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Quantification of Almond Sweeping Emission Reductions Through Changes In a Sweeper Operation

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Abstract. *Almond harvest accounts for a significant amount of PM_{10} emissions in California each harvest season. This paper addresses the reduction of blower passes during the harvest from 3 to 1 as a possible mitigation measure. Ambient total suspended particulate and PM_{10} sampling was conducted at two orchards during harvest with alternating control and experimental treatments. On-site meteorological data was used in conjunction with inverse dispersion modeling using Industrial Source Complex-Short Term version 3 to develop emission rates from the measured concentrations. A reduction of 50% in emissions was achieved by the experimental treatment representing a significant potential for emission reductions across the entire state. The harvest efficiency was also measured to determine the possible financial impacts from a crop removal aspect. The results of reducing the blower passes are that approximately 4.5 kg/ha of almond meats will be left in the field with the reduced practices.*

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

Introduction

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

The current emission factor for all almond harvesting is 45.82 kg/ha (CARB, 2003), accounting for 11Gg of PM_{10} each year. The almond harvest emission factor is composed of the sum of the emission factors for the three different harvest operations, shaking, sweeping and pickup. First, the trees are shaken to remove the product from the tree allowing it to air dry sitting on the ground, this accounts for 0.415kg/ha of the emission factor. A few days later, after the crop has dried the sweepers enter the field and sweep the almonds into wind rows, accounting for 4.15kg/ha. Finally, the pickup machines remove the product from the field accounting for 41.2kg/ha. Each harvest processes accounts for significant amounts of emissions due to the total area that each is applied to.

This research focuses on the sweeping aspect of the harvest operation. It was decided that there was the most readily available possibility of emission reductions in this area of harvest due to the wide range of cultural practices used. We primarily tested the reduction in emissions that could be achieved by reducing the number of blower passes from 3 to 1.

Ambient downwind sampling was conducted at two orchards during the 2006 harvest season. The first sampling site in the Wasco area is the same orchard that has been used for testing the past several years. It has proven to be a valuable orchard due to the cooperation of the management as well as the ideal orientation of the orchard. The soil type is a Wasco Sandy Loam with 13% clay. The average soil moisture content of the berm was 7.1% and the average soil moisture between rows was 5.8%. Sampling was conducted during the harvest of the nonpareil rows of the orchard. This consisted of every other row in the orchard. The second sampling location was in the Arbuckle area north of Sacramento. The orchard rows are oriented north south and the soil type is a Hillgate loam with 18.8% clay. Every other row was harvested at the time of the study on both orchards.

Sweeping

The machine used for sweeping almonds into windrows in the field is a highly specialized piece of equipment. For this study we used a Flory model 7677 with a 7.5' wide sweeper head. Figure 1 shows the harvester. The basic configuration is a sweeper head in front that sweeps any product to the windrow that is built on the right side of the machine. In the rear of the machine there is a high output fan that blows the remaining product across the tree row to be collected by the ensuing pass on the other side of the tree.

Figure 1. Almond sweeper moving away from the camera. The front of the machine has the sweeper head and th blower is on the back.

The difference between the two treatments is the number of blower passes used to create the windrows of almonds on the ground. The control treatment used 3 blower passes followed by three non-blower passes. The experimental treatment was 1 blower pass and three non-blower passes. The pattern used was to complete all blower passes for a given harvest row and then follow with the three non blower passes. The non blower passes would start on the same side of the harvest row as the last blower pass. Figure 2 shows the control (standard) sweeping pattern and figure 3 shows the experimental sweeping pattern.

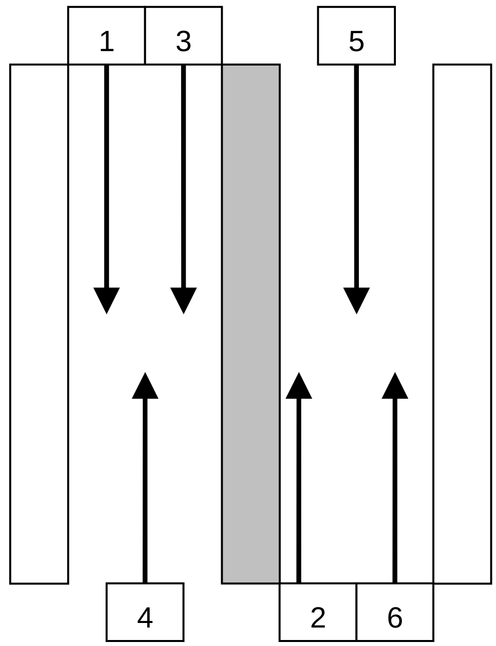

Figure 2. Standard 3 blower pass sweeping pattern. The blower is operated on the first three passes during the standard sweeping pattern. The shaded column represents the harvest row.

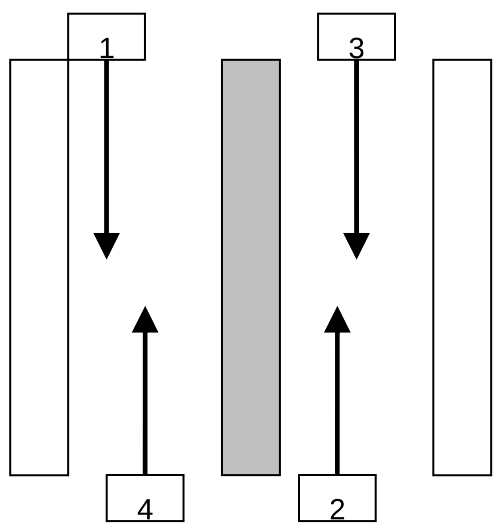

Figure 3. Experimental 1 blower pass sweeping pattern. The blower is only operated on the first blower pass during these tests.

These two treatments were selected to produce the greatest difference in emissions in order to test the robustness of emission factor development algorithm as well as to find the most emission reductions possible. By eliminating 2 blower passes it is also possible to interpolate the emission factor of eliminating a single blower pass as well.

Particulate Measurements

Particulate measurements were conducted using custom built particulate samplers with federal reference method (FRM) inlets for PM_{10} and $PM_{2.5}$ and a custom built total suspended particulate (TSP) inlet, all operating at $1m^3$/hour. The air control units were custom built to allow for more robust operation in harsh environments. The air measurement system was significantly improved over the standard FRM samplers to allow for more accurate measurement of air flow leading to more accurate measurement of concentrations. The TSP sampler was designed to obtain the same cut point as high-volume TSP samplers designated as FRM samplers prior to implementation of the PM_{10} standard. TSP samplers were used due to the well explained phenomenon of changing sampler performance characteristics in the presence of particulate matter (PM) that is larger than the cut point of the sampler (10μm for PM_{10} sampler, 2.5μm for $PM_{2.5}$ sampler) (Buser, 2007). Due to the change in performance of PM_{10} samplers particle size analysis was conducted on the TSP filters to determine the true PM_{10} concentration. This allows for the quantification of the change in performance of the PM_{10} samplers as well as allowing for the development of emission factors based on the true concentration of particulate less than 10μm.

Samplers were set up in order to measure the net concentration change across the orchard. A total of 5 sampling locations were used for each test. A single upwind location was used consisting of a TSP, PM_{10} and $PM_{2.5}$ samplers all located next to each other. Four downwind sampling locations were used for each test as well. They were spaced evenly across the width of the treatment area for the specific test. All four downwind sampling locations consisted of collocated TSP and PM_{10} samplers and 1 downwind location also had a $PM_{2.5}$ sampler. The sampler configuration is shown in figure 4. Sampling location 2 or 3 always had the $PM_{2.5}$ sampler depending on the direction of the wind for that specific test. All orchards were configured with north south rows with a southerly flow vector required for all tests.

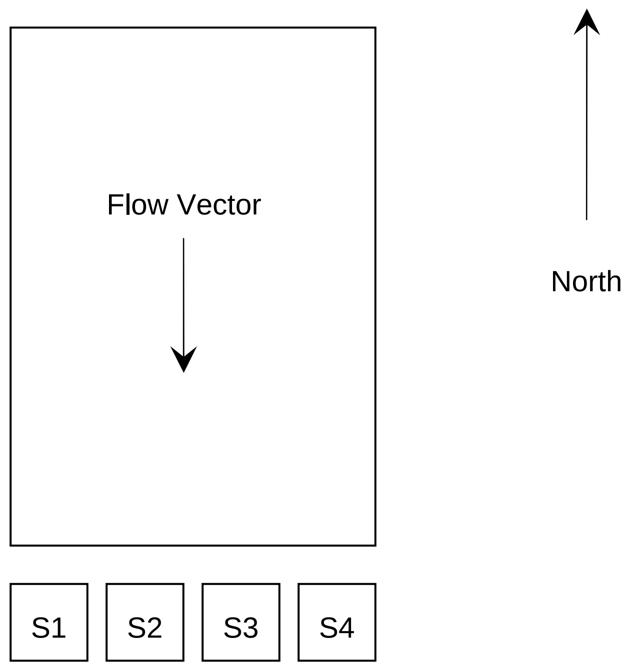

Figure 4. General sampling configuration for all tests. All prevailing winds were from a northerly direction and all orchard rows ran north-south.

Harvest Efficiency

An analysis of the harvest efficiency was conducted to determine the effectiveness of the experimental treatment in relation to the standard treatment. This was done in order to quantify the value of the product left in the field by reducing the number of blower passes used.

Test plots were usually 10 harvest rows wide and within the test plots 5 replicate sample areas were chosen in a diagonal across the plot. The sample area consisted of the area between 4 trees. String was used to delineate the berm area from the middle area. The berm area was determined as 1 meter on both sides of the tree row. The middle area went from the string to 0.3 meters away from the nut windrow. The harvestable are was determined as the windrow plus 0.3 meters on either side. The pollinator row areas were 0.3 meters from the windrow to the middle of the berm and were pre-raked before the sweeping treatment to eliminate any nuts from the area that were not attributable to the sweeping process. Nuts were collected in plastic bags and refrigerated until being weighed. Reported “weight of nut” included the total nut (hull, shell, and meat). Sample collection at the Arbuckle site only differed from the Wasco site in the number of trees sampled at each sample location within the test plot. (Wasco = 4, Arbuckle = 1). The reduction in the number of trees sampled was done due to the limited availability of labor at the second sampling site.

Modeling

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

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

where:

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

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

The ISC-STv3 area source algorithm is similar to the algorithm used in Point Area and Line Sources 2.0 (PAL) (Peterson and Rumsey, 1987). The concentration is predicted by simulating the area source as a series of line sources that are perpendicular to the wind. In ISC-STv3 the orientation of source and receptor is defined according to the wind direction for the modeling period. The crosswind distance (Y) is the distance perpendicular to the wind direction from an emission point to a receptor. The downwind distance (X) is the distance from an emissions point to the receptor, parallel with the direction of the wind.

The number of line sources used is increased until the predicted concentration using N line sources converges with the predicted concentration using N-1 line sources. The difference between ISC-STv3 and PAL is the criteria used to determine convergence of the predicted concentration. This change was made in order to optimize the computing time used to determine the concentration, but yields the same results (EPA, 1995). ISC-STv3 can also handle more variations in the configuration of area sources. PAL limits area sources to strictly North-South East-West orientations (Petersen and Rumsey, 1987), while ISC-STv3 allows for any configuration of area sources. The method used by ISC-STv3 allows for the placement of receptors at any location in or around area sources. The only limitation on placement of receptors is the upwind distance to the nearest line source, which is due to the calculation of the σ_z parameter. When the upwind distance from source to receptor approaches zero, σ_z approaches zero, yielding inconsistent results. Therefore, ISC-STv3 limits the minimum downwind distance, from source to receptor, to 1 meter.

In order to determine concentrations downwind of the source for varying wind directions ISC-STv3 effectively rotates the coordinates of the source and receptor to keep to that of the wind direction. This rotation maintains the ideal perpendicular orientation of wind direction and line source for all wind directions. Therefore, ISC-STv3 does not incorporate the change in wind direction into the Gaussian equation, but incorporates the change in wind direction before the Gaussian equation is used. This allows for much simpler calculations.

The evaluation of the area source algorithm is the result of the integration of equation 1. The integration is done numerically by using the infinite length line source model (equation 2), and then multiplying by a scalar to correct for edge effects (Turner, 1994). The effect of this calculation is that the area source closest to the receptor will have the largest effect on the total predicted concentration. As the distance from the receptor increases the relative contribution to the total concentration decreases. The decrease in concentration in the infinite length line source is attributed solely to the increased vertical dispersion of the plume with distance.

$$C = \frac{2q}{\sqrt{(2\pi)}\sigma_z u} \exp\left[-\frac{H^2}{2\sigma_z^2}\right] \tag{2}$$

- where:
  - C = concentration of pollutant ($\mu g/m^3$);
  - y_1, y_2 = extent of line source;
  - q = emission rate ($\mu g/m/s$);
  - σ_z = Pasquill-Gifford vertical plume spread parameter based on stability class (m);
  - u_s = average wind speed at pollutant release height (m/s);
  - H = emission height.

The correction for edge effects is a function of the crosswind distance from the end of each line source, to the receptor (Y), and the horizontal plume spread parameter (σ_y). This is a different value for each line source in the model.

The model was used in reverse to allow for a flux to be determined from a measured concentration. Due to the complexity of the driving equations, the flux was not solved for directly, but was determined using the direct relationship between flux and concentration in equation 1. This is done by predicting a concentration using actual meteorological conditions for a given sampling period and a unit flux emission rate of 1 $\mu g/m^2$-s. The resulting predicted concentration is called a unit flux concentration (UFC) and can is divided into the measured concentration. The resulting number is the emission flux for that sampling period. Using the actual spacing on the facility in each housing type, the emission flux can then converted to an emission rate.

Results and Discussion

Concentration Measurements

The average TSP concentration measurements for the Wasco sampling site are in table 1 below. The average upwind TSP concentration was 251 $\mu g/m^3$ and the mean downwind concentration was 916 $\mu g/m^3$. The mean upwind PM_{10} concentration was 221 $\mu g/m^3$ and the mean downwind PM_{10} concentration was 361 $\mu g/m^3$.

Table 1. Summary of the concentration measurements ($\mu g/m^3$) at the Wasco sampling location.

	TSP		PM_{10}	
	Mean	SD	Mean	SD
Up Wind	250.7	227.9	221.1	183.8
Down Wind	916.0	820.1	360.6	350.3

The average TSP concentration measurements for the Arbuckle Sampling site are in table 2. The mean upwind TSP concentration was 103μg/m^3 and the mean downwind TSP concentration was 653μg/m^3. The mean upwind PM_{10} concentration was 58μg/m^3 and the mean downwind PM_{10} concentration was 274μg/m^3.

Table 2. Summary of the concentration measurements (μg/m^3) at the Arbuckle sampling location.

	TSP		PM_{10}	
	Mean	SD	Mean	SD
Up Wind	103.4	55.2	58	22.7
Down Wind	653.1	273.5	274.3	94.2

It should be noted the significant difference in the upwind concentration measurements at each location. The Wasco sampling site is in the southern SJV and has frequently exceeded the national ambient air quality standards for PM_{10}. The Arbuckle sampling location north of Sacramento is in an area that has relatively few problems with exceedances of the national ambient air quality standards. The difference is also attributable to the different conditions immediately upwind of the samplers that directly affect the measured concentration.

Particle Size Distribution

At the current time only the samples from the Wasco sampling have been analyzed for particle size distributions. The analysis is done using a Coulter Counter Multisizer 3 from Beckman Coulter. A regression of the FRM PM_{10} concentration measurement versus the true PM_{10} portion of the collocated TSP sampler is presented in figure 5. The average aerodynamic equivalent, mass median diameter for the downwind TSP samplers for this sampling location was 15.6 μm and the geometric standard deviation was 2.2. There was no correlation between the measured PSD and the treatment. The PSD indicates that 28% of the measured TSP is PM_{10} and approximately 0.9% of the measured TSP is $PM_{2.5}$.

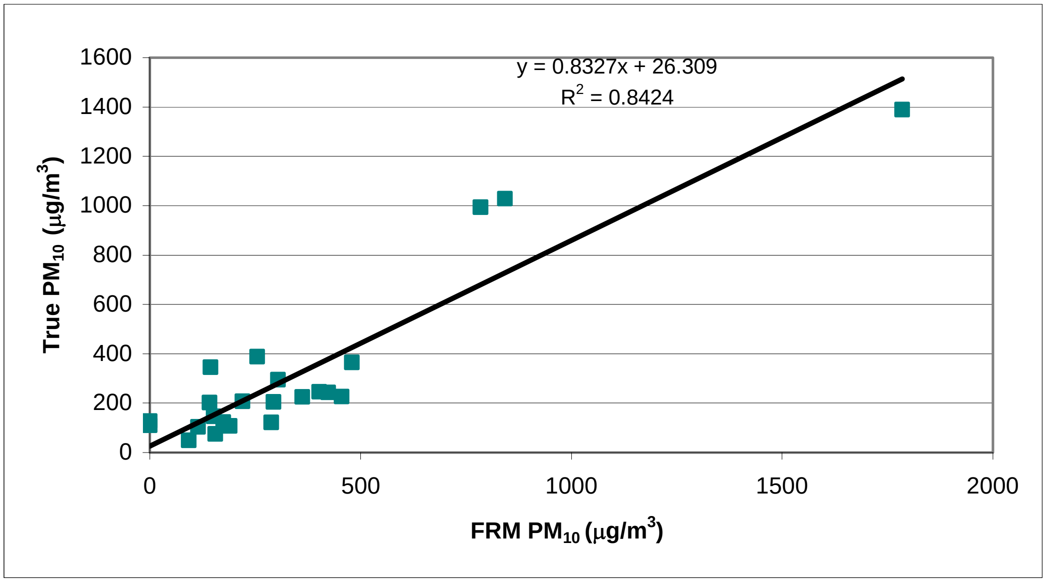

Figure 5. Regression analysis of FRM PM_{10} measurements versus the true PM_{10} fraction of collocated TSP concentration measurements.

The regression line shows that the true PM_{10} concentration is approximately 17% lower than the concentration indicated by FRM samplers. This is consistent with the theory suggested by Buser et al, (2007) for large particle size distributions.

Modeling

The sampling scheme was setup to ideally get a control and treatment test during each sampling day. Due to the extremely calm and unpredictable weather patterns in the region that was not always possible. The width of each test plot ranged between 80 and 117 meters as time went on. The depth of every plot was 185 meters which corresponded to the distance to the first turn-row of the orchard. The four downwind samplers were evenly spaced across the width of the harvested block moving from west (S1) to east (S4).

Table 3 shows the average emission rate for the Wasco sampling location. The results indicate a reduction of 44% that is significant at the 0.1 level using the student's t distribution.

Table 3. Average emission rate for the Wasco sampling location.

Treatment	Mean Emission Rate		Standard Deviation	n
Average EF 3 Blower Passes	620	kg/km^2 TSP	493	12
Average EF 1 Blower Pass	346	kg/km^2 TSP	114	12

Table 4 shows the average emission rate for the Arbuckle sampling location for both treatments. Here the results indicate a reduction of 56% that is statistically significant at the 0.05 level using the student's t distribution.

Table 4. Average emission rate for the Arbuckle sampling location.

Treatment	Mean Emission Rate		Standard Deviation	n
Average EF 3 Blower Passes	508	kg/km^2 TSP	172	9
Average EF 1 Blower Pass	222	kg/km^2 TSP	163	10

The significant reduction in emissions that can be achieved through a simple grower practice shows large promise for reducing emissions industry wide. There was an average reduction in sweeping emissions of 50% over both tests. It can be assumed that the reductions are linear to the number of sweeper passes used. Therefore, an operation that feels the need to use 2 blower passes can still achieve a 25% reduction in emissions over a standard 3 blower pass sweeping operation.

Harvest Efficiency

Harvest results are presented in kg/ha assuming 284 trees per hectare. Table 5 shows the results of the harvest efficiency tests on a kg/ha basis.

Table 5. Wasco whole almond losses.

Blower Passes	Berm		Middle		Pollinator West		Pollinator East	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
1	48.9	29.2	20.3	10.6	163.2	17.1	24.2	12.8
3	35.1	38.1	15.7	1.8	60.1	25.8	17.5	11.0

Table 6. Arbuckle whole almond losses.

Blower Passes	Berm		Middle		Pollinator West		Pollinator East	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
1	17.6	3.7	25.7	16.3	14.7	11.9	22.0	8.1
3	1.7	0.5	51.7	15.4	9.7	0.9	8.4	3.7

The berm nut losses at the Wasco site were much higher than what was observed at the Arbuckle site. A possible reason for this may be the difference in crop water status and moisture content of the nuts. The crop water demand at the Wasco site seemed to be better met when compared to the Arbuckle as the trees were defoliating during sampling. This produced almond hulls that were dry and more readily blown off the berms. The 1 blower pass treatment left 39% more nuts on the berm at the Wasco site and 9 times more nuts at the Arbuckle site, although the nuts left at the Arbuckle site were comparatively less. While the difference between the treatments was significant at both sites, the absolute mass of product missed due to reducing the number of blower passes is insignificant compared to the entire harvest. According to the preliminary yield estimates for 2006 of 1971 kg/ha (meats only), the change in yield of 14.6kg/ha (hull, shell and meat) represents an insignificant difference in yield.

The focus of this work was on the almonds left on the berm. Nuts not picked up on the pollinator rows maybe harvested during the harvest operations of the alternate variety. Nuts left in the middle of the row were not affected by the treatment of the tests conducted which was the number of blower passes.

Conclusion

Ambient sampling downwind of two almond orchards during the 2006 harvest season allowed for the quantification of PM emission reductions through the use of a minor change in grower practices. The average reduction of 50% in emissions through the use of a single blower pass versus 3 blower passes during sweeping represents a large reduction in emissions. The small amount of product left in the field during the study period also shows that reducing blower passes may have a minimal economic impact on the grower and may very well improve the growers bottom line due to increased sweeping speeds and less maintenance per acre due to less sweeper passes. The impact of testing the two extremes of operation allows for the interpolation of emissions for farmers that feel 2 blower passes are necessary due to orchard conditions.

The research also shows the robustness of the method used for emission factor development. The fact that both sampling locations showed comparable reductions in emissions for identical experimental treatments shows that even though all variables cannot be controlled or even measured during ambient sampling, inverse dispersion modeling can ameliorate many of the unknowns. This also may lead to the application of this method to the development of other mitigation practices for field operations.

Acknowledgements

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References

Compose your reference entries following the examples below or by referring to http://www.asabe.org/pubs/29_References.html. The references should be in alphabetical order. The RefListing Style will create the indents. Press Enter for the next entry. Be sure to delete these examples. *Please do not use hyperlinks*.

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