Comparison of four setback models with field odour plume measurement by trained odour sniffers

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*[1]Department of Agricultural and Bioresource Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, Saskatchewan S7N 5A9, Canada; and [2]Department of Biosystems Engineering, University of Manitoba, Winnipeg, Manitoba R3T 5V6, Canada. *Email: huiqing.guo@usask.ca*

Guo, H., Li, Y, Zhang, Q. and Zhou, X. 2006. **Comparison of four setback models with field odour plume measurement by trained odour sniffers.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 6.39 - 6.48. Odour plumes were measured downwind of two swine operations located in a flat area of southern Manitoba by 15 trained human odour sniffers at distances of 100, 500, and 1000 m from the farms. Regression models were derived from the field odour plume measurement data to predict the downwind odour intensity. Four setback distance models that have been used in North America were used to determine the required setback distances for the two farms, i.e., the Ontario MDS-II, Alberta MDS, Purdue, and Minnesota OFFSET models. The results of these setback models and the regression models were then compared. Alberta MDS, Purdue, and Minnesota OFFSET models are considered to be adequate in predicting setback distances as their predicted setbacks fall in the ranges derived by the regression models. The setback distances determined by the Ontario MDS-II model appeared insufficient, and the model could not account for the effect of covering manure storage. Setback distances determined by the OFFSET model for various odour annoyance free frequencies essentially covered the range of distances calculated by the Purdue and Alberta models and by the regression models. Hence, OFFSET is recommended as the preferred setback model. **Keywords:** odour, swine, setback, dispersion, sniffer, model**.**

Les dispersions d'odeurs ont été mesurées par 15 personnes entraînées à la détection d'odeurs à des distances de 100, 500 et 1000 m dans la direction des vents dominants en aval de deux porcheries situées dans une plaine du sud du Manitoba. Des modèles de régression ont été élaborés à partir des données mesurées au champ de la dispersion d'odeurs pour prédire l'intensité des odeurs en aval des vents dominants. Quatre modèles de distances séparatrices qui ont été utilisés en Amérique du Nord ont été utilisés pour déterminer les distances séparatrices requises pour ces deux fermes, soit le modèle MDS-II de l'Ontario, le MDS de l'Alberta, les modèles de distances séparatrices de Purdue et OFFSET du Minnesota. Les résultats obtenus à partir de ces modèles de distances séparatrices ainsi que des modèles de régression ont été comparés. Les modèles MDS d'Alberta, de Purdue et OFFSET du Minnesota peuvent être considérés aptes à prédire les distances séparatrices ; les résultats qu'ils fournissent se trouvant à l'intérieur des plages définies par les modèles de régression. Les distances séparatrices déterminées par le modèle MDS-II de l'Ontario semblaient insuffisantes et le modèle ne pouvait prendre en considération l'effet provenant du recouvrement de la structure d'entreposage du lisier. Les distances séparatrices déterminées par le modèle OFFSET pour les fréquences d'évènement sans nuisance d'odeurs englobaient les plages de distances calculées par les modèles de Purdue et de l'Alberta ainsi que les modèles de régression. Par conséquent, OFFSET est recommandé comme modèle de détermination de distances séparatrices. **Mots clés**: odeur, porc, distance séparatrice, dispersion, détecteur d'odeur, modèle.

INTRODUCTION

Swine production farms in Canada have increased in size over the last decade, and along with this increase the incidents of complaints about the odour emissions from these farms have increased. The downwind odour impact depends on many factors, including odour emission, weather conditions, topography, and odour sensitivity and tolerance of the neighbours. A common practice for reducing the impact of animal odour on the neighbouring communities is to maintain appropriate separation (setback) distance between swine farms and the neighbouring communities. The methods for estimating setback distances are either empirical (experience-based) or dispersion-based.

Some European countries and some states and provinces in North America have developed setback guidelines during the last two decades (Schauberger and Piringer 1997; Klarenbeek and Harreveld 1995; OMAFRA 1995; Lim et al. 2000; Jacobson et al. 2005; Guo et al. 2005). In Europe, the Austrian guideline is a typical model, which considers the most factors (Schauberger and Piringer 1997). It is an empirical model based on an estimation of odour sources using the following parameters: animal number, animal species, housing systems, ventilation systems, handling of manure inside the building, feeding methods, land use, and topography. This model was compared with the Swiss, German, and Dutch models and was found to be different from the others in that it: a) uses the worst-case assumption; b) has a common treatment of different animals and building systems; c) includes the meteorological and topographic effects; d) uses a power function with exponent of 0.25 to determine the interrelation between the source strength and the protection distance, whereas German and Swiss models use 0.33 for the exponent; and e) considers the effect of land use (Schauberger and Piringer 1997).

Williams and Thompson (1986), from the Warren Spring Laboratory in England, measured odour emissions from a number of processes and sources. By collating the odour emissions with data on the spatial extent of odour complaints, an empirical formula, i.e., the W-T model, was derived relating the maximum setback distance from the source. They also used dispersion models to calculate the odour concentrations downwind from the source and found the dispersion modeling approach provided reasonably accurate results as compared with the empirical formula.

A few setback models have been used in North America. For example, the *Minimum Distance Separation Guidelines for Siting Livestock Operations from Residences* (MDS-II) were developed by the Ontario Ministry of Agriculture, Food, and Rural Affairs in 1970s and have been incorporated in land use policies in Ontario, for more than 30 years (OMAFRA 1995). This model determines the setback distance according to the animal species, animal numbers, and manure handling systems. These guidelines were generated with the help of some science-based information, but were primarily experience based in determining setbacks from livestock operations in the province (OMAFRA 1995; MacMillan and Fraser 2003).

The Alberta MDS model is a modified version of the Ontario MDS-II (Anonymous 2002) that has been used in Alberta, Canada since 2002. The minimum separation distance is also empirically determined based on animal species, animal numbers, manure handling systems, and land use.

The Purdue model was developed by researchers at Purdue University for hog operations (Lim et al. 2000). It is an empirical model based on the baseline odour emission data, literature review, and studies of existing setback guidelines, particularly the Austrian (Schauberger and Piringer 1997) and W-T models (Williams and Thompson 1986). Building design and management, and odour abatement factors were introduced to replace the technical factor of the Austrian model. Outdoor manure storage sources were also accounted for in the model.

The Minnesota OFFSET (Odour From Feedlots Setback Estimation Tool) was developed to estimate the setback distance from animal production sites by the University of Minnesota (Jacobson et al. 2005; Guo et al. 2005). The model was based on extensive odour emission measurements and dispersion modeling using historical weather data from Minnesota. The odour emissions for different animal production facilities were estimated using the averages of over 200 animal buildings and manure storage units across Minnesota, which were measured between 1997 and 2001. An air dispersion model was evaluated against field odour plume data and used to estimate the odour concentration downwind from the source. Then the setback distances were determined using the desired odour "annoyance free" frequency. The annoyance free odour intensity level was set at an intensity of 2 (faint odour) on a 0 (no odour) to 5 (very strong odour) intensity scale (ASTM 1999).

Five setback models were compared by Guo et al. (2004) in order to reveal the differences in setback predictions of various models. The models compared include the Austrian, Ontario MDS-II, Purdue, Minnesota OFFSET, and W-T models. The livestock farms used in this study were swine farms of various sizes. The odour emissions were estimated using the OFFSET method. The setback distances generated by different models fell into a wide range, with distances generated by the models varying by a factor of ten. The predicted distances were also compared with very limited field odour measurement and complaint data, i.e., the detection distances found by six trained neighbourhood residents living within 4 km of the six swine farms and the distances between the five neighbors and the nearby swine farms about which the five had complained. Because actual odour emission data were not used and very limited field data were used in the study, further work on the comparison of model predicted distances and actual odour detection distances is needed.

In the current study, downwind odours from two swine farms were measured by a panel of trained human odour sniffers in Manitoba. Four setback models used in North America, i.e., the Ontario MDS, Alberta MDS, Purdue, and Minnesota OFFSET models, were selected and applied to the two swine farms. The objective was to use the field odour plume measurement data to evaluate the accuracy of these commonly used setback models for hog operations.

Table 1. Eight-point odour intensity referencing scale.

Intensity level	n-butanol in water (ppm)	Annoyance
0	0	no odour
1	120	not annoying
2	240	a little annoying
3	480	a little annoying
4	960	annoying
5	1940	annoying
6	3880	very annoying
7	7750	very annoying
8	15500	extremely annoying

MATERIALS and METHODS

Site description

Two 3000-sow farrowing operations (Farms A and B) located in southern Manitoba were selected for this study. Farm A had a two-cell earthen manure storage (EMS) with negative pressure synthetic covers (NPSC) on both cells, whereas Farm B had a single cell, open EMS. Each farm had one building (barn) and the barns on the two farms were identical except that Farm A had an extra quarantine room at the east end of the building. The barns were mechanically ventilated with wall mounted exhaust fans. The manure handling systems on the two farms were the same; both had liquid manure stored in under-floor shallow gutters and then removed to outdoor EMS once a week from the gestation/breeding rooms and once every three weeks from the farrowing rooms. The surroundings of the two farms were similar—mostly flat cropland. There were only one empty house and one farm work site within a 2-km radius around Farm A. There were trees around the northeast corner of the farm area, but no residences within a 2-km radius around Farm B.

Field downwind odour measurement

Fifteen human odour sniffers were selected and trained for conducting field odour measurements (Zhou et al. 2005). The selected sniffers went through a series of six training sessions to use an 8-point ASTM Odour Intensity Reference Scale to quantify the field odour intensity (Table 1) (ASTM 1999). The sniffers "calibrated" their noses using the standard reference n-butanol samples for each session before leaving for the field. A base point was then selected at the edge of the farm and its position was marked using longitude and latitude readings from

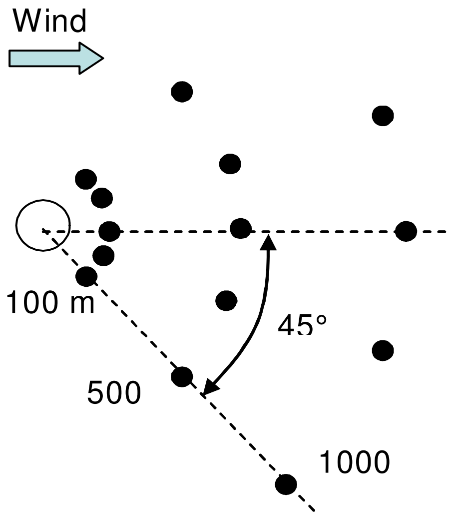

Fig. 1. Field grid (locations) for downwind odour sniffing.

a GPS positioning system. Based on the measured wind direction, 15 sniffers were placed in a three-row grid (Fig. 1) 100, 500, and 1000 m downwind from the base point with the assistance of GPS units (GPS 45, Garmin International, Lenexa, KS). Upon reaching the predetermined grid point, sniffers recorded their exact positions based on the longitude and latitude readings from the GPS units.

Every sniffer carried a two-way radio system to allow them to receive instructions from a central coordinator. Sniffing was timed by the coordinator, i.e., every 10 s the coordinator informed all sniffers to sniff. The duration of a single measurement session was 10 min. To prevent nose fatigue, the sniffers wore carbon filtered masks. They only removed the masks briefly every 10 s to sniff odour. For every sniffing event, the sniffer recorded the odour intensity and odour description on a field data recording sheet. At the end of each 10 -min session, 60 observations had been recorded by each sniffer. A total of three measurement sessions were carried out within one hour, with a 10-min break between sessions. Fifty-one field sessions was conducted around the two farms.

For each field sniffing session, a portable weather station was first set up on-site to determine the wind direction. The weather station was placed 2 m above the ground to collect weather information during the session. Solar radiation, temperature, relative humidity, and wind speed and direction were recorded every minute.

Odour emission measurement

Due to the limited number of samples that could be processed by the olfactometry lab for odour analysis, all rooms in the barn could not be sampled. Based on the production schedule, at least one room was sampled to represent other rooms at the same production stage. For each room, a composite sample was collected by sampling from two or three exhaust fans in the center of the room. Air samples were collected in 10-L Tedlar bags using a vacuum chamber (AC'SCENT Vacuum chamber, St. Croix Sensory, Inc., Stillwater, MN).

To determine the ventilation rate for each room, air velocity was measured with a hot wire anemometer (FloRite 800, Bacharach, Pittsburgh, PA) at five points or more across the radius of each operating fan depending on the fan size in the room. The airflow rate for each fan was estimated from the average air velocity and fan diameter. This is a simplified method based on a standard method of AMCA (1999) that requires four measurement points across one radius for a total of six radiuses. Due to the large number of fans in the barns (90), it was unrealistic to measure 24 points for each fan during the odour plume measurement period; therefore, the air velocity profile across one radius was considered representative for the duct cross-section. The odour emission rate from each room was calculated as the product of measured odour concentration and ventilation rate.

A floating wind tunnel with a similar design to that described by Jiang et al. (1995) was used to collect odour samples from the surface of the open manure storage on Farm B. For the NPSC covered manure storage on Farm A, one composite sample was taken from the exhaust fans on each of the two cells, and the airflow rate from the exhaust fans was measured using the same method as for the building exhaust. The odour emission rate from the NPSC EMS was calculated as the product of odour concentration and the air flow rate of the exhaust fan.

Odour samples were measured for odour concentrations at the Olfactometry Laboratory, University of Manitoba within 24 h. A single-port olfactometer (AC'SCENT, St. Croix Sensory, Inc., Stillwater, MN) with six trained panelists was used for odour concentration measurement. The panelists were selected and re-evaluated periodically following the procedure of CEN (1999). For each olfactometry session, data were retrospectively screened by comparing sniffers' individual threshold estimates with the panel average (CEN 1999).

Setback distance models

Ontario MDS-II model The Ontario MDS-II has separate procedures for buildings and manure storage facilities. The building setback distance is based on the building separation base distance, which is defined as the product of four factors:

$$F = Factor\ A \times Factor\ B \times Factor\ C \times Factor\ D \quad (1)$$

where:

F = building separation base distance (m),

Factor A = tabulated value as a function of the type of animal ranging from 0.65 for broiler chickens to 1.1 for adult mink; *Factor A* = 1.0 for hogs,

Factor B = tabulated value as a function of number of livestock units (LU), ranging from 107 for 5 LU to 1,455 for 10,000 LU; for hog facilities: five sows or boars, 20 nursery pigs, or four feeder hogs are 1 LU,

Factor C = tabulated value as a function of percent increase in animal numbers, ranging from 0.7 for 0 to 50% increase to 1.14 for 700% increase or new facility, and

Factor D = tabulated value as a function of the type of manure system, solid = 0.7 and liquid = 0.8.

The base separation distance *F* is then adjusted by a neighboring land use factor (*Factor E*) to obtain the final separation distance from the barns:

$$SD = F \times Factor\ E \quad (2)$$

where: *SD* = final separation distance (m).

Factor E is 1 for the nearest residence and areas zoned for agriculturally related commercial use, or 2 for the areas zoned for residential, commercial, or urban areas.

The separation distance from manure storage is a tabulated value that is a function of the base building distance F and the type of manure storage system (covered, open solid and runoff, open liquid tank and runoff, or earthen liquid and runoff). The value of the manure storage separation distance in MSD-II varies from a minimum of 40 m to a maximum of 550 m; it takes the same value as the base building separation distance if the base building distance is more than 550 m.

Alberta MDS model For the Alberta MDS model, the minimum separation distance (*MDS*) is determined from the Odour Production (*OP*), Odour Objective (*OB*), Dispersion Factor (*DF*), and Expansion Factor (*EF*) (Anonymous 2002).

$$MDS = OP^{0.365} \times OB \times DF \times EF \tag{3}$$

Odour Production (*OP*) Odour production is measured by Livestock Siting Units (LSU), which are tabulated in the Alberta Standards and Administration Regulation (Anonymous 2002). A number of factors contribute to odour production, including the nuisance value of livestock (*Factor* A_A), technology of production systems (*Factor* B_A), manure production (*MU*), and number of animals.

$$OP = LSU = Factor\ A_A \times Factor\ B_A \times MU\ Reciprocal \times number\ of\ animals \tag{4}$$

MU Reciprocal considers the amount of manure produced by the animal, expressed as 1/Animal Units. Values of *Factor* A_A, *Factor* B_A, and *MU* are tabulated for different livestock categories and types in the Alberta Standards and Administration Regulation (Anonymous 2002).

Odour Objective (*OB*) Odour Objective describes the sensitivity or assumed tolerance level of neighbouring land uses; its values are given as (Anonymous 2002):

Category 1: OB = 41.04 for land zoned for agricultural purposes such as farmsteads, acreage residences, etc.
Category 2: OB = 54.72 for land zoned for non-agricultural purposes such as country residential, rural commercial businesses, etc.
Category 3: OB = 68.40 for land zoned as large scale country residential, high use recreational, or commercial purposes as well as for the urban fringe boundary or land zoned as a rural hamlet, village, or town with an urban fringe.
Category 4: OB = 109.44 for land zoned as rural hamlet, village, or town without an urban fringe.

Dispersion factor (*DF*) The Dispersion Factor allows for a variance to the *MDS* based on unique climatic and topographic influences at the site that are proven to change the dispersion of odour. The standard value is 1.0. There are no specific suggestions for various topographies, screenings, or microclimate.

Expansion factor (*EF*) This factor only applies to expanding operations that are increasing the size of the facility to store more manure or to accommodate more animals.

Purdue model The equation for estimating setback distances has the form:

$$SD = 6.19 F_w LTV\left(A_E E + A_S S\right)^{0.5} \tag{5}$$

where:
F_w = wind frequency factor, 0.75 to 1.00,
L = land use factor, 0.5 to 1.0,
T = topography factor, 0.80 to 1.00,
V = orientation and shape factor, 1.00 to 1.15,
E = building odour emission, $E = N \times P \times B$ (OU/s),
N = number of pigs,
P = odour emission factor (OU/s per pig),
B = building design and management factor, $B = M - D$,
M = manure removal frequency, 0.50 to 1.00,
D = manure dilution factor, 0.00 to 0.20,
S = odour emission from outdoor storage, $S = C \times G$ (OU/s),
C = odour emission factor for outside liquid manure storage (50 OU/s per AU),
G = animal units (AU) (500 kg of pig mass),
A_E = odour abatement factor for buildings, 0.30 to 1.00 (no odour abatement measure), and
A_S = odour abatement factor for outside liquid manure storage, 0.30 to 1.00 (no odour abatement measure).

Minnesota OFFSET model Odour emission is quantified by odour emission numbers for livestock production facilities, and emission reduction by means of various odour control technologies are also accounted for in the model. The total odour emission factor is calculated as (Jacobson et al. 2000):

$$E_t = \sum_{i=1}^{n} E_i = \sum_{i=1}^{n} E_{ei} A_i f_{ci} \tag{6}$$

where:
E_t = total odour emission factor from an animal production site (dimensionless),
E_i = odour emission factor from source i (dimensionless),
E_{ei} = odour emission number per unit area from source i,
A_i = area of source i (m^2),
f_{ci} = odour control factor for source i, ranging from 0.1 to 0.6 for different odour control technologies such as biofilters, various basin covers, and oil sprinkling; f_{ci} = 1 if no odour control technology is used,
n = total number of odour sources, and
i = running index.

The odour emission number E_e for a source may be obtained from tables for various livestock operations and manure storage systems (Jacobson et al. 2005). The tabulated odour emission numbers were based on the measurements from over 200 sources on 80 farms in Minnesota between 1997 and 2001. However, these values may not be valid for other geographic areas (Jacobson et al. 2005). Alternatively, the odour emission factor E_i may be determined from the actual measured odour emission rate as:

$$E_i = KQ_{od} \tag{7}$$

where:
K = scaling factor, and
Q_{od} = odour emission rate (OU/s per m^2).

Table 2. Six typical weather conditions that disadvantage odour dispersion.

Weather condition	Conditions
W1	Stability F: wind speed ≤ 1m/s
W2	Stability F: wind speed 1 - 3 m/s
W3	Stability E: wind speed ≤ 3 m/s
W4	Stability E: wind speed 3 - 5 m/s
W5	Stability D: wind speed ≤ 5 m/s
W6	Stability D: wind speed 5 - 8 m/s

Based on the dispersion simulations, the suggested value for scaling factor K is 35 for building emission and 10 for manure storage (Zhu et al. 2000; Guo et al. 2001).

The total odour emission E_t determined by Eq. 6 is then used in the dispersion model INPUFF-2 to predict downwind odour. Dispersion simulations were conducted for six typical weather conditions W1 to W6 (Table 2) that disadvantage odour dilution, resulting in high odour concentrations at the ground level. Based on the dispersion simulations of odour concentration downwind from the sources, setback distances were determined for W1 to W6 and a correlation between the separation distance and the total odour emission was established:

$$SD = aE^b \tag{8}$$

where: a, b = weather influence factor constants for W1 to W6 (Table 3).

The occurrence frequencies of W1 to W6 were derived from the historical weather data in Minnesota. The odour annoyance free frequency (91 to 99%) in the OFFSET model is defined as the percentage of time when the odour intensity is below the selected annoyance level, i.e. 1 minus the occurrence frequency of the W1 to W6. For the 0-5 odour intensity scale (0 – no odour; 5 – very strong odour, ASTM 1999), the selected odour annoyance free level is 2 (faint odour).

Historical meteorological data

The historical weather data for the exact locations of the two study sites were not available. The two sites were within 50 km of Winnipeg, Manitoba; therefore 15 years of historical weather data (1988 to 2002) for Winnipeg were used in this study. The weather data were analyzed to generate the occurrence frequencies of typical weather conditions for setback distance calculations in the Purdue and Minnesota models.

RESULTS and DISCUSSION

Odour emissions from the hog production facilities

Large variations in odour concentration were observed for the buildings on the two farms (from 300 to 3000 OU/m^3). The average odour level on the two farms ranged from 799 to 1026 OU/m^3 (Table 4). The mean odour emission rate from the farrowing and gestation rooms were 22.7 and 11.6 OU/s per m^2, respectively, on Farm A, and the corresponding values were 23.0 and 7.6 OU/s per m^2 on Farm B.

The average measured emission rate was 22.4 OU/s per m^2 for the open EMS on Farm B. The odour concentration in the covered NPSC EMS on Farm A was much higher than that in the open EMS on Farm B (Table 4). However, because only a small amount of air was exhausted from the NPSC EMS, the odour emission rate was much lower from NPSC EMS in comparison with the open EMS. The average emission rate was 0.7 and 0.2 OU/s per m^2 for the primary and secondary cells, respectively. The total manure surface area in the primary cell was about 40% of that in the secondary cell. Based on the area ratio between the primary and secondary cells, the weighted average emission rate from the entire NPSC EMS was calculated as 0.3 OU/s per m^2. The product of the odour emission rate and the emission area is the odour emission from a source. The total odour emission from Farm A with NPSC EMS was 54% of that from Farm B with uncovered EMS (174,476 vs. 321,190 OU/s).

Table 3. Weather influence factors with various odour annoyance free frequencies for Minnesota.

Weather condition →	W1	W2	W3	W4	W5	W6
Odour annoyance free frequency (%)	99	98	97	96	94	91
a	1.685	0.729	0.446	0.180	0.131	0.051
b	0.513	0.537	0.540	0.584	0.583	0.626

Table 4. Odour concentrations and emission rates from barns and manure storages.

Odour source		Odour concentration (OU/m^3)		Odour emssion (OU/s per m^2)	
		Geometric mean	SD	Geometric mean	SD
Farm A	Farrowing	1026	487	22.7	15.2
	Gestation	927	314	11.6	6.0
	NPSC EMS primary cell	4646	3646	0.7	0.6
	NPCS EMS secondary cell	1991	1568	0.2	0.1
Farm B	Farrowing	899	505	23.0	14.4
	Gestation	799	396	7.6	3.4
	Open EMS	769	356	22.4	25.1

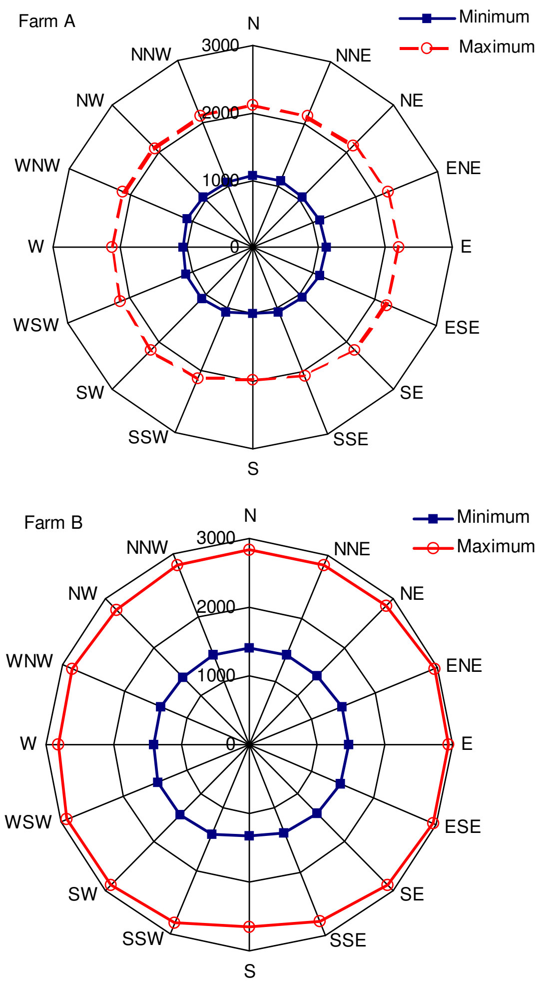

Fig. 2. The closest and farthest setback distances calculated by the Purdue model.

Setback distances predicted by the setback models

Ontario MDS-II model The setback distance from the hog barns of these two farms were the same because the two barns have the same number of animals. For the hog barn, *Factor A* takes a value of 1.0 in the Ontario MDS-II model (Eq. 1). Based on the nominal number of animals on each farm (2600 gestating sows, 400 farrowing sows, and 6 boars), the number of livestock units (LU) was determined to be 602, and *Factor B* was determined to be 611 for both farms. *Factor C* is a tabulated value as a function of percentage of increase in animal numbers and a value of 1.14 was chosen for this study (the farms were considered as new facilities). The manure systems on both farms were liquid systems; therefore, *Factor D* was 0.8. Using these parameter values, the base separation distances (*F*) were determined to be 557 m. The required setback distance from the barns was then adjusted by a neighboring land use factor (*Factor E*), which takes a value of 1.0 for the nearest residence and areas zoned for agriculturally related commercial use, or 2.0 for areas zoned for residential, commercial, or urban areas, which are 557 and 1114 m, respectively. The setback distance remained the same when the manure storage was considered because the Ontario MDS-II model considers the manure storage separation distances the same as the base building separation distance if the base building distance is more than 550 m.

Alberta MDS model *Factor* A_A, *Factor* B_A, and *MU* are 2.0, 1.1, and 0.67, respectively, in the Alberta MDS for farrowing to weaning operations. No specific information is given in the Alberta Standards and Administration Regulation (Anonymous 2002) on selecting the technology *Factor* B_A for EMS covers. In this study, covering the EMS on Farm A resulted in a 46% reduction in the total odour emission; therefore, *Factor* B_A was reduced by 46% from 1.100 to 0.594 in the following calculation. The dispersion factor was assigned a value of 1.0 considering the flat topography of the two study sites. The LSU were 2393 and 4431 for farms A and B, respectively. The setback distances determined by the Alberta MDS Model for the four zoning categories 1 to 4 were 702, 936, 1170, and 1873 m for Farm A, and 879, 1173, 1466, and 2345 m for Farm B, respectively.

Purdue model Wind frequency factor F_w in the Purdue Model was calculated from historical weather data for Winnipeg. Based on the 1988 to 2002 Winnipeg weather data, the wind frequencies in 16 directions from May to September ranged from a low of 3.0% from the east to a high of 12.8% from the south. The corresponding wind frequency factor F_w varied between 0.87 for a south wind to 0.97 for an east wind.

The land use factor *L* ranges from 0.50 for areas that need lower protection from odour to 1.00 for areas that are more vulnerable to odour. In this study, 0.50 and 1.00 were applied in calculations to determine the closest and the farthest setback distances, respectively. The topography factor ranges from 0.80 for area without vegetation, buildings, or other obstacles to 1.00 for an area in a very narrow valley or hillside. Since the two study sites were located in flat areas without obstacles, a land use factor *L* of 0.8 was chosen.

The building length to width ratio (L/W) is used to describe the shape of the encompassing rectangle and a direction is used to give its orientation. Orientation and shape factor *V* in the Purdue model is determined as follows: V= 1.00 for L/W <2; $V = 1.05$ for $2<$L/W<4; $V = 1.10$ for $4<$L/W<8; and $V = 1.15$ for L/W>8 (Lim et al. 2000). The L/W ratio of the two farms in this study ranged from 6.8 to 7.0; therefore, the orientation and shape factor *V* was chosen as 1.10. Terms $A_E E$ and $A_E S$ represent the odour emission rates from buildings and manure storage, respectively. The average odour emission rates measured from buildings and manure storage on the two farms (Table 4) were used in the setback distance calculations.

The setback distances determined by the Purdue model for the two farms are shown in Fig. 2. The average closest and farthest setback distances in the 16 directions for Farm A were 1063 m (ranging from 989 to 1100 m) and 2126 m (ranging from 1978 to 2200 m), respectively. The average closest and farthest setback distances for Farm B were 1420 m (ranging from 1321 to 1470 m in various directions) and 2841 m (ranging from 2643 to 2940 m), respectively.

Minnesota OFFSET model The measured emission rates on the two farms were used in OFFSET to estimate the setback distances. Using the average odour emission rates from the two

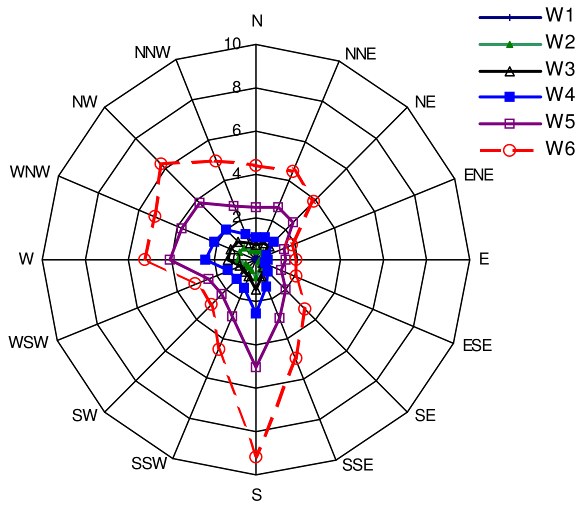

Fig. 3. Windstar of Winnipeg from 1988-2002.

farms in Table 4 and Eqs. 6 and 7, the total odour emission *Factor* E_t was determined to be 6.01×10^6 and 6.44×10^6 for Farms A and B, respectively.

Windstar is a graph that shows the occurrence frequencies of the six weather conditions in all 16 directions for a specific location. Figure 3 shows the windstar of Winnipeg based on 1988-2002 weather data.

The setback distances under the six weather conditions were calculated using Eq. 8 and are presented in Table 5. The odour annoyance free frequencies were determined from the highest occurrence frequencies of each of the six weather conditions. The odour annoyance free frequencies given in Table 5 are the lowest values for the same distances in all directions with the maximum occurrence frequencies of weather conditions W1 to W6, with winds from NW and WNW for W1 (0.05%), S and W for W2 (0.87%), and S for W3 to W6 (1.34 to 9.19%). The odour annoyance free frequencies in all other directions at the six setback distances are higher than these values, which can be determined using Fig. 3.

Setback distances derived from the odour plume measurement data

The majority (68.0%) of the odour plume measurements in the 51 field sessions conducted were taken under atmospheric stability B, followed by stability C (12.9%), E (9.3%), A (6.1%), and D (3.8%). For Farm A, no measurement was taken under stability C and at 100 m under stability D. For Farm B, no measurement was taken for stability D and at 100 m for stability E. No measurement was taken under stability F, which is more stable than the other stability classes.

At each of the three measurement distances, there would be only one sniffer located at or close to the centerline of the odour plume and this sniffer would report the highest average intensity of all five sniffers. This maximum odour intensity of each cross-section was used to develop a relationship between the odour intensity and the distance downwind. The average of these maximum intensities at different distances under various atmospheric stability classes are given in Table 6. The odour intensity generally increased with the increasing weather stability and decreased with the distance from the odour source. Odour intensities downwind of Farm A were generally lower than those of Farm B, but at 1000 m, the downwind odour intensities of the two farms were almost the same. For comparison purposes, Table 6 also gives the average intensities of all sniffers at the same distances, which were much lower than the maximum intensity.

Due to limited data obtained under all the other weather stability classes besides B, all data were pooled together to establish the relationship between the odour intensity and distance (Fig. 4), which can be best represented by a logarithmic relation:

$$I = 10.34 - 1.44\ln(D) \quad \left(r^2 = 0.60\right) \quad \textit{for Farm A} \qquad (9a)$$

$$I = 13.31 - 1.87\ln(D) \quad \left(r^2 = 0.67\right) \quad \textit{for Farm B} \qquad (9b)$$

where:

I = maximum odour intensity reported along each arc, and

D = distance directly downwind from the odour source (m).

In this study, odour intensity level 3 on the 0-8 scale is considered to be odour-annoyance free. Therefore, substituting I = 3 into Eqs. 9a and 9b yields the separation distance for *odour annoyance free* (Table 7). Similarly, substituting I = 0 gives the separation distance for *odour free*. However, the regression equation represents the relationship between the mean odour intensity and the distance. If the regression equation was to be used to predict the odour intensity at a given downwind distance, there would be a 50% probability for the

Table 5. Comparison of measured and modeled setback distances (m).

Farm	Minnesota OFFSET						Purdue		Alberta		Ontario		Measured	
	W1 99.95†	W2 99.1	W3 98.6	W4 97.5	W5 95.0	W6 90.8	Max	Min	Max	Min	Max	Min	O.A.F.+	O.F.++
A	5061	3185	2042	1638	117 3	894	2200 (2126)*	989 (1063)*	1873	702	1114	537	667	5284
B	5244	3305	2120	1705	122 2	933	2940 (2841)*	1321 (1420)*	2345	879	1114	557	926	4528

† frequency (%)
* Mean of 16 directions
\+ O.A.F. = odour anoyance free
++ O.F. = odour free

Table 6. Average measured maximum odour intensity under various stability classes.

Farm	Distance (m)	Average measured maximum odour intensity						Average odour intensity of all sniffers
		Atmospheric stability class					All weather	
		A	B	C	D	E		
A	100	3.1	3.5	3.0	N/A	N/A	3.4 (1.5*)	2.4 (1.6)
	500	0.6	1.3	1.5	N/A	2.3	1.4 (0.7)	0.5 (0.6)
	1000	0.5	0.2	0.4	N/A	0.3	0.3 (0.3)	0.07 (0.2)
	No. of data	9	126	39	N/A	12	186	186
B	100	1.7	5.1	N/A	N/A	4.7	4.7 (2.0)	3.3 (1.9)
	500	2.1	1.8	N/A	2.3	2.5	2.0 (0.9)	0.7 (0.9)
	1000	0.1	0.3	N/A	0.0	0.9	0.3 (0.4)	0.09 (0.3)
	No. of data	9	72	N/A	12	18	111	111

* Numbers in () are standard deviations.

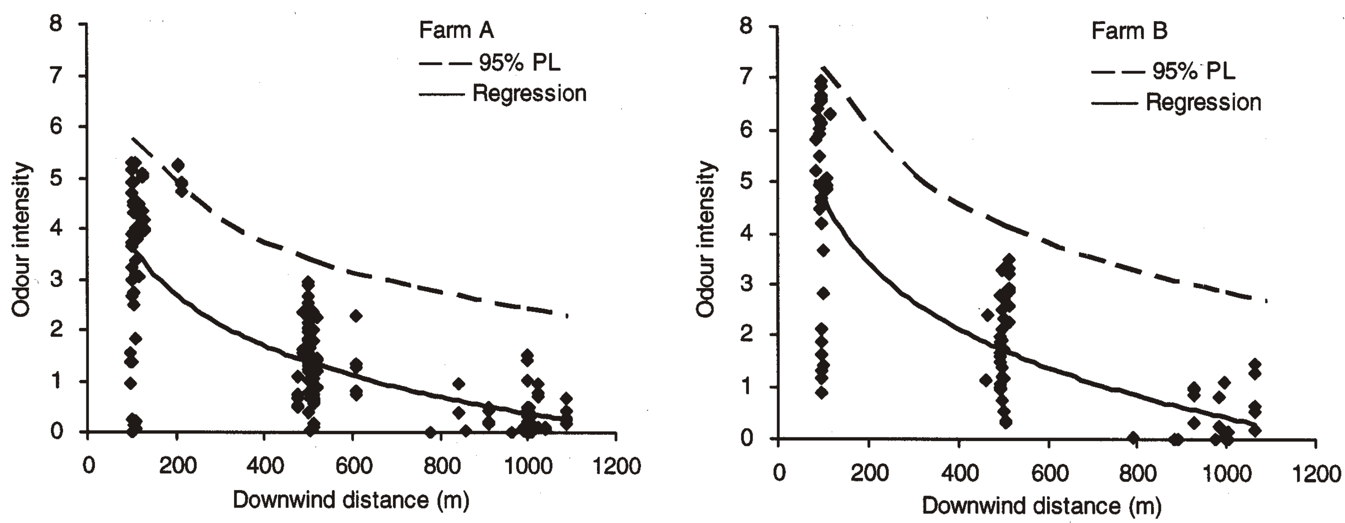

Fig. 4. Variation of odour intensity with downwind distance on two farms.

measured odour intensity to be higher than the predicted values. In other words, if the setback distance was determined from the regression equation, there would a 50% probability that the odour level would exceed the desirable level (intensity 3). A 50% probability is obviously not acceptable in defining the setback distance. To increase the prediction certainty, the upper 95% prediction limit (PL), i.e. 95% of the measured values will be lower than the predicted values, was used to define the relationship between the odour intensity and the distance (Fig. 4). The upper 95% PLs for the two farms are given in Eqs. 10a and 10b, and the setback distances determined with these two equations are summarized in Table 7:

$$I = 12.43 - 1.45\ln(D) \qquad \textit{for Farm A} \qquad (10a)$$

$$I = 15.91 - 1.89\ln(D) \qquad \textit{for Farm B} \qquad (10b)$$

Table 7. Setback distances determined from field odour intensity measurements.

	Setback distance (m)			
	Odour annoyance free (I=3)		Odour free (I=0)	
	Mean	95% PL*	Mean	95% PL
Farm A	164	667	1314	5284
Farm B	248	926	1234	4528

*PL = prediction limit

For equation 9a and 9b, the predicted distance of Farm A is lower than Farm B until the odour intensity reduces to 0.39. When intensity is 0, the odour free distance of Farm A is greater than that of Farm B (Table 7), which obviously is not reasonable considering the higher odour emission from Farm B. Similarly, for Eqs. 10a and 10b, when intensity reduces to 0.96 or lower, the predicted odour free distance is higher for Farm A than that of Farm B (Table 7). Hence, the predicted odour free distances as listed in Table 7 for the two farms should be considered similar. Because Eqs. 9 and 10 and the odour free distances given in Table 7 are obtained from field measurement data within 1000 m, when they are used for distances greater than 1000 m their accuracy may be low and needs to be validated. This study did not conduct measurements beyond 1000 m because most measurements beyond this distance will result in intensity 0 (no odour). An alternative field odour plume measurement method is needed at distances of greater than 1000 m, for example, using resident sniffers to record odour occurrences around their residences.

Comparing setback predictions by setback models and field measurement data

Setback distances determined by the four models and from field measurements are summarized in Table 5. Similar to that which have been reported by Guo et al. (2004), the required setback distances by the four setback models fall in a wide range (557 to 5244 m). The OFFSET model resulted in the widest range of setback distances for different odour annoyance free frequencies. The greatest setback distance determined by the Purdue model was between the values of the Minnesota model for W2 and W3 conditions. The minimal distances determined by the Purdue model were close to those determined by the Minnesota model under W4 and W5 conditions. The Alberta MDS model predicted lower setback distances than the Purdue model, but greater distances than the Ontario model. The maximal setback distance determined with the Alberta model was close to the W3 distance determined by the Minnesota model, and the minimal distance was lower than the lowest distance determined by the Minnesota model for W6. The Ontario MDS model produced the shortest setback distance and its maximal distance (1114 m) was between the Minnesota model W5 and W6 distance requirements.

The measurements conducted in the current study did not include the stable weather condition of stability F and very few data points were obtained under stability E. In other words, the field measurements did not include the worst weather conditions that allow maximum odour travel. Consequently, the setback distances obtained from the field data should be lower than predictions made by the setback models. The measured data for the validation of setback models are not adequate. However, given the fact that the measured data did not cover the worst weather scenarios, the setback distances derived from the data could serve as a lower limit in comparing setback models. In other words, any model that predicted a setback distance less than the measured value would be considered inadequate. Furthermore, the odour free distance derived from the measured data could also serve as a reference to the upper limit of setback distances. The shortest setback distances calculated by both the Minnesota and Purdue models were greater than the odour annoyance free distances derived from the measured data, whereas the minimum distance calculated by the Ontario model was lower than the measured value. Furthermore, the Ontario model could not account for the effect of covering manure storage. The comparison was not conclusive for the Alberta model. The greatest setback distances predicted by all four models were less than the odour free distance derived from the measure data, except the calculation for Farm B under weather condition W1 using the Minnesota model. This is understandable because weather condition W1 is more favorable for odour travel than the weather conditions under which the odour plume measurements were conducted. Hence, the Alberta MDS, Purdue, and Minnesota OFFSET models should be considered to be adequate in predicting setback distances as their predicted setbacks fall in the ranges derived by the field odour plume measurement data.

The setback distance predicted by regression models based on the field odour measurements (Eqs. 11a and 11b) for Farm A was 72% of that for Farm B (667 vs 926 m). Covering EMS had no effect on the required setback distances calculated by the Ontario model. The required distances calculated by the Purdue model for Farm A (covered EMS) were 75% of that for Farm B (open EMS) and 80% by the Alberta model. Covering EMS had little (4%) effect on the required setback distances calculated by the Minnesota OFFSET model. This was due to the low value of the scaling factor K assigned to manure storage emission (see Eq. 7 for the definition of K) when converting emission rates to emission numbers in the OFFSET model. Although the total odour emission from Farm A was 54% of that from Farm B, the emission from building sources on Farm A was 32% higher than that on Farm B. When scaling factors of K=35 for building and K=10 for manure storage are used in OFFSET model, the total emission factor E_t for Farm A was only slightly lower (8%) than that for Farm B. The difference in total emission between Farm A and Farm B was "swamped" by the higher building emission rate on Farm A. The values of the scaling factors may need to be examined using the odour plume data obtained by this study to reflect the reduction in setback by using the NPSC covers.

CONCLUSIONS

Regression models between odour intensity and distance downwind of two swine farms were obtained based on the field odour plume measurement data. The odour annoyance free (intensity of 3) and odour free (intensity of 0) distances were predicted by the regression models. The accuracy of these regression models needs to be validated for distances greater than 1000 m due to lack of field data beyond 1000 m.

Alberta MDS, Purdue, and Minnesota OFFSET models are considered to be adequate in predicting setback distances as their predicted setbacks fall in the ranges predicted by the regression models based on field odour plume measurement data. The setback distances determined by the Ontario MDS-II model appeared insufficient. Furthermore, the Ontario model could not account for the effect of covering manure storage.

Setback distances predicted by the Minnesota OFFSET model for various annoyance free frequencies essentially covered the range of distances predicted by the other models (Purdue and Alberta) and the regression models based on the field odour plume measurements. The Minnesota model predicts the expected odour annoyance free frequencies at various distances; hence the setback distance could be selected based on the desired odour annoyance free requirement. Therefore, the Minnesota OFFSET model is recommended as the preferred setback model. However, it should be cautioned that the Minnesota OFFSET model may require odour emission data and historical weather data, which are not readily available for most areas in Canada. Therefore, the Purdue and Alberta models may be used as alternatives.

The setback distance predicted by the regression models based on the field odour measurements for Farm A with NPSC EMS was 28% lower than that for Farm B with open EMS. Covering the EMS resulted in a 25% reduction in setback distance as predicted by the Purdue model, 20% by the Alberta model, and only 4% by the Minnesota OFFSET model.

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REFERENCES

AMCA. 1999. ANSI/AMCA S tandard 210-99 (ANSI/ ASHRAE Standard 51-1999) *Laboratory methods of testing fans for aerodynamic performance rating*. Arlington Heights, IL: Air Movement and Control Association, Inc.

Anonymous. 2002. *Agricultural Operation Practices Act - Standards and Administration Regulation (AR 267/2001)*. Edmonton, AB: Alberta's Queen Printer.

ASTM. 1999. E 544-75: Standard practices for referencing suprathreshold odor intensity. In *Annual Book of ASTM Standards.* Philadelphia, PA: American Society for Testing and Materials.

CEN. 1999. *Air Quality – Determination of Odour Concentration by Dynamic Olfactometry*. Draft European Standard PrEN 13725. Brussels, Belguim: Comité Européen de Normalisation (CEN).

Guo, H., L.D. Jacobson, D.R. Schmidt and R.E. Nicolai. 2001. Calibrating Inpuff-2 model by resident-panelists for long-distance odor dispersion from animal production sites. *Applied Engineering in Agriculture* 17(6): 859–868.

Guo, H., L.D. Jacobson, D.R. Schmidt, R.E. Nicolai and K.A. Janni. 2004. Comparison of five models for setback distance determination from livestock sites. *Canadian Biosystems Engineering* 46: 6.17-6.25.

Guo, H., L.D. Jacobson, D.R. Schmidt, R.E. Nicolai, J. Zhu, K.A. Janni. 2005. Development of the OFFSET model for determination of odour-annoyance-free setback distance from animal production sites, Part II: Model development and evaluations. *Transactions of ASAE* 48(6): 2269-2276.

Jacobson, L.D., H. Guo, D.R. Schmidt, R.E. Nicolai, J. Zhu and K.A. Janni. 2005. Development of the OFFSET Model for determination of odor-annoyance-free setback distance from animal production sites, Part I: Review and experiment. *Transactions of ASAE* 48(6): 2259-2268.

Jiang K., P.J. Bliss and T.J. Schulz. 1995. The development of a sampling system for determining odour emission rates from areal surfaces: Part: 1. Aerodynamic performance. *Journal of Air and Waste Management Association* 45:917-922.

Klarenbeek, J.V. and T.A. van Harreveld. 1995. On the regulations measurement and abatement of odors emanating from livestock housing in the Netherlands. In *International Livestock Odor Conference*, 16-21. St. Joseph, MI: ASABE.

Lim, T.T., A.J. Heber, J.Q. Ni, R. Grant and A.L. Sutton. 2000. Odor impact distance guideline for swine production systems. In *Proceedings of Odors and VOC Emissions 2000* (CD). Alexandria, VA: Water Environment Federation.

MacMillan, W.R. and H.W. Fraser. 2003. Toward a science based agricultural odour program for Ontario: A comparison of the MDS and OFFSET odour setback systems. In *Proceedings of the Third International Symposium: Air Pollution from Agricultural Operations III*, 336-345. St. Josephs, MI: ASABE.

OMAFRA. 1995. *Minimum Distance Separation (MDS-I and II)*. Toronto, ON: Ontario Ministry of Agriculture, Food, and Rural Affairs.

Schauberger, G. and M. Piringer. 1997. Guideline to assess the protection distance to avoid annoyance by odour sensation caused by livestock husbandry. In *Proceedings of the Fifth International Symposium on Livestock Environment,* 1.170-178. St. Joseph, MI: ASABE.

Williams, M.L. and N. Thompson. 1986. The effects of weather on odour dispersion from livestock buildings and from fields. In *Odour Prevention and Control of Organic Sludge and Livestock Farming*, ed. V.C. Nielsen, J.H. Voorburg and P. L'Hermite, 227-233. London, UK: Elsevier Applied Science Publishers.

Zhang, Q., X.J. Zhou, N. Cicek and M. Tenuta. 2005. Odour and greenhouse gas emission from swine farrowing operations. CSBE/SCGAB Paper No. 05-021. Winnipeg, MB: CSBE/SCGAB.

Zhou, X, Q. Zhang and H. Guo. 2005. Measuring odor plumes in two swine farrowing operations. ASAE Paper No. 054042. St. Joseph, MI: ASABE.

Zhu, J., L.D. Jacobson, D.R. Schmidt and R. Nicolai. 2000. Evaluation of INPUFF-2 model for predicting downwind odours from animal production facilities. *Applied Engineering in Agriculture* 16(2): 159-164.