Particulate Matter Emission Factors for Almond Harvesting Equipment as a Function of Speed

Project No.: **07-ENVIR10-Capareda**

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Interpretive Summary:

The 2007 field sampling campaign focused on developing emission factors for almond harvest operations as a function of the harvester ground speed. This was achieved through ambient particulate matter (PM) sampling downwind of the target operation and the use of inverse dispersion modeling to determine emission factors. Ambient sampling was conducted using total suspended particulate (TSP) samplers and federal reference method (FRM) PM_{10} samplers.

The equipment tested was a Flory Model 850 PTO Harvester. The equipment was operated at approximately 5mph for the high speed tests and approximately 2.5mph for the low speed tests. Each test included approximately 1 hour of harvest operations. Field size varied between tests based on harvester speed in order to maintain consistent test duration.

The true PM_{10} emission factors from the 2007 sampling campaign in Arbuckle are shown in Table 1. There were no statistically significant differences between models or treatments for the PM_{10} emission factors from this site.

Table 1. True PM_{10} emission factors for both treatments and models from Arbuckle.

kg/km^2	ISC		AERMOD	
	5 mph	2.5 mph	5 mph	2.5 mph
Mean	380	311	359	274
Std. Dev.	271	215	275	159
n	19	18	19	18

The true $PM_{2.5}$ emission factors from the 2007 sampling campaign in Arbuckle are shown in Table 2. Again, there were no statistically significant differences between models or treatments for the $PM_{2.5}$ emission factors from this site.

Table 2. True $PM_{2.5}$ emission factors for both treatments and models from Arbuckle.

kg/km^2	ISC		AERMOD	
	5 mph	2.5 mph	5 mph	2.5 mph
Mean	26	23	24	20
Std. Dev.	18	16	19	12
n	19	18	19	18

Analysis of variance tests of the calculated ISC and AERMOD emission factors for both PM_{10} and $PM_{2.5}$ showed no statistical difference between emission factors as a function of the model used. Therefore, previously calculated emission factors developed for almond harvesting with ISC are usable and should be directly comparable to those developed in the future with AERMOD.

The results of sampling at the Wasco site were unreliable due to high atmospheric stability (i.e. no wind) during sampling tests; in which neither ISCST3 nor AERMOD accurately characterize the movement of PM from source to receptor (Perry et al., 2005; Parnell, unpublished data). Sampling at the Wasco site occurred primarily in the afternoon and evening, when the Monin-Obukhov length was positive, indicating that the atmosphere is stable such that little vertical mixing occurs.

Objectives:

The goal of this ongoing research is to provide the most up to date data concerning PM emissions from almond harvesting. The ongoing improvement in harvester design and the introduction of management practices that may allow producers to mitigate emissions, thus proactively assisting the local air district in their efforts to improve air quality, make continuing evaluation of emissions from harvesting operations important.

The specific objectives are as follows:
1. Develop additional data to improve the almond harvest dataset that currently exists;

2. Quantify the change in emissions when a reduced harvest speed is implemented during harvest pick-up operations; and
3. Quantify the difference between emission factors developed with ISC and AERMOD to ensure accurate characterization of emissions from almond harvest operations as the EPA regulatory model changes.

Materials and Methods:

Test Site:
In 2007, sampling was conducted at orchards in Wasco and Arbuckle, which have been used for the past several years. The Arbuckle site was operated by the same cooperator used in past years. Sampling was conducted on the same orchard as the sweeping study in previous years, as well as an additional two fields owned by the cooperator. All trees were approximately the same age (9 years old) and the orchards had similar soil conditions.

Experiment Summary:
With the goal of quantifying the reduction in PM_{10} and $PM_{2.5}$ emissions as a result of a single conservation management practice, a completely randomized statistical design was employed. At each location, emissions were compared between a "standard" harvesting speed of 5 mph and an experimental harvest speed of 2.5 mph. A total of 5 tests at each speed were conducted at each location. Each test included approximately 1 hour of harvest operations with Flory Model 850 PTO Harvester. The PTO on the tractor was operated at the recommended speed for both tests, meaning that the fan and belts in the harvester were maintained at a constant speed for both tests. Field size varied between tests based on harvester speed in order to maintain consistent test duration. For each test, a maximum of four TSP concentrations and four PM_{10} concentrations were observed.

Particulate Measurement:
Particulate measurements were conducted using custom-built PM samplers with FRM inlets for $PM_{10,}$ and custom-built TSP inlets, all operating at $1m^3$/hour sampling flow rates. The airflow control units were custom-built to allow for more robust operation in harsh environments and to realize more accurate airflow measurement than is possible with standard FRM samplers. Because uncertainty in airflow measurement is the source of most of the uncertainty in PM concentrations measurements, use of these custom-built samplers significantly reduced the uncertainty in measured concentrations of PM_{10} and $PM_{2.5}$. The TSP sampler was designed to obtain the same cut point as high-volume TSP samplers designated as FRM samplers prior to implementation of the PM_{10} standard. TSP samplers were used due to the well-documented sampling bias of size-selective PM pre-separators when operated in the presence of particulate matter (PM) that is larger than the cut point of the sampler (10μm for PM_{10} sampler, 2.5μm for $PM_{2.5}$ sampler) (Buser et al., 2007). Particle size distribution (PSD) analyses were conducted on all TSP filters to determine the true PM_{10} and $PM_{2.5}$ concentrations. This allowed for the quantification of the sampling bias of the PM_{10} samplers, as well as allowing for the development of emission factors based on the true concentrations of particulate less than 10μm.

Samplers were set up to measure the net concentration change across the orchard during harvest operations. A total of 5 sampling locations were used for each test. A single upwind location was used consisting of collocated TSP and PM_{10} samplers. Four downwind sampling locations were spaced evenly across the width of the treatment area for a given test. All four downwind sampling locations consisted of collocated TSP and PM_{10} samplers. The sampler configuration is shown in Fig. 1. All orchards were configured with north south rows, requiring a southerly flow vector for all tests. When calculating downwind concentrations to be used for modeling and emission factor reporting, the upwind concentration (also assumed to be the background concentration) was always subtracted from the downwind concentration measurements to determine the contribution of the harvest operations to the measured concentration.

$PM_{2.5}$ samplers were not used for these tests because the short sampling period required for determining emission factors from almond harvesting does not lend itself to measuring the low concentrations of $PM_{2.5}$ generated by agricultural field operations. For example, during the 2006 sampling campaign (at the same orchards used in 2007) the mass median diameter (MMD) and geometric standard deviation (GSD) for PM from almond harvesting was 15.6µm and 2.2, respectively, in Wasco, and 12.8µm and 2.2, respectively, in Arbuckle. The resulting $PM_{2.5}$ as a percentage of TSP measurements was 0.9% for Wasco and 2.0% for the Arbuckle location. These concentrations, then, were well below the detection limit for the sampling equipment and protocols used in this study.

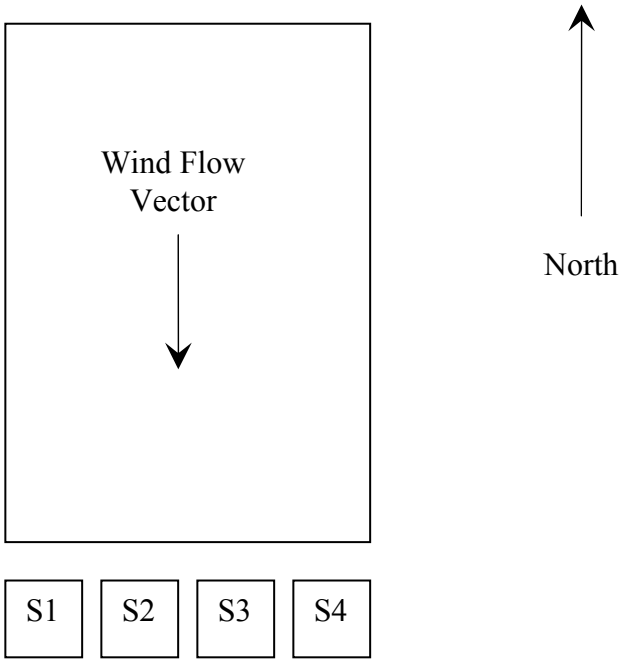

Figure 1. Sampler configuration for all tests. All prevailing winds were from a northerly direction and all orchard rows ran north-south.

Particle Size Distribution:
Due to the design of EPA FRM size-selective samplers, there is an inherent over-sampling bias when they are operated in environments that have a significant mass of PM larger than the sampler cut point (10μm for PM_{10} samplers; 2.5μm for $PM_{2.5}$ samplers). According to Buser et al. (2007), this oversampling bias can lead to over-estimation of true PM_{10} concentrations by a factor of three or more. The potential oversampling biases of $PM_{2.5}$ samplers are even greater. Therefore, particle size analyses were conducted on TSP samples to determine the true PM_{10} and $PM_{2.5}$ concentrations.

The mass distribution of most poly-disperse particles can be described by a log-normal distribution that is characterized by the mass media diameter (MMD) and geometric standard deviation (GSD) (Hinds, 1999). The PSD of the sample can then be used to determine the fraction of the measured TSP concentrations that are less than 10 and 2.5μm to determine the true concentrations of PM_{10} and $PM_{2.5}$, respectively. Furthermore, by comparing the true PM_{10} concentrations against the collocated FRM PM_{10} concentrations, the measurement bias of the FRM sampler can be determined. To determine the true PM_{10} and $PM_{2.5}$ concentrations, PSDs of TSP samples were determined using a Malvern Mastersizer 2000.

Modeling:

AERMOD
AERMOD is a steady state Gaussian dispersion model developed to model near field dispersion of pollutants from stationary industrial sources (EPA, 2004). The major improvement in AERMOD over ISCST3 is found in the incorporation of state-of-the-art relationships for flow over complex terrain, and in the ability to characterize the planetary boundary layer (PBL) under both stable and convective conditions (EPA, 2004). For air quality purposes, one is concerned with dispersion in the PBL. PBL is defined as:

…" the layer of air directly above the Earth's surface in which the effects of the surface (friction, heating, and cooling) are felt directly on time scales less than a day, and in which significant fluxes of momentum, heat or matter are carried by turbulent motions on a scale of the order of the depth of the boundary layer or less" (Garratt, 1992).

The AERMOD model architecture is comprised of two preprocessors, AERMET and AERMAP, which process standard meteorological data and terrain data, respectively, and the AERMOD dispersion model. AERMAP is used to describe the physical configuration of the model domain with regard to source-receptor orientation (i.e. source elevation and release height and receptor elevation and height above grade). AERMET is used to develop meteorological data files for use in AERMOD containing standard meteorological data (surface measurements of wind speed, wind direction, temperature, and cloud cover), as well as parameters to characterize the PBL, such as friction velocity (u_*), Monin-Obukhov length (L), convective velocity scale (w_*), temperature scale (θ_*), mixing height (z_i), and surface heat flux (H). Estimates for albedo, surface

roughness, and Bowen ratio are also input to AERMET to help calculate the PBL stability parameters. Similarity relationships are used in AERMOD with meteorological data input files from AERMET to develop vertical profiles for wind speed, lateral and turbulent fluctuations (σ_v, and σ_w respectively), potential temperature, and potential temperature gradient (EPA, 2004). As of November 2007, AERMOD replaced ISCST3 as the EPA's preferred regulatory model.

The general form of the concentration prediction equation is shown in eq. 1. In both convective and stable conditions (indicated by the c and s subscripts, respectively), the plume is contained in two plume types: 1) the horizontal plume and 2) the terrain responding plume.

$$C_t\{x_r, y_r, z_r\} = f\ C_{c,s}\{x_r, y_r, z_r\} + (1-f)\ C_{c,s}\{x_r, y_r, z_p\} \tag{1}$$

where: $C_t\{x_r, y_r, z_r\}$ represents the total concentration predicted at receptor location x_r, y_r, z_r from the horizontal plume, $C_{c,s}\{x_r, y_r, z_r\}$, and terrain following plume, $C_{c,s}\{x_r, y_r, z_p\}$. Under stable conditions, the point source dispersion equation takes the Gaussian form shown in eq. 2.

$$C_s\{x_r, y_r, z\} = \frac{Q}{\sqrt{2\pi}u\sigma_{zs}} F_y \sum_{m=-\infty}^{\infty}\left[\exp\left(-\frac{\left(z - h_{es} - 2mz_{ieff}\right)^2}{2\sigma_{zs}^2}\right) + \exp\left(-\frac{\left(z + h_{es} + 2mz_{ieff}\right)^2}{2\sigma_{zs}^2}\right)\right] \tag{2}$$

where Q is the emission rate, u is the wind speed, σ_{zs} is the total vertical dispersion coefficient (under stable conditions – s subscript), h_{es} is the plume height, and z_{ieff} is the effective mechanical mixing height. F_y accounts for the lateral meander of the plume and has the form shown in eq. 3.

$$F_y = \frac{1}{\sqrt{2\pi}\sigma_y}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y{}^2}\right) \tag{3}$$

where: σ_y is the lateral plume spread parameter evaluated at crosswind distance y.

In the convective boundary layer (CBL), the contributions from the horizontal and terrain following plumes used to calculate the total predicted concentration (eq. 1) are a consequence of three source components: the direct source, the indirect source, and the penetrated source contributions. The sum of these source contributions are used to calculate the horizontal and terrain following plume contributions (eq. 4).

$$C_c\{x_r, y_r, z_r\} = C_d\{x_r, y_r, z_r\} + C_r\{x_r, y_r, z_r\} + C_p\{x_r, y_r, z_r\} \tag{4}$$

where: C_d, C_r, and C_p are the direct, indirect, and penetrated source contributions. To calculate C_c for the terrain following plume state, "z_p" is substituted for "z_r".

The direct source contribution (C_d; eq. 5) accounts for pollutant emissions that are directly dispersed in the convective boundary layer, and are subsequently transported toward ground based receptors.

$$C_d\{x_r, y_r, z\} = \frac{Qf}{\sqrt{2\pi}u} F_y \sum_{j=1}^{2} \sum_{m=0}^{\infty} \frac{\lambda_j}{\sigma_{z,j}} \left[\exp\left(-\frac{\left(z + \psi_{dj} - 2mz_i\right)^2}{2\sigma_{zj}^2} \right) + \exp\left(-\frac{\left(z - \psi_{dj} + 2mz_i\right)^2}{2\sigma_{zj}^2} \right) \right] \quad (5)$$

where: λ is the distribution weighting coefficient and Ψ is the effective source height.

The indirect source contribution (C_r; eq. 6) is the portion of the plume reflected by the surface between the stable upper boundary layer and the mixed boundary layer at the mixing height of the convective boundary layer. The portion of the indirect plume not reflected back toward the ground is assumed to penetrate to the stable upper layer.

$$C_r\{x_r, y_r, z\} = \frac{Qf}{\sqrt{2\pi}u} F_y \sum_{j=1}^{2} \sum_{m=1}^{\infty} \frac{\lambda_j}{\sigma_{z,j}} \left[\exp\left(-\frac{\left(z + \psi_{rj} - 2mz_i\right)^2}{2\sigma_{zj}^2} \right) + \exp\left(-\frac{\left(z - \psi_{rj} + 2mz_i\right)^2}{2\sigma_{zj}^2} \right) \right] \quad (6)$$

The penetrated source contribution (C_p; eq. 7) accounts for the portion of the plume that initially penetrates the CBL above z_i, and is subsequently re-entrained by and dispersed in the CBL.

$$C_p\{x_r, y_r, z\} = \frac{Q(1-f)}{\sqrt{2\pi}u\sigma_{zp}} F_y \sum_{m=-\infty}^{\infty} \left[\exp\left(-\frac{\left(z - h_{ep} - 2mz_{ieff}\right)^2}{2\sigma_{zp}^2} \right) + \exp\left(-\frac{\left(z + h_{ep} + 2mz_{ieff}\right)^2}{2\sigma_{zp}^2} \right) \right] \quad (7)$$

ISCST3

ISCST3 is a Gaussian dispersion model that uses the normal (Gaussian) distribution to describe the horizontal and vertical dispersion of a pollutant downwind from the source. The pollutant concentration estimated by ISCST3 at a downwind receptor is influenced by meteorological factors (wind direction, wind speed, temperature, etc.), source emission characteristics (emission height, emission temperature, emission velocity, etc.), and receptor characteristics (receptor height and distance from source to receptor). State Air Pollution Regulatory Agencies have used ISCST3 in New Source Review permitting processes to determine off property concentrations resulting from emissions from the facility seeking the permit.

The Gaussian dispersion equation for a single point source is shown in eq. 8.

$$C_M = \frac{ER_{TSP}}{2\pi u\sigma_y\sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y{}^2} \right) \left\{ \exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z{}^2} \right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z{}^2} \right) \right\} \quad (8)$$

where: C_M is the time average steady state concentration at a point (x, y, z) (μg/m^3); u is average wind speed at stack height (m/s); y is the horizontal distance from plume centerline (m); z is the height of receptor with respect to ground (m); H is the effective stack height (H=h+Δh, where h is the physical stack height and Δh is the plume rise)(m); and σ_y and σ_z are the horizontal and vertical plume dispersion coefficients (m), respectively.

The area source algorithm in ISCST3 utilizes a numerical integration of eq. 8 in the upwind and crosswind directions to determine receptor concentrations. In this case, eq. 8 takes the form shown in eq. 9, and the sum of the concentration contributions from all integrated line sources is used to predict the pollutant concentration at the receptor.

$$C_M = \frac{q}{2\pi u \sigma_y \sigma_z}\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^{\,2}}\right)+\exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^{\,2}}\right)\right\}\int_{y_1}^{y_2}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^{\,2}}\right)dy \qquad (9)$$

where: q is the area source flux (g/m^2-s). ISCST3 solves the equation shown in eq. 9 using a trapezoidal approximation.

Results and Discussion:

Measured Concentrations:

Concentrations of both TSP and PM_{10} were measured during all tests at the four downwind locations and one upwind location. Table 3 shows the net concentration measurements for the TSP and FRM PM_{10} samplers during the Arbuckle and Wasco sampling campaigns. The large standard deviations in the measured TSP and PM_{10} concentrations reflect the many uncontrollable variables that affect concentration measurements. No statistical differences in measured concentrations were detected between treatments (α = 0.05) at Arbuckle. At Wasco, The measured concentrations of TSP were significantly different (p = 0.041) while no differences were detected between FRM PM_{10} concentrations. However, differences in downwind concentrations of PM do not necessarily reflect differences in emission factors.

Table 3. Average net measured TSP and FRM PM_{10} concentrations.

ug/m^3	5 mph		2.5 mph	
	TSP	FRM PM_{10}	TSP	FRM PM_{10}
Arbuckle				
Mean	1110	422	680	317
Std. Dev.	689	185	769	290
n	19	17	18	18
Wasco				
Mean	1371	455	3993	1687
Std. Dev.	683	227	4158	2283
n	12	11	15	16

Particle Size Distributions:

Particle size distribution analyses were conducted on all TSP filters, and the PSD fit with a log-normal distribution. The average MMDs and GSDs of the distributions from the Arbuckle and Wasco filters are shown in Table 4, along with the percentage of PM that is $PM_{2.5}$ and PM_{10}, respectively, and the $PM_{2.5}$ to PM_{10} ratio.

Table 4. Particle size distribution parameters from TSP filters.

Speed	MMD (um)	GSD	PM_{10} (%)	$PM_{2.5}$ (%)	$PM_{2.5}/PM_{10}$ (%)
Arbuckle					
5 mph	14.3	2.4	34	2	7
2.5 mph	11.0	2.2	45	3	7
Wasco					
5 mph	12.0	2.0	39.7	1.2	2.9
2.5 mph	11.4	1.9	43.4	1.1	2.4

The true PM_{10} and $PM_{2.5}$ concentrations can be calculated by multiplying the TSP concentrations by the fraction of PM less than 10 and 2.5µm, respectively. The average true PM_{10} and $PM_{2.5}$ concentrations from the Arbuckle and Wasco sites are shown in Table 5. No statistical differences were detected between treatments in the true concentrations of PM_{10} or $PM_{2.5}$ at the Arbuckle site. Again, differences in concentrations do not necessarily reflect differences in emission factors. The true PM_{10} concentrations were lower than those measured by the FRM PM_{10} samplers due to the oversampling bias of FRM samplers reported by Buser et al. (2007).

Table 5. True PM_{10}, and $PM_{2.5}$ concentrations.

ug/m^3	5 mph		2.5 mph	
	True PM_{10}	True $PM_{2.5}$	True PM_{10}	True $PM_{2.5}$
Arbuckle				
Mean	379	26	307	10
Std. Dev.	235	16	347	10
Wasco				
Mean	784	23	2448	63
Std. Dev.	235	8	2566	66

A comparison of the average true PM_{10} concentration from Arbuckle (Table 5) and the average FRM PM_{10} concentration for the same tests (Table 3) show a bias in the FRM sampler concentrations of approximately 11% for the 5 mph tests and 3.3% for the 2.5 mph tests. The differences in sampler bias between tests reflect the increased bias reported by Buser et al (2007) as the MMD of sampled PM increases above the sampler

cut point. The greater error in samples with larger MMDs is a direct function of the biases associated with the design of FRM samplers.

Emission Factors:

Emission factors were developed using both ISCST3 and AERMOD for the Arbuckle site. Emission factors from the Wasco site are not reported because the Monin-Obukhov length, which measures the height above the ground at which the production of turbulence by both mechanical and buoyancy forces is equal, during most of the tests at Wasco tests was positive, indicating stable atmospheric conditions. Under stable atmospheric conditions, very little pollutant dispersion occurs, and the neither ISCST3 nor AERMOD accurately characterize the movement of PM from source to receptor (Perry et al, 2005; Parnell, unpublished data). At the Arbuckle site, the Monin-Obukhov length was negative during all tests, indicating an unstable atmosphere in which ISC and AERMOD perform much better. For the Arbuckle site, four emission factors were developed for each speed with each model: a TSP emission factor, an FRM PM_{10} emission factor, a true PM_{10} emission factor, and a true $PM_{2.5}$ emission factor. Emission factors reported below were calculated by multiplying the results of modeling analyses by two to account for the harvest of both Non-Pareil and other varieties in any given year. Therefore, reported emission factors are on an annual basis rather than a per-harvest basis.

The TSP emission factors from both models for both harvester speed treatments are shown in Table 6. The TSP emission factor for harvesting at the "standard" speed of 5 mph was 1,117 kg/km^2 when using ISC or 1,057 kg/km^2 when using AERMOD. These emission factors were not statistically different (α=0.05), nor were the emission factors for the 2.5 mph harvester speed. That the emission factors developed using both ISC and AERMOD were not statistically different is an important finding in that the previous emission factors for almond harvest operations developed using ISC should produce comparable results when used in AERMOD under the same meteorological conditions. Previously, a direct comparison between emission factors from these models was not possible due to the lack of the on-site meteorological data required for accurate AERMOD dispersion modeling analysis.

Table 6. Annual TSP emission factors from Arbuckle for both models and treatments.

kg/km^2/yr	ISC		AERMOD	
	5 mph	2.5 mph	5 mph	2.5 mph
Mean	1117	691	1057	609
Std. Dev.	798	477	809	352
n	19	18	19	18

Differences were detected in AERMOD TSP emission factors between harvester speed treatments ($p = 0.038$). The TSP emission factor for the 2.5 mph harvester speed was approximately 42% lower than the TSP emission factor for the standard treatment. However, reductions in TSP emissions do not necessarily translate into reductions in PM_{10} and/or $PM_{2.5}$ emissions.

The true PM_{10} emission factors for Arbuckle are presented in Table 7. These emission factors were calculated for both models using PM_{10} concentrations as determined through the use of the PSDs and the measured TSP concentrations. Due to the differences in the PSDs between treatments presented in Table 4, the differences in TSP emission factors did not translate into differences in PM_{10} emission factors. No statistical differences were detected in PM_{10} emission factors for almond harvest between models or between treatments ($\alpha = 0.05$).

Table 7. True PM_{10} emission factors from Arbuckle for both models and treatments.

kg/km^2/yr	ISC		AERMOD	
	5 mph	2.5 mph	5 mph	2.5 mph
Mean	380	311	359	274
Std. Dev.	271	215	275	159
n	19	18	19	18

Emission factors from FRM PM_{10} concentrations at Arbuckle calculated using both ISC and AERMOD are shown in Table 8. No statistical differences were detected in FRM PM_{10} emission factors for almond harvest between models or between treatments ($\alpha = 0.05$).

Table 8. Annual FRM PM_{10} emission factors from Arbuckle for both models and treatments.

kg/km^2/yr	ISC		AERMOD	
	5 mph	2.5 mph	5 mph	2.5 mph
Mean	413	329	400	324
Std. Dev.	205	211	229	340
n	17	18	17	18

The true $PM_{2.5}$ emission factors for Arbuckle are presented in Table 9. These emission factors were calculated for both models using $PM_{2.5}$ concentrations as determined through the use of the PSDs and the measured TSP concentrations. Like the PM_{10} emission factors, due to the differences in the PSDs between treatments presented in Table 4, the differences in TSP emission factors did not translate into differences in $PM_{2.5}$ emission factors. No statistical differences were detected in $PM_{2.5}$ emission factors for almond harvest between models or between treatments ($\alpha = 0.05$).

Table 9. Annual true PM_{10} emission factors from Arbuckle for both models and treatments.

kg/km^2/yr	ISC		AERMOD	
	5 mph	2.5 mph	5 mph	2.5 mph
Mean	26	23	24	20
Std. Dev.	18	16	19	12
n	19	18	19	18

AERMOD was adopted to replace ISC as the preferred regulatory model. However, the results of the modeling for this analysis show no significant differences between the two models for the specific meteorological conditions observed in 2007. The failure to detect statistical differences is not due to any confounding affects of the measured concentrations because the concentrations were applied similarly to both models throughout the analysis. A regression analysis between all TSP emission factors derived from ISC and AERMOD (Fig. 2) shows a shows a strong correlation (R^2 = 0.901) between ISC and AERMOD emission factors for the observed conditions, with AERMOD emission factors being 0.913 times the ISC emission factors. An analysis of the regression shows that the 95% confidence interval on the slope spans from 0.810 to 1.02, and the constant (8.342) is not statistically different than zero ($\alpha = 0.05$). Because the confidence interval of the slope includes 1.0 and the value of the constant is not statistically different than zero, there is no significant difference ($\alpha = 0.05$) in the two models in this analysis.

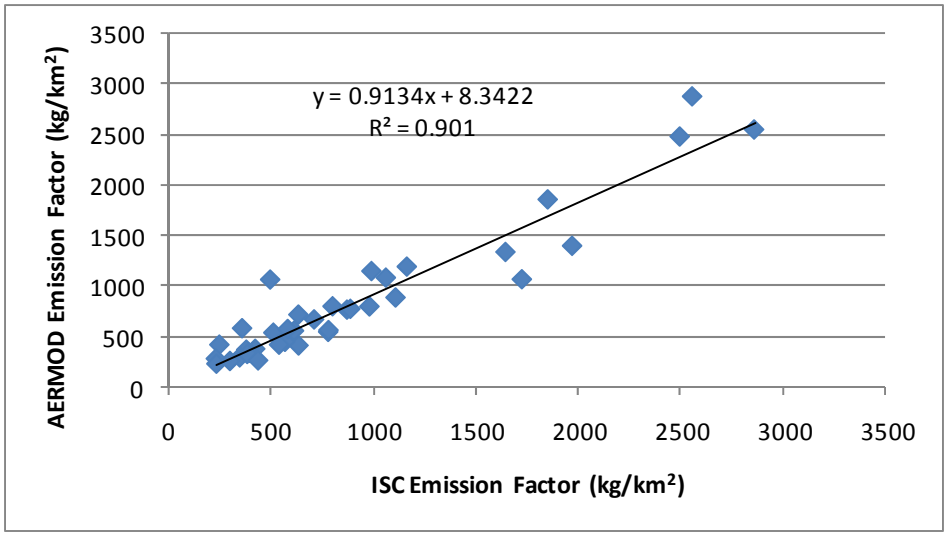

Figure 2. Regression analysis of ISC and AERMOD TSP emission factors. The slope of the regression is not statistically different from 1.0 and the regression constant is not statistically different than zero, indicating no significant difference in the models ($\alpha = 0.05$).

Conclusions:

The results from the 2007 sampling campaign showed no difference in the emissions of PM10 and PM2.5 from almond harvesters when the speed is reduced from 5 to 2.5 mph. There was a significant difference in the emissions of TSP, which may have benefits for reducing visibility impairment but not for reducing emissions of regulated pollutants. The reasons behind differences in particle size for different treatments are not known at this time.

Additionally, no differences were detected in the emission factors calculated from measured concentrations using ISCST3 and AERMOD, indicating that almond harvest emission factors previously developed using ISC can be safely used in AERMOD. While many studies have shown a difference in the modeled concentrations between

AERMOD and ISC, no differences were detected for the meteorological conditions observed during this sampling campaign. The lack of difference in models is likely due to the short-term, daytime observations used in this research. Typically dispersion models are used to predict hourly concentrations for every hour of the day, including day time and night time. This research consisted of sampling that only took place during the day, limiting some of the meteorological variation that occurs during when 24-hour modeling is conducted.

Recent Publications:

Capareda, S.C., Goodrich, L.B., C.B. Parnell, Jr. and C. Krauter. 2007. Dust Emission Factors from Almond Harvesting. Technical Presentation at the 35th Almond Industry Conference held from December 5-6, 2007 at Modesto, California Sponsored by the Almond Board of California.

Goodrich, L. B., S. C. Capareda, C. Krauter and W.B. Faulkner. 2008. Particulate Matter Emission Factors from Almond Sweeping and Reduced Pass Almond Sweeping. Technical Paper for submission to *Transactions of the ASABE*, American Society of Agricultural and Biological Engineers, St. Joseph, MI.

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Appendices:

Appendix A. Graph of PM Oversampling

As in previous years, the oversampling bias of FRM PM_{10} samplers in the presence of PM with an MMD greater than 10µm was evident during the 2007 almond harvest sampling campaign (Fig. A1).

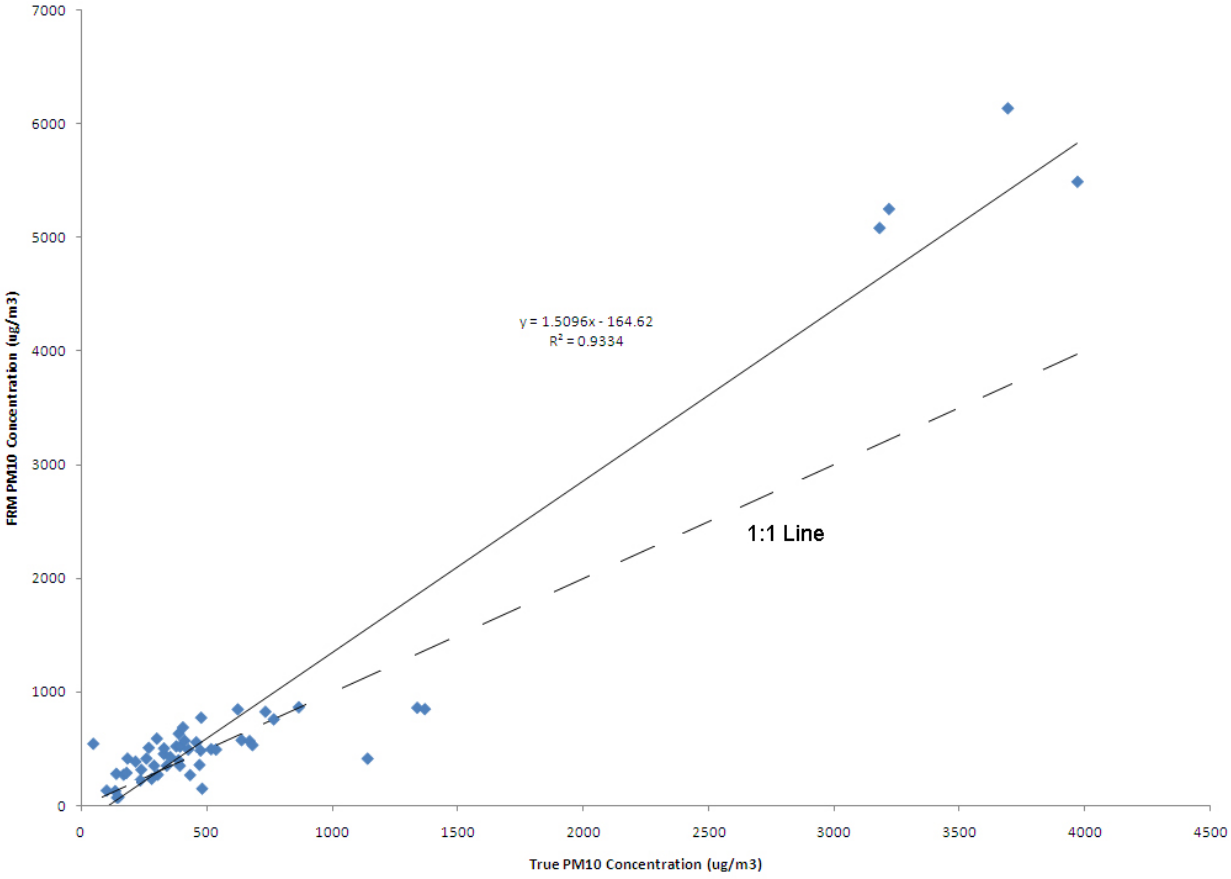

Figure A1. Regression analysis of PM_{10} concentrations measured using FRM PM_{10} samplers versus true PM_{10} concentations.

Appendix B. Raw Data for the Wasco Sampling Event

Table B1. Raw data for Wasco sampling event.

Test	Sampler	Measured Conc. ($\mu g/m^3$)
12 (5 mph)	S1PM10	222.9
	S1TSP	914.5
	S2PM10	289.6
	S2TSP	835.8
	S3PM10	456.0
	S3TSP	1187.6
	S4PM10	352.3
	S4TSP	971.4
	UWPM10	127.9
	UWTSP	254.0
13 (2.5 mph)	S1PM10	310.7
	S1TSP	969.6
	S2PM10	523.1
	S2TSP	1397.5
	S3PM10	689.5
	S3TSP	2008.4
	S4PM10	400.4
	S4TSP	2209.0
	UWPM10	5.6
	UWTSP	95.8
14 (2.5 mph)	S1PM10	5084.8
	S1TSP	9197.5
	S2PM10	5491.7
	S2TSP	9944.3
	S3PM10	6137.9
	S3TSP	10873.8
	S4PM10	5251.9
	S4TSP	12216.5
	UWPM10	5.6
	UWTSP	95.8
15 (5mph)	S1PM10	494.3
	S1TSP	1156.9
	S2PM10	90.9
	S2TSP	733.2
	S3PM10	416.0
	S3TSP	722.5
	S4PM10	No data
	S4TSP	979.1
	UWPM10	181.4
	UWTSP	477.5

Table B1 continued.

16 (2.5 mph)	S1PM10	150.4
	S1TSP	1690.9
	S2PM10	273.2
	S2TSP	1361.7
	S3PM10	539.1
	S3TSP	Invalid data
	S4PM10	74.4
	S4TSP	853.1
	UWPM10	71.7
	UWTSP	187.9
17 (5 mph)	S1PM10	428.6
	S1TSP	2101.6
	S2PM10	848.5
	S2TSP	2784.8
	S3PM10	775.1
	S3TSP	2060.0
	S4PM10	634.4
	S4TSP	2009.1
	UWPM10	71.7
	UWTSP	187.9
18 (2.5 mph)	S1PM10	558.3
	S1TSP	1720.3
	S2PM10	573.4
	S2TSP	2083.3
	S3PM10	521.0
	S3TSP	1532.5
	S4PM10	415.0
	S4TSP	1848.7
	UWPM10	71.7
	UWTSP	187.9

Appendix C. Copy of Technical Paper for Submission to a Technical Journal.

Goodrich, L.B., S.C. Capareda, C. Krauter and W.B. Faulkner. 2008. Particulate Matter Emission Factors from Almond Sweeping and Reduced Pass Almond Sweeping. Technical Paper for submission to *Transactions of the ASABE*. American Society of Agricultural and Biological Engineers, St. Joseph, MI.

Particulate Matter Emission Factors From Almond Sweeping and Reduced Pass Almond Sweeping

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Abstract. *Almond harvest accounts for a significant amount of PM_{10} emissions in California each harvest season. This paper addresses the reduction of blower-passes during the harvest from 3 to 1 as a possible mitigation measure. Ambient total suspended particulate and PM_{10} sampling was conducted at two orchards during harvest with alternating control and experimental treatments. On-site meteorological data was used in conjunction with inverse dispersion modeling using Industrial Source Complex-Short Term version 3 to develop emission rates from the measured concentrations. A baseline emission factor of 379±209 kg/km^2 was determined, and an emissions reduction of 49% was achieved by the experimental treatment, representing a significant potential for emissions reduction across the entire state. The harvest efficiency was also measured to determine the possible financial impacts from a crop removal aspect. The results of the harvest efficiency work were variable and depend on the conditions of the orchard floor.*

Keywords. *PM_{10}, TSP, almond harvest, inverse dispersion modeling, mitigation measures*

Introduction

California almond farmers produce 80% of the world's almond supply. In 2006, approximately 497Tg of almonds were harvested in California on approximately 240,800 bearing hectares with a total value of $2.2 billion (USDA, 2007). Over 70% (169,200 ha) of the bearing crop is located within the San Joaquin Valley Air Pollution Control District's (SJVAPCD) region. Due to the classification of the San Joaquin Valley (SJV) as a serious non attainment area for PM_{10}, the SJVAPCD has begun an aggressive campaign to reduce PM_{10} emissions from all sources. With the recent removal of the permitting exemption from agriculture, it has become a target of scrutiny. The SJVAPCD has found that the available information on emission factors for agricultural operations is severely limited and needs improvement.

The current emission factor for applied to all almond harvesting operations is 4,570 kg PM_{10}/km^2 (CARB, 2003), accounting for 11Gg of PM_{10} each year. The almond harvest emission factor is composed of the sum of the emission factors for the three different harvest operations: shaking, sweeping and pickup. First, the trees are shaken to remove the product from the tree allowing it to air dry sitting on the ground; this accounts for 41.5 kg PM_{10}/km^2 of the emission factor. A few days later, after the crop has dried, the sweepers enter the field and sweep the almonds into windrows, currently accounting for 415 kg PM_{10}/km^2. Finally, the pickup machines remove the product from the field, currently accounting for 4,120 kg PM_{10}/km^2. Each harvest process accounts for significant emissions due to the total area to which the emission factors are applied. The objectives of this study are as follows:

1. Quantify the possible emission reductions achieved through the use of reduced blower-passes during sweeping operations;

2. Quantify the amount of crop left in the field due to the reduction in blower-passes;

3. Propose improvements to the current baseline emission factor for standard sweeping operations by expanding the dataset used for its development.

Almond Harvesting

This research focuses on the sweeping operation of harvesting. Sweeping was targeted due to the wide range of operational characteristics employed by various operators. The sweeping operation consists of a purpose-made vehicle (sweeper) that travels up and down the rows between trees sweeping the almonds into windrows between the trees for later pickup. The sweeper used in this work had a 2.29m-wide head that swept the almonds to the right as the machine traveled. This head moves the crop from near the tree to the middle of the row between trees. The sweeper also had a blower on the back end of the equipment that pointed to the left. As the sweeper travels down the tree row, any nuts that were not swept into the windrow on the right side of the machine were blown to the other side of the tree row to be swept into the windrow on that side of the trees. The sweeper machine is designed to operate in one of two modes during all passes, sweeper only (sweeper passes) or sweeper and blower (blower passes). The traditional sweeping patter used for the development of the CARB emission factor used a six pass treatment for each harvested row of almonds. The six passes consisted of three blower passes and three sweeper passes. To achieve the goal of the research and maximize the difference between treatments the experimental treatment was defined as having four total passes and was achieved by eliminating two of the blower passes.

During sweeping the travel speed varies depending on the type of pass being made. Sweeper-only passes were conducted with a ground speed between 1.3m/s and 1.6m/s (3.0-3.5mph). Passes made with both the blower and sweeper was made at approximately 0.9m/s (2.0mph). The reduction in passes increased the average travel speed of the sweeper resulting in a greater swept area per unit time resulting in a possible costs savings to the producer.

Almonds are typically planted in alternating varieties by row. The various varieties mature at different times resulting in multiple harvests for each field. The fields sampled for this research were harvested at two different times, each harvest accounting for half the total field or every

other row. However, the harvest process is identical for the alternating rows that mature later in the season. For this reason, the emission rate developed from the sampling represents only half the total emissions from harvest operations.

Emission Factor Development

Emission factor development consisted of measuring the net PM_{10} concentration increase between samplers located upwind and downwind of the harvested area. The increase in concentration was attributed solely to the harvest activity thus eliminating any external influences. This was accomplished by placing samplers upwind and downwind of the area of interest to measure the ambient particulate matter (PM) concentrations. It is assumed that the difference in concentration is solely attributable to the activity of interest, in this case, sweeping operations.

During concentration measurements, the wind speed, direction, temperature, relative humidity, barometric pressure, and solar radiation were measured on 5-minute intervals. The dimensions of each test plot and corresponding meteorological data were then used with Industrial Source Complex-Short Term version 3 (ISC-STv3) to determine a flux ($\mu g/m^2$-s) for the given sampling period.

Ambient Sampling

Due to the errors associated with federal reference method (FRM) sampling in agricultural environments identified by Buser et al. (2007), both total suspended particulate (TSP) measurements and PM_{10} measurements were conducted. TSP measurements were conducted with samplers designed by Wanjura et al. (2005). PM_{10} measurements were conducted using the same air-flow control unit as the TSP samplers and an FRM PM_{10} sampling inlet. To correct for the errors associated with the FRM samplers, a particle size distribution (PSD) analysis was conducted on the TSP filters after the filters were post-weighed according to the protocol specified in Faulkner and Shaw (2006) with the exception that the entire filter was analyzed rather than core samples. The resulting PSD was then used to determine the true percentage of PM_{10} on each filter. The ratio of true PM_{10} to TSP was used to develop PM_{10} emission factors. Each test was conducted with an identical sampler layout as it relates to the swept area. To maximize the available orchard area for sampling, the duration of each test was between 60-150 minutes. The variation in time was due to the desire to cover similar areas for replicated tests. After it was determined by visual inspection that sufficient mass was being collected on the TSP filters, the treatment area was decreased to obtain a larger number of tests within the remaining orchard, resulting in shorter tests.

For each test, one upwind and four downwind sampling locations were utilized. All sampling locations consisted of one TSP sampler and one PM_{10} sampler. Additionally a $PM_{2.5}$ sampler was collocated at the upwind sampling location and one downwind sampling location. The upwind sampler did not move at each sampling location because it was placed to sample ambient conditions in the area. The downwind samplers were spaced evenly across the downwind edge of the treatment area for each test. The samplers were placed such that there was enough room for the sweeper to make turns and remain upwind of the sampler array. The four downwind samplers provide four independent measurements of concentration leading to four independent estimates of the flux for each test.

Industrial Source Complex

ISC-STv3 is a steady state Gaussian plume model that can be used to predict downwind concentration from area sources (EPA, 1995). ISC-STv3 is used to calculate 1-hr average concentrations at receptor locations placed anywhere around a source. The inputs for the model include the relative placement of sources and receptor locations, as well as meteorological conditions and emission fluxes. The equation that ISC-STv3 uses as the basis for all other calculations is a double Gaussian algorithm that represents a point source (eq. 1).

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(H-z)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(H+z)^2}{2\sigma_z^2}\right]\right\} \quad (1)$$

where:

C = predicted concentration ($\mu g/m^3$);
Q = emission rate ($\mu g/s$);
u = wind speed at the point of emissions release (m/s);
σ_y = Pasquill-Gifford horizontal plume spread parameter based on stability class (m);
σ_z = Pasquill-Gifford vertical plume spread parameters based on stability class (m);
H = height of plume release (m);
y = crosswind distance from source to receptor (m); and
z = height of receptor for concentration prediction (m).

Each input to ISC-STv3 is either measured in the field or are calculated from measured values. The Pasquill-Gifford dispersion parameters are calculated based on the atmospheric stability class. The stability class is determined using wind speed and incoming solar radiation during the time of interest. The stability class is then used to determine the coefficients used to calculate the plume spread parameters.

Emission Factor Calculations

An emission factor is a representative value that attempts to relate the quantity of pollutant released to the atmosphere with an activity associated with release of the pollutant (EPA, 1995). As applied to almond harvesting, the pollutant in question is PM_{10} or $PM_{2.5}$ and the activities are shaking, sweeping and pick-up operations. The factors are usually expressed as the weight of the pollutant divided by a unit weight, volume, distance, area or duration of the activity resulting in pollutant emissions. For the almond harvest operation, the emission factor is expressed in mass of pollutant per unit of area harvested.

The result of dispersion modeling is a unit flux concentration (UFC) for each test. This is acquired by using the actual conditions measured during the test in conjunction with the orchard and sampler configuration in the model. The model is executed using a flux of $1 \mu g/m^2$-s to predict a concentration at each of the four sampling locations. The predicted flux at each location is called the UFC. The UFC represents the change in predicted concentration for each unit increase of flux in the model. To obtain the estimated flux from the sweeping operation, the measured concentration at each sampling location is divided by the UFC at the corresponding sampling location resulting in the flux required to match the measured concentration (eq. 2).

This process produces an estimate of the flux for each sampling location during each test.

$$\frac{C_m}{UFC} = F \qquad (2)$$

where:

C_m = measured concentration ($\mu g/m^3$);
UFC= unit flux concentration; and
F = pollutant emission flux ($\mu g/m^2$-s).

The emission flux ($\mu g/m^2/s$) calculated by ISC-STv3 can be easily converted into units of $kg/m^2/hr$. Thus, the formula to estimate the emission factor when the emission flux is known is given in eq. 3.

$$EF\ (kg/km^2) = ER\ (kg/m^2/hr)\ X\ Time\ of\ sampling\ (hrs) \qquad (3)$$

It is implied that if one is using the same area for an operation, the emission factor is the sum of the pollutant emissions after the completion of all harvesting activities (shaking, sweeping and pick-up) in a given year or season. Note that the unit of area is the area bounded by the extent of the sweeping operation for a given test. Almond growers commonly plant a combination of almond varieties in a given area to achieve cross pollination. The usual combination is a NonPareil variety with another variety or a NonPareil with two other varieties, such as Carmel and Butte, in each orchard. The NonPareil varieties are normally planted every other row with the other varieties planted on an alternating basis, but during the harvesting of one variety, all windrows are used for the pickup operation, virtually using the whole area for the harvest process. The overall emission factor is the sum of the two harvesting operations for each variety. In an orchard that is harvested twice, the pick up operation for the second harvest period is identical to that of the first. There is no reason to expect that each of the harvest operations would result in significantly different emission factors, so the emission rate is simply doubled to yield the seasonal total emission factor.

Harvest Efficiency

Due to the reduced number of blower-passes made with this work there were more almonds left in the field that were not successfully swept into windrows. These almonds were considered lost product that would not be picked up and represent a loss to the producer. Within the test plots, five replicate sample areas were chosen in a diagonal matrix across the plot. The sample area consisted of the area between 4 trees. All nuts that were left more than 0.3048m (1ft.) from the windrow were considered non-harvestable. These nuts were collected after sweeping in sealed plastic bags and weighed. It was assumed that 25% of the nut would be almond meat.

Site Description

Sampling was conducted in the southern SJV (site 1) and the Sacramento Valley (site 2). This provided geographical variation in the results that could be used to determine if the results were applicable to a wider area. Trees at Site 1 were approximately eight years old at the time of sampling. Site 1 consisted of a sandy loam soil with 13% clay. The average soil moisture content of the berm was 7% dry basis (db) and the between-row moisture content was $6\%_{db}$. Site 1 was irrigated using micro emitters and had a small raised berm running the length of the field on which the trees were planted. The berm and between row moisture content were quantified

independently because these orchards only applied irrigation water to the berm area in order to maximize water efficiency. This site also had significant quantities of loose soil on the surface that was freely moved by the sweeper with the almonds during the operations. Site 2, in the Sacramento Valley, also had trees that were eight years old at the time of sampling. Site 2 consisted of a Hillgate loam with 19% clay. The average moisture content of the berm at site 2 was 7%$_{db}$ and the between row moisture content was 3%$_{db}$. Site 2 was irrigated using surface drip tubing and had virtually no berm in the tree rows. This site did not have significant amounts of loose soil on the surface and there was very high compaction in the orchard providing for less chance of entrainment. All orchards were oriented north-south with a prevailing southerly flow vector.

Emission factors for each sampling location were developed for TSP, FRM PM_{10} and true PM_{10}. The results were analyzed separately based on the sampling site to see if there was any effect due to the different conditions at each orchard.

Results and Discussion

TSP particulate concentrations during the Site 1 sampling campaign are presented in Table 1. All downwind concentration measurements exceeded upwind measurements as expected. Test 6 produced the highest concentration measurements. The grand mean downwind concentration measurement was 916μg/m^3 and the grand mean upwind concentration was 251μg/m^3 representing an average increase in TSP across the sampling area of 665 μg/m^3 TSP. All sampling tests lasted less than 2.5 hours. Test 1 for Site 1 was discarded due to an extremely short sampling period.

Table 1. Measured TSP concentrations for Site 1 (μg/m^3).

	Test						
Location	2	3	4	5	6	7	8
UW	137	126	126	316	745	153	153
S1	1131	352	449	1053	3265	374	401
S2	650	369	832	619	2556	668	566
S3	456	346	950	947	3332	735	422
S4	335	329	1018	1304	1324	514	350

Site 2 concentrations are presented in Table 2. All seven tests were successful from a particulate measurement stand point. The filter at sampler location S3 for Test 3 was dropped during sampling and is therefore invalid and not reported. The upwind filters were not changed between samples two and three resulting in the same upwind concentration for both. The same was done for Tests 4 and 5, and then again for Tests 6 and 7. The grand mean upwind TSP concentration was 111μg/m^3 and the mean downwind TSP concentration was 724μg/m^3 representing an average increase in TSP concentrations across the orchard of 613μg/m^3. Concentrations were measured over a time period of 1.5 to 2.5 hours.

Table 2. Measured TSP concentrations for site 2. (μg/m^3)

μg/m^3	Test #						
Location	1	2	3	4	5	6	7
UW	57	209	209	105	105	72	72
S1	1556	879	663	2407	750	910	496
S2	491	963	131	597	701	853	125
S3	773	967	N/A	590	872	638	90
S4	769	593	577	479	900	700	78

A substantial difference in the upwind concentration measurements at each location was observed. Site 1 was in the southern SJV and has frequently exceeded the National Ambient Air Quality Standards for PM_{10}. Site 2 was north of Sacramento in an area that has relatively few problems with exceedances of the National Ambient Air Quality Standards.

Particle Size Distributions

Particle size distribution analyses were completed for all TSP filters with satisfactory loading, and the resulting mass median diameter (MMD) and geometric standard deviation (GSD) were used to calculate the percent of mass less than 10- and 2.5-μm on each filter assuming a log-normal PSD. This value was then used to determine the true PM_{10} and $PM_{2.5}$ concentrations. The average MMD for Site 1 was 15.6μm with a GSD of 2.2. The resulting PM_{10} percentage was 28%. Therefore, the TSP emission factor for Site 1 was multiplied by 28% to achieve the PM_{10} emission factor. For Site 2 the average MMD was 12.8μm and the GSD was 2.2. Therefore the resulting PM_{10} percentage of the measured TSP value was 38%. The previously reported MMD and GSD recorded for sweeping was 12.8μm with a GSD of 1.9 Flocchini, et al. (2005). For Site 1, 0.9% of the TSP concentration was $PM_{2.5}$, while, for Site 2, 2.0% of the TSP concentration was $PM_{2.5}$.The PSD coefficients for each sampling location as well as the mass fraction in each size range are shown in Table 3.

Table 3. Particle size distribution parameters for both sampling sites.

Location	MMD	GSD	True PM_{10} %	True $PM_{2.5}$ %
Site 1	15.57	2.17	28	0.9
Site 2	12.81	2.21	38	2

The MMD values for each sampling site are different, but the resulting scatter plot of FRM measured PM_{10} versus true PM_{10} shows statistically similar results. Therefore the scatter plot and regression for both sampling locations are combined (fig. 1). The true PM_{10} value is 85% of the value measured using FRM PM_{10} samplers representing an over sampling rate of 17%. The measured emission factors would erroneously be 17% higher if only the FRM PM_{10} samplers were used. The difference in measured PSDs between the locations is not surprising as the significantly different soil types between locations resulted in different parent material for entrainment.

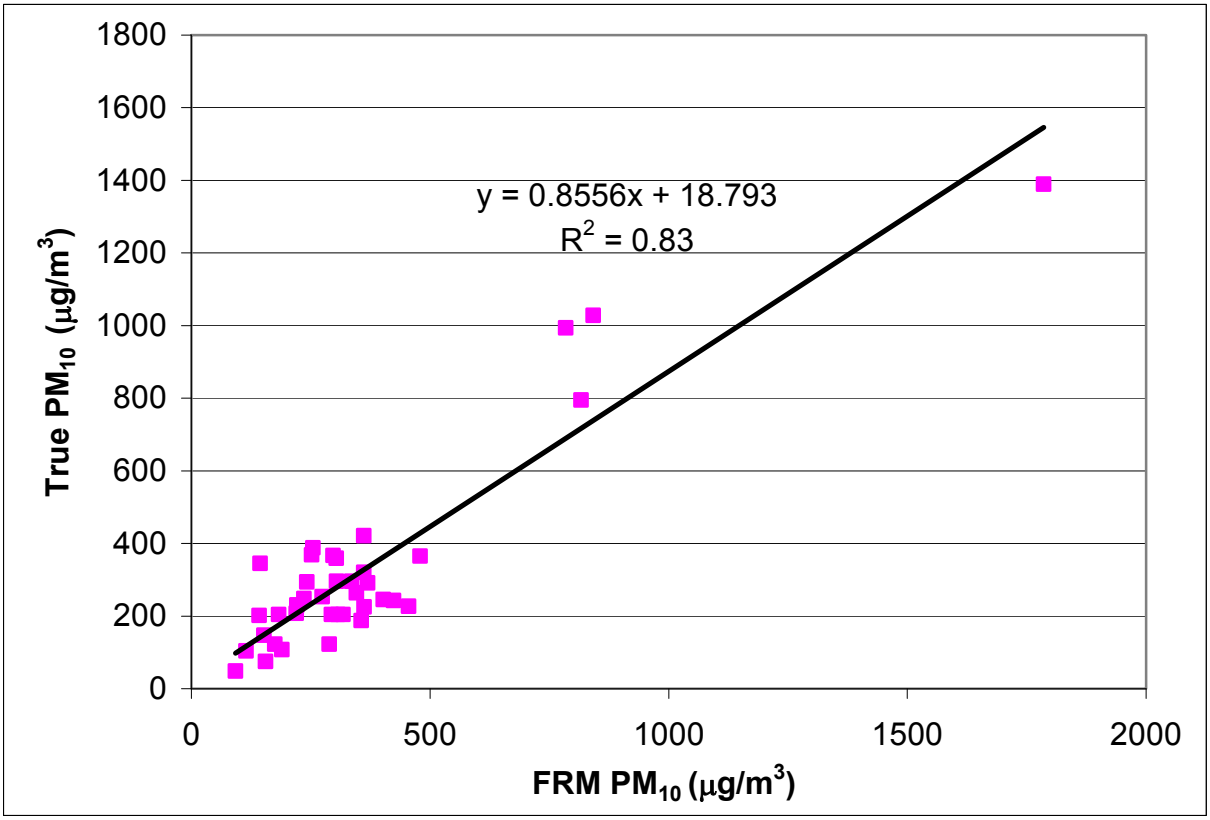

Figure 1. Scatter plot of FRM PM_{10} versus True PM_{10} concentrations for all sampling locations.

Similar $PM_{2.5}$ information is not available due to the extremely low measured $PM_{2.5}$ concentrations. Due to the short sampling time and the extremely small $PM_{2.5}$ component of the emissions, the measured $PM_{2.5}$ concentrations were below detectable levels for all samples. The extremely low sampled concentrations led to the use of the PSD information alone to determine $PM_{2.5}$ emission rates.

Emission Rates

The sampling conducted at Site 1 produced a total of 6 usable tests with four downwind sampling locations providing a potential of 24 TSP emission rates. Tests 1 and 8 did not meet the minimum time requirements due to smaller harvest areas at either end of the orchard and are not included in this analysis. Results of the emission rate analysis for the six valid tests at Site 1 are shown in Table 4.

Table 4. Site 1 TSP emission rates (kg/km^2) for half the orchard.

		Test					
		Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
# of Blower passes		3	1	1	3	3	1
Sampler Location	S1	1714	375	567	1394	905	212
	S2	359	404	483	292	621	333
	S3	189	230	404	530	989	302
	S4	116	202	397	751	353	240

The average TSP emission rate for three blower-passes was 684 kg/km^2 and the average emission factor for one blower-pass was 346 kg/km^2. This represents a reduction of 338kg/km^2 or 49% of emissions compared to the control treatment. No outliers were detected in the data set. Using the Student's t-test the null hypothesis that there was no difference between treatments was rejected, indicating that the difference was significant ($p < 0.05$).

Sampling conducted at Site 2 produced a total of six usable tests as well resulting in a total of 24 usable emission rates. At this sampling location, Test 3 did not have an adequate wind direction and is not shown in this analysis. Emission rates for the valid tests at Site 2 are shown in Table 5.

Table 5. Site 2 TSP emission rates (kg/km^2) for half the orchard.

		Test					
		Test 1	Test 2	Test 4	Test 5	Test 6	Test 7
# of Blower Passes		3	1	1	3	3	1
Sampler Location	S1	2151	387	3469	349	673	550
	S2	496	406	229	299	509	83
	S3	665	442	151	408	349	36
	S4	704	350	104	579	392	26

[a] Cells with grey backgrounds are statistical outliers.

Using SPSS (SPSS, Inc., Chicago, Ill.), outliers were identified and excluded from analysis. At site 2 the mean emission factor for three blower-passes was 493 kg/km^2 and the mean emission factor for one blower-pass was 251 kg/km^2. This represents a reduction in emission of 242 kg/km^2 or 49%. Using the Student's t-test there was a significant difference in the emission factors at α=0.05.

By combining the PSD information presented above with the TSP emission rate calculations, the true PM_{10} and $PM_{2.5}$ emission factors were computed for each test. The TSP, true PM_{10}, and true $PM_{2.5}$ emission rates for each test are shown in Table 6.

Table 6. Mean TSP, PM_{10} and $PM_{2.5}$ emission rates (kg/km^2) for both sampling locations. Values labeled with different letters are significantly different at a α=.05

		TSP		True PM_{10}		True $PM_{2.5}$	
		Mean	SD	Mean	SD	Mean	SD
Site 1	3 Passes	684^{A}	493	192^{C}	138	6^{EF}	4
	1 Pass	345^{B}	114	96^{D}	32	3^{E}	1
Site 2	3 Passes	493^{A}	145	187^{C}	55	10^{F}	3
	1 Pass	251^{B}	183	95^{D}	70	5^{E}	4

The resulting emission rate for PM_{10} at Site 1 and Site 2 was 192 kg/km^2 and 187 kg/km^2, respectively. Using the Student's t-test, the null hypothesis that there was no significant difference between locations for each treatment. Therefore, it is possible to combine the PM_{10} emission rates from both sampling sites into a single emission rate for each treatment.
Due to the extremely small $PM_{2.5}$ emission factor the statistics do not show clear differences between the treatments at site 1. The results are shown in Table 6 with significant difference indicated by different letters.

Emission Factor

As previously mentioned, emission rates presented above represent only the PM emissions measured during half of the total harvest. Due to the practice of planting alternating varieties by row it is usually necessary to return to the field to harvest the remainder of the orchard using the same methods. Therefore, annual emission factors are simply twice the emission rate for the first harvest. PM_{10} emission factors for all tests are shown in Table 7.

Table 7. Aggregated PM_{10} emission factors (kg/km^2) for the two treatments at both sampling sites.

Treatment	PM_{10} EF		% Reduction
	Mean	SD	
3 Passes	380	210	N/A
1 Pass	190	100	49

$PM_{2.5}$ emission factors are shown in Table 8. While the locations had statistically different emission for each treatment, the reduction in emissions was equivalent to the reduction in PM_{10} emissions.

Table 8. $PM_{2.5}$ emission factors (kg/km^2) for each treatment and location. Values labeled with different letters are significantly different at a α=.05

		$PM_{2.5}$ EF		
		Mean	SD	% Reduction
Site 1	3 Passes	12^{A}	9	49
	1 Pass	6^{B}	2	
Site 2	3 Passes	20^{C}	6	49
	1 Pass	10^{AB}	15	

By further examining the emission rates presented in Table 6 for the a single sweeping mode and making the assumption that the sweeper emissions are strictly from the two modes of operation (sweeper-only and blower-plus-sweeper) the emission contribution of each mode can be determined. The three blower-pass treatment has three blower and sweeper passes combined with three sweeper only passes (eq. 4). The single-blower-pass operation has the same 3 sweeper only passes, but only one blower-pass (eq. 5).

$$190\frac{kg}{km^2} = 3B + 3S \qquad (4)$$

$$96\frac{kg}{km^2} = 1B + 3S \qquad (5)$$

where:

B = emission rate for blower and sweeper passes (kg/km^2), and
S = emission rate for sweeper only passes (kg/km^2).

By solving these equations simultaneously, the resulting emission factor for sweeper-only passes is 16.3 kg PM_{10}/km^2 and 47 kg PM_{10}/km^2 for sweeper and blower-passes. By attributing the emission factor to individual sub-operations it is possible to apply emission factors to all equipment management practices utilized by equipment operators. Using this method, a producer may utilize reduced blower-passes during the first harvest but attempt to recover some of the product left in the field with the second harvest. This essentially allows the emission factor to be determined for any number of blower and sweeper pass combinations.

Harvest Efficiency

Results of harvest efficiency analyses are shown in Table 9. By assuming a 25% turnout from the collected nuts and an average planting of 288 trees per hectare, and multiplying the mass of the nuts lost by two to account for two harvests yields, a prediction of the mass of nuts left in the orchard was made. The average yield was 2125 kg/ha the year this work was completed (USDA, 2007).

Table 9. Mass of nuts left in the field (kg/ha) after all harvesting was completed for each of the treatments. Values labeled with different letters are significantly different at a α=.05

		Almond Loss (kg/ha)	
		Mean	SD
Site 1	3 Passes	36^{A}	9
	1 Pass	40^{A}	4
Site 2	3 Passes	53^{A}	35
	1 Pass	133^{B}	20

Conclusions

PM_{10} and $PM_{2.5}$ emission rates were determined for almond sweeping for both a standard treatment as well as a reduced-pass treatment as a potential conservation management practice. The reduced-pass treatment lowered emissions by 49% compared to the standard treatment. The quantity of product left in the field may be a deterrent to adopting this practice, but the increased sweeping speeds and reduced harvest time may make up for the lost crop.

The conventional sweeping emission factor using three blower-passes was found to be 379$\pm$209 kg PM_{10}/km^2. This sweeping emission factor is lower than the current sweeping emission factor of 415 kg PM_{10}/km^2. Reducing the number of blower-passes from three to one lowered the average emission factor by 49% to 192$\pm$104 kg PM_{10}/km^2.

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