Improving Particulate Matter (PM_{10} and $PM_{2.5}$) Emissions from Almond Sweeping and Harvesting Operations

Project No.: **09-AIR3-Capareda**

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Objectives:

The objectives of this study were as follows:

1. Evaluate the effectiveness of reduced-pass sweepers for reducing PM emissions from almond sweeping operations relative to conventional sweepers;
2. Evaluate the effect of reducing harvester separation fan speeds on PM emissions from almond conditioning operations; and
3. Identify changes in composition of windrowed materials and conditioned almonds based on sweeper treatment and harvester separation fan speed.

Interpretive Summary:

The effects of using reduced-pass sweepers and lower harvester separation fan speeds on particulate matter (PM) emissions from almond harvesting operations were evaluated in this study. PM concentration measurements at the orchard boundary were made and were used in conjunction with on-site meteorological data and inverse dispersion modeling to back-calculate emission rates from the measured concentrations. Reduced-pass sweeping showed the potential for reducing PM emissions, but results were confounded due to differences in orchard maturity and irrigation methods. Reducing the separation fan speed from 1080 to 930 rpm led to reductions in PM emissions. No differences were detected in the particle size distribution (PSD) characteristics of PM emitted from each operation. Reduced-pass sweeping demonstrated comparable nut recovery compared with conventional sweeping (although the conventionally-swept orchard produced 60% more product that the orchard swept using the reduced-pass sweeper). Foreign matter levels within harvested product were nominally affected by separation fan speed in the south (less mature) orchard, however in samples conditioned using the lower fan speed from the north (more mature) orchard, these levels were unacceptable.

Materials and Methods:

Sampling was conducted in two orchards in the Central Sacramento Valley near Arbuckle, California. Both orchards were planted on Hillgate loam that was 18.8 percent clay. Trees in the north orchard were eleven years old and irrigated with above ground irrigation while trees in the south orchard were nine years old and were irrigated using subsurface drip irrigation. It should be noted that the two year difference in orchard age was visibly noticeable with regards to tree size. In both orchards, trees were planted in 400 m (0.25 mile) rows oriented in a north-south direction with 6.7 m (22 ft) between rows and 5.5 m (18 ft) between trees in the same row.

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, including those in which sampling was conducted, the Nonpareil varieties are normally planted every other row with the other varieties planted on an alternating basis. However, during the harvesting of Nonpareils, all windrows are used for pickup and conditioning operations, virtually using the whole area for the harvest process. Therefore, while each plot consisted of ten tree rows and ten windrows were created, only the nuts from five tree rows were harvested during the tested harvest operations. Sampling was conducted during sweeping of all plots. Nuts were then allowed to air dry in windrows before sampling was again conducted on the same plots during windrow conditioning.

Sweeping Trials

Conventional and reduced-pass sweeping tests were conducted using Flory 77 Series sweepers (Flory Industries, Salida, CA) with and without an auxiliary sweeper unit, respectively. Windrows were prepared using a conventional sweeper (two blow passes, two sweeping passes per tree row) or a reduced-pass sweeper (two passes while simultaneously blowing and sweeping per tree row). Both the conventional and reduced-pass sweeper used similar engines (60 kW at 2500 rpm and displacement of 4.5 L). Due to constraints from the cooperating grower, all conventional sweeping trials were conducted in the north (more mature, above-ground drip irrigated) orchard, while reduced-pass trials were conducted in the south (less mature, subsurface drip irrigated) orchard **(Figure 1)**. Therefore, analyses of the effects of sweeping treatments on PM emissions and the composition of windrows may be confounded by effects of orchard age, differences in soil structure (although the soil type was consistent between orchards), and effects of irrigation methods. Eight trials were conducted using each sweeping treatment.

During sweeping operations, collocated, low-volume total suspended particulate (TSP) and federal reference method (FRM) PM_{10} samplers (Model PQ100 Inlet; BGI Inc.; Waltham, MA) were placed nominally upwind and downwind of each plot to measure the change in ambient PM concentrations due to sweeping. One collocated set of samplers was located upwind of each plot, while four collocated sets of samplers were spaced evenly along the width of each plot approximately 15 m (50 ft) downwind from the northern or southern edge of the plot **(Figure 2).**

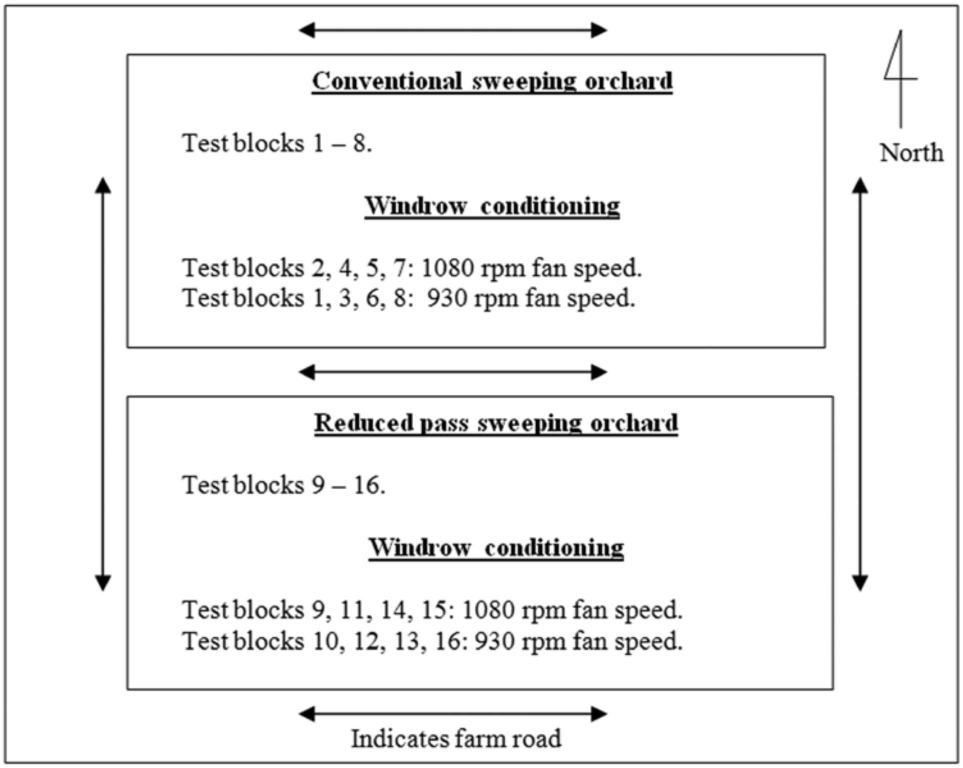

Figure 1. Orchard lay-out for sweeping and windrow conditioning tests (not to scale).

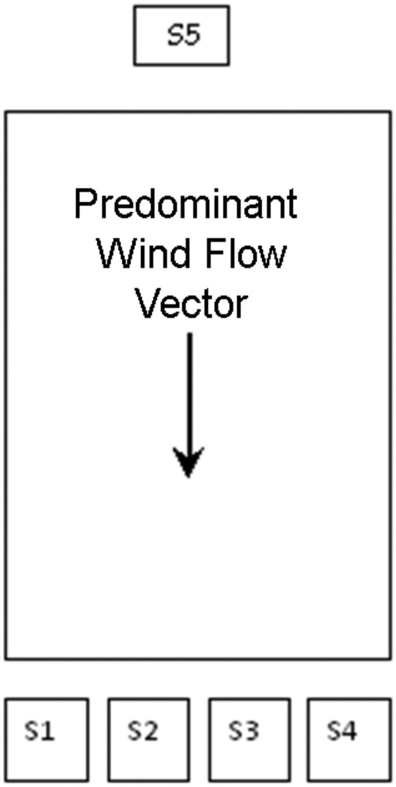

Figure 2. Sampler configuration (not to scale).

Due to the errors associated with FRM sampling in agricultural environments identified by Buser et al. (2007), TSP concentrations were measured alongside FRM PM_{10} samplers. TSP measurements were conducted with samplers designed by Wanjura et al. (2005) to reduce variations in sampler flow rate that lead to high uncertainty in FRM TSP 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. Data collection and analysis were conducted using the methods described by Faulkner et al. (2009). In summary, 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.). The PSD (described by a log-normal mass distribution) of each sample was determined and characterized by a mass median diameter (MMD) and geometric standard deviation (GSD) (Hinds, 1999). The MMDs were converted from equivalent spherical diameter (ESD) to aerodynamic equivalent diameter (AED) using a particle density (ρ_p) of 2.0 g/cm^3 and a shape factor of 1.05 (eq. 1). This shape factor was a departure from earlier work described by Faulkner et al. (2009). In the present study a particle shape factor of 1.05 was used given the slightly aspherical shape of soil particles collected from the orchards during sampling as seen using a scanning electron microscope.

$$AED = ESD\sqrt{\frac{\rho_p}{\chi}} \qquad (1)$$

where: AED = aerodynamic equivalent diameter,
ESD = equivalent spherical diameter,
ρ_p = particle density (g/cm^3), and
χ = shape factor.

The resulting PSD was then used to determine the true percentage of PM_{10} and $PM_{2.5}$ on each filter according to eq 2:

$$C_i = C_{TSP}\int_o^i f(x)dx \qquad (2)$$

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 of the dust.

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) recorded every 5 minutes;

- A temperature and relative humidity probe mounted in a solar radiation shield at 2 m (HMP50, Campbell Scientific Inc., Logan, UT) recorded 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 (USEPA, 2004). The dimensions of each test plot and corresponding meteorological data were then used with AERMOD to determine fluxes (µg/m^2-sec) from each of the downwind samplers for each sampling period according to the protocol described by Faulkner et al. (2009). Each of the four sampler sets used at each plot provided an independent measurement of concentration leading to four independent estimates of the emissions flux for each plot. These four fluxes were considered replicated measurements of emissions for a given plot, such that eight average fluxes (4 TSP; 4 FRM PM_{10}) were used to determine the emissions for each sweeping treatment.

Prior to sweeping tests, nuts were collected beneath five trees from separate rows within each plot. Due to the large mass for each sample, five 0.5 kg sub-samples were obtained from each primary sample. These sub-samples were weighed and the number of nuts determined. Results allowed transformation back to the total number of nuts per sample area based on total mass of the primary samples**. Figure 3** shows a typical sample area for nut collection. Nuts remaining after the sweeping operation were counted from the previously sampled areas to establish sweeper efficiency estimates.

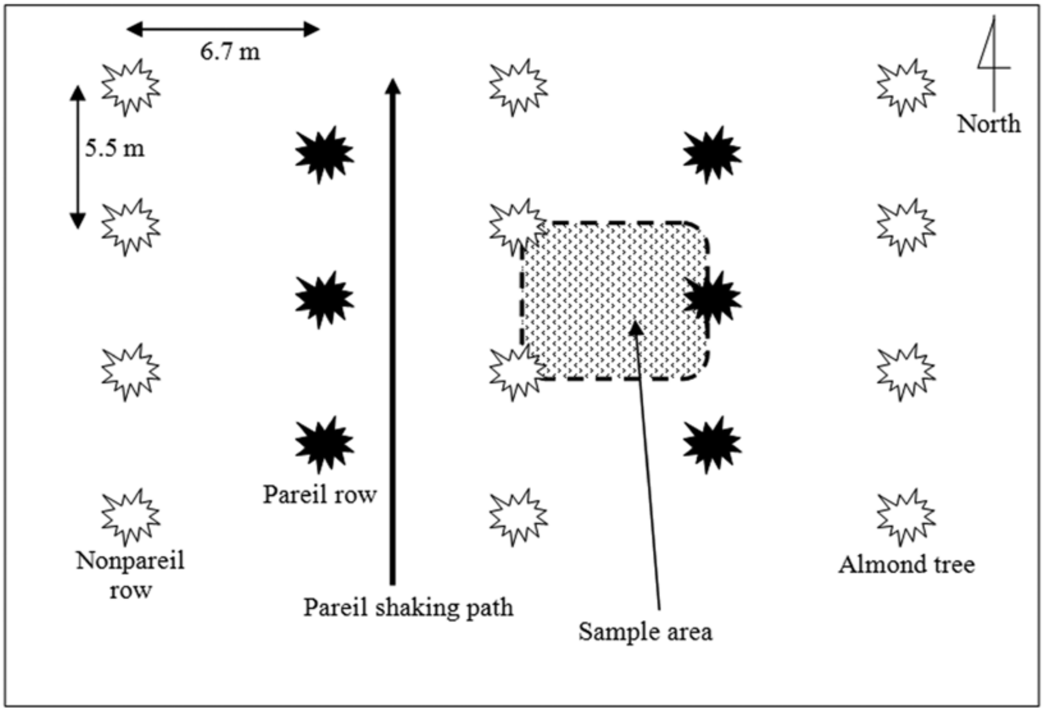

Figure 3. Example of sample area for pre- and post-sweep nut counts (not to scale).

After sweeping operations, five samples were collected from separate windrows within each plot for material separation analysis (fractionation, described later) and to determine if differences existed between windrows based on sweeper type.

Conditioning Trials

Conditioning trials were conducted using a Flory Model 8500 self-propelled harvester (Flory Industries, Salida, CA) operated at a constant ground speed averaging 5.1 km/h for both orchards. Emissions were measured using the standard fan speed for almonds of 1,080 rpm (control) and an experimental fan speed of 930 rpm, which was achieved by replacing the drive belt and sheaves such that ground speed was not altered. Although conventional and reduced-pass sweeping tests were carried out in separate orchards, harvester separation fan speed tests during windrow conditioning were randomized through both orchards. The result was that four conditioning trials at each fan speed were conducted in the north orchard (conventional sweeper) and four were conducted in the south orchard (reduced-pass sweeper). Sampling and data analysis for conditioning trials using FRM and Mini-Vol^{TM} samplers were conducted in the same manner as described for sweeping trials.

Size Fractionation

After windrow conditioning, five windrow samples were collected from each plot in the different orchards coinciding with the different separation fan speed tests. Five sub-samples (0.5 kg each) were collected from each primary sample for sieve analysis (size separation). Each sub-sample was placed in a sieve series and mechanically separated. Retained materials on the separate sieves were collected and weighed to establish if differences existed from different fan speed settings (or sweeper type, as discussed earlier). The following size ranges were used: particle size > 18.850 mm (nuts and twigs), 9.423 mm < particle size ≤ 18.850 mm (leaves, small nuts and twigs), 5.6 mm < particle size ≤ 9.423 mm (leaves and grass), 2 mm < particle size ≤ 5.6 mm (grass) and particle size ≤ 2 mm (soil).

Windrow samples were averaged based on their location and experimental treatment. That is, results from windrows after sweeping within the north orchard were averaged separate from windrow materials within the south orchard. Results from windrow conditioning samples were averaged based on fan speed and orchard location. Average mass fractions of the sieve separations were analyzed with two tests from the Statistical Analysis Software (SAS, Cary, NC): Analysis of Variance (ANOVA) and Duncan's New Multiple Range test ($\alpha = 0.05$). All other in-orchard field data results are reported as averages with standard errors based on orchard location and/or machine type.

Results and Discussion:

Meteorological conditions during sampling are shown in **Table 1**. Average characteristics of PSDs measured during sweeping and conditioning trials are shown in **Table 2**. As expected, the PSD of PM emitted during harvest operations is not dependent on sweeping or conditioning treatments but on the nature of the parent material, which did not differ between tests. No statistical differences in PSDs were detected between sweeping treatments ($p = 0.575$ for MMD; $p = 0.917$ for GSD). Similarly, no statistical differences in MMDs or GSDs measured during conditioning trials were detected between separation fan speeds ($p = 0.659$

for MMD; 0.591 for GSD), sweeping treatment (p = 0.581 for MMD; p = 0.624 for GSD) or fan-speed-sweeper interactions (p = 0.175 for MMD; p = 0.712 for GSD).

Table 1. Meteorological parameters measured onsite during sampling.

	Sweeping					
	Conventional			**Reduced Pass**		
	Min.	**Max.**	**Average**	**Min.**	**Max.**	**Average**
Albedo	0.15	0.31	0.18	0.16	0.33	0.20
Bowen Ratio	0.10	0.57	0.23	0.20	0.32	0.24
Relative Humidity (%)	47	61	54	35	47	40
Temperature (ºC)	25	29	27	31	32	32
Solar Radiation (W/m^2)	506	753	647	551	734	652
Wind Speed (m/sec)	0.9	1.8	1.4	1.0	1.6	1.3
	Conditioning					
	1080 rpm			**930 rpm**		
	Min.	**Max.**	**Average**	**Min.**	**Max.**	**Average**
Albedo	0.15	0.32	0.18	0.16	0.17	0.16
Bowen Ratio	0.15	0.21	0.19	0.10	0.22	0.15
Relative Humidity (%)	39	51	45	21	30	26
Temperature (ºC)	26	28	27	30	31	30
Solar Radiation (W/m^2)	601	749	686	613	725	671
Wind Speed (m/sec)	1.0	1.7	1.4	1.2	1.6	1.4

Table 2. Particle size distribution parameters from TSP filters[a]

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	Sweeping	
	Conventional	**Reduced-pass**
MMD (µm AED)[b,c]	10.7 x	10.5 x
GSD[d]	1.97 x	1.96 x
Average % PM$_{10}$	46.0	47.1
Average % PM$_{2.5}$	1.6	1.6
	Conditioning	
	1080 rpm	**930 rpm**
MMD (µm AED)	10.6 x	10.9 x
GSD	2.03 x	2.07 x
Average % PM$_{10}$	46.7	45.3
Average % PM$_{2.5}$	2.1	2.1

[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

Sweeping Trials

The average TSP and PM_{10} emission factors from sweeping trials and derived from ambient concentrations, inverse dispersion modeling, and particle size analysis are shown in **Table 3**. Reduced-pass sweeping resulted in 66% and 48% percent reductions in TSP and PM_{10} emissions measured using an FRM sampler, respectively. However, the different sweeping operations were carried out in two separate orchards; conventional sweeping was done within a more mature orchard (north orchard) with micro-emitter surface irrigation while reduced-pass sweeping was done within a less mature orchard (south orchard) with subsurface irrigation.

Table 3. Mass and emissions from sweeping treatments.[a,b,c]

	Measured Emissions (kg/km^2)			
	TSP	**True PM_{10}**	**True $PM_{2.5}$**	**FRM PM_{10}**
Conventional	333 (65) x	153 (30) x	5 (1) x	170 (40) x
Reduced-Pass	112 (23) y	53 (11) y	2 (0.4) y	89 (27) y

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

[b] Standard errors are shown in parentheses.

[c] All conventional sweeping conducted in north orchard; all reduced-pass sweeping conducted in south orchard.

Nut count measurements for determining the collection efficiency from the different sweeping operations are given in **Table 4**. Results indicate that the average tree within the south orchard produced approximately 60 percent less product than the north orchard. Additionally, similar numbers of nuts were left within each orchard (end row effects of nuts left after sweeping were not determined). Results indicate that both sweepers recovered more than 99.7 percent of the nuts from the orchard floor.

Table 4. Average number of nuts prior to and after sweeping operations.[a]

	Before Sweeping	**After Sweeping**	**Nut Recovery (%)**
Conventional (North orchard)	4,898 (91)	6 (0.5)	99.9
Reduced-Pass (South orchard)	1,914 (80)	5 (0.8)	99.7

[a] Standard errors shown in parentheses.

Results from size separation analysis of windrows after sweeping within the respective orchards are given in **Table 5**. An ANOVA using a one-way classification for determining the influence of sweepers within the north and south orchards found that the two largest size ranges of materials were significantly different within the separate orchards. Multiple range tests for the mass fraction size ranges were also analyzed. Results indicate that conventional sweeping within the north orchard produced more product in the largest size range, while the south orchard produced more material within the next lowest size range. This result also indicates the maturity difference of the orchards as indicated from nut count estimates. Smaller nuts were produced in the south orchard compared to the north orchard. Both orchards were similar in the amount of material represented within the smallest size ranges (leaves, grass and soil).

Table 5. Size separation results of windrow samples.[a,b]

Size separation range	Mass Fraction (%)	
	Conventional	**Reduced-pass**
Nuts and twigs	75.3 (0.4) x	69.4 (1.0) y
Leaves, small nuts, and twigs	8.1 (0.6) x	13.4 (0.5) y
Leaves and grass	5.1 (0.2) x	4.5 (0.2) x
Grass	6.7 (0.3) x	6.8 (0.3) x
Soil	4.6 (0.2) x	5.9 (0.3) x

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

[b] Standard errors are shown in parentheses.

Conditioning Trials

Although conventional and reduced-pass sweeping tests were carried out in separate orchards, harvester separation fan speed tests during windrow conditioning were randomized through both orchards. Emissions estimates derived from ambient concentrations, inverse dispersion modeling, and particle size analysis are shown in **Table 6**. Significant differences were detected in conditioning emissions as a function of fan speed ($p = 0.002$) but not sweeping method ($p = 0.397$) or sweeping method-fan speed interactions ($p = 0.592$). Reducing separation fan speed resulted in substantially lower emissions of TSP and PM_{10}. From table 6, reducing the fan speed by 14 percent led to a reduction in PM emissions of over 65 percent. While there was likely a reduction in emissions with decreased separation fan speed, it is unlikely that emission factors were reduced by 65 percent. Faulkner et al. (2009) demonstrated that AERMOD is increasingly sensitive to changes in wind speed at values below 3 m/sec. The maximum wind speed during all conditioning trials was 1.7 m/sec, so dispersion modeling of these tests all occurred within the wind speed range at which AERMOD is particularly sensitive to changes in the input parameter.

Table 6. Emissions from conditioning treatments (kg/km^2).[a,b]

	TSP	**True PM_{10}**	**True $PM_{2.5}$**	**FRM PM_{10}**
1080 rpm	4,018 (489) x	1,904 (228) x	84 (10) x	1,863 (278) x
930 rpm	1,111 (658) y	471 (298) y	22 (14) y	615 (385) y

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

[b] Standard errors are shown in parentheses.

Results from the size separation analyses after windrow conditioning for different separation fan speeds are given in **Table 7**. Results show that a larger percentage of the desired product (i.e. that within the largest size range) remained within windrows at the faster separation fan speed in the north orchard. Additionally, the slower separation fan speed resulted in retention of at least 60 percent more of the three smaller size ranges (undesirable product) within the north orchard. Comparing separation fan speeds within the south orchard showed an opposite effect with respect to the smaller size range of material within windrows. Here the slower separation fan speed resulted in approximately 50 percent less grass within the conditioned windrows, while retention in the larger sizes (representing desirable product) were similar. From these results and knowledge of the maturity and irrigation systems within these two orchards, the results imply that the standard separation fan speed should be used for windrow conditioning within mature orchards while a reduced fan separation speed may lead to comparable foreign material within harvested product in younger orchards.

Table 7. Size separation results after windrow conditioning.[a,b]

Size separation range	Mass Fraction (%)			
	North Orchard		South Orchard	
	1080 rpm	930 rpm	1080 rpm	930 rpm
Nuts and twigs	84.7 (1.2) x	66.6 (2) z	72.4 (2) y,z	73.8 (1.0) y
Leaves/ small nuts/twigs	10.5 (0.9) x	19.1 (0.9) y	21.4 (1.6) y	21.5 (0.7) y
Leaves and grass	1.6 (0.3) x	4.1 (0.4) y	1.7 (0.2) x	1.8 (0.2) x
Grass	1.3 (0.2) x	5.5 (0.6) z	2.5 (0.4) y	1.4 (0.1) x
Soil	1.9 (0.2) x	4.7 (0.5) y	2.0 (0.3) x	1.5 (0.4) x

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

[b] Standard errors are shown in parentheses.

Additional evaluation of the data using an ANOVA analysis with one-way factorial design with the test blocks randomized across both the north and south orchards found there were no significant differences between the size ranges of materials based on harvester separation fan speed. Multiple range tests found that the effects of fan speeds were similar. However, the one-way factorial design also found relatively high root mean square errors similar in magnitude to the average mass fractions of materials within the respective size ranges. This indicates large variations in the data, understandable with respect to the age of orchards and differences in product yields reported earlier, and the need for larger sample sizes in order to include product yield as a factor for further analysis.

Conclusion:

This study evaluated the effects of using reduced-pass sweepers and lower separation fan speeds on PM emissions from almond harvesting operations, In addition, the effects of these potential mitigation measures on the composition of windrows and conditioned material were analyzed.

Reduced-pass sweeping showed the potential for reducing emissions, but results were confounded by differences in orchard maturity and irrigation methods. Reduced-pass sweeping demonstrated comparable nut recovery to conventional sweeping and results indicate that both sweepers recovered more than 99.7 percent of the nuts from the orchard floor.

Reducing the separation fan speed from 1080 to 930 rpm led to reductions in PM emissions as well. Foreign matter levels within harvested product were nominally affected by separation fan speed in the south (less mature) orchard, however, in samples conditioned using the lower fan speed from the north (more mature) orchard, these levels were unacceptable.

Research Effort Recent Publications:

Faulkner, W.B.; Downey, D.; Giles, K.; Capareda, S.C. 2010. Evaluation of Particulate Matter Abatement Strategies for Almond Harvest. Under review for publication in *J. Air and Waste Management*.

Faulkner, W.B.; Capareda, S.C. 2010. Effects of Sweeping Depth on Particulate Matter Emissions from Almond Harvest Operations. Under review for publication in *Trans. ASABE*. ASABE, St. Joseph, MI.

Goodrich, L.B.; Faulkner, W.B.; Capareda, S.C.; Krauter, C.; Parnell, C.B. 2009. Particulate Matter Emission Factors from Reduced-pass Almond Sweeping. *Trans. ASABE, **Vol**.* 52 (5), 1669-1675.

Faulkner, W.B.; Goodrich, L.B.; Botlaguduru, V.S.V.; Capareda, S.C.; Parnell, C.B. 2009. Particulate Matter Emission Factors for Almond Harvest as a Function of Harvester Speed. *J. Air and Waste Management***, Volume 59**, 943-949.

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