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 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 Sites

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.

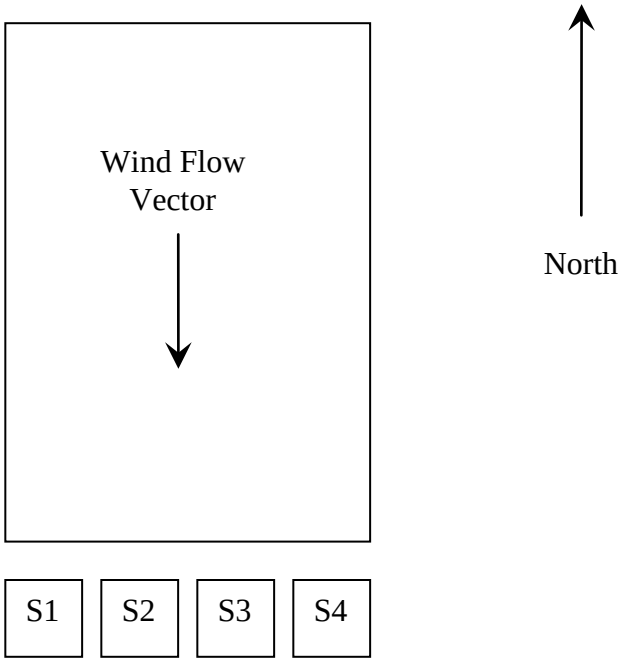

Figure 1. Sampler configuration for all tests. All prevailing winds were from a northerly direction and all orchard rows ran north-south.

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.

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

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.

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

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.

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

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).

$$C_c\{x_r, y_r, z_r\} = C_d\{x_r, y_r, z_r\} + C_r\{x_r, y_r, z_r\} + C_p\{x_r, y_r, z_r\} \quad (4)$$

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.

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

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 under 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 (α = 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 (α = 0.05) in the two models in this analysis.

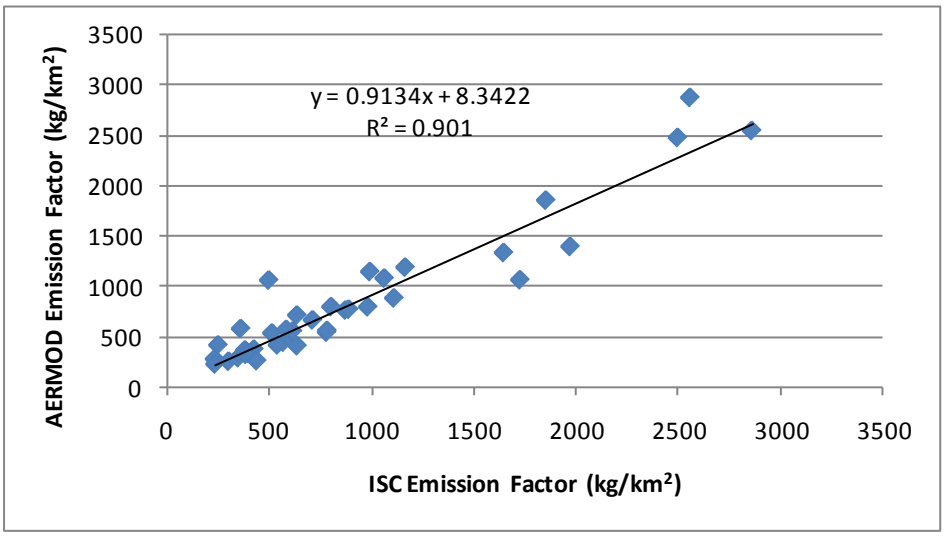

Figure 2. Regression analysis of ISC and AERMOD TSP emission factors. The slope of the regression is not statistically different from 1.0 and the regression constant is not statistically different than zero, indicating no significant difference in the models (α = 0.05).

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.

References:

Buser, M., C. Parnell Jr., B. Shaw, R. Lacey. 2007. Particulate matter sampler errors due to the interaction of particle size and sampler performance characteristics: background and theory. *Transactions of the ASABE*. 50(1):221-228.

Environmental Protection Agency (EPA). 2004. AERMOD: Description of Model Formulation. EPA-454/R-03-004. Office of Air Quality Planning and Standards - Emissions Monitoring and Analysis Division. Research Triangle Park, NC. USEPA.

Garratt, J.R. 1992. The Atmospheric Boundary Layer. New York, N.Y. Cambridge University Press.

Hinds, W. C. 1999. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*. New York, NY, John Wiley & Sons, Inc.

Perry, S.G., et al. 2005. AERMOD: a dispersion model for industrial source applications. Part 2: model performance against 17 field study databases. *J. Applied Meteorology* 44(5): 694-708.

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).

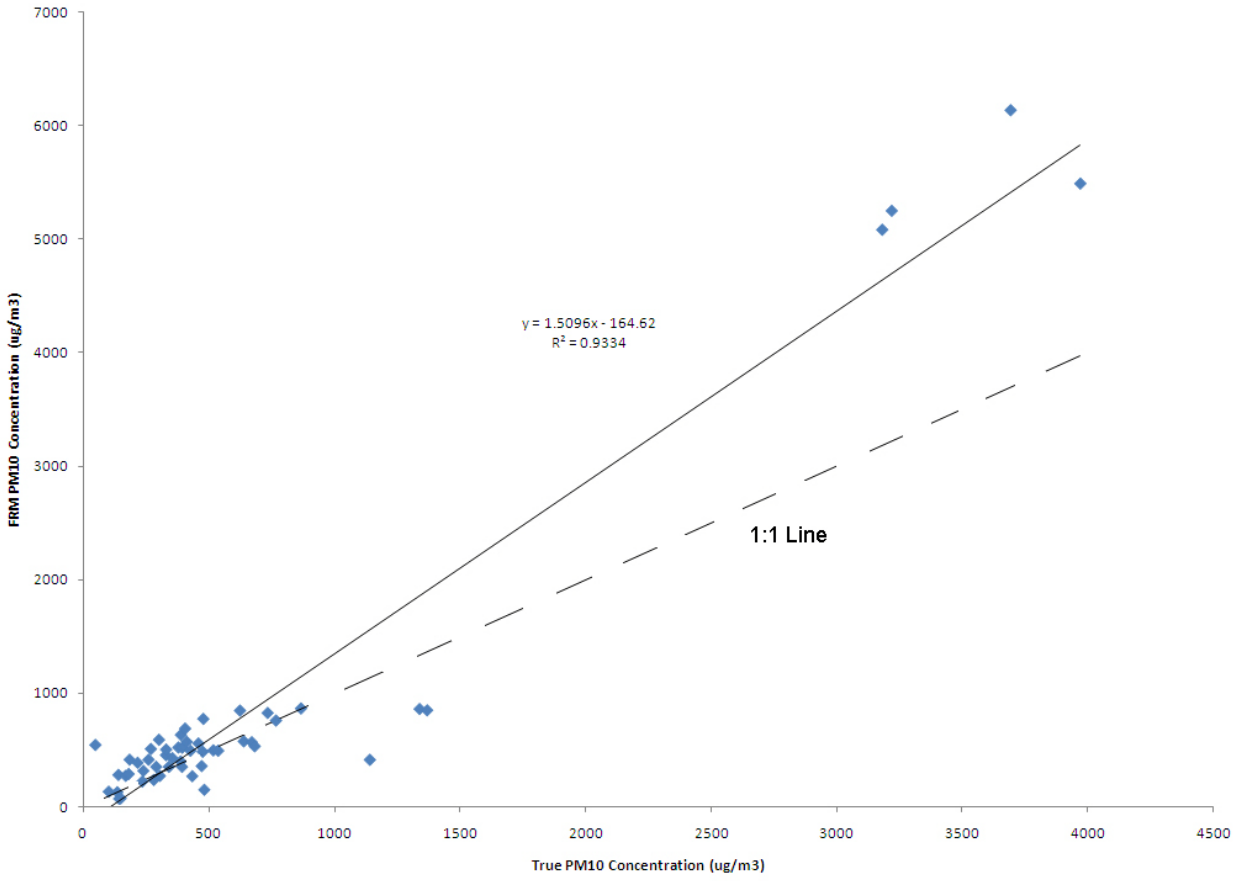

Figure A1. Regression analysis of PM_{10} concentrations measured using FRM PM_{10} samplers versus true PM_{10} concentations.

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.

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16

PARTICULATE MATTER EMISSIONS FROM 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. Baseline emission factors of 379±86 kg $PM_{10}/km^2/yr$ and 16+3.3 kg $PM_{2.5}/km^2/yr$ were determined, and an emissions reduction of 49% was achieved by the experimental treatment, representing a significant potential for emissions reduction across the state. 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, but the amount of unharvested product left in the orchard was small.*

Keywords. *PM_{10}, $PM_{2.5}$, TSP, almond harvest, inverse dispersion modeling, mitigation*

INTRODUCTION

California almond farmers produce 80% of the world's almond supply. In 2006, approximately 497 Gg 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 recent 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. PM_{10} is particulate matter with an aerodynamic equivalent diameter less than or equal to 10μm. With the recent removal of the permitting exemption for agriculture, agricultural operations have become a target of scrutiny. The SJVAPCD has found that the available information on emission factors for agricultural operations is severely limited, is based on older harvest technology, and needs improvement.

The current emission factor applied to all almond harvesting operations is 4,570 kg $PM_{10}/km^2/yr$ (CARB, 2003), accounting for 11 Gg 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 $PM_{10}/km^2/yr$ of the emission factor. A few days later, after the crop has dried, the sweepers enter the orchard and sweep the almonds into windrows, currently accounting for 415 kg $PM_{10}/km^2/yr$. Finally, the pickup machines remove the product from the orchard, currently accounting for 4,120 kg $PM_{10}/km^2/yr$. 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 orchard 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 for later pickup. The sweeper used in this work (Model 77 Series Air-Cab Sweeper; Flory Industries; Salida, California) had a 2.29 m-wide head that swept the almonds to the right as the machine traveled. This head moves the crop from near the tree into a windrow 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 California Air Resources Board (CARB) emission factor used a six-pass treatment for each harvested windrow of almonds. The six passes consisted of three blower passes and three sweeper passes (hereafter referred to as the three blower-pass treatment). To achieve the goal of this 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 (hereafter referred to as the one blower-pass treatment).

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

Almonds are typically planted in alternating varieties by tree row. The various varieties mature at different times resulting in multiple harvests for each orchard. The orchards sampled for this research were harvested at two different times, each harvest accounting for half the total orchard or every other tree row. However, the harvest process in a given orchard is identical for the alternating tree 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 particulate matter (PM) concentration increase between samplers located upwind and downwind of the harvested area. 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, wind direction, ambient temperature, relative humidity, barometric pressure, and solar radiation were measured on five-minute intervals. The dimensions of each test plot and corresponding meteorological data were then used with Industrial Source Complex-Short Term version 3 (ISCST3) to determine a flux ($\mu g/m^2$-s) for the given sampling period. ISCST3 was used because it was the EPA-preferred regulatory model in 2006, at the time the study was conducted.

AMBIENT SAMPLING

Due to the errors associated with federal reference method (FRM) samplers in agricultural environments identified by Buser et al. (2007), both total suspended particulate (TSP) measurements and FRM PM_{10} measurements were conducted. TSP measurements were conducted with low-volume samplers designed by Wanjura et al. (2005) to reduce variations in sampler flow rate that lead to high uncertainty in FRM concentration measurements. PM_{10} measurements were conducted using the same air-flow control unit as the TSP samplers and an FRM PM_{10} sampling inlet (Model PQ100 Inlet; BGI Inc.; Waltham, MA). To correct for the errors associated with the FRM samplers, a particle size distribution (PSD) analysis was conducted on the TSP filters using a Beckman Coulter Counter Multisizer^{TM} 3 (Beckman Coulter, Miami, Florida) after the filters were post-weighed. Particle size analysis was conducted according to the protocol specified by Faulkner and Shaw (2006) with the exception that the entire filter was analyzed rather than core samples. The results of the PSD analysis were converted from equivalent spherical diameter (ESD) to aerodynamic equivalent diameter (AED) using eq. 1, assuming a particle density of 2.6 g/cm^3 (based on soil particle samples taken from each orchard and analyzed using a pycnometer (AccuPyc 1330 Pycnometer, Micromeritics, Norcross, GA)) and a shape factor of 1.00.

$$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \tag{1}$$

where:

AED = aerodynamic equivalent diameter;

ESD = equivalent spherical diameter;

ρ_p = particle density (g/cm^3); and

χ = shape factor.

The resulting PSD was then used to determine the true percentage of PM_{10} and $PM_{2.5}$ on each filter.

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 to ensure a viable PSD analysis, the treatment area was set to obtain a larger number of tests within the remaining orchard.

At each sampling location, plots were organized using a split-plot design in which control (three blower-passes) and experimental (one blower-pass) treatments were tested. Eight tests were conducted at Site 1 while only seven tests were conducted at Site 2. (Only six tests from Site 1 produced usable data; the other two were excluded because the plot size was too small. Insufficient tree rows were available at Site 2 to complete the final replication in the experimental design). For each test, one upwind and four downwind sampling locations were utilized. The upwind samplers, which were not moved between test plots, were used to determine ambient (background) concentrations in the area. All sampling locations consisted of one TSP sampler and one FRM PM_{10} sampler. Additionally, FRM $PM_{2.5}$ samplers were collocated at the upwind sampling location and one downwind sampling location. The downwind samplers were spaced evenly across the downwind edge of the treatment area for each test approximately 15 m from the edge of each plot. The samplers were placed such that there was enough room for the sweeper to make turns and remain upwind of the sampler array while measuring concentrations as close to the test area as possible in order to reduce the uncertainty in modeled pollutant concentrations as discussed by Faulkner et al. (2007) . The four downwind samplers provided four independent measurements of concentration leading to four independent estimates of the flux for each test. Plots were 400 m long and consisted of tree rows planted 6.7 m apart with 5.5 m between trees within a row.

INDUSTRIAL SOURCE COMPLEX

ISCST3 is a steady state Gaussian plume model that can be used to predict downwind concentration from area sources (EPA, 1995). ISCST3 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 ISCST3 uses as the basis for all calculations is a double Gaussian algorithm that represents a point source (eq. 2).

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

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);

148 σ_z = Pasquill-Gifford vertical plume spread parameters based on stability class (m);

149 H = height of plume release (m);

150 y = crosswind distance from source to receptor (m); and

151 z = height of receptor for concentration prediction (m).

152 Each input to ISCST3 was either measured in the field or are calculated from measured values. The Pasquill-
153 Gifford dispersion parameters were calculated based on the atmospheric stability class using the Solar Radiation
154 Delta-T (SRDT) method (USEPA, 2000).

155 **EMISSION FACTOR CALCULATIONS**

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

162 The result of dispersion modeling is a unit flux concentration (UFC) for each test. This is acquired by using the
163 meteorological conditions measured during the test in conjunction with the orchard and sampler configuration in the
164 model. The model is executed using a flux of 1 $\mu g/m^2$-s to predict a concentration at each of the four downwind
165 sampling locations. The predicted flux at each location is called the UFC and represents the change in predicted
166 concentration for each unit increase of flux in the model. To obtain the estimated flux from the sweeping operation,
167 the measured concentration at each sampling location is divided by the UFC at the corresponding sampling location
168 resulting in the flux required to match the measured concentration (eq. 3). This process produces an estimate of the
169 flux for each sampling location during each test.

170 $$\frac{C_m}{UFC} = F \quad (3)$$

171 where:

172 C_m = measured concentration ($\mu g/m^3$);

173 UFC= unit flux concentration; and

174 F = pollutant emission flux ($\mu g/m^2$-s).

The emission flux ($\mu g/m^2$-s) calculated by ISCST3 can be easily converted into units of $kg/km^2/hr$. Thus, the formula to estimate the emission factor when the emission flux is known is given in eq. 4.

$$EF\ (kg/km^2) = ER\ (kg/km^2/hr)\ X \text{ time of sampling (hrs)} \quad (4)$$

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 Non-Pareil variety with another variety or a Non-Pareil with two other varieties, such as Carmel and Butte, in each orchard. The Non-Pareil varieties are normally planted every other tree 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 pickup operation for the second harvest period is identical to that of the first. Assuming negligible change in emissions between first and second harvest, the emission rate from the first harvest was doubled to yield the seasonal total emission factor.

Treatment means were compared using the Student's t-test function in SPSS (SPSS v.14.0; SPSS, Inc., Chicago, IL) with a 0.05 level of significance. The null hypothesis tested in all cases was that mean emissions from each site or treatment were equal.

HARVEST EFFICIENCY

Due to the reduced number of blower-passes made with this work there were more almonds left in the orchard 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 four trees. All nuts that were left more than 0.3048 m (1 ft.) 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 orchard 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 to maximize water use 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. As expected, all downwind concentration measurements exceeded upwind measurements. The grand mean downwind concentration measurement was 916 μg/m^3 and the grand mean upwind concentration was 251 μg/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).

Sampler	Test						
	2	3	4	5	6	7	8
UW	137	126	126	316	745	153	153
S1	1,131	352	449	1,053	3,265	374	401
S2	650	369	832	619	2,556	668	566
S3	456	346	950	947	3,332	735	422
S4	335	329	1,018	1,304	1,324	514	349

TSP concentrations from Site 2 are presented in table 2. All seven tests were successful from a PM measurement stand point. The filter at sampler location S3 for test 3 was dropped during sampling and was 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 118 $\mu g/m^3$ and the mean downwind TSP concentration was 724 $\mu g/m^3$ representing an average increase in TSP concentrations across the orchard of 613 $\mu g/m^3$. Concentrations were measured over a time period of 1.5 to 2.5 hours.

Table 2. Measured TSP concentrations for Site 2 ($\mu g/m^3$).

Sampler	Test						
	1	2	3	4	5	6	7
UW	57	209	209	105	105	72	72
S1	1,556	879	663	2,407	750	910	496
S2	491	963	131	597	701	853	125
S3	773	967	--	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 (PSD) 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 (table 3). This value was then used to determine the true PM_{10} and $PM_{2.5}$ concentrations. 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. The previously reported MMD and GSD recorded for sweeping were 12.8 μm and 1.9, respectively (Flocchini, et al. 2005).

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

Location	MMD (µm AED)	GSD	True PM_{10} (%)	True $PM_{2.5}$ (%)
Site 1	15.6	2.17	28	0.9
Site 2	12.8	2.21	38	2

True PM_{10} concentrations were compared to those measured using FRM PM_{10} samplers at both sampling sites. Using the linear regression function in SPSS (SPSS v. 14.0; SPSS Inc.; Chicago, IL), no significant differences were detected ($\alpha = 0.05$) in the slope or intercept of regressions between Sites 1 and 2, so all data is presented together in fig. 1. The true PM_{10} value was 86% of the value measured using FRM PM_{10} samplers ($p < 0.005$), indicating an over sampling rate of 17% (i.e. the measured emission factors would erroneously be 17% higher if only FRM PM_{10} samplers were used).

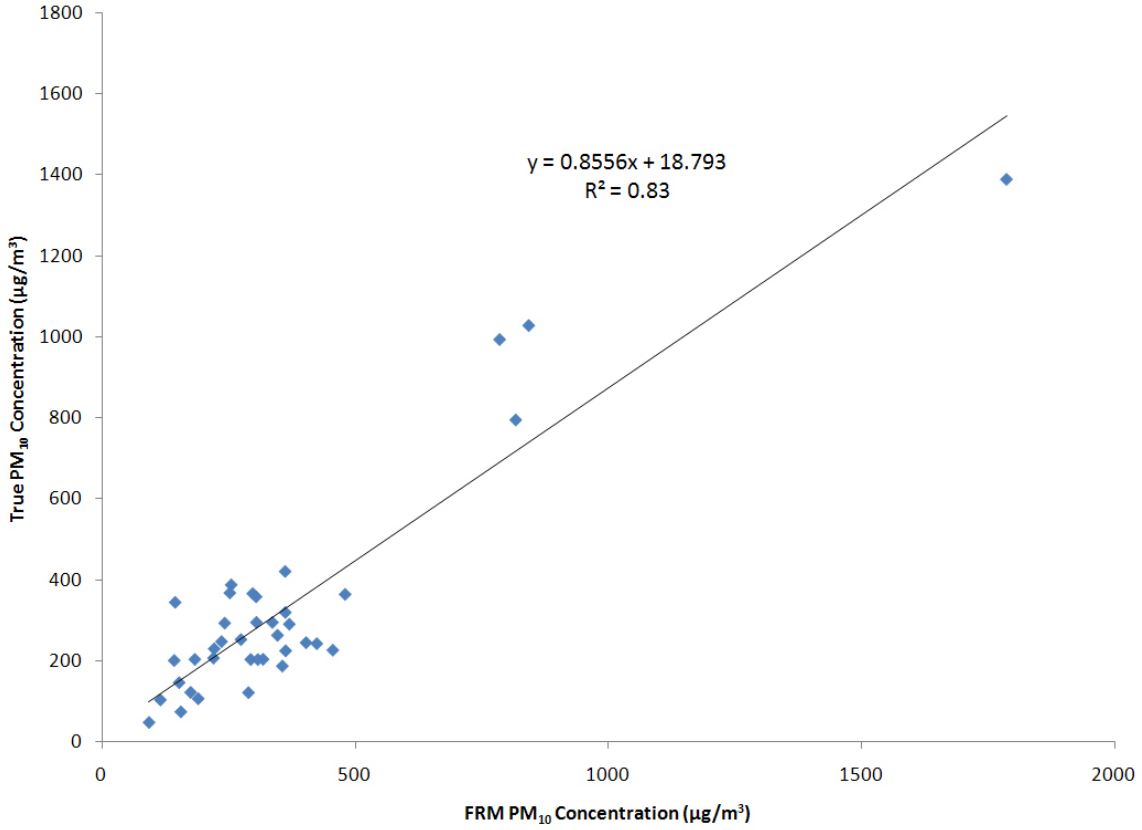

Figure 1. Scatter plot of FRM PM_{10} versus True PM_{10} concentrations for all sampling locations.

A similar comparison was not conducted for $PM_{2.5}$ concentrations due to the extremely low concentrations measured using the FRM $PM_{2.5}$ samplers. The short sampling time and the small $PM_{2.5}$ component of emissions

resulted in measured $PM_{2.5}$ concentrations 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 six 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 were 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					
Sampler /Blower Passes	**2**	**3**	**4**	**5**	**6**	**7**
	3	1	1	3	3	1
S1	1,714	375	567	1,394	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 TSP/km^2/yr and the average emission factor for one blower-pass was 346 kg TSP/km^2/yr. This represents a reduction of 338 kg TSP/km^2/yr 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 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					
Sampler /Blower Passes	**1**	**2**	**4**	**5**	**6**	**7**
	3	1	1	3	3	1
S1	2,151	387	3,469	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 gray backgrounds are statistical outliers.

Outliers were identified and excluded from subsequent analysis. The emission factors developed for sampler S1 during tests 1 and 4 were likely outliers because the sampler was located at the edge of the Gaussian plume modeled using ISCST3 where the greatest uncertainty in pollutant concentration exists. This phenomenon was discussed in detail by Faulker et al. (2007). At Site 2 the mean emission factor for three blower-passes was 493 kg TSP/km^2/yr and the mean emission factor for one blower-pass was 251 kg TSP/km^2/yr. This represents a reduction in emission of 242 kg/km^2/yr or 49%. Using the Student's t-test, there was a significant difference in the emission factors ($p < 0.05$).

By combining the PSD information (table 3) with the TSP emission rate calculations (table 4 and 5), the true PM_{10} and $PM_{2.5}$ emission factors were computed for each test (table 6).

Table 6. Mean TSP, PM_{10} and $PM_{2.5}$ emission rates (kg/km^2) for both sampling locations.[a]

Location	Blower Passes	TSP		True PM_{10}		True $PM_{2.5}$	
		Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
Site 1	3	684 a	142	192 c	40	6 e,f	1.2
	1	345 b	33	97 d	9	3 e	0.3
Site 2	3	493 a	44	187 c	17	10 f	0.9
	1	251 b	55	95 d	21	5 e	1.2

[a] No statistical difference ($\alpha = 0.05$) was detected between means followed by the same letter.

The resulting emission rate for true PM_{10} at Site 1 and Site 2 was 192 kg PM_{10}/km^2/yr and 187 kg PM_{10}/km^2/yr, respectively. Using the Student's t-test, the null hypothesis that there was no significant difference between locations for each treatment was accepted. Therefore, emission rates from both sampling sites were combined into a single emission rate for each treatment. Due to the extremely small $PM_{2.5}$ emission factors, no differences were detected between treatments at Site 1.

EMISSION FACTORS

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 tree row it is usually necessary to return to the orchard to harvest the remainder of the orchard using the same methods. Annual emission factors were calculated assuming negligible differences in emissions between first and second harvest and were, therefore, assumed to be twice the emission rate for the first harvest. Annual PM_{10} emission factors for all tests are shown in table 7.

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

Treatment	Mean	Std. Error	% Reduction
3 Passes	379	44	N/A
1 Pass	190	21	49

301

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

304 **Table 8. $PM_{2.5}$ emission factors (kg $PM_{2.5}/km^2/yr$) for each treatment and location.[a]**

Location	Treatment	Mean	Std. Error	% Reduction
Site 1	3 Passes	12 a	2.6	N/A
	1 Pass	6 b	0.6	49
Site 2	3 Passes	20 a	1.8	N/A
	1 Pass	10 a,b	2.1	49

[a] No statistical difference ($\alpha = 0.05$) was detected between means followed by the same letter.

305

306 By further examining the emission rates presented in table 6 for the single sweeping mode and making the
307 assumption that the sweeper emissions are strictly from the two modes of operation (sweeper-only and blower-plus-
308 sweeper) the emission contribution of each mode may be estimated. The three blower-pass treatment consisted of
309 three blower-and-sweeper passes combined with three sweeper-only passes (eq. 5). The single-blower-pass
310 operation has the same three sweeper-only passes, but only one blower-pass (eq. 6).

311 $$190\frac{kg}{km^2} = 3B + 3S \quad (5)$$

312 $$96\frac{kg}{km^2} = 1B + 3S \quad (6)$$

313 where:

314 B = PM_{10} emission rate for blower and sweeper passes (kg $PM_{10}/km^2/yr$), and

315 S = PM_{10} emission rate for sweeper only passes (kg $PM_{10}/km^2/yr$).

316 By solving these equations simultaneously, the resulting emission factor for sweeper-only passes and sweeper-and-
317 blower passes were estimated to be 16 kg $PM_{10}/km^2/yr$ and 47 kg $PM_{10}/km^2/yr$, respectively. By attributing the
318 emission factor to individual sub-operations it may be possible to apply emission factors to all equipment
319 management practices utilized by equipment operators. This essentially allows the emission factor to be estimated
320 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 unharvested nuts, an average of 288 trees per hectare, and equal masses of meats left behind in the first and second harvest, a prediction of the mass of nut meats in the orchard was made. The average yield of almond meats was 2,125 kg/ha the year this work was completed (USDA, 2007). While there was no significant difference between nuts left in orchard at Site 1, Site 2 showed a significant difference in the amount of product determined to be unharvestable. The same operator and equipment was used at each site, therefore, the only variable in harvest efficiency was the conditions of the orchard. However, no obvious difference between the orchards was identifiable as the cause of the varied results in table 9. It should be noted that while the results are not consistent across the two orchards involved in this study, the amount of unharvested product is relatively small, even at Site 2. This lost product would likely be offset by the concurrent reduction in operating costs achieved by reducing the number of passes through the orchard with the experimental treatment.

Table 9. Mass of nuts left in the orchard (kg/ha) after all harvesting was completed for each of the treatments.[a]

Location	Treatment	Mean	Std. Error
Site 1	3 Passes	36 a	2.0
	1 Pass	40 a	0.9
Site 2	3 Passes	53 a	7.8
	1 Pass	133 b	4.5

[a] No statistical difference ($\alpha = 0.05$) was detected between means followed by the same letter.

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 PM_{10} and $PM_{2.5}$ emissions by 49% compared to the standard treatment. The quantity of product left in the orchard 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 factors using three blower-passes were found to be 379 ± 86 kg $PM_{10}/km^2/yr$ and 16 ± 3.3 kg $PM_{2.5}/km^2/yr$. This sweeping emission factor is lower than the current sweeping emission factor of 415 kg $PM_{10}/km^2/yr$. Reducing the number of blower-passes from three to one lowered the average emission factor by 49% to 192 ± 41 kg $PM_{10}/km^2/yr$.

REFERENCES

Buser, M., C. Parnell Jr., B. Shaw, R. Lacey. 2007. Particulate matter sampler errors due to the interaction of particle size and sampler performance characteristics: background and theory. *Transactions of the ASABE* 50(1):221-228.

California Air Resources Board (CARB). 2003. Emission Inventory Procedural Manual Volume III: Methods for Assessing Area Source Emissions, Sacramento, CA.

Faulkner, W.B. and B.W. Shaw. 2006. Efficiency and pressure drop of cyclones across a range of inlet velocities. *Applied Engineering in Agriculture* 22(1): 155-161.

Faulkner, W.B., J.M. Lange, J.J. Powell, B.W. Shaw, and C.B. Parnell. 2007. Sampler placement to determine emission factors from ground level area sources. *Atmospheric Environment* 41(35): 7672-7678.

Flocchini, R.G., C.B. Parnell, Jr., T.A. Cassel, S.C. Capareda, J.D. Wanjura, P. Wakabayashi, and K. Nabaglo. 2005. Improvement of PM_{10} Emission Factors for Almond Harvesting. Report to the Almond Board. March 2005. California Almond Board, Sacramento, CA.

United States Department of Agriculture (USDA). 2007. 2006 California Almond Acreage Report. California Field Office, Sacramento, CA. United States Department of Agriculture National Agricultural Statistics Service.

United States Environmental Protection Agency (USEPA). 1995. Compilation of air pollutant emission factors, Volume I: Stationary point and area sources, Fifth edition. January 1995. U.S. EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC.

USEPA. 2000. *Meteorological Monitoring Guidance for Regulatory Modeling Applications*, EPA-454/R-99-005. U.S. Government Printing Office: Research Triangle Park, NC.

Wanjura, J.D., C.B. Parnell, Jr., B.W. Shaw, and R.E. Lacey. 2005. Design and evaluation of a low-volume total suspended particulate sampler. *Transactions of the ASAE* 48(4):1547-1552.