Development of the OFFSET Model for Determination of Odor-Annoyance-Free Setback Distances from Animal Production Sites: Part I. Review and Experiment

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Abstract. *The objective of the study was to develop a science-based model, OFFSET (Odor from Feedlot - Setback Estimation Tool), to establish setback distances from animal production sites based on the use of an air dispersion model (INPUFF-2) and the actual odor emission data from these sites. Extensive research was conducted to obtain representative odor emissions from various animal facilities and to evaluate the air dispersion model. Odor emissions were measured from 280 animal buildings and manure storage units on 85 farms in Minnesota during 1998 to 2001. The geometric means of the odor emission rates for each type of odor source were obtained to represent odor emissions of that source. The efficiencies of some odor control technologies were summarized. The air dispersion model was evaluated for short-distance (<0.5 km) odor dispersion prediction against the odor plumes measured by trained field assessors on 20 farms and also for long-distance (4.8 km) odor dispersion prediction against odor data recorded by trained resident observers living in the vicinity of livestock operations in a 4.8 × 4.8 km rural area. The relationship between odor detection threshold and intensity was obtained for swine and cattle odors in order to convert odor intensity to detection threshold. The results indicated that the INPUFF-2 model was capable of simulating odor dispersion downwind from animal production operations for low-intensity odors. Six stable or neutral weather conditions that favor odor transport were identified, and their historical occurrence frequencies in all 16 directions at six weather stations in Minnesota were obtained. The occurrence frequencies of these weather conditions were used to determine odor occurrence frequencies in the OFFSET model.*

Keywords. *Animal, Dispersion, Distances, Emission, Modeling, Odor, Separation.*

Odors generated from animal production operations have become a major concern in Minnesota and other states and provinces in North America during the past decade. Increased pressure from the public regarding the potential human health impacts of livestock odors has prompted the need to find solutions to this growing problem. Determining appropriate setback distances between neighboring residents and livestock farms in order to ensure acceptable air quality could be one of the most feasible tools for solving the problem; therefore, it has become an urgent need for the livestock industry and regulatory agencies. Large setback distances tend to restrict the development and expansion of the livestock industry, whereas insufficient separation distances may result in odor complaints and lawsuits against the animal producers. Recognizing this need, the Livestock Odor Task Force (LOTF) of Minnesota recommended developing a tool to help predict offsite odor movement from livestock operations (LOTF, 1997). The OFFSET (Odor From Feedlots - Setback Estimation Tool) model was the result of this recommended research project. This article serves as Part I of the report and presents a relevant literature review and the research work that paved the way to the development of OFFSET. A second article will serve as Part II of the report and present the OFFSET model development and evaluation of the model (Guo et al., 2005).

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Literature Review

Setback Distances Determination Guidelines or Models

Odor emissions from animal production facilities are a function of many variables including: species, housing type, feeding methods, manure storage and handling methods, size of odor sources, and weather conditions. The impact of the odor on the surrounding neighbors and communities depends on the amount and character of odor emitted from the source, the distance between the neighbor and the source, weather conditions, topography, and the odor sensitivity and tolerance of the neighbors. Because each of these factors is highly variable, determining proper setback distances is difficult. As a result, most of the setback guidelines or models that currently exist in some European countries and in some states and provinces in North America are based either on individual judgment and experience or on a combination of neighbor surveys and odor measurement (Guo et al., 2004).

Some European countries, including Austria, Germany, Switzerland, and the Netherlands, have developed setback guidelines during the past two decades (CIGR, 1994; VDI 3471, 1986; VDI 3472, 1986; VDI 3473, 1994; Klarenbeek and Harreveld, 1995; Schauberger and Piringer, 1997), most of which are empirical. Among them, the Austrian guideline is one of the typical models and considers the most factors based on an estimation of odor sources (Schauberger and Piringer, 1997).

In Canada, an empirical guideline, entitled the MDS-II Guidelines, was developed in Ontario in the 1970s and has been incorporated into land use policy for nearly 30 years (OMAFR, 1995; MacMillan and Fraser, 2003). This model determines setback distances according to animal species, animal numbers, and manure handling systems. Based on MDS-II, similar guidelines have been developed in other Canadian provinces (e.g., Manitoba, Alberta, and Saskatchewan).

In the U.S., some states have different experience-based setback guidelines according to the receptors and the sizes of the livestock operations (Redwine and Lacey, 2000). For instance, Illinois, Iowa, and Indiana (Purdue University) have developed setback guidelines in the past two decades (Klarenbeek and Harreveld, 1995; Lim et al., 2000). A model developed by Purdue University (Lim et al., 2000) is an empirical model based on the baseline odor emission data and the study of existing setback guidelines, particularly the Austrian model (Schauberger and Piringer, 1997) and the Williams and Thompson model (Williams and Thompson, 1986). Building design and management and odor abatement factors were introduced to replace the technical factor of the Austrian model. Outdoor manure storage sources were also taken into account.

A concern with the above or similar models is that they are made with the assumption that a site with greater animal numbers generates more odors, and therefore requires larger separation distances. This would be true if all operations were identical. However, with the diversity of manure handling systems, facility designs, and the new odor control technologies currently being developed, animal number is not the only variable in odor emissions (LOTF, 1997). For instance, European farms either have no outdoor manure storage or have good odor control measures for their outdoor storage facilities, while in North America, the outdoor storage units are usually uncovered. Hence, the total odor emissions from different farms with the same animal species and numbers can be quite different. Therefore, separation distance should be based on the actual odor emission instead of on animal numbers.

A different approach was taken by Williams and Thompson (1986) from the Warren Spring Laboratory in England. They measured odor emissions from a number of processes and sources. By collating the emissions with data on the spatial extent of odor complaints, an empirical formula was derived relating the maximum setback distance to the source.

Hence, the existing setback guidelines or models are lacking scientific verification. The setback distances they specify have generated considerable concern from the public, neighbors, and the livestock industry. Clearly, it is necessary to develop a science-based setback distance determination model for livestock operations.

Odor Dispersion Models

Odor dispersion models capable of taking into account various odor emission rates, weather conditions, and topography have a great potential for simulating downwind odor concentrations from animal production sites and thus determining reasonable setback distances. In response to the growing odor concerns regarding odors emanating from animal production facilities, since the 1980s there has been an intense effort both to modify existing models and to develop new mathematical models that can predict the dispersion of odors from animal buildings and manure storage units (Janni, 1982; Carney and Dodd, 1989; Mejer and Krause, 1985; Lorimer, 1986; Ormerod, 1991; Chen et al., 1998). These methods vary in complexity from fairly simple (Schauberger and Piringer, 1997) to quite complicated (Petersen and Lavdas, 1986). However, few models have been used for setback distance determination because of limited field data available to evaluate these models. In the past several years, extensive odor source measurements have been conducted on livestock farms in the U.S. (Schmidt et al., 1999; Li et al., 1994; Wood et al., 2001). In addition, downwind odor plume measurements in the field by trained field odor assessors have been done in an attempt to evaluate odor dispersion models (Li et al., 1994; Hartung and Jungbluth, 1997; Zhu et al., 2000a; Guo et al., 2001).

Challenges exist in air dispersion model evaluation using odor plume measurement. Although odor concentrations, i.e., odor detection thresholds (OU/m^3), are used as inputs to dispersion models, air samples taken in the odor plume downwind of a source are generally below the sensitivity of olfactometry panels (Zhang et al., 2003), which excludes the use of an olfactometer for odor plume determination. Instead, odor intensity, which measures odor strength by using number and word categories to describe an odor, is widely accepted to measure downwind odor plumes (Li et al., 1994; Hartung and Jungbluth, 1997; Zhu et al., 2000a; Guo et al., 2001; Zhang et al., 2003). This results in another problem to be solved in order to evaluate odor dispersion models, i.e., the odor intensity needs to be converted to the odor detection threshold in order to compare the field odor plume measurement to the result calculated by an air dispersion model.

Odor Emission Measurements

Predicting the dispersion of odor from livestock farms requires that odor emission rates from the sources be known. Unfortunately, quantifying air emissions from animal agriculture is a complex process. First, there is a multitude of individual sources responsible for emissions, extreme variability in these emissions, and a variety of gaseous components being emitted (Sweeten et al., 2001). Second, the method used to collect emission data from the variety of sources has not been standardized and involves the measurement of both the concentrations of the airborne contaminants and the airflow rates from the sources (Sweeten et al., 2001). Few researchers and engineers have taken on the task of measuring odor emission rates because of these and other difficulties.

The lack of a standard method for measurement of odor concentration is especially true for olfactometry, the most accepted odor measurement method. Olfactometry laboratories throughout the world use various methods to determine odor detection thresholds. Since differences exist between olfactometers, in protocols for panelist training and screening, and in the calculations of detection thresholds used by different laboratories, the odor detection threshold data from different laboratories cannot be compared directly (Qu et al., 2002).

Due to the lack of standardized methods to measure, calculate, and report odor emissions rates, the odor emissions from livestock buildings have been reported on various bases such as per animal unit, per animal weight, per animal place, per area, or per volume or weight of manure. Definitions of animal unit and animal place are not standardized; thus, conversion to another unit for comparison is not always possible. In addition, quantifying odor emission rates from buildings is dependent on proper determination of ventilation rate, which is often a challenge whether measured by total airflow rate of fans for mechanically ventilated barns or by carbon dioxide mass balance for naturally ventilated barns. Klarenbeek (1985) measured odor emissions from pig facilities in the Netherlands. Those values ranged from 1.01 OU/pig place-s for a pig barn with partially slatted floor (70% solid floor) to 11.15 OU/ pig place-s for a pig barn with fully slatted floor and pit ventilation. Emissions were found to be seasonally different, with levels in winter significantly lower than those in summer. Verdoes and Ogink (1997) also measured odor from “low ammonia emitting pig barns” in the Netherlands. Using a calibration fan, they found emission rates were between 9 and 12 OU/pig place-s for dry sows, 31 and 40 OU/pig place-s for farrowing sows, 3 and 8 OU/pig place-s for weaners, and 12 and 16 OU/pig place-s for finishers with a low pH diet. Hartung et al. (1998) measured odor emission rates in a gestating sow barn and a finishing barn in Germany and found that the rates varied from 16 to 495 OU/livestock unit-s. Jiang and Sands (1998) found odor emission levels from several Australian naturally ventilated broiler facilities ranging from 3.1 to 9.6 OU-m^3/m^2-s. In the U.S., Heber and Ni (1999) reported odor emissions of from 5.3 to 36.2 OU/min per animal unit (0.8 to 5.4 OU-m^3/m^2-s) from pig finishing barns with shallow gutters that were recharged with lagoon water. Wood et al. (2001) found that odor emission measured in Minnesota during 1998 to 2001 fell widely in the ranges of 0.3 to 12.6 OU/m^2-s, 0.3 to 3.5 OU/m^2-s, and 1.3 to 3.0 OU/m^2-s for various swine, poultry, and dairy barns, respectively. A distinct diurnal variation was observed in odor emissions; this was probably due to the changing ventilation rates during the day (Hartung et al., 1998; Zhu et al., 2000b).

Considerably fewer studies have measured odor emission rates from outside manure storage units or open feedlots. Watts et al. (1993) measured odor emissions from a cattle feedlot using a portable wind tunnel and found values ranging from 14 to 840 OU/s (14 to 840 OU/m^2-s) with wind tunnel air speeds of from 0.6 to 0.7 m/s. Heber and Ni (1999) measured odor from a manure storage lagoon at a swine-finishing farm in Oklahoma using a portable wind tunnel with an average air speed of 1.1 m/s. Reported odor emission rates ranged from 1.5 to 2.0 OU/m^2-s. Using a portable wind tunnel with an air speed of 0.3 m/s, Wood et al. (2001) reported that the odor emission rates for various outdoor dairy and swine manure storages in Minnesota ranged from 6.3 to 32.2 OU/m^2-s and 4.1 to 55.1 OU/m^2-s, respectively.

Objective

The objective of the study was to develop a scientific method to establish setback distances from animal production sites, based on the use of an air dispersion model that uses actual odor emission data from these sites and historical weather data for Minnesota. It was expected to provide a tool for odor nuisance control for local land-use planners, animal producers, and concerned rural residents.

Materials and Methods

Separation Distance Determination Approach

The OFFSET model was intended to be based on typical odor emission rates, an evaluated odor dispersion model, and historical weather data for Minnesota. It was expected to predict the odor intensity and frequency at a neighboring location downwind of a livestock operation so that setback distances could be determined according to the desired odor-annoyance-free frequency of the neighbors. To achieve the objective, the following steps were taken:

- Step 1: Obtaining of typical odor emission rates by extensive measurements from livestock operations in Minnesota.
- Step 2: Selection and evaluation of an air dispersion model to predict odor dispersion. To do so, the following research was needed:
  - Measurement of downwind odor plumes of livestock operations at various distances in terms of odor intensity.
  - Determination of the relationship between odor intensity and the odor detection threshold in order to convert downwind odor intensity to odor concentration for the purpose of dispersion model evaluation.
- Step 3: Collection of historical weather data in Minnesota and determination of the frequencies of typical weather conditions that favored odor transport.
- Step 4: Calculation of required setback distances by the evaluated air dispersion model based on the total odor emission rates, various weather conditions, and the desired odor-annoyance-free intensity and frequencies.
- Step 5: Verification of the setback determination model.

Odor Emission Measurements

Eighty-five farms with various animal production buildings and manure storage units were selected to represent typical livestock housing systems used in Minnesota. These buildings and the associated manure storage systems were monitored for odor emissions. Exhaust air was collected either from the exhaust fans or from the leeward sides of the curtain-side barns in 10 L Tedlar sampling bags (SKC, Inc., Eighty Four, Pa.) using a vacuum box (Vac-U-Chamber, SKC-West, Inc., Fullerton, Cal.) and an air pump (Aircheck model 224-PCXR3 [or 4], SKC, Inc., Eight Four, Pa.) and Teflon FEP tubing (Cole-Parmer Instrument Co., Vernon

Hills, Ill.). A wind tunnel (Schmidt et al., 1999) was used to collect air emissions from the manure storage surface with an average surface speed of 0.2 m/s. Air samples were also collected in Tedlar bags at the outlet of the wind tunnel, which covered an area of 0.23 m^2.

The sample bags were transported to the University of Minnesota Olfactometry Laboratory and analyzed for odor within 24 h of collection using a venturi-type dynamic dilution olfactometer (AC'SCENT International Olfactometer, St. Croix Sensory, Inc., Stillwater, Minn.). The odor detection threshold, in OU/m^3, is defined as the concentration at which the panelist first detects a difference in the air sample when comparing to two clean samples and was measured in accordance with ASTM Standard E679-97 (ASTM, 1997) using eight trained panelists.

Field measurement of the ventilation rates for animal buildings involved several methods. Ventilation rates in mechanically ventilated livestock barns were determined by recording the models of exhaust fans operating during the sampling period and using the fan manufactures' performance data to calculate the total airflow rate. For non-mechanical ventilating systems, a carbon dioxide (CO_2) balance method was used to estimate the air exchange rate from the tabulated CO_2 production rates of the animals housed and the concentration of CO_2 in the building (Albright, 1990; Phillips et al., 1998). Carbon dioxide concentrations were taken with colorimetric tubes (Gastec Corp., Ayase City, Japan) from the Tedlar bag samples immediately after sample collection. Both indoor and outdoor air temperatures as well as animal numbers and estimated weights were recorded and used in these calculations. For manure storage units, measurements of the airflow rates through the floating wind tunnel were determined using a hot-wire anemometer (model 441S air velocity meter, Kurtz Instruments, Carmel, Cal.) to measure the average velocity (0.2 m/s) over the enclosed measurement area of 0.23 m^2.

Emission rates were calculated as the product of the measured odor concentration and the ventilation rate of the building or wind tunnel, and then divided by the area of the source. This method of calculating emissions resulted in units of OU/m^2-s for odor.

Odor Dispersion Model Evaluation

Dispersion Model Selection

The INPUFF-2 (Bee-Line Software Co., Asheville, N.C.) model was selected to predict odor dispersion for this study. This is a Gaussian puff model that can simulate the dispersion of airborne pollutants from semi-instantaneous or continuous point sources. This model can deal with multiple point sources and multiple receptors at the same time. Because of high variations in odor intensity with time in downwind odor plumes due to rapidly changing wind direction and speed, in this study the trained field assessors measured short-distance odor plume intensity at an interval of 10 s, and the resident odor observers measured long-distance odor plumes for 1 to 3 min, as described in the following sections. In order to compare the measured odor concentrations with the model-simulated values, the dispersion model should be able to handle different time intervals, which is an important reason for the selection of INPUFF-2 for this study; INPUFF-2 allows for different time intervals as determined by the user, rather than the hourly intervals required by other air dispersion models (USEPA, 1999a). The inputs for the model included locations of odor sources and receptors, odor source emission information (emission rate, source height, source area, emission temperature and velocity, etc.), and weather information (stability class, temperature, wind direction, wind speed, mixing height, etc.). Weather stability is classified using Pasquill stability categories, which is the classification method used in most dispersion models (USEPA, 1999a).

As with all Gaussian dispersion models, this model is based on mass dispersion. Odor is different from particulate substances; it cannot be measured on a mass basis. Instead, it is measured by the detection threshold determined by olfactometers. The relationship between the odor detection threshold and its weight is unknown. Therefore, odor emission rates, with units of OU/s, were used as the source emission inputs for the model. The simulated odor concentration was the odor detection threshold, with a unit of OU/m^3.

Odor Intensity Measurement

The odor intensity in this study was measured by using a widely accepted n-butanol (butyl alcohol, $C_4H_{10}O$) reference scale according to ASTM E544-75, with required purity higher than 99% by gas chromatography and a neutral smell (ASTM, 1999). An adequate concentration range for most applications is between 5 and 2000 ppm of n-butanol in air, or n-butanol solution concentration in the range of 10 to 20,000 ppm in water (Moskowitz et al., 1974). Table 1 lists the 0-to-5 scale developed to describe the intensity of a series of n-butanol solutions by assigning odor intensity 5 (very strong) to the n-butanol solution of 20250 ppm (1948 ppm in air), intensity 3 (moderate) to n-butanol solution of 2250 ppm (216 ppm in air), and intensity 1 (faint) to n-butanol solution of 250 ppm (24 ppm in air) (Zhu et al., 2000a; Jacobson et al., 2000a). By comparing the strength of the air sample to the reference scale, the field assessors assigned an intensity level to the air sample based on the n-butanol level of the same strength or closest strength. The nasal rangers were allowed to report a half value between two reference levels, e.g., a report of 2.5 would be accepted if the panelist determined that the intensity was between 2 and 3.

Table 1. n-butanol odor intensity referencing scale, swine and cattle detection threshold.

Odor Intensity	Odor Intensity Description: Strength	Odor Intensity Description: Strength	n-butanol Solution (ppm)	n-butanol in Air (ppm)	Swine Odor: DT[a] (OU)	Swine Odor: Range of DT (OU)	Cattle Odor: DT[a] (OU)	Cattle Odor: Range of DT (OU)
0	No odor	Not annoying	0	0	0	<5	0	<5
1	Very faint	Not annoying	250	24	25	5-42	28	5-48
2	Faint	A little annoying	750	72	72	42-124	83	48-142
3	Moderate	Annoying	2250	216	212	124-364	244	142-420
4	Strong	Very annoying	6750	649	624	375-1070	723	420-1244
5	Very strong	Extremely annoying	20250	1948	1834	>1070	2140	>1244

[a] DT = detection threshold.

Short-Distance Odor Plume Measurements

In order to evaluate the odor dispersion model, odor plume measurements were conducted at various animal production sites with seven nasal field assessors who were trained to measure odor intensity in the ambient air based on the 0-to-5 n-butanol reference scale (ASTM, 1999). The procedure implemented was a modified version of the one used by Hartung and Jungbluth (1997). Distances between 25 to 500 m (depending on site and odor source strength) were marked off at the approximate centerline of the downwind odor plume. Perpendicular to this centerline, straight lines were marked off to locate individual nasal rangers with marker flags from 5 to 20 m apart. This was done so that the seven individuals would approximately cover the plume width. The nasal rangers were provided with stopwatches, charcoal-filtered masks, and clipboards with data sheets.

At each of the selected distances from the odor source, the field assessors sniffed the air once every 10 s during a 10 min period, for a total of 60 data points. Between sniffing times (every 10 s), the individuals put their masks on to protect their olfactory systems from fatigue.

Prior to evaluating the plume, the field assessors calibrated their noses by sniffing a static scale of n-butanol supplied to the group. A portable weather station was set up on the farm site that continually recorded wind speed, direction, temperature, air moisture content, and solar radiation during the sniffing. In addition, during the odor plume measurements, air samples were collected from the odor sources on that farm site to obtain odor emission rates. Detailed procedures were presented by Jacobson et al. (1998). More than 20 farm sites were used for odor plume measurement.

Long-Distance and Long-Term Downwind Odor Measurements

Since setback distances generally are greater than 400 or 500 m, odor dispersion to further distances also needs to be measured. Field odor assessors were not suitable for this type of measurement because odors at distances greater than 400 m are likely to be intermittent due to changing wind directions, and it is difficult to predict where the odor plumes are in order to locate field assessors. Using trained resident odor observers to measure and record odor occurrence at their residing locations was the only practical and cost-effective method for long-distance downwind odor measurement. For this purpose, a 4.8 × 4.8 km grid of farmland in Nicollet County, Minnesota, was selected (Guo et al., 2001). There were a total of 20 animal production farms in or adjacent to the grid, including 12 swine, 7 dairy/beef, and 1 poultry operation, varying from small to medium in size. Nineteen residents, ten males and nine females ranging from 25 to 62 years of age, were trained to be odor observers. They were from eleven families, of which five were animal producers and six were not. Data were collected for the five months from June 21 to November 14, 1999, a time span covering much of the warmest weather. Odor events detected by the odor observers around their residences in early mornings from 05:00 to 08:00 and evenings from 05:00 to 08:00 and during their normal daily activities were recorded. Resident odor observers recorded odor intensity, occurrence time, and a general quantitative statement on the odor (constant or intermittent, duration, possible source, etc.). A simpler 0-to-3 intensity scale was used instead of the more complicated 0-to-5 scale. The odor intensity levels of 1 (faint), 2 (moderate to strong), and 3 (very strong) on the 0-to-3 scale corresponded to 0, 2, 3.5, and 5 on the 0-to-5 scale, respectively. To avoid possible confusion resulting from reference to these two intensity scales, the 0-to-3 reference scale is reported later in the Results section using the corresponding intensities on a standard 0-to-5 scale.

A weather station was placed near the center of the grid. Temperature, relative humidity, solar radiation, wind speed, and wind direction were sampled every minute and averaged and recorded every 30 min until August 16, and every 10 min thereafter. Odor emissions from all building and manure storage sources were measured twice, once in July and once in September. Acute odor generation events (e.g., pumping of a manure storage unit) were recorded by the animal producers in order to identify sporadic odor emissions.

Relationship Between Odor Detection Threshold and Odor Intensity

To evaluate an air dispersion model by on-site odor plume measurement, the relationship between the predicted odor concentration values and the measured odor intensities needed to be known. One hundred and twenty-four air samples taken from various swine and cattle facilities were measured in the University of Minnesota Olfactometer Laboratory for both odor detection threshold and intensity (Guo et al., 2001). The samples were measured first for odor detection threshold and then for odor intensity using the 0-to-5 n-butanol reference scale (ASTM, 1999), as previously described.

METEOROLOGICAL DATA ANALYSIS

Weather is one of the most important factors that dictate odor dispersion. Critical meteorological data for dispersion model inputs include atmospheric stability class, wind speed, wind direction, temperature, solar radiation, and mixing height.

Pasquill stability classes ranging from A (strongly unstable), B (moderately unstable), C (slightly unstable, D (neutral), E (slightly stable), F (moderately stable), to G (strongly stable) are widely used for estimating atmospheric stability and are generally required by air dispersion models (USEPA, 1999a). The INPUFF-2 model uses weather stability classes from A to F. The Scram Support Center for Regulatory Air Models of the U.S. Environmental Protection Agency (USEPA) offered meteorological data that were compatible with the requirements of the various models offered by the Air Quality Modeling section of EPA (USEPA, 1999b).

Unstable weather conditions (stabilities A, B, and C) during the daytime quickly dilute odor and gases by horizontal and vertical turbulences; therefore, odor likely will not travel far. In OFFSET, only the following weather conditions from stable to neutral that favor odor transport were considered:

- Stability F with wind velocity 1.3 m/s, represented by W1 or F, $\leq$1.3 m/s
- Stability F with wind velocity 3.1 m/s, represented by W2 or F, $\leq$3.1 m/s
- Stability E with wind speed of 3.1 m/s, represented by W3 or E, $\leq$3.1 m/s
- Stability E with wind speed of 5.4 m/s, represented by W4 or E, $\leq$5.4 m/s

Table 2. Odor emission reference rate for animal housing.

Species	Animal Type	Housing Type	Odor Emission Number, OEN/m^2-s (Rate, OU/m^2-s)
Cattle	Beef	Dirt or concrete lot	44 (4.42)
	Dairy	Free stall, deep pit or scrape; loose housing, flush	70 (2.00)
		Tie stall	25 (0.70)
		Open concrete or dirt lot	40 (4.00)
Poultry	Layer	Deep pit; annual cleanout	105 (3.00)
		Deep pit; weekly cleanout	35 (1.00)
	Broiler	Litter	16 (0.45)
	Turkey	Litter	11 (0.32)
Swine	Gestation	Deep pit or pull plug; natural or mechanical vented	441 (12.60)
	Farrowing	Pull plug, scrape, or flush; mechanically vented	168 (4.80)
	Nursery	Deep pit or pull plug; natural or mechanical vented	303 (8.66)
	Finishing	Deep pit, pull plug, flush, or scrape; natural or mechanical vented	240 (6.86)

- Stability D with wind speed of 5.4 m/s, represented by W5 or D, ≤5.4 m/s
- Stability D with wind speed of 8.0 m/s, represented by W6 or D, ≤8.0 m/s

The occurrence frequency of each weather condition was calculated for each of the 16 wind directions for all of the six weather stations in Minnesota using the meteorological data provided by the Scram Support Center for Regulatory Air Models of the U.S. Environmental Protection Agency during 1984 to 1992 (USEPA, 1999b).

Results and Discussion

Odor Emissions

Over 1000 air samples from buildings and manure storage units totaling 280 sources on 85 farms in Minnesota during 1997 through 2001 were analyzed for odor detection threshold and were combined with ventilation rate data to produce odor emission rates for animal buildings (table 2) and outdoor manure storage units (table 3) (Wood et al., 2001; Jacobson et al., 2000b). The tables specify the species, the animal and housing types, and the odor emission numbers and rates for each category. The odor emission rate of each category was the geometric mean of all data from that category. The odor emission number was determined by multiplying the emission rate by the scaling factor of 35 for animal buildings or by the scaling factor of 10 for manure storage units, as determined by Zhu et al. (2000a) for use with the INPUFF-2 model.

Table 3. Odor emission reference rate for manure storage.

Species	Storage Type	Odor Emission Number, OEN/m^2-s (Rate, OU/m^2-s)
Beef cattle	Concrete tank	72 (7.32)
Dairy cattle	Concrete tank	322 (32.20)
	Earthen basin, single cell	269 (26.90)
	Earthen basin, 1st cell	63 (6.33)
	Earthen basin, 2nd cell	51 (5.07)
Swine	Concrete tank	498 (49.80)
	Earthen basin, single cell	141 (14.10)
	Earthen basin, 1st cell	155 (15.50)
	Earthen basin, 2nd cell	113 (11.27)
	Anaerobic lagoon, 1st cell	40 (4.00)
	Anaerobic lagoon, 2nd cell	12 (1.20)
	Settling tank	530 (53.00)
	Crusted stockpile or manure stack	25 (2.46)

Numerous odor control techniques have been researched, including permeable and impermeable covers, biofilters, oil sprinkling, non-thermal plasma, ozone, air filtering, and others. In order to include these technologies in the OFFSET model, table 4 compiles some of the odor control technologies that have been evaluated extensively by either the University of Minnesota or other researchers so their abilities to reduce odor emissions can be estimated (Nicolai and Janni, 1998; Clanton et al., 1999 and 2001; Bicudo et al., 2001; Jacobson et al., 2000b). Each odor control factor listed in table 4 is the decimal fraction of the odor emitted from a source with a particular control technology present versus absent. For example, a barn with a biofilter releases only 0.1 (10%) of the potential odor, or has a 90% odor reduction.

Relationship Between Odor Detection Threshold and Odor Intensity

A data set of 124 paired odor intensity and detection threshold measurements (from 60 pig buildings, 66 pig manure storage facilities, and 55 dairy and beef farms in Minnesota) was used to determine the best correlation for this study. Several different relationships between odor intensity and detection threshold, i.e., the Weber-Fechner model (Fechner, 1966), Stevens' law (Stevens, 1957), and the Beidler model (Cain and Moskowitz, 1974), were evaluated (Nicolai et al., 2000; Guo et al., 2001). The Weber-Fechner model was the best fit for both swine and cattle data. The relationship between odor intensity (on a 0-to-5 scale) and threshold can be expressed in an exponential form as (Guo et al., 2001):

For swine odor:

Table 4. Odor control factors for selected technologies.

Odor Control Technology		Odor Control Factor
Biofilter on 100% of building exhaust fans		0.1
Geotextile cover (≥2.4 mm)		0.5
Straw or natural crust cover on manure:	2 in. thick	0.5
	4 in. thick	0.4
	6 in. thick	0.3
	8 in. thick	0.2
Impermeable cover		0.1
Oil sprinkling		0.5

$$Z = 8.367e^{1.078\,I}\ (r^2 = 0.693) \quad (1)$$

For cattle odor:

$$Z = 9.429\ e^{1.085\,I}\ (r^2 = 0.894) \quad (2)$$

where

I = odor intensity on a 0-to-5 scale (I = 0 to 5)

Z = odor detection threshold or concentration (OU).

EVALUATION OF INPUFF-2 MODEL

Short-Distance Evaluation of INPUFF-2 Model

Over 20 individual farm sites were used to evaluate the short-distance performance of the INPUFF-2 model (Zhu et al., 2000a). The odor intensities reported by the field assessors were converted to detection thresholds using the empirical equations given above (eqs. 1 and 2) and were then compared with the simulated values by the INPUFF-2 model. A total of 368 paired data of measured and modeled odor thresholds were obtained. Table 5 gives the statistical analysis of the comparison of the predicted and measured odor detection thresholds, which indicates that the model is capable of predicting downwind odor concentrations at distances from 100 to 300 m with a confidence level of 81% to 95% (a total of 344 paired data). Only three field measurements with a total of 24 paired data were conducted at distances of 400 to 500 m. The modeled and measured odor concentrations all ranged from 1 to 15 OU and were not valid at such low odor levels. The model could also simulate downwind odor concentrations from multiple sources with a confidence level ranging from 81% to 90%. In simulating odor concentrations, it was found that a “scaling factor” for actual odor emission rate was needed to obtain results that fell into the same numerical range as the field monitored data. Zhu et al. (2000a) suggested that the scaling factor be 35 for animal building sources and 10 for surface sources such as manure storage facilities. Zhu et al. (2000a) gave the details for this part of study.

Long-Distance Evaluation of INPUFF-2 Model

A total of 296 odor events were detected by the resident odor observers, of which 170 odor events were simulated by the INPUFF-2 model. The other odor events could not be simulated because of missing weather data, odors coming from outside of the grid, or unclear odor sources. Table 6 gives the probability of agreement analysis results for all odor events simulated, and details were presented by Guo et al. (2001).

The comparison between simulated and measured odor intensity indicated that the model successfully estimated odor intensity 2 (faint odor) on a 0-to-5 reference scale traveling up to 3.2 km under stable weather conditions (stability F and E) ($P > 0.05$). However, the model underestimated moderate to strong or very strong odors and/or during neutral or unstable weather conditions as compared with the field-measured data ($P < 0.05$). In addition, considering the short-distance evaluation of the model (Zhu et al., 2000a), the model was capable of simulating odor dispersion downwind from animal production operations for low-intensity odors during stable weather conditions. Since the OFFSET method uses odor intensity 2 on the 0-to-5 scale as the odor-annoyance-free level for setback distance determination, the model predictions are adequate for this use.

Table 5. Statistical analysis for data from different distances (Zhu et al., 2000a).

	Distance from the Odor Source (m)				
Statistic	100	200	300	400-500	All
No. of paired data	223	86	35	24	368
Calculated P value	0.0492	0.0796	0.1936	0.8975	0.2643
Probability of accuracy (%)	95.08	92.04	80.64	10.25	73.57

Table 6 Measured and model predicted odor intensity by categorical data analysis (Guo et al., 2001).

Reported Odor Intensity	Model-Predicted Odor Intensity					Total No. Agreed	Probability of Agreement (%)
	0	2	3.5	5	Total		
1	6	117	0	0	123	117	95.1
2	0	11	21	0	32	21	65.6
3	0	3	11	1	15	1	6.7
					170	139	81.8

METEOROLOGICAL DATA FOR DISPERSION MODEL CALCULATIONS

Weather data from 1984 to 1992 were analyzed for six weather stations in Minnesota and the surroundingstates, including Minneapolis, Rochester, International Falls, Sioux Falls, Fargo, and Duluth. The average occurrence frequency was calculated for each of the 16 wind directions for each weather station and was presented in a graph format called a windstar chart. Figure 1 shows the windstar chart for the Minneapolis/Saint Paul weather station. It needs to be pointed out that the frequency in windstar charts is the accumulated frequency of the indicated weather condition in that direction and any other weather conditions that are more stable than the indicated condition in that direction. This is because if an odor travels to a specific location at a detection threshold that equals the desired odor-annoyance-free level, then under more stable weather conditions the odor detection threshold at that location would exceed the desired level. Hence, the windstar charts can be used to determine the approximate frequency of a location’s receiving a specific, or higher, odor concentration from a nearby source.

For example, figure 1 indicates that the highest annual frequency for occurrence of weather condition W1 (stability class F with wind speed $\leq$3.1 m/s) is 1.5% from the southwest direction. This indicates that 1.5% of the time annually the weather would be equal to or more stable than that, while the remaining 98.5% of the time the weather would be less stable. With the INPUFF-2 model, the odor concentration (OU) at a specific location northeast of an odor source under weather condition W1 can be calculated. At this location, the odor concentration during the accumulated time of 1.5% of a year would be equal to or stronger than the odor that occurred under this weather condition. The rest of the time (98.5%), the odor would be lower. The average highest frequencies of the six calculated weather conditions at the six weather stations (which are considered to be the average occurrence frequencies of Minnesota) are 1%, 2%, 3%, 4%, 6%, and 9%, respectively. A monthly windstar chart can also be generated if an odor problem in any one specific month is a concern.

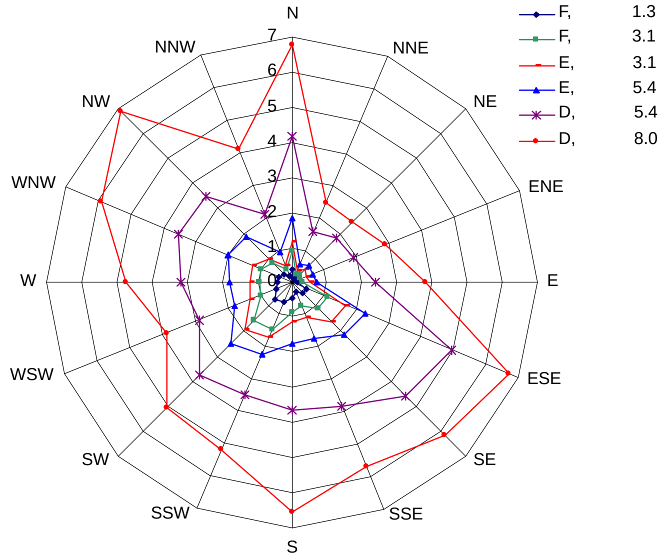

Figure 1. Annual windstar chart for Minneapolis-St. Paul, Minnesota, from 1984-1992 (Jacobson et al., 2000).

CONCLUSIONS

A systematic approach was used to develop a science-based setback determination model, i.e., the OFFSET model for livestock production sites. The model was intended to be based on an evaluated air dispersion model and on the actual odor emissions from livestock production sites. Extensive research on source odor emission and dispersion was conducted to provide data for the model development. From the results of the first part of this study, the following conclusions can be drawn:

- Odor emissions were measured from 280 animal buildings and manure storage units on 85 farms in Minnesota during 1998 to 2001. The geometric means of the measured odor emission rates on a unit area basis for each type of odor sources were obtained to represent odor emissions for different animal housing systems and various manure storage units. The efficiencies of a number of odor control technologies were summarized.
- An air dispersion model, INPUFF-2, was evaluated for short-distance (<0.5 km) odor dispersion prediction using odor plume data collected by trained field assessors on 20 farms. It was also evaluated for long-distance (4.8 km) odor dispersion prediction using odor measurement data obtained by trained resident odor observers living in the vicinity of livestock operations for more than five months. The relationship between odor detection threshold and intensity was obtained for swine and cattle odors in order to convert odor intensity to detection threshold. The result showed that the INPUFF-2 model was capable of simulating downwind odor dispersion from animal production operations for low-intensity odors under stable weather conditions.
- Six stable or neutral weather conditions that favor odor transmision were selected, and their historical occurrence frequencies in all 16 directions at six weather stations in Minnesota and surrounding states from 1984 to 1992 were obtained and presented in a graph called a windstar. The occurrence frequencies of these weather conditions were used to determine odor occurrence frequencies with the OFFSET model.

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