Ecological Risk Assessment

Bioaerosol Transport Modeling and Risk Assessment in Relation to Biosolid Placement

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ABSTRACT

A field study was performed in which bioaerosols were sampled at a field site undergoing land placement of anaerobically digested, de-watered biosolid material. The data from these field studies were then used to generate microbial release rates from the biosolids for use in modeling bioaerosol transport. Continuous-point sources represented by large biosolid piles (temporary storage before placement) in the field, and continuous-area sources represented by large fields upon which biosolids were placed by spraying, were modeled using microbial transport models; and downwind microbial concentrations were generated. These quantified transport data were then entered into microbial dose-response models in an attempt to characterize the risk of pathogenic bacteria and viruses infecting workers and nearby population centers. The risk of viral and bacterial infection to workers at biosolid land application sites is 3:100 and 2:100, respectively, under 2-m/s wind conditions and 1 hr of exposure. The route of exposure proposed in this model is the transport, inhalation, deposition, and swallowing of bacterial or viral pathogens. Note that these risk models by nature would tend to overestimate the actual risk to populations (wastewater workers) consisting primarily of immunocompetent individuals. Under these low-wind conditions, nearby population centers where such immunocompetent populations may exist (here considered to be 10 000 m from the land application sites) are predicted to be at little risk (1.95 × 10^-5:100) of infection from aerosolized bacteria and at no risk from aerosolized viruses.

The disposal of domestic sewage sludge (biosolids) has become a pressing problem in the 20th century. Today in the USA, more than 33% of all biosolids are disposed of by land placement. This means of disposal is now widely accepted and has proven to be beneficial, both as a means of land reclamation and also as a source of fertilizer. However, if not properly treated, biosolids may contain relatively high levels of pathogenic bacteria and viruses (Harding et al., 1980). There is growing concern regarding exposure to microbial pathogens from biosolids via aerosols, especially in population centers surrounding biosolid application sites (Dowd et al., 1997). This is a valid concern because aerosols can transmit many enteric microorganisms (Pahren and Jakubowski, 1980). Thus, the characterization of bioaerosols and the assessment of potential risk of enteric infections from aerosolized microbial pathogens are important.

When microorganisms are aerosolized, one of the primary questions is “How far and in what concentrations will they travel?” Mathematical models have been designed to predict the transport of microorganisms associated with the aeromicrobiological pathway. Pasquill (1961) described a classic model of particulate airborne transport of aerosols launched from a continual-point source, as might be represented by a biosolid pile. Lighthart and Frisch (1976) modified Pasquill’s equation to better model the transport of microorganisms by incorporating a microbial inactivation factor. They rationalized that microbial populations are inactivated within aerosols by environmental stresses such as ultraviolet (UV) radiation and desiccation. A second model by Parker et al. (1977) described the transport of bioaerosols originating from a continual line or area source such as an agricultural field where biosolid materials had been placed. Bioaerosol sampling used in conjunction with airborne-transport models (such as those described previously) can be used to estimate exposure during inhalation. Using this data in dose-response models for a given microorganism, the risk of infection can be determined (Haas et al., 1999).

The dose a person may receive (N) within a certain period of time can be quantified by modeling aerosolized concentrations of microbial pathogens at a given distance from the source and the numbers inhaled over a given period of time. The dose-response relation identifies the relationship between the dose and the frequency with which a certain outcome (infection, disease, and/or death) occurs (Gerba, 1996). This information is derived from exposure of humans or animals to various concentrations of infectious microorganisms. Dose-response data in humans is available for many human enteric pathogens including Salmonella, rotavirus, coxsackievirus, Shigella, etc. (Haas et al., 1999). This information has generally been found to fit the Beta–Poisson dose-response model or the Exponential dose-response model (Regli et al., 1991; Haas, 1983). These models have been validated by comparing them to outbreaks of foodborne and waterborne diseases when the exposure has been quantified (Crockett et al., 1996; Rose et al., 1995).

Because of the potential for disease transmission via aerosolized microbial pathogens, determining the risk associated with field-placed biosolids is important. An early study by Pahren and Jakobowski (1980) documented the relationships between land application of biosolids and aerosolization of pathogens. Recent studies by Dowd et al. (1997) and Pillai et al. (1996) have documented that under proper biosolid-management practices, the likelihood of airborne transport of microbial pathogens into population centers is extremely low.
The modified point-source equation is given as follows:

\[ Q \times \exp(-0.5y^2) \times \exp(-X) \times \exp(-0.5(z-z_y)z^2) \]

where

- \( Q \) = concentration of particles/m³ of air at \( x, y, \) and \( z \)
- \( y \) = The axis lateral to the direction of flow
- \( x \) = The axis extending along the mean direction of air flow
- \( z \) = The axis vertical to the direction of flow

The point-source model used in this study did not provide the necessary detail to evaluate the impact of increased distance from the source on the dispersion and inactivation of microorganisms. To address this issue, a variable was added to account for the distance from the source (\( x \)).

Microbial dose-response models were subsequently used to determine the risk of infecting populations (such as land application workers or residents of nearby population centers) that inhale pathogenic organisms originating from locations where land placement of biosolids is occurring. The point-source model requires the input of variables such as the inactivation rate of the microorganism, the mean wind velocity, diffusion constants, the downwind distance from the source, and the height from which the sample was taken. The microbial inactivation constant \( \theta \) must be determined experimentally for each organism and environmental condition. The values for several aerosolized microorganisms have been determined experimentally by various researchers (Ijaz et al., 1985). For this study, we have chosen values (Table 1).

| Microorganism | Indicator virus obtained at a biosolid-placement site | Microbial inactivation constant \( \theta \) |
|---------------|-----------------------------------------------------|----------------------------------|
| E. coli       | Salmonella enterica                                    | \( 1.92 \times 10^4 \) \( \text{(Mitscherlich and Marth, 1984)} \) |
| Salmonella    | Various enteric organisms                              | \( \leq 10^{-4} \) \( \text{(Mitscherlich and Marth, 1984)} \) |
| Coronavirus   | Rotavirus                                            | \( 2.66 \times 10^{-2} \) \( \text{(Ijaz et al., 1985)} \) |
| Enterovirus   | Rotavirus                                            | \( 2.35 \times 10^{-4} \) \( \text{(Ijaz et al., 1985)} \) |
| Mycobacterium | Salmonella enterica                                    | \( 2.35 \times 10^{-4} \) \( \text{(Ijaz et al., 1985)} \) |

In the point-source model, values for \( Y \) and \( Z \) (Eq. [2]) are based upon meteorological conditions (uneven agricultural). The source height (\( H \)) of the biosolid pile was approximately 2 m. Ranges of wind velocities were also considered: low velocity at 2 m/s, medium velocity at 5 m/s, high velocity at 10 m/s, and extreme conditions at 20 m/s.

Wind speed (moderate to fast), and the terrain conditions increase with increasing height above the ground (daytime), and sampling procedures for the site modeled in this study are based upon lapse conditions, such as those modeled in area application models. The model used for area sources in the current study was first described by Parker et al. (1977). This model predicts concentrations of microorganisms downwind from an area source by taking into account the length and width of the source and the height from which the sample was taken. The distance from the source to the sampler is described by Eq. 3:

\[ tt = K(x/p\theta) \]

where

- \( K \) = Plume spread factor
- \( x \) = Distance from the source
- \( p \) = Easting coordinate
- \( \theta \) = Microbial inactivation constant

The factors accounting for the downwind distance, the height of the sampler, and the source height (\( H \)) are similar to those described below for the area application model.

Environmental conditions include certain source heights and sampling heights returned for this study. Other problems with the original version of this model is that it does not account for the expected decrease in concentration of microorganisms with increased distance from the source, and the height from which the sample was taken. The factor accounting for microbial inactivation is described by Eq. 3:
by increases in wind speed, is given as:

modifications to account for increases in release rate caused with an increase in surface area. This model, which includes the subsequent increase in the aerosol loading rates that occurs agricultural field where the biosolids have been applied and

Adapted from Pasquill, 1961.

Windspeed, m/s 2 5 10 20

Table 2. Typical depths of the boundary layer in quasi-neutral

For this purpose, levels of airborne

the particle and wind velocity are essentially the same.

Direction are constant (or averaged) over the modeled time

The particles display Gaussian distribution in both vertical (y)

also made for the two models (point and area source): (i).

for the vertical source height ((rzo). Several assumptions

based upon the size of each biosolid plot. Because the biosolids

area source used in our modeling were 100 by 100 m and

source dimension (meters). The dimensions (Xo and yo) of

the along-wind dimension (meters) of the source area; Yo is the

estimated depth of the atmospheric mixing layer (meters)

sants based upon lapse meteorological conditions as de-

dision coefficients measured in meters; ~rE' and ~rA' are con-

A ratio was established between the concentration of indicator

used as indicators of enterovirus levels (Dowd et al., 1997).

solved for Q (rate of release from the source). Male-specific

actual sampling were used in the simulation to prevent the

et al., 1992) air sampling device as previously described (Dowd

viruses (coliphage) were obtained using an AGI-30 (Jensen

source; hence it was necessary to use actual sampling data in

rates of release of microorganisms from a large point or area

the gravitational settling of particles is negligible; and (vii)

is a continuous point or area source; (iv) the wind velocity and

and distance; (v) the modeled surface is relatively flat; (vi)

It is extremely difficult to accurately measure the overall

coxsackievirus B3, which ranges between 0.2 and 200 PFU/g (dry weight), was then

In Eq. 4, ~rx{X} and

Table 3. Predicted rates of release of indicator organisms.

Table 4. Parameters used in the risk-assessment models based

Risk assessment was performed using two models

infection rate.

values are based upon the probability of infection from expo-

parameters for the organisms modeled in this study. These

et al. (1984), and Rose et al. (1991) have defined the values

of organisms inhaled, 13 is the IDs0, and a and r are parameters

In these models, p = probability of infection, N = the number

distribution model (p = 1 - [1 + (N/13)(2lj~ - 1)]-a) best

Beta-

Coxsackievirus B3, while the Beta-

Salmonella typhi),

back-calculate the rates of release from the source (Table 3).

virus, like the values for enteric bacteria, were then used to

wastewater treatment plant. The values of airborne enteric

coxsackievirus B3, detected by Fannin et al. (1985) around

ally ranges between 0.2 and 200 PFU/g (dry weight), was then

rates of release for viruses from each source was 4 to 5

predicted rate of release. The predicted

isms originating from the two sources, airborne micro-

infection rate.

inhalation of one organism as well as the minimum dose for a 1%

fied previously. The values for N, which refers to

described previously. The values for N, which refers to

Risk-Assessment Models

| Parameter | Coxsackievirus B3 | Salmonella typhi |
|-----------|------------------|-----------------|
| Rate (organisms/s) | 2.7 × 10^1 | 5.11 × 10^6 |
| Rate (logs) | -4.8 | -13 |
| IDs0 | 0.3126 | 0.05 |
| a | 1.3563 | 1.0 |
| r | 0.0540 | 0.004 |

To determine the rate of release of the microorgan-

To assess the probability of infection to workers and nearby

parameters for the organisms modeled in this study. These

infection rate.

infection rate.


Table 5. Concentrations of organisms per cubic meter of air

| Wind speed | Bacteria point source | Bacteria area source | Viruses point source | Viruses area source |
|------------|-----------------------|----------------------|----------------------|----------------------|
| 2 m/s      | 2.2 × 10^-3           | 4.0 × 10^-3          | 1.2 × 10^-12          | 2.3 × 10^-27          |
| 5 m/s      | 5.8 × 10^-3           | 7.6 × 10^-3          | 2.0 × 10^-6           | 1.8 × 10^-9           |
| 10 m/s     | 1.3 × 10^-2           | 3.3 × 10^-2          | 5.1 × 10^-14          | 3.1 × 10^-6           |
| 20 m/s     | 2.0 × 10^-1           | 8.0 × 10^-1          | 1.2 × 10^-9           | 7.0 × 10^-6           |

Table 6. Predicted risk from virus originating from area source

| Exposure | Risk associated with 1 hr | Risk associated with 100 m | Risk associated with 500 m | Risk associated with 1000 m | Risk associated with 10 000 m |
|----------|---------------------------|----------------------------|-----------------------------|-----------------------------|-------------------------------|
| 1 hr     | 1.0                        | 1.0                        | 1.0                         | 1.0                         | 1.0                            |
| 100 m    | 0.997                      | 0.688                      | 6.5 × 10^-14                | 3.1 × 10^-6                 | 0                             |
| 500 m    | 0.523                      | 0.039                      | 0                           | 0                           | 0                             |
| 1000 m   | 0.779                      | 5.6 × 10^-3                | 5.1 × 10^-6                 | 0                           | 0                             |
| 10 000 m | 0.395                      | 1.8 × 10^-3                | 1.7 × 10^-6                 | 0                           | 0                             |

Table 7. Predicted risk from bacteria originating from area source

| Exposure | Risk associated with 1 hr | Risk associated with 100 m | Risk associated with 500 m | Risk associated with 1000 m | Risk associated with 10 000 m |
|----------|---------------------------|----------------------------|-----------------------------|-----------------------------|-------------------------------|
| 1 hr     | 1.0                        | 1.0                        | 1.0                         | 1.0                         | 1.0                            |
| 100 m    | 0.907                      | 0.613                      | 0.316                       | 3.9 × 10^-7                 | 0                             |
| 500 m    | 0.99                       | 0.85                       | 0.322                       | 2.2 × 10^-6                 | 0                             |
| 1000 m   | 0.6                       | 0.211                      | 0.047                       | 2.7 × 10^-15                | 0                             |
| 10 000 m | 0.936                      | 0.218                      | 0.013                       | 0                           | 0                             |

Table 8. Predicted risk from virus originating from point source

| Exposure | Risk associated with 1 hr | Risk associated with 100 m | Risk associated with 500 m | Risk associated with 1000 m | Risk associated with 10 000 m |
|----------|---------------------------|----------------------------|-----------------------------|-----------------------------|-------------------------------|
| 1 hr     | 1.0                        | 1.0                        | 1.0                         | 1.0                         | 1.0                            |
| 100 m    | 0.12                       | 8.2 × 10^-3                | 0                           | 1.1 × 10^-9                 | 0                             |
| 500 m    | 0.02                       | 2.6 × 10^-5                | 3.4 × 10^-4                 | 2.6 × 10^-16                | 0                             |
| 1000 m   | 0.04                       | 2.8 × 10^-8                | 1.3 × 10^-7                 | 1.3 × 10^-16                | 0                             |
| 10 000 m | 0.09                       | 5.5 × 10^-11               | 9.2 × 10^-10                | 9.2 × 10^-16                | 0                             |

Table 9. Predicted risk from bacteria originating from point source

| Exposure | Risk associated with 1 hr | Risk associated with 100 m | Risk associated with 500 m | Risk associated with 1000 m | Risk associated with 10 000 m |
|----------|---------------------------|----------------------------|-----------------------------|-----------------------------|-------------------------------|
| 1 hr     | 1.0                        | 1.0                        | 1.0                         | 1.0                         | 1.0                            |
| 100 m    | 0.40                       | 0.06                      | 3.4 × 10^-9                 | 0                           | 1.1 × 10^-9                   |
| 500 m    | 0.12                       | 0.02                      | 2.6 × 10^-5                 | 0                           | 1.3 × 10^-5                   |
| 1000 m   | 0.04                       | 0.01                      | 1.3 × 10^-7                 | 0                           | 1.3 × 10^-7                   |
| 10 000 m | 0.09                       | 0.01                      | 5.5 × 10^-11                | 0                           | 5.5 × 10^-11                  |

The use of models enables quantification of complex processes. Aerosol-transport models were used to generate N as N = X 0.83 E, where X is the volume of air (m³) inhaled by the average person in 1 hr; and E is the length of exposure time. Dose-response processes, such as bioaerosol concentrations, were then used to estimate the probability of infection. The risk assessment is provided in Tables 6 through 9. The acceptable risk of infection from drinking water as suggested by the Environmental Protection Agency (EPA) is one infection per 10 000 individuals per year. The risk of infection from a biosolid land placement site was not delineated; however, the acceptable risk of infection from this type of source has not been determined; how-
### Table 9: Predicted risk from bacteria originating from point placement of biosolids.

| Wind Velocity (m/s) | Time (h) | Distance (m) | Risk of Infection |
|---------------------|----------|--------------|-------------------|
| 2.0                 | 24       | 100          | 4.4 × 10⁻³        |
| 5.0                 | 24       | 100          | 7.8 × 10⁻³        |
| 10.0                | 24       | 100          | 1.6 × 10⁻²        |

Increasing wind velocity may result in a higher risk of infection. The risk of infection may be greater than that of other enteric viruses; (ii) the conduction of enteric pathogens may establish throat and respiratory infections that can increase the risk of swallowing an infectious dose (Clemmer et al., 1960). Previous studies have also shown that the infectious dose for enteric pathogens may be lower than 10⁻¹⁴ infectious virus particles per m³ during the time it takes to travel distances in the x direction. At this distance (100 m), the risk of infection by viral pathogens to nearby population centers is <1 × 10⁻¹².

Factors that could result in overestimating the risk include: (i) underestimating the time it takes to be transported longer than the distance from the source, (ii) not considering wind direction, (iii) not considering the infectious dose; and (iv) the wind does not always come from the same direction or at a constant speed. Underestimating these factors may result in a lower risk than expected. The risk of infection from bacteria (4.4 × 10⁻³) in comparison to the viruses (7.8 × 10⁻³) will also become ill. Only about half of the persons will become sick. However, it should be noted that this type of microbial transport represents an unlikely scenario, however.

### Table 8: Risk of infection from viral pathogens originating from the area source.

| Wind Velocity (m/s) | Time (h) | Distance (m) | Risk of Infection |
|---------------------|----------|--------------|-------------------|
| 2.0                 | 1        | 100          | 8.0 × 10⁻³        |
| 5.0                 | 1        | 100          | 2.3 × 10⁻²        |
| 10.0                | 1        | 100          | 7.8 × 10⁻²        |

The risk of bacterial infection to workers at the application sites, the risk of infection from pathogens originating from the biosolid material, has been minimized and weighed with the benefits and the need for the disposal of biosolid material. Excluding biosolid workers, the risk of infection from pathogens originating from the biosolid material is very low. The risk of infection from the area source as influenced by wind velocity and duration of exposure.

Population centers 10 000 m from placement sites. Not all individuals who become infected will become ill. Only about half of the persons will become sick. However, it should be noted that this type of microbial transport represents an unlikely scenario, however.

### Table 7: Risk of infection from viral pathogens originating from the area source.

| Wind Velocity (m/s) | Time (h) | Distance (m) | Risk of Infection |
|---------------------|----------|--------------|-------------------|
| 2.0                 | 1        | 100          | 8.0 × 10⁻³        |
| 5.0                 | 1        | 100          | 2.3 × 10⁻²        |
| 10.0                | 1        | 100          | 7.8 × 10⁻²        |

The risk of bacterial infection to workers at the application sites, the risk of infection from pathogens originating from the biosolid material, has been minimized and weighed with the benefits and the need for the disposal of biosolid material. Excluding biosolid workers, the risk of infection from pathogens originating from the biosolid material is very low. The risk of infection from the area source as influenced by wind velocity and duration of exposure.

Population centers 10 000 m from placement sites. Not all individuals who become infected will become ill. Only about half of the persons will become sick. However, it should be noted that this type of microbial transport represents an unlikely scenario, however.
bacteria in biosolids and aerosols are not 100% effective. Pathogens are not evenly distributed in the biosolids and infectivity may be greater by respiratory route than ingestion.

**CONCLUSIONS**

Bioaerosol concentrations downwind of areas undergoing land placement of biosolids were quantified using transport models. These values were then used to quantify the risk associated with airborne viral and bacterial pathogens originating from these sources. The results predict that there may be some risk of infection to biosolid land placement site workers both from viruses and bacteria. These results agree with numerous epidemiological studies performed on other types of wastewater workers. The results also show that the risk of viral or bacterial infection in population centers lying at least 10,000 m away appear insignificant under realistic conditions. Any risk would likely be well below the detection level of epidemiological studies and may also be considered insignificant from a public health standpoint. This modeling effort represents a worst-case scenario and as such only indicates there may be a need for epidemiological screening of biosolid placement workers to further assess and confirm the results of the modeling performed in this study.