Integration of remote lidar and in-situ measured data to estimate particulate flux and emission from tillage operations.

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ABSTRACT

Agriculture, through wind erosion, tillage and harvest operations, burning, diesel-powered machinery and animal production operations, is a source of particulate matter emissions. Agricultural sources vary both temporally and spatially due to daily and seasonal activities and inhomogeneous area sources. Conventional point sampling methods originally designed for regional, well mixed aerosols are challenged by the disrupted wind flow and by the small mobile source of the emission encountered in this study. Atmospheric lidar (LIght Detection And Ranging) technology provides a means to derive quantitative information of particulate spatial and temporal distribution. *In situ* point measurements of particulate physical and chemical properties are used to characterize aerosol physical parameters and calibrate lidar data for unambiguous lidar data processing. Atmospheric profiling with scanning lidar allows estimation of temporal and 2D/3D spatial variations of mass concentration fields for different particulate fractions (PM₁, PM_{2.5}, PM₁₀, and TSP) applicable for USEPA regulations. This study used this advanced measurement technology to map PM emissions at high spatial and temporal resolutions, allowing for accurate comparisons of the Conservation Management Practice (CMP) under test. The purpose of this field study was to determine whether and how much particulate emission differs from the conventional method of agricultural fall tillage and combined CMP operations.

Keywords: Remote sensing, lidar, aerosols, aerosol profiling, air pollution, fluxes, agriculture operations

1. INTRODUCTION

Agricultural facilities and operations are sources of emissions of gases and particulates in the atmosphere. Quantifying those emissions has proven to be difficult because of the variation among facilities, the spatial arrangement of the emission sources, and the temporal variation in emissions caused by variations in management, biological systems, and weather. Typically, monitoring systems for agricultural systems have employed instrumentation designed to evaluate the concentrations of gases or particulates at a specific location around the facility or within the operation. The dynamics of airflow and particulate movement around facilities raise the question of how improved methods of measuring particulate emission and movement might aid in our understanding of emissions from agricultural facilities and in the long-term provide a method of comparing systems or management practices [1].

Light detection and ranging (lidar) technology has been successfully applied to qualitatively characterize particulate emissions from agricultural sources [1-3]. The physical properties of an aerosol can be retrieved from lidar data using the measured backscatter coefficients and the known relationship between aerosol physical properties and backscatter [4-6].

This study used advanced measurement technologies such as lidar system [7] coupled with conventional point measurement air quality samplers to map PM emissions at high spatial and temporal resolutions [1, 6], allowing for accurate comparisons of the Conservation Management Practices (CMP) under test. The

purpose of this field study was to determine whether and how much particulate emission differs from the conventional method of agricultural fall tillage and a “Combined Operations” Conservation Management Practice.

The tillage site for this study was near Los Banos, California and consisted of two adjacent fields that were cultivated in cotton for the 2007 growing season and were planned to grow similar crops in the 2008 growing season. The test fields were adjacent on a north/south orientation. Conventional tillage operations were applied to the north field 25.5 hectares. The combined operations tillage was applied to the south field 51.8 hectares. Soil type distribution for both fields was practically identical. The conventional tillage method included two disc passes, separated by a chisel operation, followed by a land plane pass. A precipitation event occurred before the land plane event, which left the surface layer slightly moist reducing emissions for the land plane operation. The Combined Operation CMP chosen for examination was the Optimizer, which is designed to perform the work of several pieces of equipment in one pass, thereby reducing the number of passes and time spent on the tillage operation. A chisel pass preceded the Optimizer.

2. METHODS AND INSTRUMENTATION EMPLOYED

Adequately describing the aerosols encountered at agricultural facilities is a complex process. Particle size distributions are often described using a bimodal lognormal distribution with six independent parameters and different indexes of refraction in different modes. This may require a total of twelve independent parameters to describe the aerosol, while Aglite lidar system used in this study has only three spectral channels. Uncertainties in aerosol chemical composition, non-spherical particle shape, and the variety of environmental conditions combine to make it unfeasible to measure mass concentration purely optically.

In the approach applied in this study, the particulate chemical and physical properties are measured *in situ* using point sensors that measure the particle size distribution of both particulates emitted at the experiment site and background aerosols. The details of this approach described in our recent publications [1, 6]. In summary, these point measurements are used to establish the parameters required to invert the lidar data and retrieve the aerosol concentration. Point measurements are also used to calibrate the results of the lidar retrievals to derive 2D-3D distribution of the mass concentration fields. These measurements are made by MetOne 9722 Optical Particle Counters (OPCs) and AirMetric MiniVol Portable Air Samplers (Filter Particulate Samplers or FPS) aerodynamic particle sampler instruments.

The calibration process consists of two major steps. First, the lidar line of site is placed next to the OPC used for calibration to establish a reference calibration point that will be used to convert the lidar return signal to aerosol optical parameters. This calibration step is typically performed every 2-5 min to account for variability of the background aerosols. Secondly, the relationship between aerosol data acquired optically (OPC and lidar) and aerodynamically (FPS) is derived for each experiment setup as a mass calibration parameter. This relationship is described by the mass conversion factor (MCF) and used to convert particle concentration retrieved from the scanning lidar system to mass concentration fields with accordance to the lidar scanning pattern.

The Aglite lidar system utilized in this work is described in details in [7]. It is a single diode-pumped 10 kHz Nd:YAG laser co-aligned with a Newtonian telescope with a 28-cm diameter primary mirror. The laser operates simultaneously at 1.064 μm (IR), 0.532 μm (VIS), and 0.355 μm (UV) wavelengths with pulse energies of 435, 50, and 93 μJ , respectively. The lidar utilizes a turning mirror turret mounted on the top of a small trailer to direct the beam -10 to + 45° vertically and $\pm 140^\circ$ horizontally. Lidar scan rates from 0.5 – 2°/s are used to develop the 2D-3D map of the emission source(s), dependent on range and concentration of the aerosol.

To measure the background and emission aerosol properties, OPCs and FPS are mounted on the array of towers around the facility under study. The OPC sensors have the ability to count and size airborne particles into eight size ranges from 0.3 to greater than 10 μm in diameter with a selectable sample averaging time between 2 and 60 s. Clusters of filter-based portable FPS are collocated with the OPCs. Each sampler in the cluster has a different impaction head that aerodynamically separates the aerosol into the mass fraction of TSP (Total Suspended Particulate), PM_{10} , $\text{PM}_{2.5}$ or PM_1 . This allows simultaneous

measurement of each mass fraction concentration at the cluster location. The sampling period varies from 4 to 24 hours, based on the estimated background aerosol and emitted particulate concentrations. Each sampler is fitted with a conditioned, pre-weighed Teflon filter and operates at a flow of approximately five liters per minute. Following sampling, the filters are recovered, conditioned, and reweighed for filter catch and determination of each location's mass concentrations.

Two methods of emission rates estimations during tillage operations were used in this study:

1. EPA-approved models were used to assess emission rates based on the particulate FPS sampler data: the Industrial Source Complex Short-Term Model, version 3 (ISCST3) [8] and the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD), which as of November 2005 is recommended for all regulatory applications [9]. Both models assume steady-state conditions, continuous emissions, and conservation of mass. ISCST3 assumes a Gaussian distribution of vertical and crosswind pollutant concentrations based on time averaged meteorological data. AERMOD uses continuous functions for atmospheric stability determinations, and based on stability determines the appropriate distribution, a Gaussian distribution for stable atmospheric conditions, and a non-Gaussian distribution for unstable, or turbulent conditions. Final emission rates were estimated using inverse modeling coupled with observed facility-derived concentrations:

$$E_{derived} = E_{seed} \left(\frac{C_{measured}}{C_{modeled}} \right) \quad (1)$$

2. The concept behind our flux measurement approach using lidar data is demonstrated in Figure 1A, where the facility is treated as the source strength in a bioreactor. Detailed description of this method can be found in [1]. In this simplified approach, the source strength is determined using the mean flow rate through the reactor and the difference in reactive species concentration entering and leaving the vessel. The scanning lidar samples the mass concentration fields entering and leaving the facility, while standard cup anemometers provide the mean wind speed profile. An example of Aglite lidar derived concentration data is shown in Figure 1B.

Figure 1. (A) Conceptual illustration of the method for using lidar to generate time resolved local area particulate fluxes. (B) An example of a “staple” lidar scan over the facility showing aerosol concentration on the three sides of the box.

The concentration plot pattern from scanning up one side, across the top, and down the other looks like the common office staple, and will be referred to as a “staple” scan. The data from the top of the box is regularly examined to be sure that no significant particulate transport is passing through the top. The data for the left side panel of the staple provides the background concentration entering the box, while that on the right provides the background plus facility concentrations leaving the box. The integrated mass concentration difference multiplied by the wind speed during the scan completes the flux emission calculation by yielding a mass per unit time emission from the facility. The flux calculation in the integral form can be expressed as following:

$$F = \iint_{r,h} \bar{v}_{\perp}(r,h) \cdot (\cos \theta_D C_D(r,h) - \cos \theta_U C_U(r,h)) dr dh \quad (2)$$

where $\bar{v}_{\perp}$ is the average wind speed component, defined as parallel to the long axis of the box, and $C_D - C_U$ form the mass concentration difference downwind and upwind, integrated over the range (width) and height of the sides of the staple. In our routine, Equation 1 is calculated as:

$$F = \sum_{i=R_0}^R \sum_{j=H_0}^H \bar{v}_{\perp ij} (\cos \theta_D C_{Dij} - \cos \theta_U C_{Uij}) \cdot \Delta r \cdot \Delta h \quad (3)$$

where R_0 and R are the near and far along beam edges of the box and H_0 and H form the top and bottom of the box. (In many cases, H_0 is set above eye level and concentration is extrapolated to the ground to avoid illuminating personnel and animals.) The $\Delta r \cdot \Delta h$ term is the individual area element for which each flux component is calculated by each step in the double summation.

The number of scans utilized to assess each operation varied from 47 to 122, with the sample number reduced during some operations by light and variable wind conditions. Emission rate values were estimated dividing the flux averaged over all staple scans passed quality control by the area of the field under tillage operation.

A set of meteorological instrumentation was employed on the experimental site to support aerosol flux and emission rate measurements. A Vantage Pro2 Plus weather station from Davis Instruments, Inc. (Hayward, CA) was used to monitor wind speed, wind direction, temperature, humidity, precipitation, barometric pressure, and solar radiation. It was located on top of the Air Quality sampling trailer, at an approximate height of 5 m above ground level. Two 15.2 m towers were instrumented with 3-cup anemometers (model 12102) and relative humidity/temperature sensors (Vaisala HMP45C) from Campbell Scientific, Inc. (Logan, UT) at 5 heights (2.5, 3.9, 6.2, 9.7 and 15.3 m) to provide profiles of wind speed, temperature, and relative humidity. A Met One Instruments, Inc. (model 024A, Grants Pass, OR) Wind Vane was stationed at a height of 15 m on each tower. A tethersonde system from Atmospheric Instrumentation Research, Inc. (Boulder, CO) was employed to provide vertical wind speed, wind direction, temperature, humidity, and pressure profiles. The tethersonde meteorological package was a Model TS-3A-SP, which transmits 10 second averaged data to a receiver package (Atmospheric Data Acquisition System Model AIR-3A) at ground level.

3. LIDAR MASS CONCENTRATION RETRIEVAL

The process of retrieving aerosol mass concentration from the Aglite lidar data is discussed in details in our previous publications [6, 10]. The retrieval process can be summarized as following (see Figure 2). First, the lidar data are preprocessed. The relationships between backscatter, extinction, volume concentration, and mass concentration of the aerosol components are established using collocated *in situ* point sensors described in previous section. Then the inversion of the lidar equation for backscatter is performed using the form of Klett's solution [11] including background where extinction is proportional to backscatter.

Finally, a least-squares method is used to convert backscatter values to the aerosol volume and mass concentrations using previously established relationships.

The best results using Klett's analytical solution are achieved when the boundary/reference point for the solution is chosen at the far end of the aerosol cloud. The solution beyond reference point is very unstable and in most practical cases diverges. Moreover this reference data are not always readily available. Secondly the signal-to-noise ratio (SNR) of the lidar return signal strongly decreases with the distance and the retrieval errors consequently degrade when reference point is chosen far away from the lidar. In most of practical cases it leads to the strong decrease in the accuracy of retrievals [6]. If the boundary point can be placed at a range relatively close to the instrument where the signal-to-noise ratio (SNR) is still high the accuracy of lidar retrieval and calibration will increase significantly.

To overcome these drawbacks of the Klett's analytical approach, the SDL has developed a novel method of retrieving aerosol concentration from elastic lidar data. The detailed description of this method was published elsewhere [12].

This method operates by formulating the lidar equation in vector form, linearizing it around some solution value, and computing the least square solution. This process is repeated until the solution converges, similar to the Newton-Raphson method. As Klett's solution, this method requires *a priori* knowledge of backscatter values at boundary point as well as defined relationship between backscatter, extinction, and mass-fraction concentration for all scattering components.

Figure 2. The Aglite retrieval algorithm flow chart, showing the input locations for the *in situ* data.

The new method is capable of handling an arbitrary number of lidar channels and generates stable solutions at ranges beyond the reference point and at low SNR values. The ability of this method to account for different channel noise, to use all spectral channels in the retrieval simultaneously, and its stability at all ranges before and beyond the reference point makes this method particularly useful for extracting maximum information at the far end of the lidar signal.

An algorithm using this method was validated using both simulated and experimental data [12]. However, due to time limitations and huge volume of data the results of this study were processed with old version of the Aglite algorithm depicted in Figure 2.

4. RESULTS

4.1 ISC/AEROMOD dispersion models.

The FPS measured concentrations upwind and downwind were evaluated to determine if they were significantly different for each operation (see Figure 3). TSP emissions from agricultural tillage should be

typically 21% PM₁₀ and 4.2% PM_{2.5} [14]. In this case, concentrations of PM₁ and PM_{2.5} should not vary greatly between the upwind and downwind sampling locations, whereas concentrations of PM₁₀ and TSP should be more variable, as seen in this study. In cases where the downwind concentration was significantly higher than the upwind concentration, based on a 67% confidence interval, emission rates were calculated using the measured concentrations (downwind minus upwind), modeled concentrations and the seed emission rate as shown in Equation 1. On five of seven and one of seven days for PM_{2.5} and PM₁₀, respectively, the difference between average upwind and downwind measured concentrations were not significant at the 67% confidence interval.

Figure 3. Average measured PM concentrations, upwind and downwind, with the particle size contributions to the total PM.

ISCST3 modeled concentrations ranged from 0.0 to 676 $\mu\text{g}/\text{m}^3$ with the highest concentrations typically modeled at a height of 2 m on the southern edge of the tillage sites, although this varied slightly with shifting wind directions. Figure 4 shows an example of ISCST3 modeled concentrations for the Disc 1 pass as part of the conventional tillage operations with 1.6 m/s average north winds.

AERMOD modeled concentrations ranged from 0.0 to 419 $\mu\text{g}/\text{m}^3$ with the highest concentrations typically modeled at a height of 2 m on the southern edge of the tillage sites, although this varied slightly with shifting wind directions.

Figure 4. ISCST3 modeled results for the Disc 1 pass of the traditional tillage operations on October 23, 2007 with light north winds. The area of operations and sampler locations are denoted in white.

The ratios of measured and modeled concentrations at the southern edge of the tillage site are very similar; however at other locations, depending on wind direction, the modeled concentrations dropped off much more quickly than the measured concentration values, resulting in large measured to modeled concentration ratios. The overall ratios ($\pm 1\sigma$) using all sampling locations were 139 ± 757 , 45 ± 832 , and $2,587 \pm 7,317$ for PM_{2.5}, PM₁₀, and TSP respectively.

These large ratios significantly affected the average when determining an emission rate. Arya [13] suggests that the plume edge be defined as 10 percent of the maximum modeled concentration. Defining the edges of the plume in this way and using only the ratios calculated for the in-plume locations the average ratios for PM_{2.5}, PM₁₀, and TSP were found to be 0.031 ± 0.051 , 0.093 ± 0.098 , and 0.39 ± 0.26 respectively. Multiplying the average ratio for each operation by the original “seed” emission rate yielded the emission rates found in Table 2.

To compare combined and conventional operations, the emission rates of individual operations were normalized by the operation area and time of the sample run. The mass per unit area of PM emitted by the individual operations could then be summed to provide total mass emitted from the combined and conventional tillage operations.

4.2 Lidar based fluxes and emission rates.

Examples of the lidar-derived upwind and downwind plume area average volume concentrations used in the flux calculations are shown in Figure 5. The two top panels show the profile averaged wind speed and direction values used in the flux calculation, with the third and fourth panels showing the area averaged volume concentrations measured upwind (CU) and downwind (CD) in $\mu\text{g}^3/\text{cm}^3$. Wind speeds and directions for some of the days that measurements were made were light and variable and challenged the measurement system.

Figure 5. Wind speed, wind direction, upwind and downwind volume concentrations, and mass flux calculated using the lidar data collected on October 19, 2007 during the chisel pass of the combined operation tillage method.

The concentrations derived from the lidar scans to be used in flux calculations were carefully quality controlled to assure that the upwind and downwind measurements were not contaminated by road traffic or

mixed airflows that did not represent the operation under test. The quality control rejects experimental data based on three conditions that violate the flux measurement assumptions:

- Wind direction more than $\pm 80^\circ$ from the mean direction at the time of the scan
- External fugitive dust entering from the upwind side of the field due to traffic or other non-stationary anomaly (e.g. dust devil).
- Contamination of the reference OPC from the upwind side of the field.

The combination of 'staple' and 'stare' measurements of the mass concentration distribution measurements from the upwind and downwind sides of the field were performed continuously during the each tillage operation of the field campaign. Figure 6 shows an example of calculated net flux measurements for sequential lidar measurements taken during the Optimizer pass in the combined operation tillage method on 10/20/2007. The net flux is the product of the plume area averaged volume concentration (CD-CU) difference multiplied by the daily average MCF and the component of the wind velocity that is perpendicular to the lidar beam (Equation 3). This quantifies the mass passing through the lidar's vertical scan per unit time.

Figure 6. Lidar derived fluxes (g/s) of PM_{2.5}, PM₁₀, and TSP for the October 20, 2007 Optimizer pass of the combined operation tillage.

Using the series of flux measurements collected during each tillage operation, similar to those in Figure 6, the mean fluxes were calculated for all days and are presented in Table 1 with respective 95% confidence intervals. The error bars used here for the lidar data denote our confidence in the mean due to the scan to scan variability due to the wind transport process occurring on that day, and not to the accuracy of the individual measurements.

The flux data presented in Table 1 were multiplied by the total tractor operation time to yield a total mass emitted, and then normalized by area tilled to calculate emission rates presented in Table 2. While the lidar-measured fluxes for the Optimizer pass in Table 1 are higher than the chisel pass of the same treatment, the emission rates reported in Table 2 for the Optimizer are lower because the Optimizer pass treats two times as much area in the same amount of time as the chisel pass.

Table 1. Mean fluxes (g/s) $\pm$ 95% confidence interval from quality-controlled samples for each tillage operation.

Date	Operation	PM _{2.5} (g/s)	PM ₁₀ (g/s)	TSP (g/s)
10/19/07	Combined: Chisel	0.33 $\pm$ 0.15	0.09 $\pm$ 0.02	1.91 $\pm$ 0.88
10/20/07	Combined: Optimizer	0.43 $\pm$ 0.10	0.56 $\pm$ 0.13	2.23 $\pm$ 0.51
10/23/0	Traditional: Disc 1	0.13 $\pm$ 0.02	0.62 $\pm$ 0.12	1.00 $\pm$ 0.19
10/25/2008	Traditional: Chisel	0.30 $\pm$ 0.08	0.66 $\pm$ 0.17	1.96 $\pm$ 0.50
10/26/2008	Traditional: Disc 2A	0.41 $\pm$ 0.12	0.72 $\pm$ 0.21	1.45 $\pm$ 0.43
10/27/2008	Traditional: Disc 2B	0.22 $\pm$ 0.05	0.53 $\pm$ 0.13	0.90 $\pm$ 0.22
10/29/2008	Traditional: Land plane	0.09 $\pm$ 0.02	0.15 $\pm$ 0.04	0.22 0.06

5. DISCUSSION

Two emission rate determination approaches were employed in this study to calculate three different sets of emission rates in order to quantify the differences between conventional tillage methods and a combined operations tillage method using the Optimizer. A summary of the PM10 emission rate estimations using lidar data and inverse modeling with ISCST3 and AERMOD dispersion models is given in Table 2 for comparison.

Table 2. Calculated PM10 emission rates ($\pm$ 95% confidence interval) from OPCs, the lidar, and inverse modeling using two dispersion models.

Operation	This study		
	Lidar	ISCST3	AERMOD
	(mg/m ²)	(mg/m ²)	(mg/m ²)
Disc 1	99.7 $\pm$ 12.5	99.5 $\pm$ 64.0	119.2 $\pm$ 57.2
Chisel	79.5 $\pm$ 13.1	122.5	160.4
Disc 2	80.7 $\pm$ 20.5	204.2 $\pm$ 240.8	147.8 $\pm$ 90.9
Land Plane	21.9 $\pm$ 6.2	45.4 $\pm$ 32.3	44.8 $\pm$ 10.8
Conventional Method Sum	281.9 $\pm$ 28.0	472.0 $\pm$ 289.5	472.2 $\pm$ 109.7
Chisel	69.0 $\pm$ 19.9	103.6 $\pm$ 83.4	185.3 $\pm$ 159.2
Optimizer	42.7 $\pm$ 6.6	79.0 $\pm$ 94.9	90.9 $\pm$ 106.3
Combined Operations Method Sum	111.6 $\pm$ 20.9	182.5 $\pm$ 126.4	276.2 $\pm$ 191.4

The 95% confidence interval of the total mass emitted per day was calculated by using the sample statistics (standard deviation) for each day. The 95% confidence interval for the total emission, on the other hand, was derived using the assumption that the average emission rate of each day can be treated as a random variable. The variance of the total emission for each technique was calculated as the sum of the variances of each operation. The 95% confidence interval was then calculated again assuming a Gaussian distribution. It

should be noted that up- and down-wind PM10 concentrations were not statistically different at the 67% confidence level on 10/25/07, the chisel pass in the Conventional Tillage Method, and the sum of emission rates for the Conventional Method from the ISCST3 and AERMOD approaches do not account for this lack of data.

The derived emission rates, while carefully collected and analyzed show conclusively the limitations of using even large arrays of point samples to measure the emissions associated with weak, mobile sources. The upwind and downwind concentration differences due to plume impact on the scattered samplers on these days were simply below the detection limit of the sampling system.

The lidar system, however, effectively sampled the vertical downwind plane and measured time-resolved plume characteristics for each operation at each particulate size fraction.

The calculated PM10 emission rates demonstrate that for total mass of PM10 per unit area the Combined Operations method produced between 40% and 65% as much as the conventional method based on all employed measurement systems. The models predicted PM10 values within the range of lidar measurements based on the 95% confidence intervals.

The emission rate in (mg/m^2) of the Optimizer pass is equal to or less than the emission rate of the chisel pass in the same treatment for all three emission rate calculations, despite the fact it resulted in higher downwind concentrations, as measured by the lidar and point samplers. One reason for this is that the tillage rate (hectares/hr) of the chisel pass was about half that of the Optimizer pass. For treatment comparisons within a single measurement system, statistically significant differences between the Combined Operations method and the Conventional method for PM10 are seen.

While the dispersion model estimated emission rates are generally about the same, the largest difference is between the two models and the lidar. This is likely due to the fact that ISCST3 and AERMOD are nearly identical numerical models while the lidar measures actual fluxes. The models are limited to the types of sources that can be used (point source, volume source, area source, or line source), which means that a compromise must be made when dealing with a small, moving area source such as is the case of agricultural tillage. In addition, the temporal and spatial resolution of the lidar allows it to see micro-scale variations in plume characteristics and movement such as plume strength, frequency, lofting and detachment from the surface, wind direction effects and wind speed effects. This allows for careful quality control of the fast sampled lidar data that is impossible for inverse modeled data based on the long term FPS sampled data.

6. CONCLUSION

Emission data calculated for each measurement method for the conventional and conservation tillage operations are presented. The study showed that the conservation practice under study has reduced the number of tillage passes by 50%, with similar reductions in fuel use and associated PM10 emissions. Lidar-derived emission rates for PM2.5, PM10, and TSP by operation along with the average tillage rate in hours per hectare were summarized from the experiment. The Combined Operations tillage method reduced PM2.5 emission by 29%, PM10 by 60%, and TSP by 24%.

The filter sampling/inverse model methods were severely challenged by the small mobile source emissions encountered in this study, and differences between average upwind and downwind concentrations for several of the operations were not statistically significant. However, the scanning lidar provided highly significant emission measurements for all measurement periods.

The large difference in the emission rates between the two dispersion models and the lidar estimations were observed. The models must assume a constant emission from the entire emitting surface area, while the lidar sees the plume movement as the tractor moves. This kind of microstructure cannot be captured by the long term sampling required for implementation of ISCST3 and AERMOD, and these models are incapable of generating fine levels of spatial and temporal detail.

Differences not statistically significant between average upwind and downwind concentrations, prevented PM2.5 emission rate determination using the models for five of the seven measurement periods, as well as one day for PM10 emission rates. The scanning lidar technology employed was able to calculate emissions for all measurement periods.

Moreover, the plumes measured by the lidar were detected much higher (up to and exceeding 100 m) than the model predicts (~10-30m) and lidar measurements clearly indicate the presence of far more suspended particulate. The modeling results indicate that ISCST3 and AERMOD are at the limit of their designed performance because they do not accurately represent the actual plume. Lidar, on the other hand, is capable of measuring aerosol concentrations at elevations up to thousand meters.

It is clear that the incorporation of lidar measurements is an important complement to the ground based sensors because ground based sensors cannot measure elevated plumes. ISCST3 and AERMOD would realize significant benefits if lidar-derived information could be incorporated into their calculations.

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