orchards for evaluating the capability of the vertical profiling method to quantify differences in almond pick-up PM_{10} emission rates between any two variants of a single parameter. On Site 4 we compared pick-up following a catch-frame harvester to the same pick-up following conventional shaking and wind rowing. On Site 5 we compared a conventional and modified pick-up machine on identically prepared wind rows. In both cases, we were able to demonstrate that PM_{10} emission factors for alternate almond pick-up operations were decreased with respect to the more conventional methods.

In both experiments the orchards offered by the producers had a North to South row direction. The vertical profiling method of emission factor quantification is much more robust when the implement passes are perpendicular to the wind direction. This is because a long pass across the wind is likely to generate a plume at some point along that pass that will be carried to the samplers on the wind. As long as the implement generates a steady plume it doesn’t matter where along each pass the plume that hits the sampler comes from and deviation from the ideal wind direction has a small and quantifiable effect on the measurements. When the implement passes are perpendicular to the wind direction, however, small deviations from the ideal wind direction can easily transport the plume away from the samplers. Thus, for the purposes of assessing PM_{10} emission rates measured at Sites 4 and 5, valid comparisons shall only be made among tests within each experiment.

Site 4: The grower-cooperator providing access to this site had harvested half of the orchard in the conventional manner using mechanical shakers and sweeper. The other half of the orchard was harvested using a catch frame harvester modified to produce an even and uninterrupted windrow. Thus, half of the orchard had a windrow on both sides of each tree row harvested and the other half had windrows on only one side of each tree row harvested. While all tests on Site 4 covered the same harvested area (three tree rows), the tests on the conventionally harvested half (tests 10 and 11) had 6 passes each while those on the catch frame harvested half (tests 12 and 13) had 3 passes each.

The four tests at Site 4 were conducted under very similar meteorological conditions and, thus, results of these tests provide a valid comparison (Table 8). As discussed above, the PM_{10} concentrations measured using the two methods (LoVol TSP followed by PSD and FRM) were not identical. This may be due to the sensitivity of the measurements to slight deviations in wind direction when using a north-south row configuration or the placement of the inlets for the two samplers at different heights. A combination of the necessity of moving the samplers rapidly to keep up with the pick-up operation and limited availability of research personnel at the time this orchard was ready made the use of the vertical profiling tower and the lidar impossible at this site. The reported FRM measured PM_{10} concentrations were all at 3 m height. With the exception of the LoVol TSP measurement of test 11, measured PM_{10} concentrations were lower downwind of the pick up operation on the catch frame harvested half of the orchard (tests 12 and 13) than on the conventionally harvested half (tests 10 and 11). Using the PM_{10} concentrations measured by the

FRM, that translated into an average reduction in the pick-up emission factor of 47 to 61% (by the ISCST3 and box models, respectively) when catch frame harvesting replaces conventional shaking and sweeping. It is impossible to deduce from these data whether the reduction is solely due to the decrease in the number of passes or is also attributable to some other aspect of catch frame prepared windrows.

Table 8: Meteorological conditions, QA parameters, and PM_{10} emission factors for 2003 tests of the pick-up of conventionally (Conv.) vs. catch-frame (Catch) harvested windrows.

Test	Treat ment	Temp. (°C)	Relative humidity (%)	Wind Direction (°)*	PM_{10} concentrations (μg/m^3) LoVol TSP and PSD (1 m)	FRM (3 m)	PM_{10} Emission Factors (mg/m^2)** By ISCST3	By Box
010	Conv.	31.0	32	346 (14)	891	1189	887	2934
011	Conv.	33.4	29	344 (17)	312	932	687	3089
012	Catch	34.0	28	346 (18)	493	662	435	1515
013	Catch	32.4	32	344 (15)	408	806	407	860

*arithmetic means, (standard deviations) in parentheses.
** using the same FRM measured PM_{10} concentrations for both models.

Site 5: The experiments conducted at this final site were similar in design to those that took place on Site 4. In this case the entire orchard was harvested using a conventional shaker and sweeper. Then, a novel implement was used to "condition" all wind rows, removing foreign material from the nuts. On the day of measurements, a conventional pick-up machine was used on half the orchard and a modified machine was used on the other half. All tests covered the same area and number of passes.

Table 9: Meteorological conditions, QA parameters, and PM_{10} emission factors for 2003 tests of pick up by conventional (Conv.) vs. modified (Mod.) pick-up machines.

Test	Treat ment	Temp. (°C)	Relative humidity (%)	Wind Direction (°)*	PM_{10} concentrations (μg/m^3) Upwind 3m	Downwind 3m	PM_{10} Emission Factors (mg/m^2)** By ISCST3	By V.P.
014	Conv.	35.7	21	303 (10)	126	1120	4568	
015	Conv.	37	19	356 (11)	89	2538	4966	3688
016	Mod.	37	22	26 (8)	100	744	3048	
017	Mod.	35	26	20 (2)	388	1317	1872	530

*arithmetic means, (standard deviations) in parentheses.
** using the same FRM measured PM_{10} concentrations for both models. V.P. = vertical profile

Although tests 14 – 17 were performed sequentially on the same day, the wind direction shifted significantly between the measurements of the conventional pick up machine (tests 14 and 15) and the modified machine (tests 16 and 17). This may have impacted the comparability of the results of these tests. For example, the more directly northerly wind recorded during test 03-015 (Table 9) may be responsible for the relatively higher PM_{10} concentrations seen. The relatively high PM_{10} concentration measured at the upwind location during test 03-017 was likely due to the increased truck traffic at the perimeter of the orchard towards the end of the day. The effect of a possibly contaminated upwind sample on the calculated PM_{10} emission factors is not likely to be significant, but may explain why the ISCST3 modeled emission factor for test 03-016 exceeded that for test 03-017 while the downwind PM_{10} concentration for the latter was greater than that for the former. Even with a full crew of researchers present, the time required to move the vertical profiling tower restricted it's use to every other test and vertical profiles are not available for tests 03-014 and 03-016.

Both the ISCST3 and vertical profiling models correct for deviations in wind direction, though the vertical profiling method correction is less robust when applied to the north-south row configuration than in the standard application. Thus, the ISCST3 modeling results for tests 03-014 and 03-015 are very similar even though there is a two fold difference in the downwind PM_{10} concentrations (Table 9). Other meteorological conditions, such as relative humidity and wind speed, can significantly effect the shape of a plume. Generally, atmospheric stability increases as the sun goes down and plumes generated during test 03-017, conducted in the 5:00 hour, were likely lower to the ground than they may have been earlier in the day. But atmospheric stability is also a variable the ISCST3 model takes into consideration when used to compute emission factors, so comparisons between the results of the earlier and later tests are valid. Lidar data collected during tests 03-015, 03-016, and 03-017 clearly illustrate the changes in the plume shape. While changing atmospheric stability contributed to the observed differences in plume shape, the tested treatment of the modified vs. conventional harvester also appears to have had an effect.

The lidar instrument was positioned approximately 440 meters east of the downwind sampler location for PM tests 03-015, 03-016 and 03-017. Lidar data were collected during the almond harvest operation (plume scans) and during breaks in harvest operation (background scans). Two-dimensional (2D) vertical scans were collected at the location of the downwind tower by making changes in the elevation angle of the lidar at constant azimuth. The majority of scans were collected at the downwind location (PM sampler location) to assure the ability to qualitatively assess PM concentrations at this location and consequently, assess emission factors from this operation. Background scans for each test were collected after completing each test. Individual 2D vertical scans were grouped for each test and “valid” files were chosen for the further analysis as described above in Site 1 analysis. The range corresponding to the location of the downwind tower (distance from lidar to the tower +/- 20 meters) during each specific test was chosen. The averaged vertical profiles of lidar data for heights from 2 to 50 meters were calculated for both background atmosphere and the plume by averaging lidar backscatter signal at specific height at specific range during the PM test. The point where vertical profiles of the dust plumes intersect with the vertical profile of the background atmosphere is considered to correspond to the maximum height of the plume.

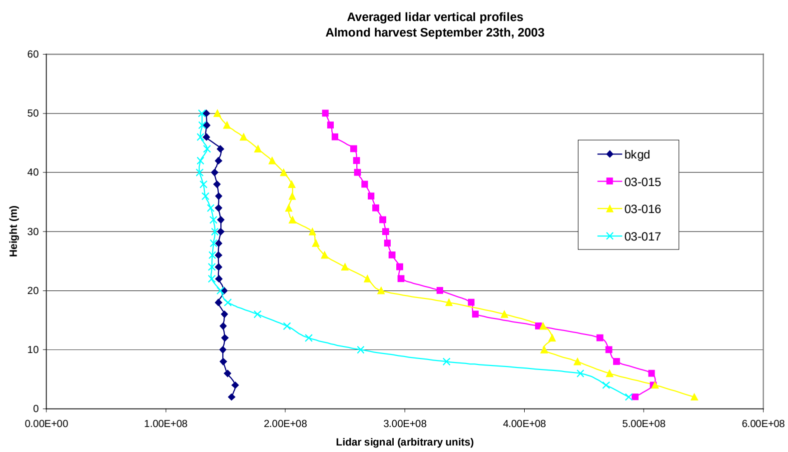

Figure 4: Background and downwind profiles of PM for conventional pick-up operations monitored at Site 5.

Figure 4 shows the averaged lidar vertical profiles obtained for tests 03-015, 03-016 and 03-017 and background scans. The background for all three tests was stable and similar, thus the averaged background is shown (Figure 4). Heights of the dust plumes generated during each test vary significantly and seem to be strongly dependent on the type of harvester used. For the conventional harvester (test 03-015) the plumes reached heights above 50 meters, for the modified harvester (test 03-016 and 03-017) the plume heights are below 50 meters (lower, about 18 meters, for test 03-017). Although the lidar data was not collected to height of the top of the plume generated in test 03-015 we can estimate the point at which the downwind concentration will return to background using a functional fit to the available data. When this is done, the plume height for test 03-015 is found to be approximately 80 m. The difference in the height of plume development between those measured in tests 03-015 and 03-016 (80 vs. 50 m) can most likely be attributed to differences in the way the conventional and modified pick-up machines generate PM_{10}. The difference between the plume heights measured in tests 03-016 and 03-017 (50 vs. 18 m) is at least partially attributable to changes in atmospheric stability.

A closer examination of the emission factors generated from the same FRM PM_{10} concentration measurements by the ISCST3 and vertical profiling methods helps quantify the relative reductions in measured PM_{10} emission factors among these tests. The ISCST3 model results show an average decrease in PM_{10} emissions of 48% due to the treatment (different pick-up machines). Those results also show a 39% decrease in PM_{10} emissions that may be due to changes in atmospheric stability (tests 03-016 vs. 03-017, Table 9). The plume shape and estimated height derived from the profiling data matched very well with the lidar results and provided quantification of the overall effect of both the treatment and the changing atmospheric conditions as producing an 86% decrease in PM_{10} emissions. So, the sum of the percentage differences measured by the ISCST3 model (87%) is approximately equal to that measured using the vertical profiling method.

Again, measurement and model were both able to show differences in PM_{10} concentrations between the conventional and modified harvester and as a result, the emissions. However, because of the specific conditions (e.g. N-S rows direction) for these tests, the results obtained cannot be compared with emission factors measured on any other orchard. We believe that improvements can be made to both the method of measuring PM_{10} concentrations and the ISCST3 dispersion model itself to customize a procedure for quantifying PM_{10} emission differences in almond orchards in a more globally applicable approach. Some changes that could be made to avoid some of the problems encountered this year and make the results more quantitative might be:

- Change the placement of the PM_{10} monitors downwind of the orchard to better approximate the source to receptor distances for which the ISCST3 dispersion model was written.
- Restrict measurements to orchards with tree rows planted east to west (in areas with predominant north winds) to avoid edge effects where the tractor turns in very close proximity to the monitors.
- Extend the sample collection period to two hours and make the length of the sample collection more consistent from test to test.

Therefore, at this point in the research, these results may serve only as qualitative information. Further work in this area is needed to accurately quantify the reduction.