Particulate Matter Emission Factors for Almond Harvest As A Function of Sweeping Depth

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Interpretive Summary:

Almond harvest accounts for a significant amount of PM_{10} emissions in California each harvest season. This paper addresses the adjustment of sweeper depth and its effect on PM_{10} emissions from sweeping and pickup operations. Ambient total suspended particulate (TSP) and PM_{10} sampling was conducted during harvest with alternating control (proper sweeper setting) and experimental treatment (sweeper depth 1.27cm [0.5 in.] that is lower than recommended treatments). On-site meteorological data was used in conjunction with inverse dispersion modeling using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) to develop emission rates from the measured concentrations.

The emission factors developed from this study using proper sweeper settings are 1,725 $\pm$1,345 kg $PM_{10}/km^2/yr$ for sweeping and 2, 232 $\pm$ 1,929 kg$PM_{10}/km^2/yr$ for pickup operations. The emission factor for sweeping is significantly higher than those reported in previous studies and is higher than the emission factor currently in use by the California Air Resources Board. The emission factor for nut pickup is similar to those reported in previous studies but lower than the emission factor of 4,120 kg PM_{10}/km^2 currently in use by the California Air Resources Board.

The results of this research showed no differences in emissions of regulated pollutants during the sweeping process as a function of sweeper depth, but emissions during pickup were significantly lower (by about half) for windrows formed using proper sweeper settings versus those formed using improper sweeper settings (i.e. 2,232 versus 4,858 kg $PM_{10}/km^2/yr$).

Objectives:

The objectives of this study are as follows:

1. Quantify the possible emission reductions during sweeping and pickup operations achieved through the use of proper sweeper height settings;

2. Quantify the difference in soil content of almonds taken to the huller between almonds windrowed using proper and improper sweeper height settings; and

3. Generate additional data regarding PM_{10} and $PM_{2.5}$ emissions from almond harvest to augment the existing dataset.

Introduction

California almond farmers produce over 75% of the world's almond supply. In 2007, approximately 617Gg of almonds were harvested in California on approximately 249,000 bearing hectares with a total value of $2.3 billion.[1] Over 70% (174,217 ha) of the bearing crop is located within the San Joaquin Valley Air Pollution Control District (SJVAPCD), which was only recently removed from non-attainment status for PM_{10} under the National Ambient Air Quality Standards (NAAQS). Due to the recent classification of the San Joaquin Valley (SJV) as a serious non attainment area for $PM_{10,}$ the SJVAPCD is in the midst of an aggressive campaign to reduce PM_{10} emissions from all sources. With the removal of the permitting exemption from agriculture in 2007 and as a result of California Senate Bill 700, agricultural industries have 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 applied to all almond harvesting operations is 4,570 kg PM_{10}/km^2, accounting for 11Gg of PM_{10} each year.[2] 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. The almonds are then swept into windrows, accounting for 415 kg PM_{10}/km^2. Finally, 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.

Goodrich et al.[3] used inverse dispersion modeling with Industrial Source Complex Short Term version 3 (ISCST3) to determine a PM_{10} emission factor for conventional almond sweeping (using three blower-passes per harvested row) and reduced-pass almond sweeping (using one blower-pass per harvested row). They reported an emission factor of 379 ± 209 kg $PM_{10}/km^2/yr$ for conventional sweeping, which is slightly lower than the current emission factor for sweeping developed in the early 1990s. Goodrich et al.[3] also reported that reducing the number of blower-passes

from three to one lowered the average PM_{10} emission factor by 49% to 192±104 kg $PM_{10}/km^2/yr$.

Downey et al.[4] tested the effect of reducing harvester ground speed on opacity measurements in the exhaust plume of almond pick-up machines. They found that reducing harvester ground speed without reducing the PTO speed of the tractor led to lower opacity measurements in the plume relative to emissions from typical harvest operations, but Downey et al.[4] did not report emissions of PM_{10} or $PM_{2.5}$.

Faulkner et al[5] used inverse dispersion modeling with both ISCST3 and the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) to test the effect of reduced harvester ground speed on emissions of TSP, PM_{10}, and $PM_{2.5}$ from nut pickup operations in an effort to determine the implications of the work of Downey et al.[4] for regulated pollutants. Faulkner et al [5] reported no statistical differences in PM_{10} or $PM_{2.5}$ emission factors as a function of harvester speed or dispersion model used, but TSP emission factors were lower for the slower harvester speed, which supports the findings of Downey et al.[4] that plume opacity varies with harvester speed. The emission factors developed using AERMOD were 359±275 kg $PM_{10}/km^2/yr$ and 24±19 kg $PM_{2.5}/km^2/yr$. The PM_{10} emission factor developed by Faulkner et al[5] was significantly lower than the emission factor of 4,120 kg $PM_{10}/km^2/yr$ currently in use by the California Air Resources Board.

According to current emission factors, sweeping accounts for 10% of the total PM_{10} emissions from almond harvesting operations. As demonstrated by Goodrich et al[3], sweeping practices may dramatically affect PM emissions from sweeping operations. Sweeping practices may also affect emissions from pickup operations as increased soil material in the windrow may increase PM emissions during nut pickup. Sweeper manufacturers recommend setting the sweeper head such that the steel teeth of the implement just clear the surface of the orchard floor without causing ground interference. However, many sweeper operators set the sweeper head lower than recommended by manufacturers in an attempt to decrease the number of unharvested nuts left on the orchard floor. This lower setting leads to ground interference by the sweeper unit, which may increase emissions from sweeping operations, increase emissions from pickup operations, and increase the amount of dirt transported to the huller with the almonds, thus leading to increased processing costs for the producer. Downey et al.[4] reported a 32% increase in opacity measurements in the dust plume from nut pickup operations harvesting windrows of nuts formed using improper sweeper depth adjustments (1.27 cm [0.5 in.] lower than recommended by the manufacturer) compared to dust emitted from harvest operations of windrows formed with proper settings. Again, Downey et al.[4] did not report emissions of regulated pollutants.

Materials and Methods:

This research focuses on the emissions from sweepeing and pickup operation of almond harvesting as a function of sweeper height setting. Sweeping treatments included a control treatment of proper sweeper setting (no ground interference) and an

experimental treatment in which 1.27 cm (0.5 in.) ground interference occurred between the steel teeth of the sweeper and the orchard floor. Pickup operations for both sweeper treatments were identical in order to isolate the effect of sweeper setting on PM emissions. The sweeper used in this work was a Flory Model 9610, and the pickup machine was a Flory Model 850 PTO Harvester.

Plots were organized in a randomized complete block design with replication as the blocking factor. Each plot consisted of ten tree rows. 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 a "pollinator" variety or a Nonpareil with two "pollinator" 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. Therefore, while each plot consisted of ten tree rows and ten windrows were created, only five tree rows were harvested.

The remaining tree rows are harvested when the nuts mature using an identical harvest process. The overall emission factor is the sum of the two harvesting operations for each variety Because the harvest processes are identical for each variety, the emission rates developed from sampling were assumed represent half the total annual emissions from harvest operations.

Sampling was conducted in the Central Sacramento Valley near Arbuckle, California, in an orchard with a Hillgate loam which was 18.8% clay. The trees in this orchard were ten years old and were oriented north-south. Trees were planted in 400 m rows with 6.7 m between rows and 5.5 m between trees in the same row. Sampling was conducted during sweeping of all plots. Nuts were then allowed to air dry in windrows for several days before sampling was again conducted on the same plots during nut pickup.

Ambient Sampling

Samplers were placed upwind and downwind of each plot to measure the ambient particulate matter (PM) concentrations during sweeping and pickup operations. At each sampling location, collocated, low-volume TSP and federal reference method (FRM) PM_{10} samplers (Model PQ100 Inlet; BGI Inc.; Waltham, MA) were used to determine PM concentrations. FRM $PM_{2.5}$ samplers were not used because the low concentrations of $PM_{2.5}$ emitted during almond harvest operations during the sampling period did not allow for sufficient loading on the filters to render reliable FRM $PM_{2.5}$ measurements. (According to Goodrich et al.[3] $PM_{2.5}$ constituted only 0.9% of TSP sampled during sweeping operations). Sampler sets were placed at four locations approximately 15 m from the edge of the plot such that there was enough room for the sweeper or harvester to make turns and remain upwind of the sampler array. The downwind sampling locations were spaced evenly along the width of each plot (Fig. 1). The four downwind sampler sets provided four independent measurements of concentration leading to four independent estimates of the flux for each test. Samplers were set up at both upwind and downwind locations to measure the net increase in PM concentrations due to the harvesting process.

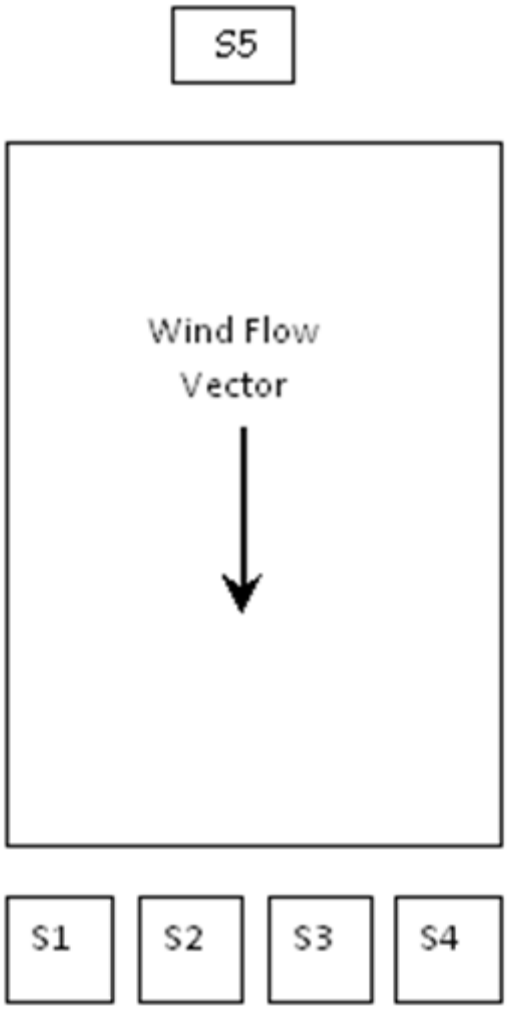

Figure 1. Sampler Configuration.

Due to the errors associated with FRM sampling in agricultural environments identified by Buser et al.[6], both TSP measurements and FRM PM_{10} measurements were conducted. TSP measurements were conducted with samplers designed by Wanjura et al.[7] 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.

The filters used in the TSP and PM_{10} samplers were weighed using a 10 µg analytical balance (AG245; Mettler-Toledo International Inc.; Columbus, OH). Each filter was pre- and post-weighed three times. If the standard deviation of the three weights was less than 50 µg, the average of the three weights were taken as the pre- and post-weights, respectively. If the standard deviation of the three weights was greater than 50 µg, the filter was reweighed. The change in filter mass, flow rate

through the sampler, and sampling duration for each sampler and test were used to calculate the PM concentration (eq 1).

$$C = \frac{\Delta m_f}{Q_{air} \cdot t_D} \quad (1)$$

where: C = concentration (μg/m^3),
Δm_f = change in mass on the filter (μg),
Q_{air} = sampling flow rate (m^3/sec), and
t_D = sampling duration (sec).

The particle size distribution (PSD) of PM collected on TSP filters having more than 200 μg of PM were analyzed using a particle size analyzer (Mastersizer 2000, Malvern Instruments Inc.) with a detection range of 0.2 μm to 2000 μm. Samples were prepared according to the procedure described by Faulkner and Shaw[8] with the exception that the entire filter was analyzed rather than core samples. A minimum net filter mass of 200 μm was required to obtain accurate PSDs. The PSD of most ambient PM can be described by a log-normal distribution, characterized by a mass median diameter (MMD) and geometric standard deviation (GSD).[9] The best-fit log-normal distribution of the percent mass vs. equivalent spherical diameter (ESD) was determined for each sample. The MMDs were converted from ESD to aerodynamic equivalent diameter (AED) using a particle density (ρ_p) of 2.6 g/cm^3 and a shape factor of 1.00.

$$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \quad (2)$$

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 according to eq 3:

$$C_i = C_{TSP}\int_o^i f(x)dx \quad (3)$$

where: C_i = concentration of PM smaller than or equal to size i,
C_{TSP} = concentration of total suspended particulate (TSP),
i = indicator size (10 μm for PM_{10} and 2.5 μm for $PM_{2.5}$), and
f(x) = probability density function of particle size distribution function of the dust.

The net increase in concentrations of TSP, PM_{10}, and $PM_{2.5}$ between upwind and downwind samplers was assumed to be solely attributable to the activity of interest (i.e. sweeping or pickup operations, respectively). During concentration measurements, the following instruments were used to collect onsite meteorological data:

- A 2D sonic anemometer (WindSonic1, Gill Instruments Ltd., Lymington Hampshire) was used to measure the wind speed and direction 3 m above the ground surface at a frequency of 4 Hz;

- A 3D sonic anemometer (Model 81000, R.M. Young Co., Traverse City, MI) was used to collect data for use in defining the stability of the surface layer at 2 m above the ground at a sampling frequency of 4 Hz;
- A barometric pressure sensor (Model 278, Setra Systems Inc., Boxborough, MA) recording every 5 minutes;
- A temperature and relative humidity probe mounted in a solar radiation shield at 2 m (HMP50, Campbell Scientific Inc., Logan, UT) recording every 5 minutes.
- Two pyranometers, one mounted face up (CMP 22, Kipp and Zonen, Delft, The Netherlands) and one mounted face down (CMP 6, Kipp and Zonen, Delft, The Netherlands) were used to measure net solar radiation at a sampling frequency of 5 minutes.

The dimensions of each test plot and corresponding meteorological data were then used with AERMOD to determine fluxes (µg/m^2-sec) for the each sampling period.

Modeling

AERMOD is a steady-state plume model used to relate near-field pollutant concentrations to pollutant emissions. AERMOD assumes that the horizontal distribution of a pollutant throughout the planetary boundary layer (PBL) can be described by a Gaussian distribution. The vertical distribution in the stable boundary layer (SBL) is also described by a Gaussian distribution, but in the convective boundary layer (CBL), the vertical distribution is described with a bi-Gaussian probability distribution function.[11] For this research, the model-user interface for AERMOD was BREEZE AERMOD 6 version 6.2.2 (Trinity Consultants, Dallas, TX).

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.[10] For this research, emission factors were developed for PM_{10} or $PM_{2.5}$ from almond sweeping and pick-up operations.

- Meteorological data measured onsite during each test and site data such as source-receptor orientation were processed into the proper formats and in put input into each dispersion model. A unit emission flux of 1 µg/m^2/sec was modeled.

- True PM_{10} and $PM_{2.5}$ concentrations were determined using the TSP filters and PSD analysis according to eq 3.

- The result of dispersion modeling runs (step 1) was a unit flux concentration (UFC) for each test at each sampling location. The UFC represents the change in predicted concentration for each unit increase of flux. The actual flux from the harvesting operation at each sampling location was obtained by dividing the measured pollutant concentration by the UFC (eq 4).

$$F = \frac{C_m}{UFC} \quad (4)$$

where: F = pollutant emission flux (µg/m^2-sec),
C_m = measured concentration (µg/m^3), and
UFC= unit flux concentration.

- Step 3 was repeated for TSP, FRM PM_{10}, true PM_{10}, and true $PM_{2.5}$ concentrations.

- Fluxes were converted to emission factors by manipulating the units (eq 5) and multiplying by two to account for the multiple harvest operations required to harvest Nonpareil and "pollinator" varieties.

EF (kg/km^2) = ER (kg/km^2-hr) X Time of sampling (hrs) (5)

An analysis of variance (ANOVA) test was conducted using the General Linear Model function is SPSS (SPSS v. 14.0; SPSS, Inc.; Chicago, IL) to determine whether differences existed in emission factors between treatments (α = 0.05). For both sweeping and pickup tests, the null hypothesis tested was that the means from each sweeping treatment were equal. Means were compared with the Least Significant Difference (LSD) pair-wise multiple comparison test.

Soil Content

The soil content of the windrowed materials was compared by collecting three samples from the windrows of each plot. Samples weighed approximately 750g and were collected using a flat-blade shovel to pickup all of the material in 30.5 cm (12 inch) length of windrow.

During pickup operations, three samples from each plot were collected of the materials that were being transferred into the nut cart from the chain conveyor of the pickup machine after being conditioned by passing under the blower. Conditioned samples were collected within 25 feet of the windrow samples. Each conditioned sample was collected by filling a 2.0 gallon bucket as the material fell from the chain conveyor at the rear of the pickup machine. Because the samples were collected from the material stream that would have entered the nut cart to be taken to the huller, the soil content of the samples was representative of the soil content seen by the processors. Any differences in foreign matter contect between the windrow samples and the conditioned samples were assumed to be removed during pickup either by falling through the chain conveyor or being blown into air by the fan on the pickup machine.

After collection, all windrow and conditioned samples were analyzed using a RoTap sieve shaker (Model RX-94; W.S. Tyler; Mentor, OH) to determine the mass percent of soil less than 1 mm (#18 sieve) and 75 µm (#200 sieve), respectively . Samples were processed through a set of sieves for 20 min. each. The designation of the sieves used were: 16 mm (5/8 in), 9.5 mm (3/8 in), 8 mm (5/16 in), 1 mm (#18) and

75 µm (#200). The sieves were arranged in decreasing opening size from top to bottom. The net mass remaining in each sieve was used to determine the mass percent of the original sample mass within each size range. Stones, sticks, and leaves were also separated from the samples by hand and their masses determined.

An analysis of variance (ANOVA) test was conducted using the General Linear Model function is SPSS (SPSS v. 14.0; SPSS, Inc.; Chicago, IL) to determine whether differences existed in the composition of samples formed with proper and improper sweeper settings as well as conditioned nuts that were windrowed with proper and improper sweeper settings ($\alpha = 0.05$). For both sweeping and pickup tests, the null hypothesis tested was that the mean masses of sieved samples per kilogram of raw nuts from each sweeping treatment were equal. Means were compared with the Least Significant Difference (LSD) pair-wise multiple comparison test.

Results and Discussion:

Emission Factors

Four emission factors were developed for each harvester speed treatment 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 were calculated on an annual basis rather than a per-harvest basis.

TSP and FRM PM_{10} concentrations were measured during all tests at the four downwind locations and one upwind location. Net concentration measurements from the TSP and FRM PM_{10} samplers were used to develop the annual TSP and FRM PM_{10} emission factors shown in tables 1 and 2, respectively. Statistical outliers, which occurred at the edge of the pollutant plume where the greatest uncertainties in dispersion calculations exist, were excluded. Statistical differences between treatments were detected in TSP emission factors from sweeping ($p = 0.014$) and pickup operations ($p = 0.009$). Surprisingly, the TSP emissions from sweeping with the improper sweeper setting were lower than those from the proper setting, but the TSP emissions from pickup of windrows formed with the improper sweeper setting were higher than those from pickup of windrows formed with proper sweeper setting. The emission factors for all treatments were highly variable as shown by the high standard deviations. TSP emission factors for sweeping using both treatments were substantially higher than those reported by Goodrich et al. (2008), and emission factors for nut pickup were higher than those reported by Faulkner et al. (2007). The results validate the results reported by Downey et al.[4] in that the higher TSP emissions from pickup of windrows formed with improper sweeper settings would lead to less opacity in the plume emitted by the pickup machine. It should be noted that differences in TSP emissions do not necessarily translate into differences in PM_{10} and/or $PM_{2.5}$ emissions.

Table 1. Annual TSP emission factors (kg/km^2/yr).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	12,282 x	3,514 y
Standard Deviation	13,395	2,494
N	21	16
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	4,223 x	14,885 y
Standard Deviation	3,965	15,208
N	17	14

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).

Table 2. Annual FRM PM_{10} emission factors (kg/km^2/yr).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	5,771 x	5,287 x
Standard Deviation	1,710	1,667
n	19	20
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	2,348 x	4,672 x
Standard Deviation	2,481	3,855
n	16	12

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).

No statistical differences were detected between treatments in FRM PM_{10} emissions from sweeping (p = 0.840) or pickup operations (p = 0.063), however differences in pickup operations were significant at the α = 0.10 level. Again, FRM PM_{10} emission factors for sweeping using both treatments were substantially higher than those reported by Goodrich et al[3], and emission factors for nut pickup were higher than those reported by Faulkner et al[5].

Measured emissions for sweeping were substantially higher than the current PM_{10} emission factor for almond sweeping of 415 kg PM_{10}/km^2, while emissions for nut pickup using a proper sweeper setting were approximately half of the current emission factor of 4,120 kg PM_{10}/km^2. Emissions from pickup of windrows formed using improper sweeper settings are close to the current pickup emission factor for PM_{10}.

PSD analyses were conducted on all TSP filters for which sufficient loading was present (i.e. obscurance above 1%), and the PSDs were fit with log-normal distributions. Average MMDs and GSDs of the distributions are shown in Table 3, along with the average percentages of PM that are PM_{10} and $PM_{2.5}$, respectively. No statistical

differences were detected in the MMDs or GSDs between treatments for sweeping (p = 0.449 for MMD; p = 0.546 for GSD) or pickup operations (p = 0.236 for MMD; p = 0.622 for GSD).

Table 3. Particle size distribution parameters from TSP filters.[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
MMD (µm AED)[b,c]	11.7 x	12.7 x
GSD[d]	3.0 x	2.9 x
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
MMD (µm AED)	12.3 x	11.3 x
GSD	2.6 x	2.5 x

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).
[b] MMD = mass median diameter
[c] AED = aerodynamic equivalent diameter
[d] GSD = geometric standard deviation

The average true PM_{10} and $PM_{2.5}$ emission factors are shown in tables 4 and 5, respectively. No statistical differences were detected between treatments in the emission factors for true PM_{10} from sweeping operations (p = 0.413), but emission from pickup operations of windrows formed using proper sweeper settings were less than half of those of pickup operations of windrows formed using improper sweeper depth setting (p = 0.033). Similarly, no statistical differences were detected between treatments in the emission factors for true $PM_{2.5}$ from sweeping operations (p = 0.215), but emission from pickup operations of windrows formed using proper sweeper settings were less than half of those of pickup operations of windrows formed using improper sweeper depth setting (p = 0.005). Again, both true PM_{10} and true $PM_{2.5}$ emission factors for sweeping using both treatments were substantially higher than those reported by Goodrich et al[3], and emission factors for nut pickup were higher than those reported by Faulkner et al[5].

Table 4. Annual true PM_{10} emission factors ($kg/km^2/yr$).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	1,725 x	1,335 x
Standard Deviation	1,345	517
n	7	10
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	2,232 x	4,858 y
Standard Deviation	1,929	2,846
n	10	8

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).

Table 5. Annual true $PM_{2.5}$ emission factors ($kg/km^2/yr$).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	298 x	173 x
Standard Deviation	282	65
n	7	9
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	158 x	500 y
Standard Deviation	117	291
n	9	8

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).

Again, measured emissions for sweeping were substantially higher than the current PM_{10} emission factor for almond sweeping of 415 kg PM_{10}/km^2, while emissions for nut pickup using a proper sweeper setting were approximately half of the current emission factor of 4,120 kg PM_{10}/km^2. Emissions from pickup of windrows formed using improper sweeper settings are close to the current pickup emission factor for PM_{10}.

A comparison of the average true PM_{10} concentration and the average FRM PM_{10} concentration for the same tests show a bias in the FRM sampler concentrations of approximately 20%, likely due to the inherent over-sampling bias of FRM samplers reported by Buser et al.[6] when sampling large particles. Correspondingly, true PM_{10} emission factors were lower than those calculated using FRM PM_{10} concentrations. No statistical differences were detected in the mean oversampling rates of sweeping and pickup operations (p = 0.175), as would be expected given the similarities in PSDs between operations.

Soil Content

After sieving, the hulls, and shells with meat remained on the 16 mm (5/8 in) and 9.5 mm (3/8 in) sieves along with most of the stones, sticks, and leaf material. All other foreign matter was contained in smaller sieves or the pan. The mass of foreign matter per kilogram of raw nuts (i.e. hulls, shells, and meats) from windrow and conditioned samples are shown in Table 6. As expected, the mass of all materials less than 8mm was reduced by conditioning. However, no differences were detected in the composition of windrow samples or conditioned samples as a function of sweeper setting indicating that producers likely do not introduce more soil into the hulling process by using a lower sweeper setting than that recommended by the manufacturer.

Table 6. Composition of windrow and conditioned samples (g/kg raw nuts[a]).[b]

Windrow Samples							
	Stones	**Sticks**	**Leaves**	**8-9.5mm**	**1-8mm**	**75µm-1mm**	**< 75µm**
Proper sweeper setting	23.9 x	1.95 x	2.23 x	45.8 x	403.1 x	140.0 x	64.1 x
Improper sweeper setting	43.1 x	4.72 x	1.54 x	40.1 x,y	400.6 x	128.8 x	64 6 x
Conditioned Samples							
	Stones	**Sticks**	**Leaves**	**8-9.5mm**	**1-8mm**	**75µm-1mm**	**< 75µm**
Proper sweeper setting	22.6 x	2.30 x	0.00 x	22.9 y,z	54.7 y	22.9 y	15.6 y
Improper sweeper setting	23.5 x	3.13 x	0.00 x	17.5 z	46.5 y	21.8 y	17.8 y

[a] "Raw nuts" includes meats, shells, and hulls.
[b] No statistical differences were detected in means in the same column followed by the same letter (α = 0.05).

Conclusions:

TSP, PM_{10}, and $PM_{2.5}$ emission factors were determined for almond sweeping and pickup operations for windrows formed using the recommended sweeper height adjustment and those formed using a sweeper height 1.27 cm (0.5 inches) lower than that recommended by the manufacturer. The results of this research showed no differences in emissions of regulated pollutants during the sweeping process, but emissions during pickup were significantly lower for windrows formed using proper sweeper settings versus those formed using improper sweeper settings.

The emission factors developed from this study using proper sweeper settings are 1,725±1,345 kg $PM_{10}/km^2/yr$ for sweeping and 2,232 ± 1,929 kg$PM_{10}/km^2/yr$ for pickup operations. The emission factor for sweeping is significantly higher than those reported in previous studies and is higher than the emission factor currently in use by the California Air Resources Board. The emission factor for nut pickup is similar to those reported in previous studies but lower than the emission factor of 4,120 kg PM_{10}/km^2 currently in use by the California Air Resources Board.

IMPLICATIONS

The results of this research indicate that PM_{10} emissions from modern almond pickup operations are substantially lower than the current emission factor. They also demonstrate that use of proper sweeper depth settings may reduce emissions of PM_{10} or $PM_{2.5}$, thus demonstrating this as a potential conservation management practice for reducing emissions of regulated pollutants from almond harvesting operations.

ACKNOWLEDGEMENTS

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Appendix A. List of Publications

1. Faulkner, W. B., L. B. Goodrich, V. S. V. Botlaguduru, S. C. Capareda and C. B. Parnell, Jr. 2009. Particulate matter Emission factors for Almond Harvest as a Function of Harvester Speed. Manuscript accepted for publication for the Journal of Air and Waste Management (JWMA).

2. Faulkner, W. B. and S. C. Capareda. 2009. Particulate Matter Emission factors for Almond Harvest as a Function of Sweeping Depth. Manuscript submitted for publication to the Journal of Air and Waste Management (JWMA).

Particulate Matter Emission Factors for Almond Harvest as a Function of Harvester Speed

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ABSTRACT

Almond harvest accounts for substantial PM_{10} emissions in California each harvest season. This paper addresses the reduction of harvester ground speed from a standard 8.0 km/hr (5 mph) to 4.0 km/hr (2.5 mph) as a possible mitigation measure for reducing PM_{10} emissions. Ambient total suspended particulate (TSP) and PM_{10} sampling was conducted during harvest with alternating control (8.0 km/hr [5 mph]) and experimental (4.0 km/hr [2.5 mph]) treatments. On-site meteorological data were used in conjunction with both Industrial Source Complex-Short Term version 3 (ISCST3) and the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) dispersion models to back-calculate emission rates from the measured concentrations. Baseline annual emission factors for nut pickup of 381 ± 122 kg PM_{10}/km^2-yr and 361 ± 123 kg PM_{10}/km^2-yr were determined using ISCST3 and AERMOD, respectively. Both of these values are substantially lower than the current PM_{10} emission factor for almond pickup of 4,120 kg PM_{10}/km^2-yr. The $PM_{2.5}$ emission factors for nut pickup developed from this study were 25 ± 8 kg $PM_{2.5}/km^2$-yr and 24 ± 8 kg PM_{10}/km^2-yr were determined using ISCST3 and AERMOD, respectively. Reducing harvester speed resulted in an emissions reduction of 42% for TSP, but no differences were detected in emissions of PM_{10} and $PM_{2.5}$. Differences detected in the emission factors developed using ISCST3 and AERMOD

were not statistically significant, indicating that almond harvest emission factors previously developed using ISCST3 may be applied appropriately in AERMOD.

IMPLICATIONS

The results of this research indicate that PM_{10} emissions from modern almond harvest operations are an order of magnitude lower than the current emission factor. They also demonstrate that reducing harvester ground speed leads to reductions in emissions of total suspended particulate (TSP) but has no effect on emissions of PM_{10} or $PM_{2.5}$, thus eliminating this as a potential conservation management practice for reducing emissions of regulated pollutants from almond harvesting operations.

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

INTRODUCTION

California almond farmers produce over 75% of the world's almond supply. In 2007, approximately 617Gg of almonds were harvested in California on approximately 249,000 bearing hectares with a total value of $2.3 billion.[1] Over 70% (174,217 ha) of the bearing crop is located within the San Joaquin Valley Air Pollution Control District (SJVAPCD), which was only recently removed from non-attainment status for PM_{10} under the National Ambient Air Quality Standards (NAAQS). 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. With the recent removal of the permitting exemption from agriculture, agricultural industries have 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 applied to all almond harvesting operations is 4,570 kg PM_{10}/km^2-yr, accounting for 11Gg of PM_{10} each year.[2] 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. The almonds are then swept into windrows, accounting for 415 kg PM_{10}/km^2-yr. Finally, pickup

machines remove the product from the field, 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.

Goodrich et al.[3] used the Industrial Source Complex Short Term version 3 (ISCST3) dispersion model to back-calculate a PM_{10} emission factor for conventional almond sweeping (using three blower-passes per harvested row) and reduced-pass almond sweeping (using one blower-pass per harvested row). They reported an emission factor of 379±86 kg PM_{10}/km^2-yr for conventional sweeping, which is slightly lower than the current emission factor for sweeping that was developed in the early 1990s. Goodrich et al.[3] also reported that reducing the number of blower-passes from three to one lowered the average PM_{10} emission factor by 49% to 192±41 kg PM_{10}/km^2-yr.

Downey et al.[4] tested the effect of reducing harvester ground speed on opacity measurements in the exhaust plume of almond pick-up machines. They found that reducing harvester ground speed without reducing the PTO (power take-off) speed of the tractor lead to lower opacity measurements in the plume relative to emissions from typical harvest operations, but Downey et al.[4] did not report emissions of PM_{10} or $PM_{2.5}$.

Dispersion models are used in the air pollution regulatory process to predict downwind concentrations from a source with a given emission factor and meteorological data. As of December 2006, the Environmental Protection Agency (EPA) changed the approved model from ISCST3 to the American Meteorological Society/EPA Regulatory Model (AERMOD). Due to differences in model formulation, predicted concentrations downwind of a given source may be different between models. Emission factors for agricultural sources have been developed through back-calculating emission fluxes using a dispersion model and simultaneously collected concentration and meteorological data (e.g. Goodrich et al.[3]). In previous studies, ISCST3 was used to develop emission factors for agricultural operations such as cattle feedyards, dairies, and cotton harvest systems. However, due to EPA's switch from ISCST3 to AERMOD as the preferred regulatory model, emission factors developed previously may not be applicable for use in AERMOD.[5] Faulkner et al.[5] showed that fugitive emissions from an area source may be over-estimated by AERMOD compared to ISCST3 when using the same emission factor and meteorological data.

The objectives of this study are as follows:

1. Quantify the possible emission reductions achieved through the use of reduced harvester ground speed during pickup operations;
2. Develop additional data regarding PM_{10} and $PM_{2.5}$ emissions from almond harvest to augment the existing dataset; and
3. Quantify the differences between emission factors developed with ISCST3 and AERMOD.

METHODS

This research focuses on the pickup operation of almond harvesting. Similar sweeping treatments were used in all plots to isolate the effect of harvester ground speed on PM_{10} and $PM_{2.5}$ emissions. Sampling was conducted in the Central Sacramento Valley near Arbuckle, California, in an orchard with a Hillgate loam which was 18.8% clay. The trees in this orchard were nine years old and were oriented north-south. Trees were planted in 400 m rows with 6.7 m between rows and 5.5 m between trees in the same row. The prevailing wind during sampling was from the north.

The pickup machine used in this work was a Flory Model 850 PTO Harvester. Plots were organized in a completely randomized design with a control (8.0 km/hr [5.0 mph] ground speed) and experimental (4.0 km/hr [2.5 mph] ground speed) treatment. The tractor PTO was operated at the recommended speed for both tests, resulting in equivalent harvester fan and belt speeds for all tests. Plot size was adjusted by varying the number of tree rows harvested so that each test lasted approximately one hour. A total of five replications were conducted for each treatment.

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 a "pollinator" variety or a Nonpareil with two "pollinator" 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, but the harvest process is identical for the alternating rows that mature later in the season. For this reason, the emission

rates developed from sampling were assumed to represent half the total annual emissions from harvest operations.

Ambient Sampling

Samplers were placed upwind and downwind of each plot to measure the ambient particulate matter (PM) concentrations. At each sampling location, collocated, low-volume TSP and federal reference method (FRM) PM_{10} samplers (Model PQ100 Inlet; BGI Inc.; Waltham, MA) were used to determine PM concentrations. FRM $PM_{2.5}$ samplers were not used because the low concentrations of $PM_{2.5}$ emitted during almond harvest operations during the sampling period did not allow for sufficient loading on the filters to render reliable FRM $PM_{2.5}$ measurements. (According to Goodrich et al.[3] $PM_{2.5}$ constituted only 0.9% of TSP sampled during sweeping operations). Sampler sets were placed at four locations approximately 15 m downwind from the edge of the plot such that there was enough room for the harvester to make turns and remain upwind of the sampler array. The downwind sampling locations were spaced evenly along the width of each plot (fig. 1). The four downwind sampler sets provided four independent measurements of concentration leading to four independent estimates of the flux for each test. Samplers were set up at both upwind and downwind locations to measure the net increase in PM concentrations due to the harvesting process.

Due to the errors associated with FRM sampling in agricultural environments identified by Buser et al.[6], both TSP measurements and FRM PM_{10} measurements were conducted. TSP measurements were conducted with samplers designed by Wanjura et al.[7] 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.

The filters used in the TSP and PM_{10} samplers were weighed using a 10 μg analytical balance (AG245; Mettler-Toledo International Inc.; Columbus, OH). Each filter was pre- and post-weighed three times. If the standard deviation of the three pre- or post-weights was less than 50 μg, the average of the three weights were taken as the pre- and post-weights, respectively. If the standard deviation of the three weights was greater than 50 μg, the filter was reweighed. The change in filter mass, flow rate through the sampler, and sampling duration for each sampler and test were used to calculate the PM concentration (eq 1).

$$C = \frac{\Delta m_f}{Q_{air} \cdot t_D} \quad (1)$$

where: C = concentration ($\mu g/m^3$),

Δm_f = change in mass on the filter (μg),

Q_{air} = sampling flow rate (m^3/sec), and

t_D = sampling duration (sec).

The particle size distribution (PSD) of PM collected on TSP filters having more than 200 μg of PM were analyzed using a particle size analyzer (Mastersizer 2000, Malvern Instruments Inc.) with a detection range of 0.2 μm to 2000 μm. Samples were prepared according to the procedure described by Faulkner and Shaw[8] with the exception that the entire filter was analyzed rather than core samples. A minimum net filter mass of 200 μm was required to obtain accurate PSDs. The PSD of most ambient PM can be described by a log-normal distribution, characterized by a mass median diameter (MMD) and geometric standard deviation (GSD).[9] The best-fit log-normal distribution of the percent mass vs. equivalent spherical diameter (ESD) was determined for each sample. The MMDs were converted from ESD to aerodynamic equivalent diameter (AED) using a particle density (ρ_p) of 2.0 g/cm^3 and a shape factor of 1.00.

$$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \quad (2)$$

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 according to eq 3:

$$C_i = C_{TSP}\int_o^i f(x)dx \quad (3)$$

where: C_i = concentration of PM smaller than or equal to size i,

C_{TSP} = concentration of total suspended particulate (TSP),

i = indicator size (10 μm for PM_{10} and 2.5 μm for $PM_{2.5}$), and

f(x) = probability density function of particle size distribution function of the dust.

The net increase in concentrations of TSP, PM_{10}, and $PM_{2.5}$ between upwind and downwind samplers was assumed to be solely attributable to the activity of interest, in this case, pickup operations. During concentration measurements, the following instruments were used to collect onsite meteorological data:

- A 2D sonic anemometer (WindSonic1, Gill Instruments Ltd., Lymington Hampshire) was used to measure the wind speed and direction 3 m above the ground surface at a frequency of 4 Hz;
- A 3D sonic anemometer (Model 81000, R.M. Young Co., Traverse City, MI) was used to collect data for use in defining the stability of the surface layer at 2 m above the ground at a sampling frequency of 4 Hz;
- A barometric pressure sensor (Model 278, Setra Systems Inc., Boxborough, MA) recording every 5 minutes;
- A temperature and relative humidity probe mounted in a solar radiation shield at 2 m (HMP50, Campbell Scientific Inc., Logan, UT) recording every 5 minutes.
- Two pyranometers, one mounted face up (CMP 22, Kipp and Zonen, Delft, The Netherlands) and one mounted face down (CMP 6, Kipp and Zonen, Delft, The Netherlands) were used to measure net solar radiation at a sampling frequency of 5 minutes.

The dimensions of each test plot and corresponding meteorological data were then used with ISCST3 and AERMOD to determine fluxes ($\mu g/m^2$-sec) for the each sampling period. Each test lasted approximately one hour.

Modeling

Industrial Source Complex. ISCST3 is a steady state Gaussian plume model that can be used to predict pollutant concentrations downwind from area sources.[10] ISCST3 was the EPA-preferred near-field dispersion model until 2006. Goodrich et al.[3] used ISCST3 to determine emission fluxes from sweeping operations.

The basis for all ISCST3 calculations is a double Gaussian algorithm representing a point source (eq 4). Eq. 4 is integrated by ISCST3 along a path to represent a finite line source, and multiple line-source algorithms are used in ISCST3 to model area sources.

$$C = \frac{Q}{2\pi\, u \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(H-z)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(H+z)^2}{2\sigma_z^2}\right]\right\} \quad (4)$$

where: C = predicted concentration ($\mu g/m^3$),

Q = emission rate ($\mu g/sec$),

u = wind speed at the point of emissions release (m/sec),

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).

For this research, each input to ISCST3 was either measured in the field or calculated from measured values. Five-minute averages of all inputs were used. The Pasquill-Gifford dispersion parameters were calculated based on the atmospheric stability class using the Solar Radiation Delta-T (SRDT) method.[11] For this research, the model-user interface for ISCST3 was BREEZE ISC GIS Pro version 5.2.1 (Trinity Consultants, Dallas, TX).

AERMOD. AERMOD is also based on a steady-state plume model, but it also incorporates recent advances in atmospheric science, especially in the planetary boundary layer (PBL).[12] AERMOD assumes that the horizontal distribution throughout the entire PBL can be described by a Gaussian distribution. The vertical distribution in the stable boundary layer (SBL) is also described by a Gaussian distribution, but in the convective boundary layer (CBL), the vertical distribution is described with a bi-Gaussian probability distribution function.[13] AERMOD also incorporates more meteorological data into the model than ISCST3, such as albedo, Bowen ratio, and more resolved surface roughness. Again, five-minute averages of all inputs were used. For this research, the model-user interface for AERMOD was BREEZE AERMOD 6 version 6.2.2 (Trinity Consultants, Dallas, TX), and the AERMOD version 07026 was used.

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.[10] For this research, emission factors were developed for PM_{10} or $PM_{2.5}$ from almond pick-up operations.

1. Meteorological data measured onsite during each test (table 1) and site data such as source-receptor orientation were processed into the proper formats and input into each

dispersion model. A unit emission flux of 1 μg/m^2-sec was modeled using a surface roughness value of 0.5 m.

2. True PM_{10} and $PM_{2.5}$ concentrations were determined using the TSP filters and PSD analysis according to eq 3.
3. The result of dispersion modeling runs (step 1) was a unit flux concentration (UFC) for each test at each sampling location. The UFC represents the change in predicted concentration for each unit increase of flux. The actual flux from the harvesting operation at each sampling location was obtained by dividing the measured pollutant concentration by the UFC (eq 4).

$$F = \frac{C_m}{UFC} \quad (4)$$

where: F = pollutant emission flux (μg/m^2-sec),

C_m = measured concentration (μg/m^3), and

UFC= unit flux concentration.

4. Step 3 was repeated for TSP, FRM PM_{10}, true PM_{10}, and true $PM_{2.5}$ concentrations.
5. Fluxes were converted to emission factors by manipulating the units (eq 5) and multiplying by two to account for the multiple harvest operations required to harvest Nonpareil and "pollinator" varieties.

$$EF\ (kg/km^2) = ER\ (kg/km^2\text{-}hr)\ X\ Time\ of\ sampling\ (hrs) \quad (5)$$

An analysis of variance (ANOVA) test was conducted using the General Linear Model function is SPSS (SPSS v. 14.0; SPSS, Inc.; Chicago, IL) to determine whether differences existed in emission factors between treatments ($\alpha = 0.05$). The null hypothesis tested was that the means from each harvester speed treatment were equal. Means were compared with the Least Significant Difference (LSD) pair-wise multiple comparison test.

RESULTS AND DISCUSSION

Concentrations

TSP and FRM PM_{10} concentrations were measured during all tests at the four downwind locations and one upwind location. Net concentration measurements for the TSP and FRM PM_{10} samplers are shown in table 2. The large standard errors in the measured TSP and PM_{10} concentrations reflect the many uncontrollable variables that affect concentration measurements

such as variations in wind speed and direction during a given test. No statistical differences in measured TSP or FRM PM_{10} concentrations were detected between treatments ($\alpha = 0.05$).

PSD analyses were conducted on all TSP filters, and the PSDs were fit with log-normal distributions. Average MMDs and GSDs of the distributions are shown in table 3, along with the percentage of PM that is PM_{10} and $PM_{2.5}$, respectively.

The average true PM_{10} and $PM_{2.5}$ concentrations are shown in table 4. The true PM_{10} concentrations were lower than those measured by the FRM PM_{10} samplers due to the over-sampling bias of FRM samplers reported by Buser et al.[6]. No statistical differences were detected between treatments in the true concentrations of PM_{10} or $PM_{2.5}$. Again, differences in concentrations do not necessarily reflect differences in emission factors.

A comparison of the average true PM_{10} concentration (table 4) and the average FRM PM_{10} concentration for the same tests (table 2) show a bias in the FRM sampler concentrations of approximately 11% for the 8.0 km/hr (5 mph) tests and 3.3% for the 4.0 km/hr (2.5 mph) tests. The differences in sampler bias between tests reflect the increased bias reported by Buser et al.[6] 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

Four emission factors were developed for each harvester speed treatment 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 were calculated 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 5. The TSP emission factor for harvesting at the "standard" speed of 8.0 km/hr (5 mph) was 1,117 kg TSP/km^2-yr when using ISC or 1,057 TSP kg/km^2-yr when using AERMOD. These emission factors were not statistically different (α=0.05), nor were the emission factors for the 4.0 km/hr (2.5 mph) harvester speed. The lack of significant difference between the emission factors developed using both ISC and AERMOD is an important finding in that the previous emission factors for almond harvest operations developed using ISC may produce comparable results when used in AERMOD under the same meteorological conditions.

Differences were detected in both ISCST3 and AERMOD TSP emission factors between harvester speed treatments The TSP emission factor for the 4.0 km/hr (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 are presented in table 6. These emission factors were calculated for both models using true PM_{10} concentrations determined from TSP concentrations and particle size analysis. Due to the differences in the PSDs between treatments (table 3), 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 ($\alpha = 0.05$).

Emission factors from FRM PM_{10} concentrations calculated using both ISC and AERMOD are shown in table 7. No statistical differences were detected in FRM PM_{10} emission factors for almond harvest between models or between treatments ($\alpha = 0.05$).

True $PM_{2.5}$ emission factors are presented in table 8. These emission factors were calculated for both models using $PM_{2.5}$ concentrations determined from TSP concentrations and particle size analysis. No statistical differences were detected in $PM_{2.5}$ emission factors for almond harvest between models or between treatments ($\alpha = 0.05$).

No significant differences were detected in predicted concentrations between ISCST3 and AERMOD 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 (4.195) 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. 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 when 24-hour modeling is conducted.

CONCLUSIONS

PM_{10} and $PM_{2.5}$ emission factors were determined for almond harvesting operations for both a standard speed (8.0 km/hr [5 mph]) and an experimental slower low-speed (4.0 km/hr [2.5 mph]) being evaluated as a potential mitigation practice. The results of this research show that there is no statistical difference in the emissions of PM_{10} or $PM_{2.5}$ per unit area from harvesters when harvester speed is reduced. A significant difference was detected in the emission of TSP, which may affect visibility impairment, but no differences were detected in emissions of regulated pollutants. The emission factors developed from this study are 381 ± 122 kg PM_{10}/km^2-yr with ISCST3 and 361 ± 123 kg PM_{10}/km^2-yr with AERMOD. These emission factors are significantly lower than the emission factor of 4,120 kg PM_{10}/km^2-yr currently in use by the California Air Resources Board. The $PM_{2.5}$ emission factors for nut pickup developed from this study were 25 ± 8 kg $PM_{2.5}/km^2$-yr and 24 ± 8 kg PM_{10}/km^2-yr were determined using ISCST3 and AERMOD, respectively.

No differences were detected in the emission factors calculated from measured concentrations using ISCST3 and AERMOD, indicating that almond harvest emission factors previously developed by Goodrich et al.[3] using ISCST3 may be applicable in AERMOD without modification.

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TABLES

Table 1. Meteorological parameters measured onsite during sampling.

Table 1. Meteorological parameters measured onsite during sampling.

	Min.	Max.	Average
Albedo	0.10	0.20	0.14
Bowen Ratio	0.1	0.89	0.1
Relative Humidity	30%	50%	40%
Temperature (ºC)	18	29	23
Solar Radiation (W/m^2)	563	965	837
Wind Speed (m/s)	0.3	2.9	1.9

Table 2. Average net measured TSP and FRM PM_{10} concentrations (µg/m^3).

Table 2 Average net measured TSP and FRM PM_{10} concentrations (µg/m^3).

	8.0 km/hr (5 mph)		4.0 km/hr (2.5 mph)	
	TSP	FRM PM_{10}	TSP	FRM PM_{10}
Mean	1,110 x	422 y	680 x	336 y
Standard Error	158	45	181	70
Minimum	274	184	68	17
Maximum	3,192	851	2,891	867
n	19	17	18	17

[a] No statistical differences were detected in means followed by the same letter.

Table 3. Particle size distribution parameters from TSP filters.

Table 3. Particle size distribution parameters from TSP filter.

Speed	MMD (µm AED)	GSD	% PM_{10}	% $PM_{2.5}$
8.0 km/hr (5 mph)	14.3	2.4	34	2
4.0 km/hr (2.5 mph)	11.0	2.2	45	3

415

416 Table 4. True PM_{10} and $PM_{2.5}$ concentrations ($\mu g/m^3$).

Table 4. True PM_{10} and $PM_{2.5}$ concentrations ($\mu g/m^3$).

	8.0 km/hr (5 mph)		4.0 km/hr (2.5 mph)	
	True PM_{10}	**True $PM_{2.5}$**	**True PM_{10}**	**True $PM_{2.5}$**
Mean	379 x	26 y	307 x	20 y
Standard Error	54	4	82	2
Minimum	94	6	31	2
Maximum	1,090	74	1,306	87
n	19	19	18	18

[a] No statistical differences were detected in means followed by the same letter.

417

418 Table 5. Annual TSP emission factors (kg/km^2-yr).[a]

Table 5. Annual TSP emission factors (kg/km^2-yr).[a]

	ISCST3		AERMOD	
	8.0 km/hr (5 mph)	**4.0 km/hr (2.5 mph)**	**8.0 km/hr (5 mph)**	**4.0 km/hr (2.5 mph)**
Mean	1,117 x	691 y	1,057 x	609 y
Standard Error	183	113	186	83
Minimum	234	238	272	222
Maximum	2,860	1,972	2,884	1,396
n	19	18	19	18

[a] No statistical differences were detected in means followed by the same letter.

419

420 Table 6. Annual true PM_{10} emission factors (kg/km^2-yr).[a]

Table 6. Annual true PM_{10} emission factors (kg/km^2-yr).[a]

	ISCST3		AERMOD	
	8.0 km/hr (5 mph)	**4.0 km/hr (2.5 mph)**	**8.0 km/hr (5 mph)**	**4.0 km/hr (2.5 mph)**
Mean	381	312	361	275
Standard Error	62	51	63	37
Minimum	80	107	93	100
Maximum	977	891	985	630
n	19	18	19	18

[a] No statistical differences were detected between means ($\alpha = 0.05$).

421

422 Table 7. Annual FRM PM_{10} emission factors (kg/km^2-yr).[a]

Table 7. Annual FRM PM_{10} emission factors (kg/km^2-yr).[a]

	ISCST3		AERMOD	
	8.0 km/hr (5 mph)	**4.0 km/hr (2.5 mph)**	**8.0 km/hr (5 mph)**	**4.0 km/hr (2.5 mph)**
Mean	413	340	400	336
Standard Error	50	52	55	84
Minimum	118	61	91	57
Maximum	821	728	926	1,545
n	17	17	17	17

[a] No statistical differences were detected between means ($\alpha = 0.05$).

423

Table 8. Annual true $PM_{2.5}$ emission factors (kg/km^2-yr).[a]

Table 8. Annual true $PM_{2.5}$ emission factors (kg/km^2-yr).[a]

	ISCST3		AERMOD	
	8.0 km/hr (5 mph)	**4.0 km/hr (2.5 mph)**	**8.0 km/hr (5 mph)**	**4.0 km/hr (2.5 mph)**
Mean	26	21	25	18
Standard Error	4	4	4	3
Minimum	5	7	6	7
Maximum	66	59	67	42
n	19	18	19	18

[a] No statistical differences were detected between means ($\alpha = 0.05$).

FIGURE CAPTIONS

Figure 1. . Sampler configuration.

Figure 2. Regression analysis of ISC and AERMOD TSP emission factors.

Particulate Matter Emission Factors for Almond Harvest as a Function of Sweeping Depth

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ABSTRACT

Almond harvest accounts for substantial PM_{10} emissions in California each harvest season. This paper addresses the adjustment of sweeper depth and its affect on PM emissions from sweeping and pickup operations. Ambient total suspended particulate (TSP) and PM_{10} sampling was conducted during harvest with alternating control (proper sweeper setting) and experimental (sweeper depth 1.27 cm [0.5 in.] lower than recommended) treatments. On-site meteorological data were used in conjunction with dispersion modeling using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) to back-calculate emission rates from the measured concentrations. The PM_{10} emission factors developed from this study using proper sweeper settings are 1,725$\pm$996 kg PM_{10}/km^2-yr for sweeping and 2,232$\pm$1,196 kg PM_{10}/km^2-yr for pickup operations. The emission factor for sweeping is significantly higher than those reported in previous studies and is higher than the emission factor currently in use by the California Air Resources Board. The emission factor for nut pickup is higher than those reported in previous studies but lower than the emission factor of 4,120 kg PM_{10}/km^2-yr currently in use by the California Air Resources Board. The $PM_{2.5}$ emission factors developed from this study using proper sweeper settings are 298$\pm$208 kg $PM_{2.5}/km^2$-yr for sweeping and 158$\pm$76 kg $PM_{2.5}/km^2$-yr for pickup operations. The results of this research showed no differences in emissions of regulated pollutants during the sweeping process as a function of sweeper depth, but emissions during pickup were significantly lower (by about half) for windrows formed using proper sweeper settings versus those formed using improper sweeper settings.

IMPLICATIONS

The results of this research indicate that PM_{10} emissions from modern almond pickup operations are substantially lower than the current emission factor. They also demonstrate that use of proper sweeper depth settings may reduce emissions of PM_{10} and $PM_{2.5}$ during nut pickup, thus validating this as a potential conservation management practice for reducing emissions of regulated pollutants from almond harvesting operations.

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

INTRODUCTION

California almond farmers produce over 75% of the world's almond supply. In 2007, approximately 617Gg of almonds were harvested in California on approximately 249,000 bearing hectares with a total value of $2.3 billion.[1] Over 70% (174,217 ha) of the bearing crop is located within the San Joaquin Valley Air Pollution Control District (SJVAPCD), which was only recently removed from non-attainment status for PM_{10} under the National Ambient Air Quality Standards (NAAQS). Due to the recent classification of the San Joaquin Valley (SJV) as a serious non-attainment area for PM_{10}, the SJVAPCD is in the midst of an aggressive campaign to reduce PM_{10} emissions from all sources. With the removal of the permitting exemption from agriculture in 2003 as a result of California Senate Bill 700, agricultural industries have 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 applied to all almond harvesting operations is 4,570 kg PM_{10}/km^2-yr, accounting for 11 Gg of PM_{10} each year.[2] 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 while sitting on the ground; this accounts for 41.5 kg PM_{10}/km^2-yr of the emission factor. The almonds are then swept into windrows, accounting for 415 kg PM_{10}/km^2-yr. Finally, pickup machines remove the product from the field, currently accounting for 4,120 kg PM_{10}/km^2-yr. Each harvest process accounts for substantial emissions due to the total area to which the emission factors are applied.

Goodrich et al.[3] used the Industrial Source Complex Short Term version 3 (ISCST3) dispersion model to back-calculate a PM_{10} emission factor for conventional almond sweeping (using three blower-passes per harvested row) and reduced-pass almond sweeping (using one blower-pass per harvested row). They reported an emission factor of 379±86 kg PM_{10}/km^2-yr for conventional sweeping, which is slightly lower than the current emission factor for sweeping developed in the early 1990s. Goodrich et al.[3] also reported that reducing the number of blower-passes from three to one lowered the average PM_{10} emission factor by 49% to 192±41 kg PM_{10}/km^2-yr.

Downey et al.[4] tested the effect of reducing harvester ground speed on opacity measurements in the exhaust plume of almond pick-up machines. They found that reducing harvester ground speed without reducing the PTO speed of the tractor led to lower opacity measurements in the plume relative to emissions from typical harvest operations, but Downey et al.[4] did not report emissions of PM_{10} or $PM_{2.5}$.

Faulkner et al.[5] used both ISCST3 and the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) dispersion models with measured ambient concentrations to test the effect of reduced harvester ground speed on emissions of total suspended particulate (TSP), PM_{10}, and $PM_{2.5}$ from nut pickup operations in an effort to determine the implications of the work of Downey et al.[4] for regulated pollutants. Faulkner et al.[5] reported no statistical differences in PM_{10} or $PM_{2.5}$ emission factors as a function of harvester speed or dispersion model used, but TSP emission factors were lower for the slower harvester speed, which supports the findings of Downey et al.[4] that plume opacity varies with harvester speed. The emission factors for nut pickup developed using AERMOD were 361±123 kg PM_{10}/km^2-yr and 25±8 kg $PM_{2.5}/km^2$-yr. The PM_{10} emission factor developed by Faulkner et al.[5] is significantly lower than the emission factor of 4,120 kg PM_{10}/km^2-yr currently in use by the California Air Resources Board.

According to current emission factors, sweeping accounts for 9% of the total PM_{10} emissions from almond harvesting operations. As demonstrated by Goodrich et al.[3], sweeping practices may dramatically affect PM emissions from sweeping operations. Sweeping practices may also affect emissions from pickup operations as increased soil material in the windrow may increase PM emissions during nut pickup. Sweeper manufacturers recommend setting the sweeper head such that the steel teeth of the implement just clear the surface of the orchard floor

without causing ground interference. However, many sweeper operators set the sweeper head lower than recommended by manufacturers in an attempt to decrease the number of unharvested nuts left on the orchard floor. This lower setting leads to ground interference by the sweeper unit, which may increase emissions from sweeping operations, increase emissions from pickup operations, and increase the amount of dirt transported to the huller with the almonds, thus leading to increased processing costs for the producer. Downey et al.[4] reported a 32% increase in opacity measurements in the dust plume from nut pickup operations harvesting windrows of nuts formed using improper sweeper depth adjustments (1.27 cm [0.5 in.] lower than recommended by the manufacturer) compared to dust emitted from harvest operations of windrows formed with proper settings. Again, Downey et al.[4] did not report emissions of regulated pollutants.

The objectives of this study are as follows:

1. Quantify the possible emission reductions during sweeping and pickup operations achieved through the use of proper sweeper depth settings;
2. Quantify differences in foreign matter content of almonds taken to the huller between those windrowed using proper and improper sweeper depth settings; and
3. Develop additional data regarding PM_{10} and $PM_{2.5}$ emissions from almond harvest to augment the existing dataset.

METHODS

This research focuses on the emissions from sweeping and pickup operations of almond harvesting as a function of sweeper depth settings. Sweeping treatments included a control treatment of proper sweeper setting (no ground interference) and an experimental treatment in which 1.27 cm (0.5 in.) ground interference occurred between the steel teeth of the sweeper and the orchard floor. Pickup operations for both sweeper treatments were identical in order to isolate the effect of sweeper setting on PM emissions. The sweeper used in this work was a Flory 77 Series, and the pickup machine was a Flory Model 850 PTO Harvester (Flory Industries, Modesto, CA).

Plots were organized in a randomized complete block design with replication as the blocking factor. Each plot consisted of ten tree rows. Almond growers commonly plant a combination of almond varieties in a given orchard to achieve cross pollination. The usual

combination is a Nonpareil variety with a "pollinator" variety or a Nonpareil with two "pollinator" varieties, such as Carmel and Butte, in each orchard. In newer orchards, 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. Therefore, while each plot consisted of ten tree rows and ten windrows were created, only five tree rows were harvested. The remaining tree rows are harvested when the nuts mature using an identical harvest process. The overall emission factor is the sum of the two harvesting operations for each variety. Because the harvest processes are identical for each variety, the emission rates developed from sampling were assumed to represent half the total annual emissions from harvest operations.

Sampling was conducted in the Central Sacramento Valley near Arbuckle, California, in an orchard with a Hillgate loam which was 18.8% clay. The trees in this orchard were ten years old and were oriented north-south. Trees were planted in 400 m rows with 6.7 m between rows and 5.5 m between trees in the same row. Sampling was conducted during sweeping of all plots. Nuts were then allowed to air dry in windrows for several days before sampling was again conducted on the same plots during nut pickup.

Ambient Sampling

Samplers were placed upwind and downwind of each plot to measure the ambient particulate matter (PM) concentrations during sweeping and pickup operations. At each sampling location, collocated, low-volume TSP and federal reference method (FRM) PM_{10} samplers (Model PQ100 Inlet; BGI Inc.; Waltham, MA) were used to determine PM concentrations. FRM $PM_{2.5}$ samplers were not used because the low concentrations of $PM_{2.5}$ emitted during almond harvest operations during the sampling period did not allow for sufficient loading on the filters to render reliable FRM $PM_{2.5}$ measurements. (According to Goodrich et al.[3] $PM_{2.5}$ constituted only 0.9% of TSP sampled during sweeping operations). Sampler sets were placed at four locations approximately 15 m downwind from the edge of the plot such that there was enough room for the sweeper or harvester to make turns and remain upwind of the sampler array. The downwind sampling locations were spaced evenly along the width of each plot (fig. 1). The four downwind sampler sets provided four independent measurements of concentration leading to four independent estimates of the flux for each test. Samplers were set

154 up at both upwind and downwind locations to measure the net increase in PM concentrations due
155 to the harvesting process.

156 Due to the errors associated with FRM sampling in agricultural environments identified
157 by Buser et al.[6], both TSP measurements and FRM PM_{10} measurements were conducted. TSP
158 measurements were conducted with samplers designed by Wanjura et al.[7] to reduce variations in
159 sampler flow rate that lead to high uncertainty in FRM concentration measurements. PM_{10}
160 measurements were conducted using the same air-flow control unit as the TSP samplers and an
161 FRM PM_{10} sampling inlet.

162 The filters used in the TSP and PM_{10} samplers were weighed using a 10 μg analytical
163 balance (AG245; Mettler-Toledo International Inc.; Columbus, OH). Each filter was pre- and
164 post-weighed three times. If the standard deviation of the three pre- and post-weights was less
165 than 50 μg, the average of the three weights were taken as the pre- and post-weights,
166 respectively. If the standard deviation of the three weights was greater than 50 μg, the filter was
167 reweighed. The change in filter mass, flow rate through the sampler, and sampling duration for
168 each sampler and test were used to calculate the PM concentration (eq 1).

169 $$C = \frac{\Delta m_f}{Q_{air} \cdot t_D} \quad (1)$$

170 where: C = concentration ($\mu g/m^3$),

171 Δm_f = change in mass on the filter (μg),

172 Q_{air} = sampling flow rate (m^3/sec), and

173 t_D = sampling duration (sec).

174 The particle size distribution (PSD) of PM collected on TSP filters having more than 200
175 μg of PM were analyzed using a particle size analyzer (Mastersizer 2000, Malvern Instruments
176 Inc., Westborough, MA) with a detection range of 0.2 μm to 2000 μm. Samples were prepared
177 according to the procedure described by Faulkner and Shaw[8] with the exception that the entire
178 filter was analyzed rather than core samples. A minimum net filter mass of 200 μm was required
179 to obtain accurate PSDs. The PSD of most ambient PM can be described by a log-normal
180 distribution, characterized by a mass median diameter (MMD) and geometric standard deviation
181 (GSD).[9] The best-fit log-normal distribution of the percent mass vs. equivalent spherical
182 diameter (ESD) was determined for each sample. The MMDs were converted from ESD to
183 aerodynamic equivalent diameter (AED) using a particle density (ρ_p) of 2.6 g/cm^3 (based on soil

184 samples taken from the orchard and analyzed using a pycnometer (AccuPyc 1330 Pycnometer,
185 Micrometrics, Norcross, GA)) and a shape factor of 1.00.

186 $$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \quad (2)$$

187 where: AED = aerodynamic equivalent diameter,
188 ESD = equivalent spherical diameter,
189 ρ_p = particle density (g/cm^3), and
190 χ = shape factor.
191 The resulting PSD was then used to determine the true percentage of PM_{10} and $PM_{2.5}$ on each
192 filter according to eq 3:

193 $$C_i = C_{TSP}\int_o^i f(x)dx \quad (3)$$

194 where: C_i = concentration of PM smaller than or equal to size i (μg/m^3),
195 C_{TSP} = concentration of total suspended particulate (μg/m^3),
196 i = indicator size (10 μm for PM_{10} and 2.5 μm for $PM_{2.5}$), and
197 f(x) = cumulative probability density function of particle size distribution function of the
198 dust.
199 The net increase in concentrations of TSP, PM_{10}, and $PM_{2.5}$ between upwind and
200 downwind samplers was assumed to be solely attributable to the activity of interest (i.e.
201 sweeping or pickup operations, respectively). During concentration measurements, the
202 following instruments were used to collect onsite meteorological data:

203 • A 2D sonic anemometer (WindSonic1, Gill Instruments Ltd., Lymington Hampshire) was
204 used to measure the wind speed and direction 3 m above the ground surface at a frequency
205 of 4 Hz;
206 • A 3D sonic anemometer (Model 81000, R.M. Young Co., Traverse City, MI) was used to
207 collect data for use in defining the stability of the surface layer at 2 m above the ground at a
208 sampling frequency of 4 Hz;
209 • A barometric pressure sensor (Model 278, Setra Systems Inc., Boxborough, MA) recording
210 every 5 minutes;
211 • A temperature and relative humidity probe mounted in a solar radiation shield at 2 m
212 (HMP50, Campbell Scientific Inc., Logan, UT) recording every 5 minutes.

- Two pyranometers, one mounted face up (CMP 22, Kipp and Zonen, Delft, The Netherlands) and one mounted face down (CMP 6, Kipp and Zonen, Delft, The Netherlands) were used to measure net solar radiation at a sampling frequency of 5 minutes.

Additional meteorological parameters were calculated according to USEPA guidance.[10] The dimensions of each test plot and corresponding meteorological data were then used with AERMOD to determine fluxes ($\mu g/m^2$-sec) for the each sampling period.

Modeling

AERMOD is a steady-state plume model used to relate near-field pollutant concentrations to pollutant emissions. AERMOD assumes that the horizontal distribution of a pollutant throughout the planetary boundary layer (PBL) can be described by a Gaussian distribution. The vertical distribution in the stable boundary layer (SBL) is also described by a Gaussian distribution, but in the convective boundary layer (CBL), the vertical distribution is described with a bi-Gaussian probability distribution function.[10] For this research, the model-user interface for AERMOD was BREEZE AERMOD 6 version 6.2.2 (Trinity Consultants, Dallas, TX), and AERMOD version 07026 was used.

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.[11] For this research, emission factors were developed for TSP, PM_{10}, or $PM_{2.5}$ from almond sweeping and pick-up operations using the following protocol:

1. Meteorological data measured onsite during each test and site data such as source-receptor orientation were processed into the proper formats and input into AERMOD. A unit emission flux of 1 $\mu g/m^2$-sec was modeled using a surface roughness value of 0.5 m and five-minute averages of all measured meteorological inputs.
2. True PM_{10} and $PM_{2.5}$ concentrations were determined using the TSP filters and PSD analysis according to eq 3.
3. The result of dispersion modeling runs (step 1) was a unit flux concentration (UFC) for each test at each sampling location. The UFC represents the change in predicted concentration for each unit increase of flux. The actual flux from the harvesting operation at each sampling location was obtained by dividing the measured pollutant concentration by the UFC (eq 4).

$$F = \frac{C_m}{UFC} \quad (4)$$

where: F = pollutant emission flux ($\mu g/m^2$-sec),

C_m = measured concentration ($\mu g/m^3$), and

UFC = unit flux concentration.

4. Step 3 was repeated for TSP, FRM PM_{10}, true PM_{10}, and true $PM_{2.5}$ concentrations.
5. Fluxes were converted to emission factors by manipulating the units (eq 5) and multiplying by two to account for the multiple harvest operations required to harvest Nonpareil and "pollinator" varieties.

$$EF\ (kg/km^2) = ER\ (kg/km^2\text{-}hr) \times Time\ of\ sampling\ (hrs) \quad (5)$$

An analysis of variance (ANOVA) test was conducted using the General Linear Model function is SPSS (SPSS v. 14.0; SPSS, Inc.; Chicago, IL) to determine whether differences existed in emission factors between treatments ($\alpha = 0.05$). For both sweeping and pickup tests, the null hypothesis tested was that the means from each sweeping treatment were equal. Means were compared with the Least Significant Difference (LSD) pair-wise multiple comparison test.

Foreign Matter Content

The foreign matter content of the windrowed materials was compared by collecting three samples from the windrows of each plot. Samples weighed approximately 750 g and were collected using a flat-blade shovel to pickup all of the material in 30.5 cm (12 in) length of windrow.

During pickup operations, three samples of the materials that were being transferred into the nut cart from the chain conveyor of the pickup machine after being conditioned by passing under the blower were collected from each plot. Conditioned samples were collected within 25 feet of the windrow samples. Each conditioned sample was collected by filling a 7.6 L (2.0 gallon) bucket as the material fell from the chain conveyor at the rear of the pickup machine (fig. 2). Because the samples were collected from the material stream that would have entered the nut cart to be taken to the huller, the foreign matter content of the samples was representative of the foreign matter content seen by the processors. Any differences in foreign matter content between the windrow samples and the conditioned samples were assumed to be removed during pickup either by falling through the chain conveyor or being blown into air by the fan on the pickup machine.

After collection, all windrow and conditioned samples were analyzed using a RoTap sieve shaker (Model RX-94; W.S. Tyler; Mentor, OH) to determine the mass percent of foreign matter of various sizes. Samples were processed through a set of sieves for 20 min. each. The designation of the sieves used were: 16 mm (5/8 in), 9.5 mm (3/8 in), 8 mm (5/16 in), 1 mm (#18) and 75 μm (#200). The sieves were arranged in decreasing opening size from top to bottom. The net mass remaining in each sieve was used to determine the mass percent of the original sample mass within each size range. Stones, sticks, and leaves were also separated from the samples by hand and their masses determined.

An analysis of variance (ANOVA) test was conducted using the General Linear Model function is SPSS (SPSS v. 14.0; SPSS, Inc.; Chicago, IL) to determine whether differences existed in the composition of windrow samples formed with proper and improper sweeper settings as well as conditioned samples that were windrowed with proper and improper sweeper settings ($\alpha = 0.05$). For both sweeping and pickup tests, the null hypothesis tested was that the mean masses of sieved samples per kilogram of raw nuts (i.e. hulls, shells, and meats) from each sweeping treatment were equal. Means were compared with the Least Significant Difference (LSD) pair-wise multiple comparison test.

RESULTS AND DISCUSSION

Emission Factors

Four emission factors were developed for each sweeping treatment for each operation: 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 were calculated on an annual basis rather than a per-harvest basis.

TSP and FRM PM_{10} concentrations were measured during all tests at the four downwind locations and one upwind location. Net concentration measurements from the TSP and FRM PM_{10} samplers were used to develop the annual TSP and FRM PM_{10} emission factors shown in tables 1 and 2, respectively. Statistical outliers, which occurred at the edge of the pollutant plume where the greatest uncertainties in dispersion calculations exist, were excluded. Statistical differences between treatments were detected in TSP emission factors from sweeping ($p = 0.009$) and pickup operations ($p = 0.009$). Surprisingly, the TSP emissions from sweeping with the improper sweeper setting were lower than those from the proper setting, but the TSP emissions

from pickup of windrows formed with the improper sweeper setting were higher than those from pickup of windrows formed with proper sweeper setting. The emission factors for all treatments were highly variable as shown by the large standard errors.

TSP emission factors for sweeping using both treatments were substantially higher than those reported by Goodrich et al.[3], and emission factors for nut pickup were higher than those reported by Faulkner et al.[5]. The results validate those reported by Downey et al.[4] in that the higher TSP emissions from pickup of windrows formed with improper sweeper settings would lead to greater opacity in the plume emitted by the pickup machine. It should be noted that differences in TSP emissions do not necessarily translate into differences in PM_{10} and/or $PM_{2.5}$ emissions.

No statistical differences were detected between treatments in FRM PM_{10} emissions from sweeping ($p = 0.342$) or pickup operations ($p = 0.149$). Again, FRM PM_{10} emission factors for sweeping using both treatments were substantially higher than those reported by Goodrich et al.[3], and emission factors for nut pickup were higher than those reported by Faulkner et al.[5].

Measured emissions of FRM PM_{10} for sweeping were substantially higher than the current PM_{10} emission factor for almond sweeping of 415 kg PM_{10}/km^2-yr, while emissions for nut pickup using a proper sweeper setting were approximately half of the current emission factor of 4,120 kg PM_{10}/km^2-yr. Emissions from pickup of windrows formed using improper sweeper settings are close to the current pickup emission factor for PM_{10}.

PSD analyses were conducted on all TSP filters for which sufficient loading was present (i.e. obscuration above 1%), and the PSDs were fit with log-normal distributions. Average MMDs and GSDs of the distributions are shown in table 3, along with the average percentages of PM that are PM_{10} and $PM_{2.5}$, respectively. No statistical differences were detected in the MMDs or GSDs between treatments for sweeping ($p = 0.449$ for MMD; $p = 0.546$ for GSD) or pickup operations ($p = 0.236$ for MMD; $p = 0.622$ for GSD).

The average true PM_{10} and $PM_{2.5}$ emission factors are shown in tables 4 and 5, respectively. No statistical differences were detected between treatments in the emission factors for true PM_{10} from sweeping operations ($p = 0.413$), but emission from pickup operations of windrows formed using proper sweeper settings were less than half of those of pickup operations of windrows formed using improper sweeper depth setting ($p = 0.033$). Similarly, no statistical differences were detected between treatments in the emission factors for true $PM_{2.5}$ from

sweeping operations ($p = 0.215$), but emissions from pickup operations of windrows formed using proper sweeper settings were less than half of those of pickup operations of windrows formed using improper sweeper depth setting ($p = 0.005$). Again, both true PM_{10} and true $PM_{2.5}$ emission factors for sweeping using both treatments were substantially higher than those reported by Goodrich et al.[3], and emission factors for nut pickup were higher than those reported by Faulkner et al.[5].

Again, measured emissions of true PM_{10} for sweeping were substantially higher than the current PM_{10} emission factor for almond sweeping of 415 kg PM_{10}/km^2-yr, while emissions for nut pickup using proper sweeper settings were approximately half of the current emission factor of 4,120 kg PM_{10}/km^2-yr. Emissions from pickup of windrows formed using improper sweeper settings are close to the current pickup emission factor for PM_{10}.

A comparison of the average true PM_{10} concentration and the average FRM PM_{10} concentration for collocated samplers during the same test shows a bias in the FRM sampler concentrations of approximately 20%, likely due to the inherent over-sampling bias of FRM samplers reported by Buser et al.[6] when sampling large particles. When comparing the oversampling rates detected during sweeping and pickup operations, no statistical differences were detected ($p = 0.175$), as would be expected given the similarities in PSDs between operations.

Foreign Matter Content

After sieving, the hulls, and shells with meat remained on the 16 mm (5/8 in) and 9.5 mm (3/8 in) sieves along with most of the stones, sticks, and leaf material. All other foreign matter was contained in smaller sieves or the pan. The mass of foreign matter per kilogram of raw nuts (i.e. hulls, shells, and meats) from windrow and conditioned samples are shown in table 6. As expected, the mass of all materials less than 8mm was reduced by conditioning. However, no differences were detected in the composition of windrow samples or conditioned samples as a function of sweeper setting indicating that producers likely do not introduce more foreign matter into the hulling process by using a lower sweeper setting than that recommended by the manufacturer.

CONCLUSIONS

TSP, PM_{10}, and $PM_{2.5}$ emission factors were determined for almond sweeping and pickup operations for windrows formed using manufacturer recommended sweeper depth settings and those formed using a sweeper depth 1.27 cm (0.5 inches) lower than that recommended by the manufacturer. The results of this research showed no differences in emissions of regulated pollutants during the sweeping process, but emissions during pickup were significantly lower (by about half) for windrows formed using proper sweeper settings versus those formed using improper sweeper settings.

The PM_{10} emission factors developed from this study using proper sweeper settings are 1,725$\pm$996 kg PM_{10}/km^2-yr for sweeping and 2,232$\pm$1,196 kgPM_{10}/km^2-yr for pickup operations. The emission factor for sweeping is significantly higher than those reported in previous studies and higher than the emission factor currently in use by the California Air Resources Board. The emission factor for nut pickup is similar to those reported in previous studies but lower than the emission factor of 4,120 kg PM_{10}/km^2-yr currently in use by the California Air Resources Board. The $PM_{2.5}$ emission factors developed from this study using proper sweeper settings are 298$\pm$208 kg $PM_{2.5}/km^2$-yr for sweeping and 158$\pm$76 kg $PM_{2.5}/km^2$-yr for pickup operations.

ACKNOWLEDGEMENTS

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429 **TABLES**

430 Table 1. Annual TSP emission factors (kg/km^2-yr).[a]

Table 1. Annual TSP emission factors (kg/km^2-yr).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	10,301 x	2,734 y
Standard Error	2,260	2,092
N	20	14
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	4,223 x	14,885 y
Standard Error	962	4,065
N	17	14

[a] No statistical differences were detected in means in the same row followed by the same letter ($\alpha = 0.05$).

431

432 Table 2. Annual FRM PM_{10} emission factors (kg/km^2-yr).[a]

Table 2. Annual FRM PM_{10} emission factors (kg/km^2-yr).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	3,450 x	5,287 x
Standard Error	1,098	1,515
n	18	20
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	2,348 x	3,783 x
Standard Error	620	735
n	16	11

[a] No statistical differences were detected in means in the same row followed by the same letter ($\alpha = 0.05$).

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434 Table 3. Particle size distribution parameters from TSP filters.[a]

Table 3. Particle size distribution parameters from TSP filters.[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
MMD (µm AED)[b,c]	11.7 x	12.7 x
GSD[d]	3.0 x	2.9 x
Average % PM_{10}	44.3	41.1
Average % $PM_{2.5}$	8.0	6.3
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
MMD (µm AED)	12.3 x	11.3 x
GSD	2.6 x	2.5 x
Average % PM_{10}	41.4	44.7
Average % $PM_{2.5}$	4.8	5.0

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).
[b] MMD = mass median diameter
[c] AED = aerodynamic equivalent diameter
[d] GSD = geometric standard deviation

435 Table 4. Annual true PM_{10} emission factors (kg/km^2-yr).[a]

Table 4. Annual true PM_{10} emission factors (kg/km^2-yr).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	1,725 x	1,335 x
Standard Error	508	163
n	7	10
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	2,232 x	4,858 y
Standard Error	610	1,006
n	10	8

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).

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437 Table 5. Annual true $PM_{2.5}$ emission factors (kg/km^2-yr).[a]

Table 5. Annual true $PM_{2.5}$ emission factors (kg/km^2-yr).[a]

Sweeping		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	298 x	173 x
Standard Error	106	22
n	7	9
Pickup		
	Proper Sweeper Setting	**Improper Sweeper Setting**
Mean	158 x	500 y
Standard Error	39	103
n	9	8

[a] No statistical differences were detected in means in the same row followed by the same letter (α = 0.05).

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439 Table 6. Composition of windrow and conditioned samples (g/kg raw nuts[a]).[b]

Table 6. Composition of windrow and conditioned samples (g/kg raw nuts[a]).[b]

Windrow Samples							
	Stones	**Sticks**	**Leaves**	**8-9.5mm**	**1-8mm**	**75µm-1mm**	**< 75µm**
Proper sweeper setting	23.9 x	1.95 x	2.23 x	45.8 x	403.1 x	140.0 x	64.1 x
Improper sweeper setting	43.1 x	4.72 x	1.54 x	40.1 x,y	400.6 x	128.8 x	64 6 x
Conditioned Samples							
	Stones	**Sticks**	**Leaves**	**8-9.5mm**	**1-8mm**	**75µm-1mm**	**< 75µm**
Proper sweeper setting	22.6 x	2.30 x	0.00 x	22.9 y,z	54.7 y	22.9 y	15.6 y
Improper sweeper setting	23.5 x	3.13 x	0.00 x	17.5 z	46.5 y	21.8 y	17.8 y

[a] "Raw nuts" includes meats, shells, and hulls.
[b] No statistical differences were detected in means in the same column followed by the same letter (α = 0.05).

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FIGURE CAPTIONS

Figure 1. Sampler configuration.

Figure 2. Nut harvester.[12]

FIGURES

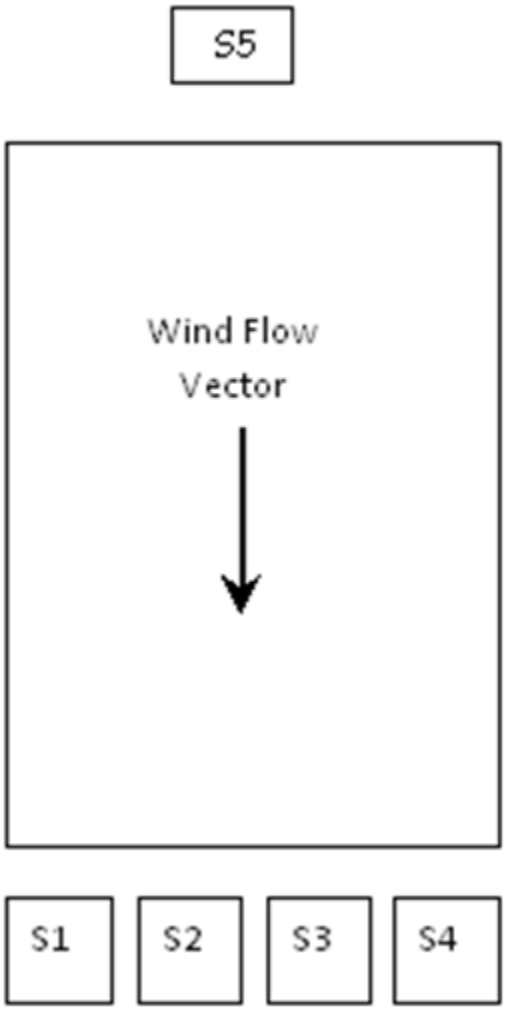

Figure 1. Sampler configuration.

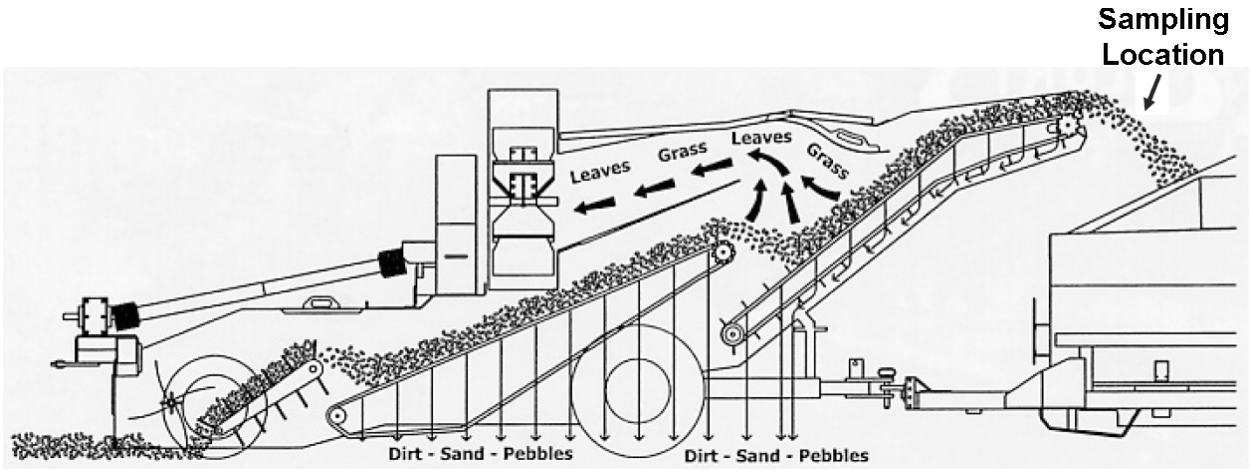

Figure 2. Nut harvester.[12]