Measurement of Harvest Dust Generation

Project No.: **09-AIR1-Giles**

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Objectives:

1. Compare differences from conventional and reduced pass sweeping operations by measuring within canopy gravimetric dust, machine time in field and estimated fuel use; determine sweeper efficiency through nut counts prior to and after sweeping.
2. Measure the relative differences of harvester separation fan speeds during windrow conditioning using opacity, gravimetric sampling and material size separation (sieve analyses) of windrows prior to and after conditioning operations.

Interpretive Summary:

Orchard operations during almond harvesting produces visible dust and have recently become a regulatory concern. Previous studies (Giles et al., 2007, 2008, 2009; Ponpesh et al., 2010) have shown that equipment operating conditions (sweeper head height, separation fan outlet direction, ground speed of harvester and separation fan speed of harvester) can decrease the visible dust component during field operations. In on-going work to characterize the differences in orchards and equipment settings, a collaborative project was carried out this year with researchers from Texas A&M University (TAMU). Concurrent sampling for emission determinations by TAMU coincided with standard sampling procedures developed over the years by UC Davis (e.g., Downey et al., 2006; Giles et al., 2007).

The present study consisted of two main components: establishing if differences exist between (1) a conventional sweeper versus a reduced pass sweeper and (2) standard and reduced separation fan speeds during windrow conditioning. Results were analyzed based on the following criteria: gravimetric measurement of total suspended particulate matter (TSP) and particulate matter less than 10 μm diameter (PM10), measurements of visible opacity of fan exhaust plume and time span of fan exhaust plume, establishing nut counts prior to and after sweeping, estimating fuel consumption during sweeping and determining size separation of windrow materials prior to and after sweeping and windrow conditioning.

Conventional and reduced pass sweepers were compared for two test orchards. Conventional sweeping was done within a more mature orchard (north orchard) versus the reduced pass sweeper (south orchard), however results found that both sweepers produced similar harvest efficiencies. In both cases greater than 99.7% of the nuts were recovered from the orchard floor and placed within windrows. During the sweeping operations, results from gravimetric sampling indicated that the younger orchard produced approximately 33% less TSP and PM10 during the reduced pass sweeping. Fuel efficiency results indicated that the conventional sweeper was 27% more fuel efficient on a time basis; however it required 34% longer to sweep the north orchard. This result was not unexpected as the conventional sweeper makes two additional passes per windrow compared to the reduced pass sweeper. On a per acre basis the reduced pass sweeper was 12% more time efficient versus the conventional sweeper. Size separation analyses of windrows after sweeping also indicated more product was produced within the mature orchard, however both orchards were similar with respect to small debris (leaves, grass and soil) found in windrows.

Results from separation fan speed tests indicated that the reduced fan speed resulted in 27% less TSP and 30% more PM10 versus the standard fan speed within the canopy during windrow conditioning in the north orchard. The reduced fan speed for windrow conditioning in the south orchard found that within canopy TSP was 33% less than the standard fan speed while PM10 measurements were similar. In all cases, the south orchard in-canopy measurements of TSP, PM10 were less than the north orchard. Opacity measurements signatures and time spans of dust plumes were of similar magnitude within each orchard when comparing separation fan speeds, however when comparing the north (more established) orchard to the south orchard, opacity measurements were close to 50% larger and time spans of fan exhaust plume 30% longer.

Size separation analyses indicated that more product was collected within windrows at the standard separation fan speed in the north orchard. Additionally, the reduced separation fan speed collected at least 60% more debris (leaves, grass and soil) within the north orchard. Comparing separation fan speeds within the south orchard showed an opposite effect with respect to the small size range of material within windrows. Here the reduced separation fan speed resulted in approximately 50% less debris (grass and soil) within the windrows, while the larger sizes collected (representing product) were similar.

Materials and Methods:

Experiments were conducted in a commercial almond orchard near Arbuckle, CA. **Figure 1** shows the testing conditions for sweeping and windrow conditioning tests; the two adjacent orchards were nominally ½ mile by ¼ mile. The north orchard was irrigated with a drip system while the south orchard incorporated sub-surface irrigation. Almond trees were aligned along a North-South direction. Replicate test blocks within each orchard consisted of ten tree rows and nine windrows. Mini-Vol gravimetric samplers were placed within the middle of each replicate test block during all sweeping and windrow conditioning tests. Three replicate opacity measurements were taken for each test block only for windrow conditioning tests and consisted of measuring material exiting the fan of the harvester two rows away from the row the harvester traversed.

Prior to sweeping tests, nuts were collected beneath five trees from separate rows within each orchard. **Figure 2** shows a typical sample area for nut collection. Windrows were prepared using a conventional sweeper (2 blow passes, 2 sweeping passes per tree row) and reduced pass sweeper (two passes while simultaneously blowing and sweeping per tree row). After the respective conventional and reduced pass sweeping operations, five samples were collected from separate windrows within each orchard for further material separation analyses. Additionally, nuts left within the area of the previously sampled trees (for nut counts) were determined for sweeper efficiency estimates. Sweeper time within the field was determined for all tests blocks and averaged. Sweeper fuel consumption was determined by annotating engine hours after the tank was topped off prior to field deployment, refilling the tank after experimental runs and annotating refill volume and elapsed engine hours. Both the conventional and reduced pass sweeper used similar engines (80 hp at 2500 rpm and displacement of 4.5 L).

Windrow conditioning was done using a standard harvester (Model 850, Flory Industries, Salida, CA) operated at a constant ground speed averaging 3.2 mi/hr for both orchards. Separation fan speed tests were done using the normal operating speed of the harvester fan, 1080 rpm (at a tractor PTO speed of 540 rpm) and a reduced harvester fan speed of 930 rpm. The reduced fan speed was achieved by replacement of the drive belts and sheaves. During all windrow conditioning tests, all other components (chains, etc.) on the harvester were operated at normal speeds (at 540 rpm tractor PTO speed). Separation fan exhaust was measured using standard opacity and gravimetric devices reported in earlier work (e.g., Giles et al., 2008).

After windrow conditioning, multiple windrow samples were collected from the different orchards coinciding with the different separation fan speed tests. Five sub-samples (0.1 lbs each) were collected from each primary sample for sieve analysis (size separation). Each sub-sample was placed in a sieve series and mechanically shaken under similar conditions as reported previously (Giles et al., 2009). Retained materials on the separate sieves were collected and weighed to establish if differences existed from different harvester fan speed conditions. The following size ranges were used (size range spans 3/4 - 1/10 in.): particle size (nuts and large twigs) ≥ 18.850 mm, 9.423 mm ≤ particle size (nuts, leaves, small twigs) ≤ 18.850 mm, 5.6 mm ≤ particle size (leaves and grass) ≤ 9.423 mm, 2 mm ≤ particle size (grass) ≤ 5.6 mm and particle size (soil) ≤ 2 mm.

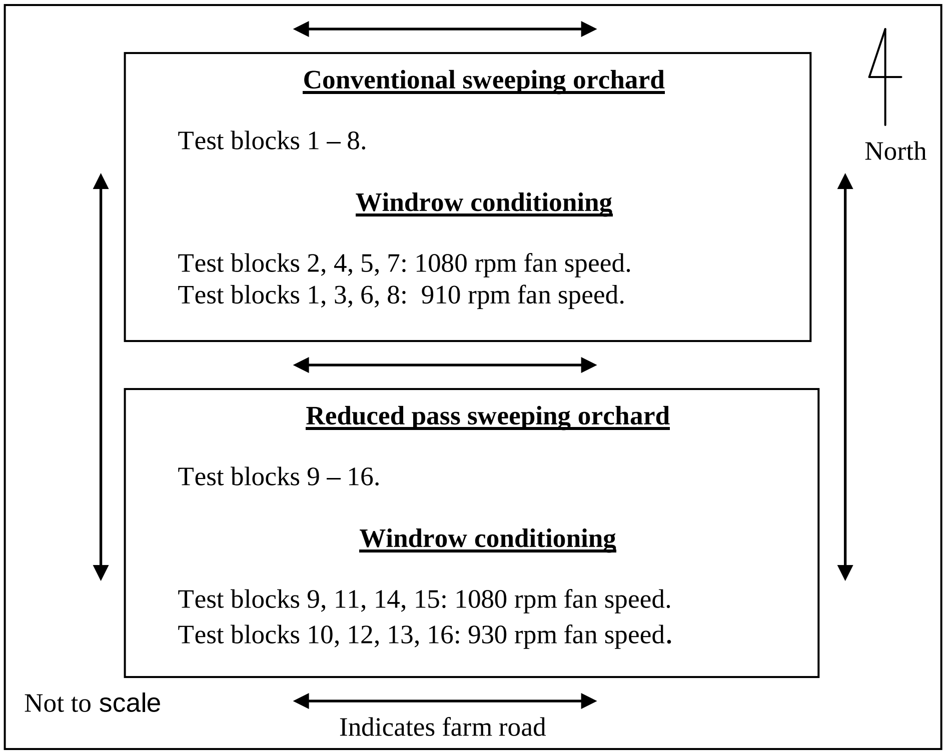

Figure 1. Orchard layout for field tests (from Faulkner et al., 2010).

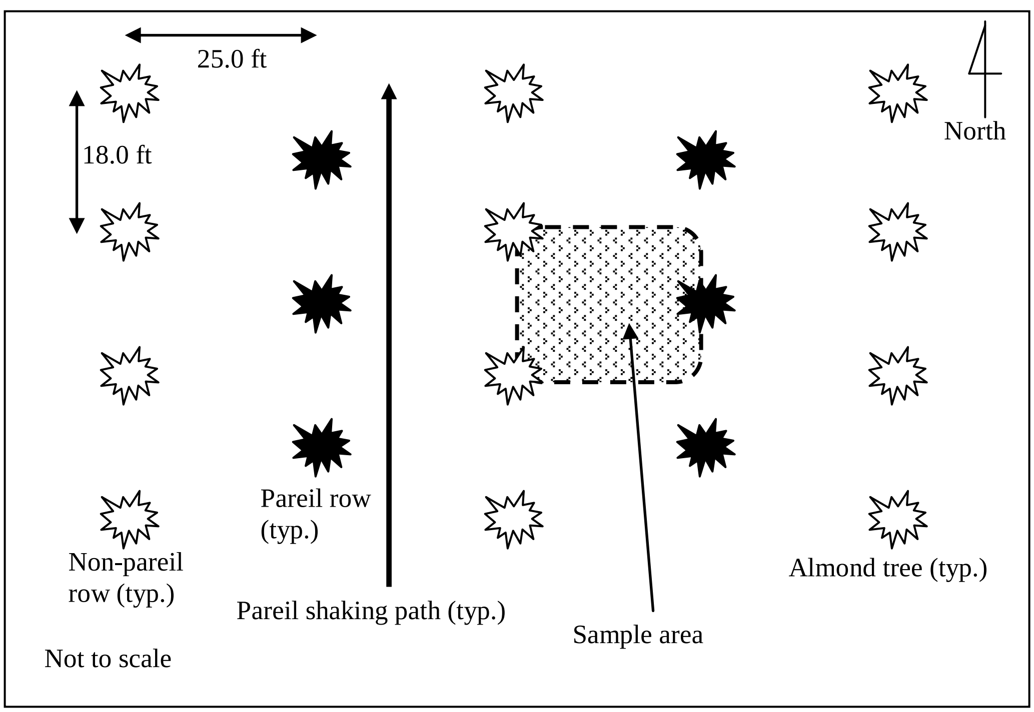

Figure 2. Example of sample locations for nut counts pre- and post-sweeping operations (from Faulkner et al., 2010).

Samples were averaged based on their field location or field equipment application. That is, results from windrows after sweeping within the north field were averaged separate from windrow materials within the south field. Results from windrow conditioning samples were averaged based on fan speed and field location. Average mass fractions of the sieve separations were analyzed with tests from the Statistical Analysis Software (SAS, Cary, NC): Analysis of Variance (ANOVA) and Duncan's New Multiple Range Test. All tests were evaluated with significance levels of 5% resulting in a statistical confidence of 95% when comparing size differences of windrow material after sweeping.

Results and Discussion:

Sweeping Tests

Results, given in **Table 1**, indicate that the reduced pass sweeping operation resulted in approximately 33% less total suspended particulates (TSP) and particulate matter less than 10 μm in diameter (PM10) within the orchard canopy. However, the different sweeping operations were carried out in orchards of different maturity.

Table 1. Average gravimetric sampler results (standard deviations in parentheses) from sweeping comparisons for respective test blocks (from Faulkner et al., 2010).

North orchard Conventional sweeping		South orchard Reduced pass sweeping	
TSP mg	PM10 mg	TSP mg	PM10 mg
0.56 (0.20)	0.15 (0.03)	0.38 (0.17)	0.10 (0.04)

Conventional sweeping was done within a more mature orchard (north orchard) with above ground irrigation while reduced pass sweeping was done within a less mature orchard (south orchard) with subsurface irrigation. Estimates from nut counts for determining the efficiency from the different sweeping operations are given in **Table 2**. After sweeping operations were completed, sample locations (excluding windrows) were evaluated for the number of nuts left within the pre-swept sampled area. The total number of nuts collected from the sample trees were determined by taking three sub-samples, counting the number of nuts (hulls and husks were not separated) in each sub-sample, and determining the mass of the sub-samples. The number of nuts per sample prior to sweeping was determined by dividing the total mass of each sample by the average sub-sample mass (with known nut count). Results were averaged for all samples.

Table 2. Estimates for average number of nuts (based on sample area – see **Figure 2**) prior to and after sweeping operations in north and south orchards; averages were based on eighteen sub-samples, standard deviations in parentheses (from Faulkner et al., 2010).

Mass per tree lbs	Nuts per tree prior to sweeping	Nuts left after sweeping	Nut Recovery %
North orchard - Conventional sweeper			
51.02 (4.04)	4898 (573)	6 (3)	99.88
South orchard - Reduced pass sweeper			
25.87 (5.11)	1914 (504)	5 (5)	99.74

From **Table 2**, the data indicate that the average tree within the south orchard produced approximately 60% less product than the north orchard. Additionally, from these data, similar numbers of nuts were left within each orchard (end row effects of nuts left after sweeping were not determined). Based on these estimates, over 99.7% of the product was recovered from both conventional and reduced pass sweeping operations.

Sweeper fuel use and time-in-field estimates are given in **Table 3**; results were based on several measurement criteria. Sweepers were topped off at the beginning of the day and engine hours were annotated. Sweepers were timed for each two-row pass giving an estimated ground speed. Time in test block was measured for the sweeper run for the entire 10-row test block. Engine hours including idle time were tracked. Sweepers were topped off at the end of the day to determine fuel consumption. Based on these data, the conventional sweeper was 27% more fuel efficient on a time basis, however required 45% more time to sweep the north orchard. A comparison of sweeper fuel efficiency on an acreage basis indicated the reduced pass sweeper was approximately 12% more efficient.

Results from size separation analysis of windrows after sweeping within the respective orchards are given in **Table 4**. The results indicate that conventional sweeping produced a greater amount of harvested product in the largest size range, while the south orchard produced a larger amount of material within the next lowest size range. This result also indicates the maturity difference of the orchards as indicated from nut count estimates. The south orchard producing more material within the next lowest size range is indicative of the size of product within the windrow, that is, there are a larger number of smaller nuts versus the north orchard. Both orchards were similar in the amount of material represented within the smaller size ranges (leaves, grass and soil).

Table 3. Average (standard deviations in parentheses) results for sweeper ground speed, time in test block, and fuel consumption/efficiency (from Faulkner et al., 2010).

Ground Speed mph	Time in test block h	Fuel consumed Per engine hour Gal/h	Per unit area Gal/ac
North field – conventional sweeper			
3.35 (0.46)	1.42 (0.11)	1.53 (0.32)	0.34 (-)
South field – reduced pass sweeper			
2.67 (0.12)	0.94 (0.03)	2.09 (0.09)	0.30 (-)

Table 4. Size separation results for windrows after conventional (north orchard) and reduced pass sweeping (south orchard); standard deviations are reported in parentheses (from Faulkner et al., 2010).

Material description	Conventional	Reduced Pass
	-------- Mass Fraction, %	--------
Nuts, twigs	75.3 (2.3)[a]	69.4 (6.5)[b]
Nuts, leaves, small twigs	8.1 (3.6)[a]	13.4 (3.3)[b]
Leaves, grass	5.1 (1.1)[a]	4.5 (1.1)[a]
Grass	6.7 (1.6)[a]	6.8 (1.7)[a]
Soil	4.8 (1.1)[a]	5.9 (1.8)[a]

[a] Letters indicate significant differences within a row at $\alpha = 0.05$ using Duncan's New Multiple Range Test.

Windrow Conditioning Tests

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. Results, given in **Table 5**, from these studies indicated that the reduced separation fan speed resulted in 27% less TSP and 30% more PM10 within the canopy during conditioning within the north orchard. Reduced fan speeds within the south orchard found that within canopy TSP was 33% less than the standard separation fan speed while PM10 measurements were similar. In all cases, the south orchard in-canopy measurements of TSP, PM10 were less than the north orchard. Opacity measurements signatures and time spans of dust plumes were of similar magnitude within each orchard when comparing the separation fan speeds, however when comparing the north (more established) orchard to the south orchard, opacity measurements were close to 50% larger and time spans of exhaust plume 30% longer.

Table 5. Average gravimetric and opacity results (standard deviations in parentheses) for standard and reduced separation fan speeds during windrow conditioning (from Faulkner et al., 2010).

---------- 930 rpm separation fan speed ----------							
North field: Test blocks 1, 3, 6, 8				South field: Test blocks 10, 12, 13, 16			
TSP mg	PM10 mg	Opacity %	Time span, s	TSP mg	PM10 mg	Opacity %	Time span, s
0.34 (0.28)	0.10 (0.08)	4.0 (1.5)	28 (12)	0.26 (0.12)	0.04 (0.02)	1.8 (0.6)	19 (6)
---------- 1080 rpm separation fan speed ----------							
North field: Test blocks 2, 4, 5, 7				South field: Test blocks 9, 11, 14, 15			
TSP mg	PM10 mg	Opacity %	Time span, s	TSP mg	PM10 mg	Opacity %	Time span, s
0.46 (0.23)	0.07 (0.06)	4.4 (1.5)	26 (3)	0.39 (0.31)	0.05 (0.03)	2.2 (0.6)	20 (4)

Results from windrow material size separation (sieve analyses) after conditioning for different separation fan speeds are given in **Table 6**. A larger amount of harvested product (i.e., within the largest size range) was collected within windrows at the standard fan speed in the north orchard. Additionally, the reduced fan speed collected at least 60% more debris (leaves, grass and soil) within the north orchard. Comparing standard versus reduced fan speeds within the south orchard showed an opposite effect with respect to the small size range of material within windrows. A reduced fan speed in the southern (younger orchard) resulted in approximately 50% less material (grass and soil, however only grass was significantly different) within the windrows, while the larger sizes collected (representing product) were similar.

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 range of materials based on harvester 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 result implies large variations in the data, understandable with respect to the age of orchards and a difference in product yield reported earlier, and indicates a need for larger sample sizes to include product yield as a factor for further analysis.

Table 6. Size separation results (standard deviations in parentheses) for conditioned windrows at two separation fan speeds (from Faulkner et al., 2010).

	----- North Orchard -----		----- South Orchard -----	
	---- Fan speed, rpm ----		---- Fan speed, rpm ----	
Material	1080	930	1080	930
description	-- Mass Fraction, % --		-- Mass Fraction, % --	
Nuts and twigs	84.7 (5.2)[a]	66.6 (8.9)[c]	72.4 (8.9)[b,c]	73.8 (4.5)[b]
Nuts, leaves, small twigs	10.5 (3.9)[a]	19.1 (4.1)[b]	21.4 (7.3)[b]	21.5 (3.2)[b]
Leaves and grass	1.6 (1.2)[a]	4.1 (1.9)[b]	1.7 (0.9)[a]	1.8 (0.9)[a]
Grass	1.3 (0.9)[a]	5.5 (2.5)[c]	2.5 (1.6)[b]	1.4 (0.5)[a]
Soil	1.9 (0.8)[a]	4.7 (2.2)[b]	2.0 (1.3)[a]	1.5 (0.4)[a]

[a] Letters indicate significant differences within a row at $\alpha = 0.05$ using Duncan's New Multiple Range Test.

Research Effort Recent Publications (also cited within this report):

Faulkner, W.B., Downey, D., Giles D.K., Capareda, S.C. 2010. Evaluation of Particulate Matter Abatement Strategies for Almond Harvest. *In Review for Journal of Air and Waste Management*.

Ponpesh, P., Giles, D.K., Downey, D. 2010. Mitigation of In-Orchard Dust Through Modified Harvester Operation. *In Press for Transactions of the American Society if Agricultural and Biological Engineers 53(4): xxx-xxx*.

References Cited:

Downey, D, Thompson, J.M., Giles, D.K., Southard, R. 2006. Evaluating dust generation from nut harvesting equipment – Final report to the Almond Board for 2005-2006, Project No.: 05-DD-01. Almond Board of California, Modesto, CA.

Giles, D.K., Downey, D., Thompson, J.M., Ponpesh, P. 2007. Measurement of harvest dust generation using opacity and gravimetric sampling - Final report to the Almond Board for 2006-2007, Project No.: 06.ENVIR4.GILES.

Giles, D.K., Downey, D., Thompson, J.M., Ponpesh, P. 2008. Measurement and reduction of in-orchard dust generation from harvesting - Final report to the Almond Board for 2007-2008, Project No.: 07-ENVIR4. Almond Board of California, Modesto, CA.

Giles, D.K., Downey, D., Thompson, J.M., Ponpesh, P. 2009. Measurement of Harvest Dust Generation - Final report to the Almond Board for 2008-2009, Project No.: 08-AIR1-Giles. Almond Board of California, Modesto, CA.