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The influence of process variables on bioaerosol emission flux and exposure - estimating fugitive bioaerosol releases from static compost windrows

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Abstract

An assessment of the fugitive release of bioaerosols from static compost piles was conducted at a green waste composting facility in South East England; this representing the initial stage of a programme of research into the influence of process parameters on bioaerosol emission flux. Wind tunnel experiments conducted on the surface of static windrows generated specific bioaerosol emission rates ($SBER_2$s) at ground level of between 13 - 22 $x10^3$ cfu/m^2/s for mesophilic actinomycetes and between 8 - 11 $x10^3$ cfu/m^2/s for *Aspergillus fumigatus.* Air dispersion modelling of these emissions using the SCREEN3 air dispersion model in area source term mode was used to generate source depletion curves downwind of the facility for comparative purposes.

1 Introduction

The operation of composting facilities in the vicinity of residential and public places has generated concerns over the potential impacts these facilities may pose to public health. Fugitive dusts emitted during waste decomposition releases a variety of bioaerosols (Fischer *et al.,* 1999). In addition, the shredding of waste and the agitation and turning of compost during processing results in significant episodic releases to air. Bioaerosol particles are airborne organisms or biological agents that may act as toxicants. They include allergens such as bacteria, fungi, actinomycetes, arthopods, protozoa as well as microbial products such as endotoxin, microbial enzymes, β-1,3-glucans and mycotoxins (Millner *et al.*, 1994). As a result of public health concerns and a need for operators to demonstrate the safe and responsible operation of these facilities, environmental regulators are now requesting risk assessments of operators prior to licensing composting plants. The estimation of bioaerosol exposures to downwind receptors is becoming important for large scale facilities sited in sensitive environmental settings close to the public.

Understanding the baseline emission of bioaerosols at source, and the factors and process variables that influence their generation and off-site dispersal is critical to meaningful risk assessment. Bioaerosol emission rate and dispersal are influenced by a large number of factors, including the materials being composted, the on-site processes involved, the associated vehicle movements, the process equipment used, individual bioaerosol properties and the geographical, topographical and meteorological conditions on- and off-site. This is a complex set of variables and in our research we have set out to understand one aspect alone; the baseline fugitive emissions and the influence of composting processing variables on bioaerosol flux at source.

This paper presents the initial results of a study on estimating fugitive emissions at source. We use a portable wind tunnel to capture bioaerosols above compost windrows in the absence of turning. The data generated provides a baseline assessment of

fugitive emissions and has been used as input to an air dispersion model (SCREEN3) for assessing potential dispersal off-site under static conditions. Subsequent work will examine the influence of process variables on episodic bioaerosol flux from a range of on-site unit processes.

2 Material and Methods

The experimental and methodological rationale is summarised in Figure 1. Bioaerosol flux measurements were conducted at a green waste, open windrow composting facility in the SE of England where waste unloading, shredding, turning activities were concurrent. Fugitive emission rates were estimated from wind tunnel experiments and used to generate hypothetical source depletion curves at distance from the facility.

2.1 Wind tunnel measurements and control

A portable wind tunnel [Figure 2] was located on top of compost windrows to allow the measurement of bioaerosol emission flux under static conditions. The fugitive dust emitted from the surface area was sampled within the horizontal air stream of the wind tunnel at a known velocity (*ca.* 3 m/s) across the surface. In the tunnel, incoming air is filtered by activated carbon and blown into the inlet duct with a fan. A convective mass transfer takes place above the emitting surface and bioaerosols are then mixed into the bulk of the carrier air and vented from the hood. The base of the wind tunnel was embedded *ca.* 25 mm inside the surface of the pile to ensure no loss of air volume around the sides. Samples were taken from the hood outlet and the air flow velocity measured using a hot wire anemometer (Kestral 3000). Three compost pile locations were selected on the basis of access and suitability (the availability of power supply and of a flat surface). Ambient (*i.e.* on-site background) air bioaerosol concentrations were measured at 1.8m height close to the compost windrow, downwind of the pile. A filled filter cassette was exposed without air pumping as a field blank.

2.2 Bioaerosol sampling

Bioaerosols were sampled using a medium flow personal aerosol filter sampler (SKC Universal dust and vapour sampling pump). Pumps were operated at 2.0 ± 0.1 l/min and fitted with SKC dust sampling IOM heads (25mm) loaded with mixed cellulose ester filters (25 mm x 0.8 µm pore size). Sampling took place for *ca.* 30 min. As a control, a sample was taken directly from the outlet of activated carbon filter to measure the quality of the cleaned the inlet air supply. Microorganisms were quantified by using CAMNEA-method (Collection of airborne microorganisms on Nuclepore filters, Estimation and Analysis; Palmgren *et al.* (1986)). After sampling, filters were placed inside a 30ml vial containing 10ml 0.05%v/v Tween-80 mixed with 0.1%w/w NaCl to prevent cell osmosis. On return to the laboratory, bioaerosols were re-suspended and cultured on to nutrient plates.

2.3 Bioaerosol enumeration

Aspergillus fumigatus (average size of 2-50µm) and mesophilic actinomycetes (average size of 1µm) were enumerated by visual inspection. Media preparation, inoculation, dilution and sterilisation were performed in accordance with BS 5763: Part 0. For mesophilic actinomycetes, two media were used and developed simultaneously: (i) half strength nutrient agar (Oxoid); and (ii) soil compost agar (a supernatant of 10%w/w of

loam-based compost John Innes No. 1 compost in agar). After preparation, both media were autoclaved (105°C, 15 minutes), left to cool to below 47°C and then treated with 1%v/v antifungal cycloheximide. For *Aspergillus fumigatus*, malt extract agar (Merck) was mixed with 0.01%w/w of antibacterial chloramphenicol (Sigma). Nutrient agar plates and soil compost agar plates were incubated at 44^0C. Malt extract agar plates were incubated at 37°C. Colonies growing on both media were enumerated visually after 3 to 7 days.

2.4 Estimating the fugitive bioaerosol emission rate

Bioaerosols concentrations for the ambient air sample, the filtered input air and wind tunnel outlet air at locations 1 and 3 are presented in Table 1. Wind tunnel 2 data was invalidated due to pump malfunction. The net bioaerosol concentrations in the wind tunnel were estimated by subtracting the inlet concentrations from the measured data at the outlet. The air velocity inside the wind tunnel is calculated from:

$V_1 = V_2 x A_2 / A_1$ [1]

where:
V_1 and A_1 = air velocity (m/s) and area (m^2) of the main section of wind tunnel; and
V_2 and A_2 = air velocity (m/s) and area (m^2) of the mixing chamber, where sampling is carried out.

The specific bioaerosol emission rate (SBER) is the quantity of bioaerosol emitted per unit time from a unit surface. The equation is adopted from that used to determine the specific odour emission rate (Jiang *et al.* 2001) from surfaces and for this initial assessment, an assumption was made that bioaerosols exhibit gaseous-like properties:

$$SBER = \frac{QxBC}{A} \qquad [2]$$

where:
SBER= specific bioaerosol emission rate (cfu/m^2/s);
Q = flow rate through the wind tunnel (m^3/s);
BC = bioaerosol concentration in air (cfu/m^3); and
A= area covered by the wind tunnel (m^2)

Bioaerosol concentrations measured in the mixing chamber were taken as an average of those measured at the top and the bottom of the chamber. The specific bioaerosol emission rate corresponding to actual ground level wind speeds, as opposed to those in the chamber, is then estimated using:

$$SBER_2 = SBER_1 \times \left(\frac{V_2}{V_1} \right)^{0.5} \qquad [3]$$

where:
$SBER_1$= specific bioaerosol emission rate measured using the wind tunnel (cfu/m^2/s);
$SBER_2$= specific bioaerosol emission rate corresponding to ground level wind velocity (cfu/m^2/s);
V_1= air velocity inside wind tunnel for sample collection; and
V_2= actual ground level wind velocity (m/s)

2.5 Estimating bioaerosol dispersal

Bioaerosol concentrations downwind of the facility were estimated using SCREEN3 in area source term mode, a source area of 20m x 80m, an emission height of 2 m and a moderate sky insulation setting. The power-law equation was used to determine the velocity at 10m height to select the Pasquill stability categories and inputs to SCREEN3.

Power-law: $u_z = u_a(z/z_a)^P$ [4]

Where u_z= wind velocity (m/s) at a vertical height z above ground;
U_a= wind velocity (m/s) at the anemometer height;
z = vertical height above ground (1.8m);
z_a = anemometer height above ground (10m); and
p = exponent dependent on stability; 0.07 (unitless) for unstable.

3. Results and discussion

Bioaerosol release, like fugitive dust emission, is dependent upon on particle size, surface loading, surface conditions, wind speeds, atmospheric and surface moisture and the presence of dust suspending activities. Watson *et al.* (2000) suggest that wind speeds of more than 0.19 m/s have the capacity to elevate loose dust particles and transport them for long distances. The dispersal of bioaerosol is subject to physical, meteorological and operational considerations. Meteorological characteristics at a site, in conjunction with topography, will affect bioaerosol exposures to workers and the nearby public. Wind conditions and the height of the location or point of release of the facility determine the diffusion and distribution of bioaerosols over a spatial area and so where the intent is to maintain the mass of airborne material close to the facility, then composting facilities should be shielded from wind and preferably emit aerosols at low heights, or at elevations below surrounding sensitive areas. Diffusion models can be used to estimate the impact of composting emissions on sensitive receptors, but at present, only limited data are available to quantitatively evaluate the effectiveness of process operational characteristics on the bioaerosol emission flux.

The measured bioaerosol data and estimated specific bioaerosol emission rates ($SBER_2$s) for the fugitive release of mesophilic actinomycetes and *Aspergillus fumigatus* in this study are presented in Table 1. Air dispersion modelling estimates at distances downwind of the facility are presented in Table 2. Caution must be exercised in interpreting bioaerosol data. There are several important sources of analytical and methodological uncertainty in quantifying these agents and wind tunnel experiments may add an additional source of model artefact to the analysis. Nevertheless, these initial data do allow quantification of fugitive bioaerosol release at source above static compost windrows and an estimation of source depletion with distance for comparison with other literature studies.

These data must be interpreted in the context of their acquisition. Data were acquired during normal operations in which waste unloading, shredding, windrow piling and turning were concurrent. We were unable to interrupt normal operations during the sampling period to specifically disaggregate ambient contributions from windrows from associated activities at the site.

Wheeler *et al.* (2001) has suggested that the best available estimates for threshold limit values ('natural' background) for gram-negative bacteria, total bacteria and fungi in air are 300, 1000 and 1000 cfu/m^3 respectively though the scientific consensus is limited. Some bioaerosol risk assessments have used low (5000 cfu/m^3), medium (10 000 cfu/m^3) and high (30 000 cfu/m^3) estimates of bioaerosol concentrations at proposed or existing facilities to represent source data for onward dispersion modelling. In this context, the ambient air concentrations of *A. fumigatus* (77000 cfu/m^3) and mesophilic actinomycetes (10300 cfu/m^3) measured in this study are high. Net fugitive bioaerosol data [Table 1] for windrow samples 1 and 3 samples in the wind tunnel outlet are of a similar order of magnitude, though lower than this ambient sample for *A. fumigatus* and higher for actinomycetes. In practice, large variations are associated with ambient bioaerosol monitoring data; for example on previous occasions at this facility, ambient *A. fumigatus* concentrations of 120 x 10^3 cfu/m^3 and 21.5 x 10^3 cfu/m^3 (c.f. 77 x 10^3 cfu/m^3) have been measured using an identical filter sampler technique. A further issue relates to the observation (Wheeler *et al.,* 2001) that bioaerosol data collected using Anderson samplers frequently report an order of magnitude less than those collected using filter samplers. Irrespective, it is clear from our study that there are contributions to the site bioaerosol load beyond fugitive emissions from static windrows, as one would expect.

For the wind tunnel bioaerosol data, activated carbon influent air is demonstrably 'cleaned' by comparison with the ambient background sample, these data suggesting adsorption efficiencies of 99%w/w and 92%w/w for *A. fumigatus* and actinomycetes, respectively. For the outlet data, fair agreement is demonstrated between locations 1 and 2 [Table 1] (with location 2 providing a greater flux for both determinands) suggesting less variability for consecutive wind tunnel experiments on material from a common source. Transformation of the concentration data provide fugitive specific bioaerosol emission rates ($SBER_2$s) at ground level of between 13 - 22 x10^3 cfu/m^2/s for mesophilic actinomycetes and between 8 - 11 x10^3 cfu/m^2/s for *Aspergillus fumigatus.* These rates are used as the area source emission input data for the air dispersion modelling of these emissions using the SCREEN3 air dispersion model to generate source depletion curves downwind of the facility for comparative purposes [Table 2].

The modelled *A. fumigatus* source depletion curves for these data using the area source term emission rates generated in wind tunnel experiments are shown in Figure 3, alongside literature data acquired by environmental sampling at distance from composting facilities (Figure 4; wind tunnel data removed). Figure 3 mixes modelled and monitored data and studies from a range of facilities. These studies are not directly comparable and used for illustrative purposes alone. Two observations are worthy of merit however, notwithstanding the additional difficulties and artificial nature of using Gaussian distribution models for bioaerosol dispersion. Comparing Figures 3 and 4, one notices the rapid depletion of bioaerosol concentrations from source in both monitored and modelled data. Further, source depletion to proposed background values of 1000 cfu/m^3 typically occurs between 250-500m from source in the wind tunnel data and typically within 250m for the monitoring studies. We propose that the data generated by our study are generally consistent with literature data. For example, for *A fumigatus* and mesophilic actinomycetes, Sanches-Monedero and Stentiford (2003) have recently reported that at up to 40m from composting sites the concentrations of these bioaerosols are between 3.8x10^3 and 98x10^3 cfu/m^3 and between 23 x10^3 and 110 x10^3 cfu/m^3, respectively.

4 Conclusions

We have presented initial data from a wind tunnel experiment demonstrating the ability to measure the fugitive emission flux of bioaerosols from static windrows. We conclude:

- wind tunnels can be used to measure the emission flux of fugitive bioaerosol that are aerosolized by wind energy;
- the emission fluxes estimated can be used within the SCREEN3 air dispersal model for estimating bioaerosol concentrations downwind of composting facilities;
- these data and the bioaerosol characteristics they help illustrate are important for environmental risk assessment that support the licensing of larger composting plants in sensitive locations;
- our methodology forms the basis for estimating specific bioaerosol emission rates from other activities, including shredding, screening, turning, vehicles movement, loading and waste unloading;
- future work will focus on improving the measurement and analysis of bioaerosols during compost processing.

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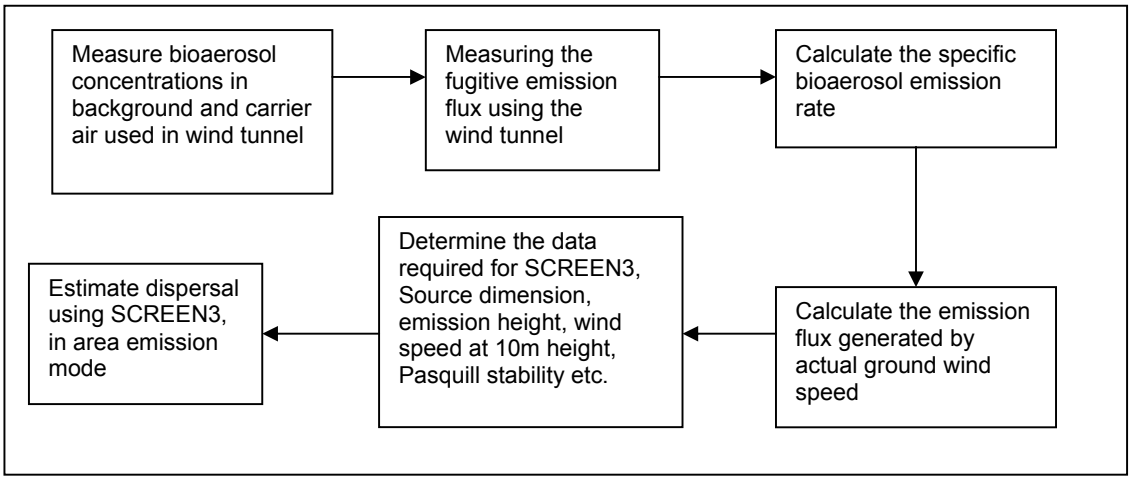


Figure 1. Rationale and steps in measuring the emission flux and dispersal of bioaerosols

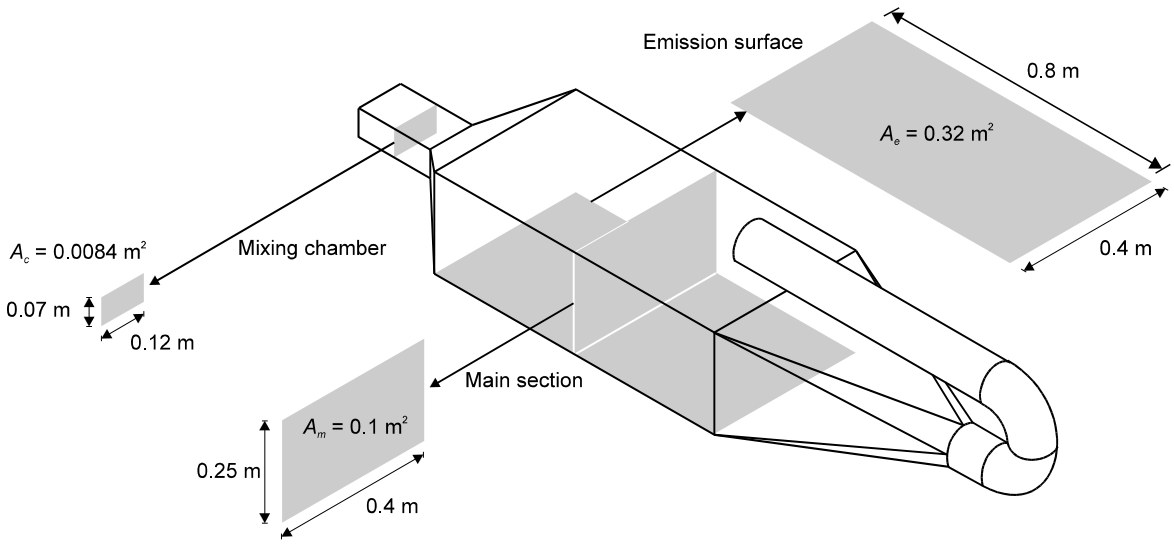


Figure 2 Schematic of wind tunnel and dimensions

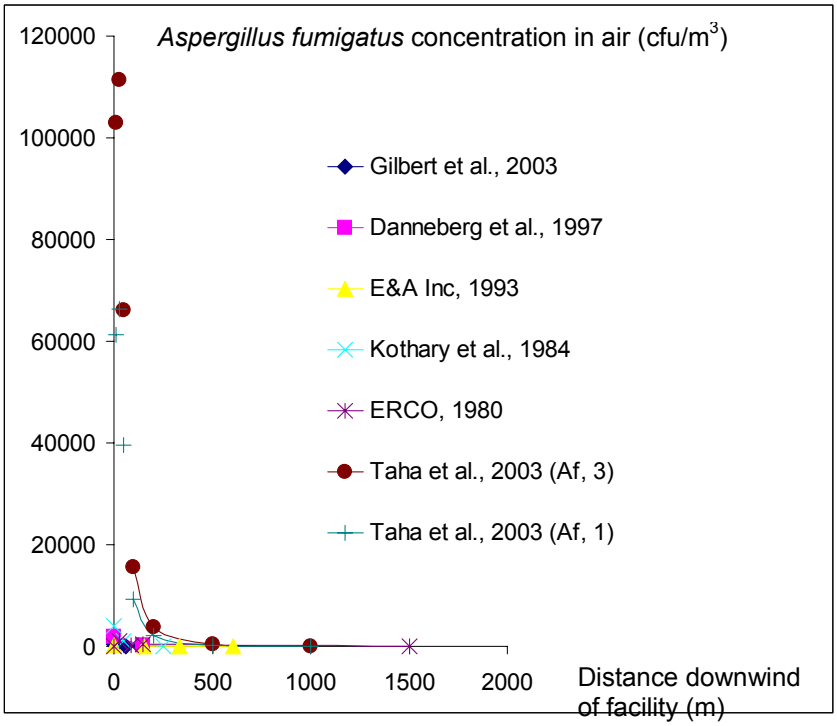


Figure 3

Source depletion curves (cfu/m^3) for *Aspergillus fumigatus* from selected monitoring studies (Millner *et al.,* 1994) alongside modelled data using fugitive emission rates generated in wind tunnel experiments.

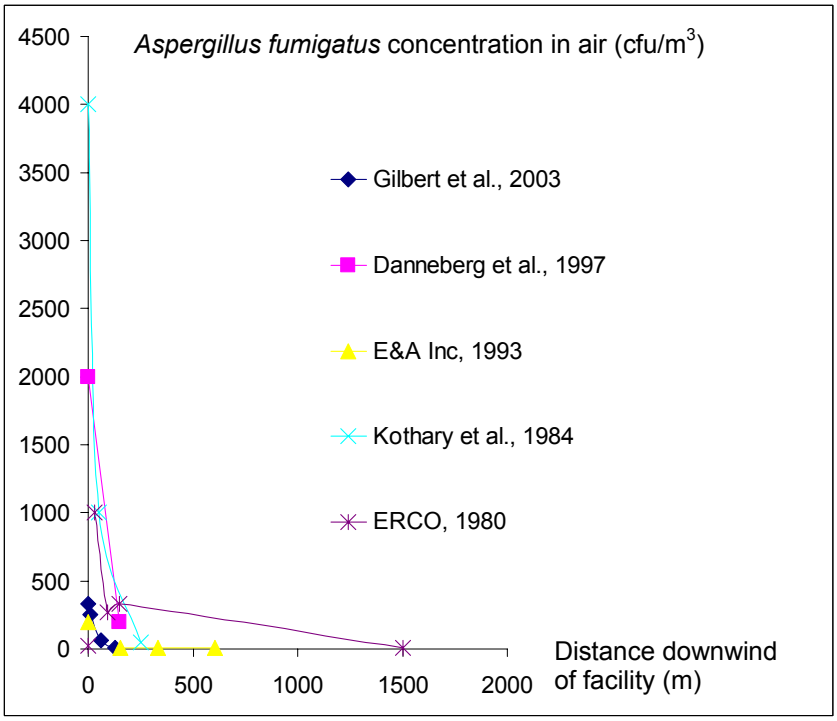


Figure 4

Source depletion curves for *Aspergillus fumigatus* (cfu/m^3) from selected monitoring studies (Millner *et al.,* 1994) (wind tunnel data removed; note scale)

sample and location	mean wind speed (m/s) (at 1.8 m)	mean air velocity (m/s) mixing chamber	air velocity inside wind tunnel (m/s)	bioaerosol concentration in air samples (x10^3 CFU/m^3)		net bioaerosol in carrier air (x10^3 CFU/m^3)		SBER$_1$ (x10^3 CFU/m^2/s)		SBER$_2$ (x10^3 CFU/m^2/s)	
				Af	Ac	Af	Ac	Af	Ac	Af	Ac
ambient, background; 1m from compost pile-down wind, 1.8m above ground	1			77	10.3			-			
incoming air; air filtered by carbon as carrier in wind tunnel	*ca.* 3			0.6	0.8			-			
wind tunnel - location 1; located at the top and bottom of outlet mixing chamber	1	2.0	0.19	19.7	31.0	19.1	30.2	3.6	5.5	8.3	13.1
wind tunnel - location 3; located at the top and bottom of outlet mixing chamber	0.8	1.8	0.19	29.0	56.6	28.4	55.8	5.4	10.6	11.1	21.7

1 wind tunnel 2 data invalidated due to pump malfunction; 2 Af, *Aspergillus fumigatus*; Ac, mesophilic *actinomycetes*)

Table 1 Measured bioaerosol data and estimated specific bioaerosol emission rate for fugitive release

wind tunnel and bioaerosols	wind speed at 1.8 m (m/s)	wind speed at 10m	Pasquill stability	Concentrations estimated by SCREEN3 at various distances (m) from compost windrow x 10^3 cfu/m^3 (1 hour average)								
				1 m	10 m	30 m	50 m	100m	200	250	500	1000
1 (Af)	1	1.33	A-B (1)	57.8	61.3	66.3	39.5	9.3	2.2	1.4	0.3	0.05
1 (Ac)				91.3	96.7	104.7	62.3	14.8	3.7	2.2	0.5	0.07
3 (Af)	0.8	1.06	A-B (1)	97.1	102.9	111.3	66.2	15.5	3.7	2.4	0.5	0.09
3 (Ac)				189.8	201.2	217.5	129.5	30.4	7.3	4.6	0.8	0.18

Table 2 Estimated bioaerosol dispersal downwind of facility using SCREEN3



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