

THE EMISSION RATE, BIOLOGICAL CHARACTERIZATION, AND TRANSPORT OF AEROSOLS EMITTED DURING THE DISK INCORPORATION OF CLASS B BIOSOLIDS

Tania Paez-Rubio* and Jordan Peccia**

* Department of Civil and Environmental Engineering, Arizona State University,
Engineering Center G-Wing Room 252
Tempe, AZ 85287, USA

** Department of Chemical Engineering, Yale University
Environmental Engineering Program,
New Haven, CT 06520, USA

ABSTRACT

Biosolids contain metal, biotoxin, and pathogen concentrations that are greater than the agricultural soils to which they are applied. Once applied, biosolids are incorporated into soils by disking and this process generates aerosols that may be a health hazard to workers and nearby residents. Field studies at a Central Arizona biosolids land application site were conducted to characterize the physical, chemical, and biological content of the source aerosols produced during biosolids disking and to validate a model for the off-site transport of these aerosols. Source aerosol concentrations and calculated emission rates reveal that disking is a substantial source of biosolids-derived aerosols. Biosolids disking emitted between 9.91 to 27.25 mg biosolids s^{-1} and these rates were greater than previously measured emission rates produced during the spreading of dewatered biosolids or the spraying of liquid biosolids. While source PM_{10} concentrations emitted during biosolids disking averaged 1.5 mg m^{-3} , comparisons with source PM_{10} concentrations produced during the disking of fields that did not have biosolids amendments revealed that adding biosolids to dry soils increased the moisture content and reduced the total PM_{10} emissions by at least three times. Using real-time PM_{10} concentration downwind field measurements, a Gaussian plume model for predicting off-site transport of aerosolized biosolids was validated.

KEYWORDS

biosolids, disking, aerosol, transport modeling

INTRODUCTION

Sixty percent of the class B biosolids produced in the US are reused by application to agricultural land. Land application results in a soil conditioning product that has the advantageous properties of slower and steadier nutrient availability that are unmatched by conventional chemical fertilizers (Bastian 1997). Aerosols are emitted at biosolids land application sites when biosolids are loaded into spreading equipment, while biosolids are spread onto fields, and during subsequent incorporation of biosolids into soils by disking. Thus far, the focus of biosolids

aerosol studies has been to characterize the aerosols emitted during the spreading and loading process (Brooks et al., 2005; Paez-Rubio, 2006). However, the disking step also logically provides a large potential for aerosol generation (Clausnitzer and Singer, 2000). Given this potential, prudent investigation of the health risk posed by the land application processes must include a description of the aerosols generated during disking activities.

In response we conducted field experiments to determine the biological, chemical, and physical characteristics of source and downwind aerosols emitted during disk incorporation. To enable transport modeling and allow for comparison of disking emissions with other emissions at land application sites, disking source emission rates (mg s^{-1}) were also estimated. Emission rates and downwind aerosol concentrations were then used to validate a transport model for estimating downwind biosolids aerosol concentrations produced during the disk incorporation process.

METHODOLOGY

Two disk incorporation aerosol sampling scenarios were considered. The first was sampling at the aerosol source. Aerosol samples were taken immediately downwind at the source of where biosolids were being incorporated onto soil by disking. Biological, PM_{10} , and metals concentration samplers were evenly distributed downwind from the edge of the disked zone, and were placed at the breathing zone height of 1.5 m (Figure 1). In the second scenario, aerosol samples were taken at different downwind distances from the source when biosolids were being incorporated onto soil by disking. Biological and PM_{10} samplers were located downwind at the plume source (0 m), at 70 m, and at 170 m (Figure 2). Controls for both scenarios consisted of background ambient aerosol concentration measurements as well as disk incorporation experiments in fields where biosolids had not been applied (termed “control disking”). Ambient background samplers for biological aerosols, PM_{10} , and airborne metals were located a minimum of 100 m upwind of the disking activity and were performed at the same time of the day as the disking experiments. Sampler location and operation was the same for control disking (no biosolids) and biosolids disking. Dewatered class B biosolids (20% to 30% water content) were used in all experiments. These biosolids were produced during anaerobic mesophilic digestion. The solid content of the mixture of dewatered biosolids and soil (soil/biosolids mixture) after disking the field ranged from 88% to 94%. The soil solids content before disking was 96% on average and the texture was sandy loam. Biosolids composed between 4% to 11% of the soil/biosolids mixture by mass.

For all disking experiments, downwind samplers were operated for the approximate 10 minute duration in which biosolids were incorporated into soil. The duration of upwind ambient control experiments was 45 minutes. Both source experiments and downwind transport experiments (including ambient controls) were repeated in four independent trials. Control disking experiments were repeated two independent times for source aerosol and downwind transport experiments. To ensure a constant downwind flow and control for wind aerosolization, these sampling events were performed only if wind speeds were above 0.8 m s^{-1} and below 4.0 m s^{-1} . A weather station (Weather Monitor II, Davis instrument Corp., Hayward, CA) was used in each field experiment to measure and log wind speed and direction, temperature, and relative humidity.

Figure 1 - Description of aerosol measurement during biosolids diking. Diking equipment pathway was parallel to the aligned samplers that were evenly distributed in the field.

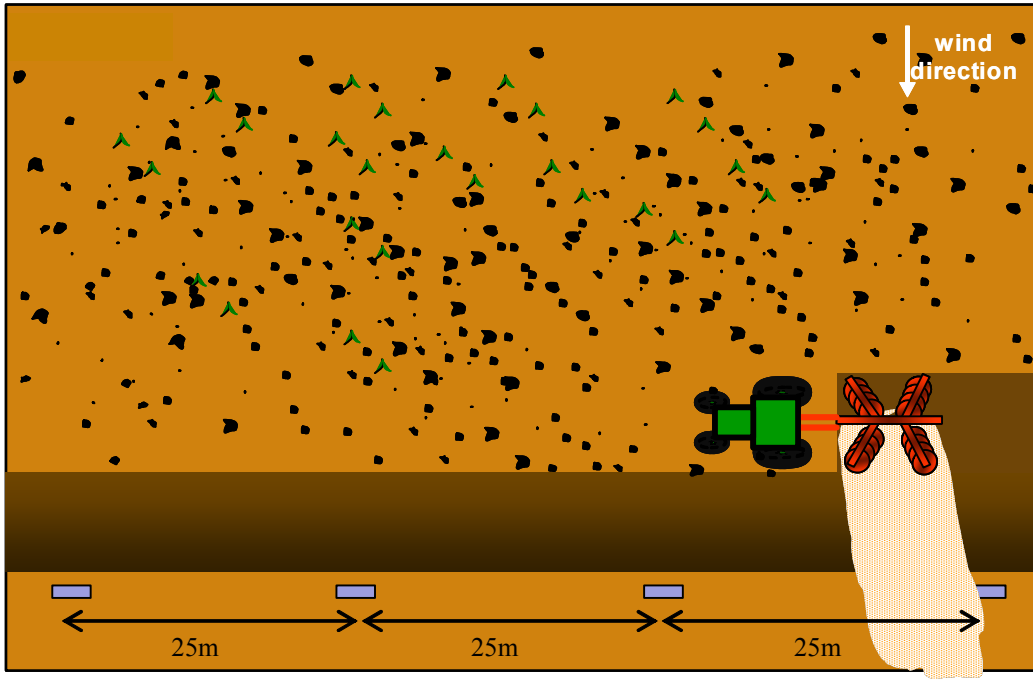
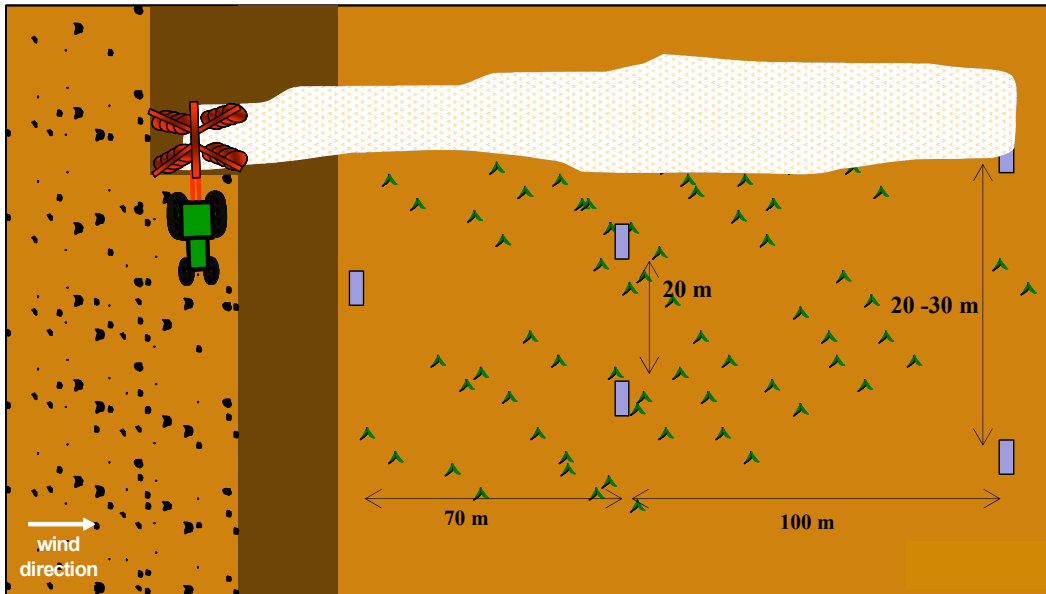


Figure 2 - Description of downwind aerosol measurement during biosolids diking. Downwind samplers were placed at 0 m, 70 m and 170 m from the source.



Aerosol Collection and Laboratory Analysis

Sterile liquid impingers (SKC Inc., Eighty Four, PA) were used to collect aerosol samples for total bacteria, heterotrophic plate count bacteria (HPC), total coliforms, sulfite reducing *Clostridia* and endotoxin. Impingers were operated at a flow rate of 12.5 l min⁻¹ in accordance with manufacture specifications and flow was calibrated by a flow meter (Dry Cal DC-Lite, BIOS, Butler, NJ). The impingers were filled with 20 ml of sterile phosphate buffer saline (PBS) solution (pH 7.2, 10 mM NaPO₄, 125 mM NaCl). After sampling, the impinger contents were decanted into sterile 50 ml conical tubes and the volume recorded. Particulate matter (PM₁₀) was measured using real-time PM₁₀ monitors (DustTrak™ Aerosol Monitor, Model 8520, TSI Inc., St. Paul, MN). These monitors recorded aerosol PM₁₀ concentrations at one second intervals. For metal aerosol analysis, total suspended aerosol particles were collected onto a 47 mm diameter, 1µm pore-size Teflon™ filter (Pall Corp., Ann Arbor, MI). The filter was attached to an open face filter support and a flow rate of 31 l min⁻¹ was used during collection. Finally, aerosol samples for particle size distribution measurements were collected onto 47 mm diameter, 0.4 µm pore size polycarbonate membranes (Whatman, Florham Park, NJ). These membranes were supported by polypropylene holders (Advantec MFS, Inc., Pleasanton, CA) and loaded at flow rates ranging from 11 l min⁻¹ to 15 l min⁻¹.

Composite samples of bulk soil/biosolids mixture and bulk soil were collected simultaneously with air samples. At least 150 grams of solids were collected from over five locations. Samples were placed in sterile Whirl-Pak® bags (Nasco, Fort Atkinson, WI) and sealed for transportation. Within two hours of sampling, moisture content was determined gravimetrically by drying 10 g (wet weight) of soils or soil/biosolids mixture for 18 hours at 105°C. Soil texture was determined by sieve analysis to measure size distribution for the largest particles, and hydrometer analysis for particles smaller than 75 µm (Bardet 1997).

Culture-based assays for all aerosol and biosolids samples were started within 4 hours after collection. Microorganisms were extracted from soil/biosolids mixture or soil in accordance to previously described methods (Moce-Llivina et al. 2003). Briefly, ten grams (wet weight) of bulk material was added into 100 ml of a sterile 0.25 x Ringer Solution (38 mM NaCl, 1.4 mM KCl, 1.1 mM CaCl₂, 0.6 mM NaHCO₃) and stirred rapidly for 15 minutes. The mixture was centrifuged at 1500 g for 15 minutes to remove large particles and the supernatant was then used for the analysis of total bacteria, total coliforms, HPC, sulfite reducing *Clostridia*, and endotoxin. For the microbial aerosol analyses, impinger samples from each experiment were pooled in order to decrease the limit of detection to approximately 50 CFU m⁻³ for indicator microorganisms downwind and 1 CFU m⁻³ upwind. For downwind aerosol samples during disking, which contained four sampling stands each with two impingers, two impingers from each sampling stand were pooled for HPC and total bacteria counts, and the contents of all eight impingers were pooled to determine total coliforms, sulfite reducing *Clostridia* and endotoxin concentrations. In downwind transport experiments, the impinger sampler layout contained one stand with two impingers at the source; two stands each with two impingers at 70 m and two stands each with two impingers at 170 m. For microbial analysis, impingers at each separate distance (source, 70m, and 170m) were pooled.

Epifluorescent microscopy was used to enumerate total bacteria in accordance with previously described methods (Kepner and Pratt 1994). HPC and total coliform plate count analysis was performed in accordance with standard methods (Clesceri and Greenbert 1995). The enumeration of sulfite reducing *Clostridia* was performed using a modified membrane filtration technique (Sartory et al. 1993). Endotoxin concentration analysis was conducted using the Limulus Amebocyte Lysate (LAL) Pyrochrome® Kit in accordance with manufacturer instructions (ACCIUSA, Falmouth, MA).

To determine aerosol particle size distribution, particles collected on 0.4 µm polycarbonate filters (Whatman Inc, Florham Park, NJ) were analyzed by electronic microscopy with an automated JEOL Model JXA-8600 electron microprobe in accordance with the method described by Anderson and coworkers (Anderson et al. 1996). Particle sizes were reported as the average geometric diameter, $(l+d)/2$ where l and d represent the length and the width of each particle counted, respectively. Particle sizes were arranged into bins of 0.1 µm increments and the percentage of particles within each bin was plotted against average geometric diameter. The geometric mean and standard deviation of the log normally distributed data as well as the percentage of particles under a specific size was calculated using statistical software (MINITAB® 14, Minitab Inc., State College, PA).

Aerosol metal concentrations were quantified using inductively coupled plasma mass spectrometry (ICP-MS) in accordance with methods for low level aerosol particulate matter samples described by Lough and coworkers (Lough et al. 2005). Filters were digested in a microwave-assisted acid bath prior to analysis. For bulk samples, a representative portion of the sample was digested with nitric acid and hydrogen peroxide in a hot block digester and then refluxed with hydrochloric acid. Elements from air and bulk samples were quantified using standard hot-plasma ICP-MS conditions. The bulk and aerosol concentrations of the ten metals (As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, Zn) that are regulated in the USEPA biosolids land application guidelines were quantified (USEPA 1994).

Source Emission Rate Calculation

Emission calculations were based on a previously described method for estimating PM₁₀ flux produced during the tilling of agricultural soils (Holmen et al. 2001b). The aerosol PM₁₀ emission factor (mg m^{-2}), E_d , was calculated as the product of the background corrected aerosol concentration, $C(h)$, that is a function of height (mg m^{-3}), the exposure time, t (s), and the horizontal wind speed, $U(h)$, (m s^{-1}), integrated from the soil roughness length, z_0 , to the height of the plume, H , and normalized by the upwind width of the disked soil:

$$E_d = \frac{1}{w} \int_{z_0}^H U(h) \cdot C(h) \cdot t \, dh$$

Overall emission factors for each experiments were calculated as the average emission of four passes in front of the source samplers. The vertical aerosol concentration profile was determined in triplicate independent experiments where real-time PM₁₀ monitors at the emission source were placed vertically at 1.5 m, 2.7 m, 3.9 m, and 5.7 m. Based on these profiles, H was defined as

the height where source PM₁₀ concentrations were equal to ambient PM₁₀ concentrations. A first order decay with height model provided a best fit to the vertical concentration profile measured data (see Figure 5). Using this model profile and the wind profile proposed by Peterson (Peterson et al. 1978) for flat fields, E_d can be expressed as:

$$E_d = \frac{1}{w} \sum_i \int_{z_0}^{H_i} U_{H_0} \cdot \left(\frac{h}{H_0}\right)^p \cdot (a_i \cdot \ln(h) + b_i) \cdot t_i \cdot \cos \theta_i \, dh$$

where: i is each tractor's pass, H_0 is the wind speed measurement height, U_{H_0} is wind speed at H_0 , p is coefficient dependent on atmospheric stability class (Peterson et al. 1978), a and b are respective slope and intercepts coefficients from the linearized first order PM₁₀ concentration profile (see Figure 5), and θ is the angle between the wind direction and the plane perpendicular to the travel direction of the tractor. In order to compare disking emission with biosolids spreading emission, emission factors were converted to emission rates (mg s^{-1}) (ER) by multiplying the emission factor by the area disked (m^2), A_d , in a second.

PM₁₀ emission were converted to chemical and biological emissions by first normalizing the PM₁₀ emission rates by the PM₁₀ concentration at 1.5 m and then multiplying by the average metal or biological concentration at 1.5 m. This method implicitly assumes that the vertical chemical or biological concentration profile is the same as the PM₁₀ profile:

$$ER_{chem/bio} = \frac{ER_{PM_{10}}}{C_{PM_{10}}} \cdot C_{chem/bio-1.5m}$$

To estimate the contribution of only biosolids to the source emission rate, the chemical and biological aerosol concentrations determined during the control disking experiments were subtracted from the biosolids disking concentrations. The aerosol concentrations produced during control disking were adjusted by multiplication with the ratio of biosolids disking PM₁₀ concentration to the control disking PM₁₀ concentration (1:3.2) to account for inhibition in aerosol production observed during biosolids disking. Emission rate error is based on standard deviations for individual measurements and propagation of these standard deviations through emission calculations in accordance with accepted methods (Miller and Miller 1984).

Transport Modeling

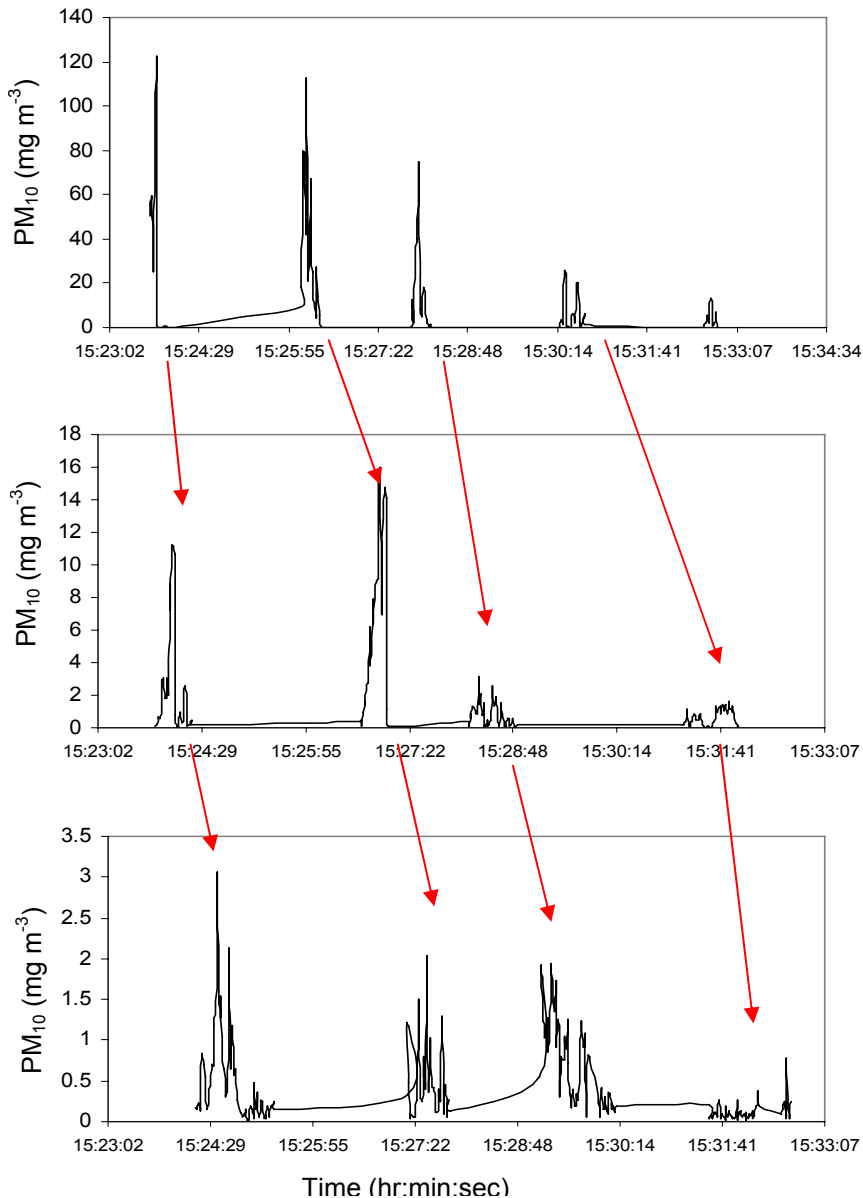
A simplified version of the Gaussian plume dispersion equation neglecting settling velocities (Lighthart and Mohr 1987) was validated using biosolids-derived PM₁₀ concentrations measured at the source, at 70 m and 170 m downwind from disking.

$$X = \frac{E}{2\pi\mu\sigma_y\sigma_z} * \exp\left(-\frac{(H)^2}{2\sigma_z^2}\right)$$

where X is the downwind airborne concentration for either total biosolids-derived PM_{10} ($mg\ m^{-3}$), σ_y and σ_z are horizontal and vertical dispersion factor (m) respectively, E is the emission rate ($mg\ s^{-1}$), μ is the mean wind speed at 1.5 meters height ($m\ s^{-1}$), and H is the receptor height of 1.5 m. The dispersion factors, σ_y and σ_z were calculated based in empirical formulas proposed in Gifford (Gifford 1975), and are specific for smooth terrain conditions. Atmospheric stability classification was based on Paquill-Gifford method chart (Turner 1970).

The Gaussian equation was used to model each peak in the six data sets (six independent experiments and four sets of peaks per distance per experiment) (Figure 3). Validation entailed first back-

Figure 3 - Characteristic example of PM_{10} peaks generated during each disking transport experiment. Real time measurements correspond to measurements at the source (top), 70 m (middle) and 170 m (bottom).



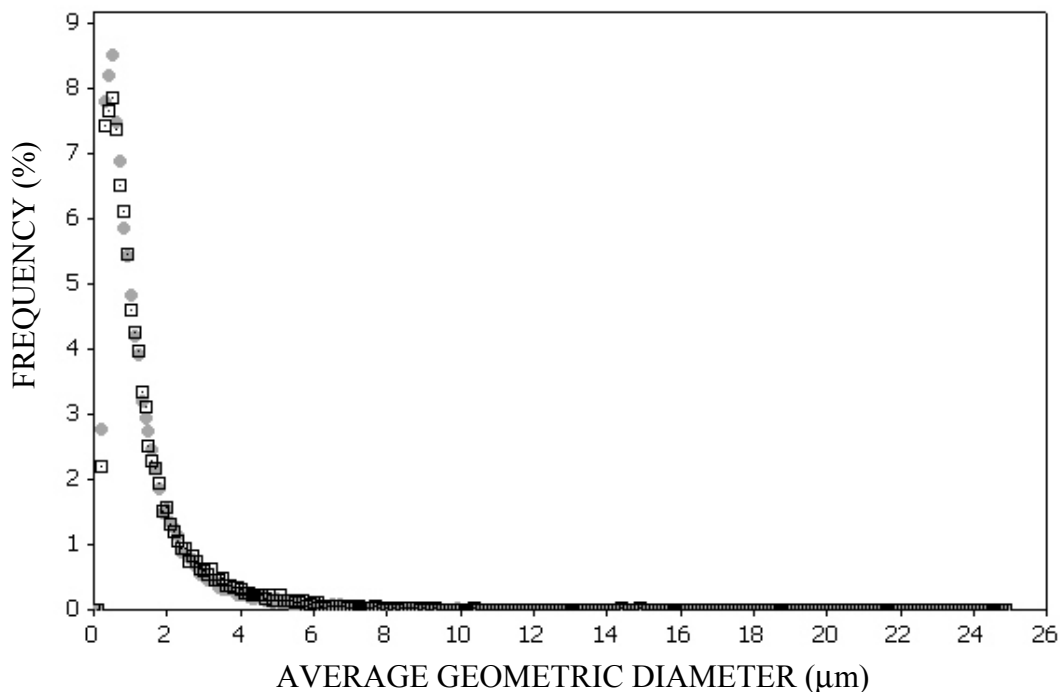
calculating an emissions rates such that the model concentration and the measured concentration at the source would be the same. The motivating factor behind testing the model in this way was to exclude any error in model fit caused by an incorrect emission factor. Field emissions rates are inevitably subjected to measurement errors, and using them would penalize the model unfairly during the goodness-of-fit test. Setting the model and field data equal at the source effectively eliminates the errors in emissions rate measurements and allows for the model to be compared on the basis of the relevant advection and dispersion transport processes.

RESULTS AND DISCUSSION

Particle Size Distribution-Source

Biosolids disk incorporation generates aerosols with a distinct size range of suspended particles. Figures 4 depicts the geometric diameter size distribution frequency for source aerosol samples

Figure 4 - A characteristic profile for the geometric diameter aerosol size frequency distribution of aerosols generated during biosolids disk incorporation into soils. Grey solid circles and black clear squares represent the particle size distribution frequency for samples taken during control disking and disking, respectively.



collected during disking at a 1.5 m height. The log normal distributed data during biosolids disking demonstrates that the particles size distribution was similar to the distribution during control disking. More than 99.0% of the particles emitted were below 10 µm. The mean geometric diameter from disking was $1.55 \mu\text{m} \pm 1.55 \mu\text{m}$ (GSD). Particles with aerodynamic diameters of 10 µm and below have very low settling velocities and consequently long residence times in the atmosphere. In this case, less than 5% of particles with less than a 10 µm diameter

would be expected to deposit in the first 100 m of transport (Etyemezian et al. 2004). From a health perspective, particles with an aerodynamic diameter less than 10 µm are considered inhalable into the lung and, if soluble, can be dispersed throughout the body in blood or if insoluble, deposited onto lung surfaces causing cellular damage or effecting responses via various airway receptors (Raabe 1999). Smaller particles, typically represented by PM_{2.5}, can more efficiently travel into the lungs and also enter the alveolar or deepest portions of the lung.

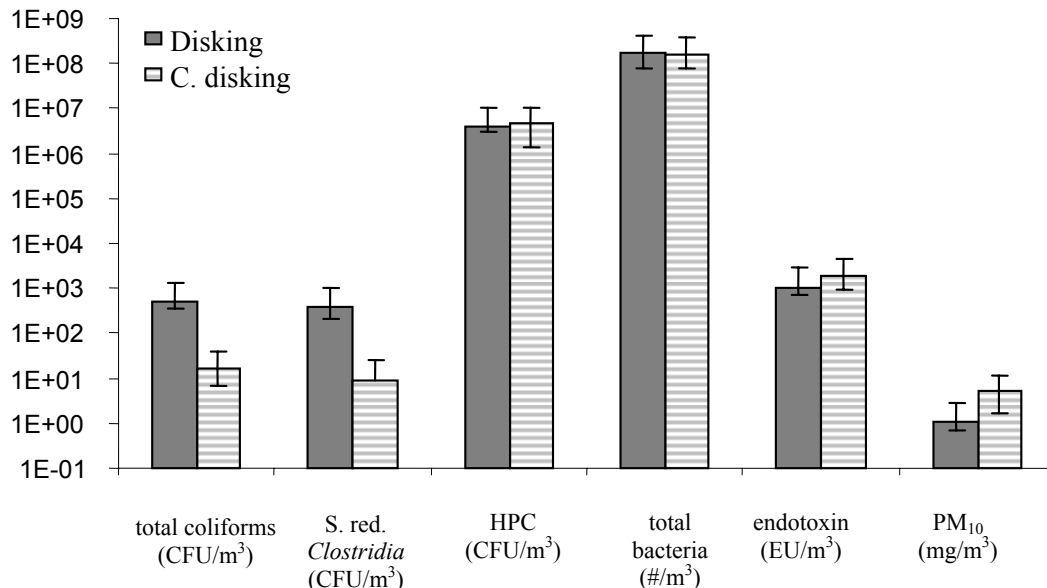
PM₁₀ Concentrations-Source

Real-time PM₁₀ concentration measurements immediately downwind of the land application source and at upwind control sites confirmed the generation of aerosols during biosolids disking. Because texture and moisture should affect aerosolization during disking (Baker et al. 2005; Holmen et al. 2001b; Smith and Lee 2003), these experiments were designed to control for soil moisture and texture in order to accurately investigate the differences in aerosol emissions and aerosol characteristics caused by the addition of biosolids to soils. The average PM₁₀ concentration during control disking was 5.12 mg m⁻³ and decreased to 1.58 mg m⁻³ during biosolids disking. Presumably this difference was due to the moisture that biosolids added to the soil. The addition of biosolids to soil increased the average moisture content from 4.9% to 8.0%. Similar decreases in agriculturally produced particulate matter concentrations have been observed due to an increase in soil moisture. In California’s Central Valley, Clausnitzer and Singer (Clausnitzer and Singer 2000) evaluated respirable dust emissions during agricultural soil preparation at variable moisture levels and observed that the average respirable dust concentration emitted decreased 5 times when water content increased from 4.5% to 10%.

Aerosol Biological Characterization-Source

Figure 5 presents source aerosol concentration during biosolids disking and control disking for

Figure 5 - Average downwind source concentrations during biosolids disking and control disking. Error bars correspond to the range of values (n=2).

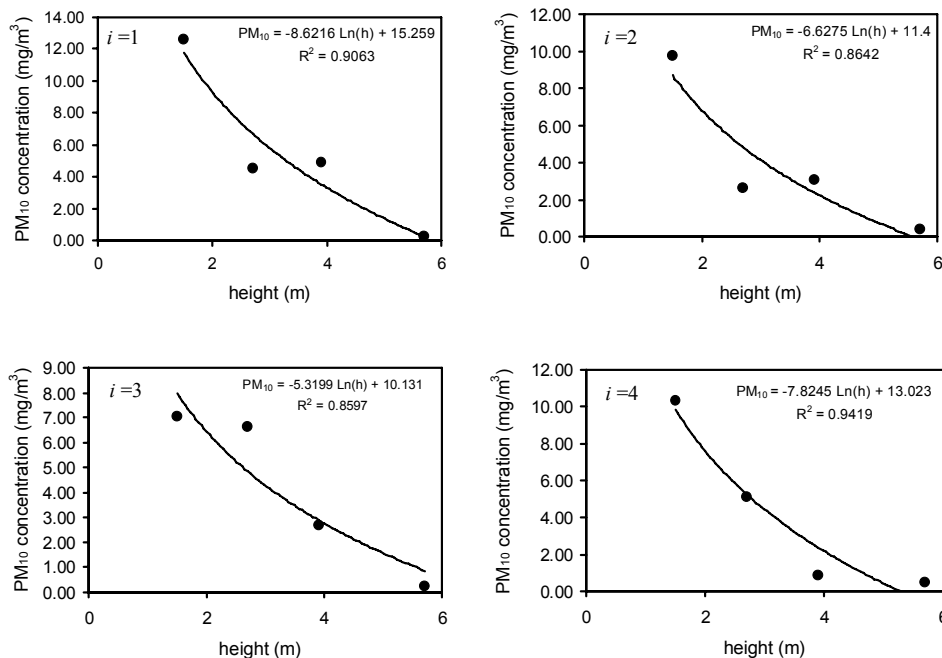


total coliforms, sulfite reducing *Clostridia*, total bacteria, HPC and endotoxin. All values were corrected by the background ambient concentrations. The biological measurements that are indicative of biosolids, total coliform and sulfite reducing *Clostridia*, were 15 and 30 times greater ($p < 0.05$), respectively, during disking than control during disking experiments. For total bacteria, HPC, and endotoxin, no significant difference between biosolids disking and control disking could be observed. The similar aerosol concentrations, despite the enrichment in the bulk biosolids/soil mixture is explained by the lower amount of particulate matter that was aerosolized during disking (see section above), presumably caused by the moisture added due to biosolids application.

Source Aerosol Emission Rates

The source PM₁₀ concentration versus height profile is the key variable in estimating source emission factors or rates. For calculating this profile, the real-time PM₁₀ readings in all four monitors (1.5 m, 2.7 m, 3.9 m, and 5.7 m) were normalized to the maximum concentration (at 1.5 m) and plotted versus height. Figure 6 presents a characteristic profile for one experiment in which all four tractor passes are included. The normalized PM₁₀ concentration versus height data is fit with logarithmic decay curves. Holmen and coworkers. (Holmen et al. 2001a) conducted a thorough study on emissions from agricultural tilling. They analyzed different model fits to best approximate the measured PM₁₀ vertical profiles during tilling. According to their results and corroborated here, the measured profile called “decline” in which PM₁₀ mass concentration decreases with height gives reasonable and equivalent heights when using the logarithmic profile model.

Figure 6 – A source plume PM₁₀ concentration versus height characteristic profile. Dots represent the average PM₁₀ concentration measured at four different heights when the tractor passed within the following distances from the samplers: 0-6 m for i=1, 6-12 m for i=2, 12-18 m for i=3, and 18-24 m for i=4.



The estimated biosolids source emission factors and emission rates with associated standard deviations are presented in Table 1 for total bacteria, HPC, sulfite-reducing *Clostridia*, total coliforms, endotoxin, EPA biosolids regulated metals, total PM₁₀ and biosolids PM₁₀. The emission rates reported here, while specific to the biosolids application rate, soil moisture, and soil texture, reveal that disking can be a significant source of biosolids-derived aerosols during the land application process. On a biosolids-derived PM₁₀ basis, emission rates from disking are approximately 2 times greater than emissions measured during spreading (Paez-Rubio 2005) of dewatered biosolids and over 100 times greater than the emissions produced during spraying of dewatered biosolids (Tanner et al., 2005).

Table 1 - Bulk biosolids concentrations and source emission rates

parameter	Bulk biosolids concentration ^a	aerosol source emission factor ^b	aerosol source emission rate ^c
total bacteria(number)	1.55±19.7 x10 ⁸	1.37±2.15x10 ⁹	1.09±1.72x10 ¹⁰
HPC (CFU)	1.51±0.68 x10 ⁷	3.16 ±6.15 x10 ⁷	2.53 ±4.92 x10 ⁸
total coliforms (CFU)	8.56±4.06 x10 ⁴	4.55±7.75 x10 ³	3.64±6.20 x10 ⁴
sulfite-reducing <i>Clostridia</i> (CFU)	6.52±5.55 x10 ³	3.34±5.23 x10 ³	2.67±4.18 x10 ⁴
endotoxin (EU)	5.7±13.8 x10 ³	1.66±2.76 x10 ³	1.33±2.21 x10 ⁴
cadmium (µg)	0.15±0.15	6.12±4.11 x10 ⁻²	4.90±3.28 x10 ⁻¹
chromium (µg)	3.61±3.49	2.72±1.72	2.17±1.38 x10 ¹
copper (µg)	2.57±3.07 x10 ¹	1.58±2.22 x10 ¹	1.27±1.78 x10 ¹
lead (µg)	7.13±5.69	6.22±8.07	4.97±6.46 x10 ¹
mercury (µg)	7.00±8.00 x10 ⁻²	1.64±2.25 x10 ⁻¹	1.32±1.8
molybdenum (µg)	1.82±1.82	1.57±3.56 x10 ⁻²	1.26±2.58 x10 ⁻¹
nickel (µg)	4.06±2.64 x10 ¹	1.70±1.11	1.36±0.89 x10 ¹
zinc (µg)	4.68±4.16 x10 ¹	0.96±1.74 x10 ¹	0.77±1.39 x10 ²
total EPA regulated metals (µg)	125.88±109.93	36.28±50.80	176.63±246.49
biosolids PM ₁₀ (mg) ^d	--	1.24-3.41	9.91 -27.25
total (soil and biosolids) PM ₁₀ (mg)	--	31.0	247.75

^a Calculated as the concentration_{soil/biosolids mixture} – concentration_{soil} measured per dry g.

^b Aerosol source emission factor measured per m² disked

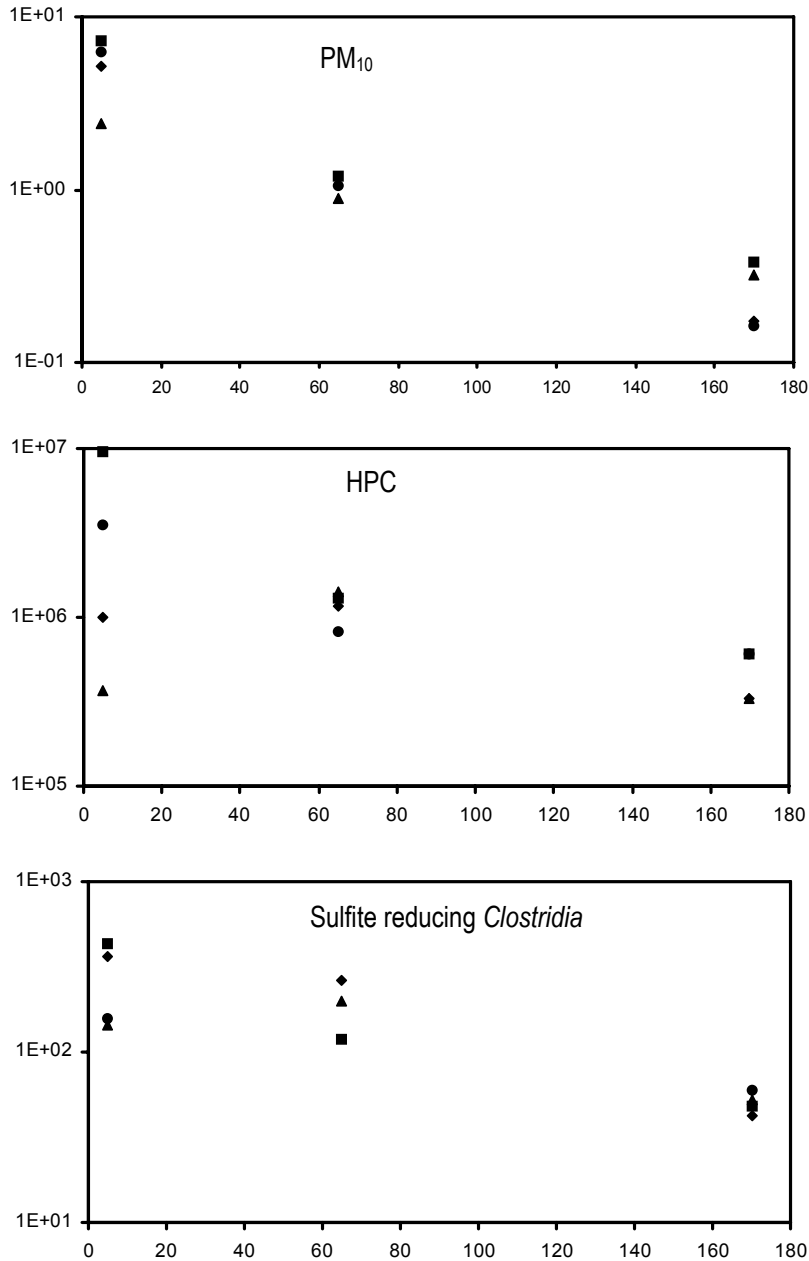
^c Aerosol source emission rate measured per s.

^d Ranges correspond to a soil biosolids mixture of 4% to 11% biosolids

Downwind Transport.

The previous section described source concentrations and emission rates. This section focuses on measurement of downwind aerosol concentrations and validation of a transport model. Figure 7 summarizes the concentrations measured in the four independent

Figure 7 - Downwind concentrations for PM₁₀ (mg m⁻³), HPC (CFU m⁻³), and sulfite reducing *Clostridia* (CFU m⁻³). Values on x axis correspond to distance from source in meters. Symbols on graphs correspond to average concentrations for each of the four experiments.

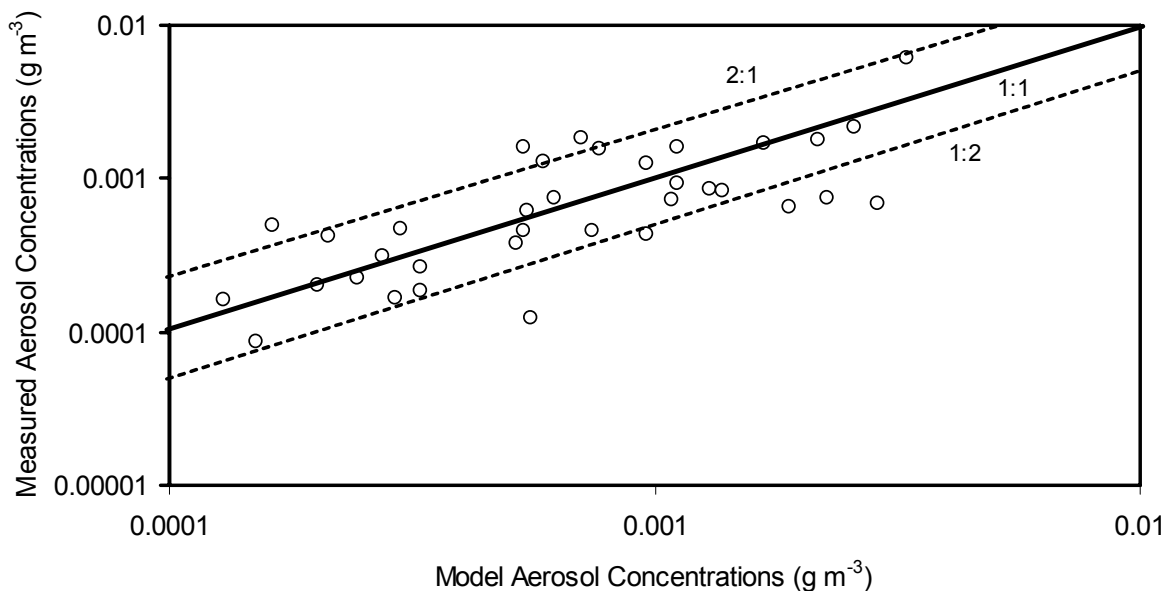


downwind concentration experiments performed during biosolids diskings. In these experiments samplers were installed at an upwind control site and at 0 m, 70 m, and 170 m downwind from the biosolids diskings source. The parameters included are aerosol concentrations of PM₁₀, sulfite reducing *Clostridia*, and HPC. All sampling occurred under slightly unstable to neutral atmospheric conditions and average wind speed ranged from 1.35 to 4.13 m s⁻¹. Based on the average concentrations measured in each of the four experiments, PM₁₀ concentrations decreased by 94% between the source and 170 meters downwind, sulfite reducing *Clostridia* decreased by 72% and HPC by 62%.

A Gaussian plume model applied to estimate off-site diskings PM₁₀ concentrations and was validated using these PM₁₀ measurements. PM₁₀ measurements (rather than biological measurements) were chosen for model validation due to the ease of obtaining results, the precision of these measurements, and the ability to obtain results on a near real-time basis. Model results were compared with individual PM₁₀ concentrations that correspond to each tractor pass (Figure 3) rather than using the average (average of the four tractor passes) PM₁₀ concentration for each distance (Figure 7).

Figure 8 shows the 1:1 correlation between PM₁₀ measured at 70 m and 170 m and PM₁₀ estimated by the model at 70 m and 170 m. Prediction by the Gaussian plume model is generally considered satisfactory if it does not underestimate or overestimate the corresponding field measurements by two times (Irwin 1983). Twenty five out of the 35 available points (71%) fell within this acceptable envelope. Of the 10 points which fell outside the envelope, 5 were overestimates (up to a 4.5-fold overestimate) and 5 were underestimates (up to a 3-fold underestimate).

Figure 8 - Measured PM₁₀ versus Modeled PM₁₀.



Initially, the Gaussian plume model was developed for stack emissions and/or gaseous emissions elevated above the ground. These circumstances (elevated source and buoyancy) limited model

validation to distances greater than 100 m. However, during land application practices the source emission occurs at ground level and the biosolids or soil/biosolids mixture are at ambient temperature. These conditions allow for Gaussian plume model application at distances less than 100 m (Gifford 1975).

CONCLUSIONS

This study provides enabling information for researchers and practitioners to estimate biosolids-derived aerosol exposure to workers and nearby residents at land application sites. Important conclusion of these field experiments include the following:

- The particulate matter generated during the disk incorporation of dewatered biosolids is respirable. Greater than 99% of the particles aerosolized during disking had geometric diameters of less than 10 μm .
- Biosolids disk incorporation resulted in an average maximum disking source aerosol concentration of 1.5 mg m^{-3} , in which an estimated 4% to 11% of the aerosol mass was of biosolids origin. Spreading dewatered biosolids (70% to 80% water content) onto soils (4% water content) suppressed aerosol concentrations generated during disking by 3 times.
- Total coliforms and sulfite-reducing *Clostridia* aerosol concentrations were 15 and 30 times greater during biosolids disking than during control disking experiments (no biosolids). Due to both the suppression of aerosols by the addition of biosolids to dry soils and the lower level presence of metals, HPC, total bacteria, and endotoxin in soils, significant differences between aerosols produced during biosolids disking and control disking were not observed.
- Source emission rates of biosolids derived chemicals ($\mu\text{g s}^{-1}$) and indicator microorganisms ($\# \text{ s}^{-1}$) were estimated for disking. Comparison of these values and other literature values suggests that different types of emissions produced during land application rank (highest to lowest) in accordance with the following: disking > dewatered spreading >>> liquid biosolids spraying.
- PM_{10} concentrations and biosolids indicator measurements suggest that measurable concentrations of biosolids derived bioaerosols can be transported at least 170 m downwind a the source during biosolids disk incorporation.
- A Gaussian transport model can be used to accurately estimate aerosol concentration and human exposure to biosolids derived aerosols.

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