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Comparison of the Predictions of Four Setback Models with Field Odour Plume Measurement by Trained Odour Sniffers

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Abstract:

Odour plumes were measured downwind of two 3000-sow swine farrowing operations located in southern Manitoba during the summer of 2004. Instantaneous downwind odour dispersion from the two farms was quantified by 15 trained human odour sniffers at distances of 100, 500, and 1000 m from the farms. A total of 51 field measurement sessions were conducted. Four setback distance models that have been used in North America were used to predict the setback distances for the two farms, i.e. Ontario MDS-II model, Alberta MDS model, Purdue model, and Minnesota OFFSET model. The modeled results were compared with the measured downwind odour intensities. Alberta MDS, Purdue, and Minnesota OFFSET models are considered to be adequate in predicting setback distances. The setback distances determined by the Ontario MDS-II model appeared insufficient and it could not account for the effect of covering manure storage. Setback distances predicted by the OFFSET model for various annoyance free frequencies essentially covered the range of distances predicted by the Purdue and Alberta model and the regression models derived from the field odour plume measurement data. The Minnesota OFFSET model is recommended as the preferred setback model. However, it should be cautioned that this model requires odour emission data and historical weather data, which may not readily available for most areas. The Purdue and Alberta models may be used as alternatives.

Key Words: *Odour emission; Odour sniffer, Odour measurement; Swine; Setback distance model*

INTRODUCTION

Swine production farms in Canada have increased in size over the last decade, and along with this increase have come complaints due to odour emissions from the farms. 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 of reducing the impact of livestock odour on the neighbouring communities is to maintain appropriate separation (setback) distance between the swine farm and the neighbouring communities. The methods for estimating setback distances are either empirical (experience-based) or dispersion-based.

Some European countries and some states or 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. 2000). In Europe, the Austrian guideline is one of the typical models that considered the most factors (Schauberger and Piringer 1997). It is an empirical model based on an estimation of odour sources by the following parameters: animal number, animal species, housing systems, ventilation systems, handling of manure inside the building, the feeding methods, land use and topography. This model was compared with the Switzerland, Germany, and Netherlands 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 Germany 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 emissions with data on the spatial extent of odour complaints, an empirical formula, i.e. 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. The *Minimum Distance Separation Guidelines for Siting Livestock Operations from Residences* (MDS-II) was developed by the Ontario Ministry of Agriculture, Food, and Rural Affairs in 1970's and have been incorporated in land use policies in Ontario, Canada for more than 30 years (OMAFRA 1995). The models determine 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 mostly personal experience in determining setbacks from livestock operations in the province (OMAFR, 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, and 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 model (Schauberger and Piringer

1997) and the W-T model (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 University of Minnesota, the U.S.A. (Jacobson et al. 2000). The model was based on extensive odour emission measurements and dispersion modeling with historical weather data of Minnesota. The odour emissions for different animal production facilities were estimated by using the averages of over 200 animal buildings and manure storage units across Minnesota 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 by the desired odour "annoyance free" frequency. Odour intensity level for annoyance free was set at an intensity of 2 (faint odour) on a 0 (no odour) to 5 (very strong odour) intensity scale (ASTM 1999).

Because different setback models have been developed based on different methods, to reveal the differences in setback predictions of various models, five typical setback models were compared by Guo et al. (2004) including the Austrian, Ontario MDS-II, Purdue, Minnesota OFFSET, and W-T models. The livestock farms used in this study were various sized of swine farms. The odour emissions were estimated using OFFSET method. It was found that the setback distances generated by different models fall into a wide range and the difference might be as much as ten times. The predicted distances were also compared with limited field odour measurement and complaint data, i.e., the detection distances by the trained neighborhood residents living within 4 km from the swine farms and the distances between the five neighbors and nearby swine farms that were complaint against by their neighbors. Because actual odour emission data were not used and very limited field data were used in the study, further work on 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, Canada. Four setback models used in North America, i.e. Ontario MDS model, Alberta MDS model, Purdue model, and Minnesota OFFSET model, were selected and applied to the two swine farms. The objective is to use the field odour plume measurement data to evaluate the accuracy of these commonly used setback models for hog operations.

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), whereas Farm B had a single cell, open EMS. Each farm has one barn. 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 system on the two farms were the same, both with liquid manure stored in under-floor shallow gutters and then removed to outdoor EMS once a week from gestation/breading rooms and once every three weeks from 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 north east corner of the farm area, but no residences within a 2-km radius around Farm B.

Selection And Training Of Human Odour Sniffers

Fifteen human odour sniffers were selected and trained. A preliminary screening test was performed for each participant. The standard 8-point referencing n-butanol solutions were used for the screening test (Table 1). This Odour Intensity Reference Scale with n-butanol (in water) was based on the ASTM standards (ASTM 1999). N-butanol solutions were prepared in 45 ml glass bottles with Teflon coated lids. Samples were presented to the participant in a randomly order and the participant was asked to evaluate the samples and place them in the order from the weakest to the strongest odour levels. The inversion (error) value was then calculated and those who scored at 0 or 1 were selected for further training.

Then the selected sniffers went through a series of six training sessions. The focus of these sessions was to train the sniffers in "memorizing" the odour reference scale which they would be using in the field. The following procedure was performed during each of the 6 training sessions. Firstly, each sniffer was provided with a set of eight n-butanol samples, and they sniffed the samples from the weakest to the strongest for several times. In between each sniffing, the sniffers wore carbon filtered masks for 10 to 20 seconds to "rinse" their noses. Secondly, each sniffer was given 3 to 6 coded samples of known intensity (but unknown to the sniffer). They evaluated one sample at a time, assigned an intensity level (1 to 8) to this sample. Those who correctly rated the sample were asked to check with the standard solution bottle of n-butanol and sniff the sample again to reinforce the rating. Sniffers who incorrectly rated the sample had to sniff both the standard and the coded sample to "feel" the difference. After the training, two to three samples of simulated hog odour were presented to sniffers for assessment. Group consensus had to be reached for each of the samples. Each sniffer was allowed for one level off for the wrong identification; otherwise further training had to be conducted.

Field Downwind Odour Measurement

The sniffers "calibrated" their noses using the standard reference n-butanol samples in each session before leaving for the field. For each field sniffing session, a portable weather station was set up on-site first to determine the wind direction. The weather station was placed 2 m above the ground to collect weather information during the field sniffing session. Solar radiation, temperature, relative humidity, and wind speed and direction were recorded every minute.

A base point was then selected at the edge of the farm and its position was marked by the longitude and latitude readings from the GPS positioning system. Based on the measured wind direction, 15 sniffers were placed in a three-row grid (Fig. 1) downwind from the odour sources (farm) with the assistance of GPS. Upon reaching the predetermined grid point, sniffers recorded their exact positions based on the longitude and latitude readings from the GPS.

Every sniffer was carrying a two-way radio system to allow them to receive instructions from a central coordinator. Sniffing was timed by the coordinator, i.e., the coordinator informed all sniffers when to start and then broadcast every 10 s to remind the sniffers to conduct sniffing. The duration of a single measurement session was 10 minutes. To prevent nose fatigue, the sniffers wore the carbon filtered masks. They only removed the masks briefly every 10-second to sniff odour. For every sniffing, the sniffer recorded the odour intensity and odour description on a field data recording sheet. At the end of each 10-minute session, 60 observations were recorded by each sniffer. A total of 3 measurement sessions were carried out within one hour, with a 10-minute break between sessions.

Odour Emission Measurement

Barn emission measurement

Due to the limit of the number of samples that could be handled in the olfactometry lab for odour analysis, taking samples from all rooms in the building was not feasible. 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 at five points across the radius of each running fan in the room with a hot wire anemometer. The airflow rate for each fan was estimated as the product of average air velocity and fan diameter. The odour emission rate from each room was calculated as the product of measured odour concentration and ventilation rate.

Manure storage emission measurement

A floating wind tunnel with similar design of Schmidt et al. (2002) was used to collect odour samples from the surface of the open manure storage on Farm B. The wind tunnel covered a surface area of 0.3 m^2 (0.75 m x 0.4 m). Fresh air was drawn through a carbon filter, and introduced into the sample collection part through a 100 mm diameter PVC duct. Airflow rates were measured inside the duct using a hot wire anemometer and were adjusted if necessary to maintain an air velocity of 0.3 m/s inside the hood over the manure surface (Schmidt et al. 2002). For each sampling session, two odour samples were collected at the outlet of the hood, and one reference sample was collected after the carbon filter using a vacuum chamber and Tedlar bags. The odour emission rate from the EMS was calculated as the product of odour concentration and air flow rate of the wind tunnel.

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 airflow rate from the exhaust fans was measured using the same method as for building exhaust. The odour emission rate from the NPSC EMS was calculated as the product of odour concentration and air flow rate of the exhaust fan.

Odour sample analysis

Odour samples were measured within 24 hours for odour concentrations at the Olfactometry Laboratory, University of Manitoba. A single-port olfactometer (AC'SCENT, St. Croix Sensory, Inc., Stillwater, Minnesota, the U.S.A.) with six trained panelists was used for odour concentration measurement. The triangular forced-choice method was used to present samples to the sniffers, with a 3-s sniff time. 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 separation base distance is defined as the product of the following four factors:

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

where: F = building separation base distance (m)

Factor A = tabulated value as a function of type of animal, ranging from 0.65 for broiler chickens to 1.1 for adult minks. 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

Factor D = tabulated value as a function of 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 (SD) from the barns:

$$SD\ (m) = F \times \text{Factor E} \quad (2)$$

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, and earthen liquid and runoff). The value of manure storage separation distance in MSD-II varies from a minimum of 40 m to a maximum of 550 m, and 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) as follows (Anonymous, 2002):

$$MDS\ (m) = OP^{0.365} \times OB \times DF \times EF \quad (3)$$

Odour Production

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 nuisance value of livestock (Factor A), technology of production systems (Factor B), manure production (MU), and number of animals.

$$OP = LSU = (\text{Factor A}) \times (\text{Factor B}) \times (\text{MU Reciprocal}) \times (\text{No. of Animals}) \qquad (4)$$

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

Odour Objective

Odour Objective describes the sensitivity or assumed tolerance level of neighbouring land uses and its value are given as follows (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 from the urban fringe boundary or land zoned as rural hamlet, village or town which has an urban fringe.

Category 4: OB = 109.44, for land zoned as rural hamlet, village or town without an urban fringe.

Dispersion Factor

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

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 of:

$$SD = 6.19\, F \cdot L \cdot T \cdot V\, (A_E \cdot E + A_S \cdot S)^{0.5} \qquad (5)$$

where: SD = setback distance (m)
F = 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× P× B (OU/s)
N = number of pigs
P = odour emission factor (OU/s-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×G (OU/s)
C = odour emission factor for outside liquid manure storage (50 OU/s-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)
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 various odour control technologies are also accounted in the model. The total odour emission factor is calculated as (Jacobson et al. 2000):

$$E=\sum_{i=1}^{n} E_i=\sum_{i=1}^{n}(E_{ei}\times A_i\times f_{ci}) \tag{6}$$

where: E = 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 biofilter, various basin covers, and oil sprinkling. f_{ci} = 1 if no odour control technology is used
n = total number of odour sources.

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. 2000). 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., 2000). Alternatively, the odour emission factor E_i may be determined from the actual measured odour emission rate as follows:

$$E_i = K\times Q_{od} \tag{7}$$

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

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

The total odour emission E determined by equation 7 is then used in the dispersion model INPUFF-2 to predict downwind odour. Dispersion simulations were conducted for six typical weather conditions (W1 – W6) (Table 2) that disadvantage odour dilution, resulting in high odour concentrations at the ground level. Under the other weather conditions that are less stable than W6, vertical mixing normally would not allow odour to travel for long distance. The occurrence frequencies of these six weather conditions were derived from the historical (1984 to 1992) weather data from six weather stations in Minnesota. Based on the dispersion simulations of odour concentration downwind from the sources, setback distances were determined for the desired odour "annoyance free" frequencies (91 to 99%) and a correlation between the separation distance and the total odour emission was established:

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

where: SD = separation distance (m)
a, b = weather influence factors constants for various odour annoyance free frequency requirements (Table 3).

The odour annoyance free frequency in the Minnesota model is defined as the percentage of time when the odour intensity is below the annoyance level. For the 0-5 odour intensity scale (0- no odour; 5 - very strong odour, ASTM, 1999), the 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 from Winnipeg; therefore, fifteen-year (1988 to 2002) historical weather data 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 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 farrowing and gestation rooms were 22.7 and 11.6 OU/s-m^2, respectively on Farm A, and the corresponding values were 23.0 and 7.6 OU/s-m^2 on Farm B.

The average measured emission rate was 22.4 OU/s-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-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-m^2. The total odour emission from Farm A with NPSC EMS was 54% of that from Farm B with open EMS (17,4476 vs. 32,1190 OU/s).

The 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 amount of animals. For the hog barn, Factor A takes a value of 1.0 in the Ontario MDS-II model (equation 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 to be 611 for both farms. Factor C is a tabulated value as function of percentage of increase in animal numbers and a value of 1.14 was chosen for this study (as new facilities). The manure systems on both farms were liquid system; 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 Ontario MDS-II model does not take account for odour control technologies on manure storages. The setback distance remained the same as the Ontario MSD-II 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, Factor B, and MU are 2.000, 1.100, and 0.670, respectively in the Alberta MDS for farrow to wean operations. No specific information is given in the Alberta Standards and Administration Regulation on selecting the technology Factor B 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 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 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 in the Purdue Model were 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 the lowest of 2.96% from the east to the highest of 12.77% from the south. The correspondent wind frequency factor F varied between 0.872 for south wind to 0.970 for 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, building or other obstacles to 1.00 for area in very narrow valley or hillside. Since the two study sites 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 dour emission rates measured from buildings and manure storage on the two farms (Table 4) were used in setback distance calculations.

The setback distances determined by the Purdue model for 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 farms in Table 4, and equations 6 and 7, the total odour emission factor E 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 the 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 by using equation 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 with the maximum occurrence frequencies of weather conditions W1 to W6, with winds from NW and WNW for W1, S and W for W2, and S for W3 to W6. These are the worst case scenarios for the downwind areas. 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 distance predictions by the odour plume measurement data

A total of 51 field measurement sessions were conducted. The majority of the odour plume measurements (68.0%) were taken under atmospheric stability B, which was 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.

The 15 sniffers were located in three cross-sections transverse to the wind direction and each cross-section had five measurement locations. The distances of three cross-sections were about 100, 500, and 1000 m to the odour source. At each of the three 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 the 5 sniffers. This maximum odour intensity of each cross-section was used to develop a relationship between the odour intensity and the distance (directly 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 increasing of distance from the odour source. Most odour intensities downwind of Farm A were higher than those of Farm B. At distance of 1000 m, odour downwind odour intensities of the two farms were almost the same. For comparison purpose, Table 6 also gave the average intensities of all sniffers at the same distances, which were much lower than the maximum intensity.

Figure 4 also shows all the cross-section maximum data. The relationship between the intensity and the distance was best fit as following:

$$I = k_3 + k_4 \ln(D) \qquad (9)$$

where: I = maximum odour intensity reported at each of the three cross-sections
D = distance directly downwind from the odour source
k_3 and k_4 = constants.

The regression equations for the two farms were obtained as follows:

$$I = 10.34 – 1.44\ln(D) \quad \text{for Farm A} \qquad (10a)$$
$$I = 13.31 – 1.87\ln(D) \quad \text{for Farm B} \qquad (10b)$$

In this study, odour intensity level 3 on the 0-8 scale is considered to be odour-annoyance free. Therefore, substituting I = 3 into equations 10a and 10b yields the separation distance for *odour annoyance free* (Table 7). Similarly, substituting I = 0 would 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 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) was used to define the relationship between the odour intensity and the distance (Fig. 4). The upper 95% PLs for the two farms, determined by using MINITAB (Minitab Inc., State College, PA), are given by equations 11a and 11b, and setback distance determined with these two equations are summarized in Table 7:

$$I = 12.43 – 1.45\ln(D) \quad \text{for Farm A} \qquad (11a)$$
$$I = 15.91 – 1.89\ln(D) \quad \text{for Farm B} \qquad (11b)$$

It should be noted that because the regress equations 10 and 11 were based on the field measurement data, their predictions increase with the decrease of the odour intensity. For equation

10a and 10b, 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 equations 11a and 11b, 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.

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 8. The Minnesota 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 by the Purdue model was close to those by the Minnesota model under W4 and W5 conditions. Alberta MDS predicted lower setback distances than the Purdue model, but greater than the Ontario model. The maximal setback distance determined with the Alberta model was close to the W3 distance by Minnesota model, and the minimal distance was lower than the lowest Minnesota distance 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.

It must be pointed out that 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 odour travel for furthest distances. Consequently, the setback distances obtained from the field data should be lower than predictions by setback models. This also means that it is not adequate to use the measured data for validation of setback models. 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 by the Ontario model was lower than the measured value. 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 Minnesota model for Farm B under weather condition W1. It is understandable because weather condition W1 is more favorable for odour travel than the weather conditions under which the odour plume measurements were conducted.

The setback distance predicted by regression models based on the field odour measurements (equations 11a and b) for Farm A was 72% of that for Farm B (667 vs. 926 m). Covering EMS had no effect on the required setback distances by the Ontario model. The required seatback 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. It appears that covering EMS had little (4%) effect on the required setback distances by the Minnesota model. This was due to the low value of the scaling factor K assigned to manure storage emission (see equation 7 for the definition of K) when converting emission rates to emission numbers in the Minnesota model. The building emission and manure storage emission are not treated equally in the Minnesota model. Zhu et al. (2000) suggested scaling factors of K = 35 for building emission and K=10 for manure storage emission in their dispersion simulations with INPUFF-2, based on which the OFFSET model was developed.

The total odour emission from Farm A was 54% of that from Farm B because of lower emission from the NPSC EMS on Farm A. However, the emission from building sources on Farm A was 32% higher than that on the Farm B. When a high value of scaling factor (K=35) is assigned to building emission and a low value (K=10) to manure storage emission, the total emission factor E for Farm A was only slightly lower (8%) than that for Farm B (6.01×10^6 vs. 6.44×10^6). In other words, the difference in total emission between Farm A and Farm B, which was primarily due to the covered EMS, was "concealed" in the Minnesota model by the higher building emission rate on Farm A because a low scaling factor was assigned to manure storage.

The scaling factor K was used to adjust (minimize) the differences between dispersion simulations and field measurements (Zhu et al. 2000), and its value was determined by comparing model predictions and field measured odour plume intensities. To assess values of the scaling factor K for the two farms in the current study, emission numbers were determined by using tables provided in the user guide for the OFFSET (Jacobson et al. 2000), and the ratio of manure storage emission number to building emission number was calculated. This ratio was 0.8 averaged from the two farms. It should be noted that when using tabulated data for Farm A, the emission number for EMS was first determined without considering the NPSC, and then the emission number was multiplied by a reduction factor of 0.1 (impermeable cover) (Jacobson et al. 2001). The emission number for EMS became negligible (<2%) after applying the reduction factor in comparison with the building emission number for Farm A. To achieve a ratio of 0.8 between building and EMS emission numbers for Farm B when using the measured emission rates to calculate emission numbers, the scaling factor K for EMS had to be increased from 10 to 19 while maintaining K = 35 for building emission, or alternatively decreasing K for the building emission from 35 to 18 while keeping K = 10 for manure storage. It was determined to change K for manure storage because the high degree of uncertainty associated with odour emission measurement for manure storage. Odour emission from the manure surface is highly dependent on the wind speed which is highly variable, but the wind speed is maintained constant (0.3 m/s) when using a wind tunnel to measure odour emission rate. Therefore, scaling the emission rate for EMS in dispersion simulations would be necessary to improve the agreement between model predictions and field measurements. Using K=35 for building emission and K = 19 for manure storage, the total emission number factor was determined to be 6.00×10^6 and 8.23×10^6 for Farms A and B, respectively, and the calculated setback distances are summarized in Table 9. On average, the setback distance for Farm A was 84% of that for Farm B. It should be noted that the 16% difference in setback distance between Farms A and B was due to the reduction caused by NPSC, less the increase due to the higher building emission from Farm A. To remove the effect of building emission from the comparison, setback distances for Farm A were re-calculated by using the building emission rate of Farm B, i.e., assuming that Farm A had the same building emission as Farm B. It was found that the net reduction in setback distance by the NPSC was 28% (Table 9).

CONCLUSION

1. Alberta MDS, Purdue, and Minnesota OFFSET are considered to be adequate in predicting setback distances. The setback distances determined by the Ontario MDS-II mode appeared insufficient. Furthermore, the Ontario model could not account for the effect of covering manure storage.

2. 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 setback distance could be selected based on desired odour annoyance free requirement. Therefore, 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.

3. 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 28% by the Minnesota OFFSET model (after adjusting the odour emission scaling factor for EMS).

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Table 1. Eight-point odour intensity referencing scale (ASTM 1999)

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

Table 2. Six typical weather conditions that disadvantage odour dispersion

W1	Stability F; wind velocity ≤1 m/s
W2	Stability F; wind velocity from 1 to 3 m/s
W3	Stability E; wind speed ≤3 m/s
W4	Stability E; wind speed of from 3 to 5 m/s
W5	Stability D; with wind speed ≤5 m/s
W6	Stability D; with wind speed from 5 to 8 m/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 emission ($OU/s\text{-}m^2$)	
		Geometric mean	Standard deviation	Geometric mean	Standard deviation
Farrowing	Farm A	1026	487	22.7	15.2
	Farm B	899	505	23.0	14.4
Gestation	Farm A	927	314	11.6	6.0
	Farm B	799	396	7.6	3.4
NPSC EMS on Farm A	Primary cell	4646	3646	0.7	0.6
	Secondary Cell	1991	1568	0.2	0.1
Open EMS on Farm B		769	356	22.4	25.1

Table 5. Setback distances calculated by the Minnesota OFFSET model

Weather condition		W1	W2	W3	W4	W5	W6
Maximum occurrence frequency (%) (Wind direction)		0.05 (NW, WNW)	0.87 (S, W)	1.34 (S)	2.51 (S)	5.00 (S)	9.19 (S)
Odour annoyance free frequency (%)		99.95	99.1	98.7	97.5	95.0	90.8
Setback distance (m)	Farm A	5061	3185	2042	1638	1173	894
	Farm B	5244	3305	2120	1705	1222	933

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		
Farm 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
Farm 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

*Standard deviation.

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

Table 8. 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.++
Farm A	5061	3185	2042	1638	1173	894	2200 (2126)*	989 (1063)*	1873	702	1114	557	667	5284
Farm B	5244	3305	2120	1705	1222	933	2940 (2841)*	1321 (1420)*	2345	879	1114	557	926	4528

* Mean of 16 directions; +O.A.F. = odour annoyance free; ++O.F. = odour free

Table 9. Setback distances (m) determined by Minnesota OFFSET model with emission scaling factor K = 35 for buildings and K=19 manure storage

	W1 99.95%	W2 99.1%	W3 98.6%	W4 97.5%	W5 95.0%	W6 90.8%
Farm A	5076	3194	2048	1643	1177	897
Farm B	5924	3755	2410	1959	1403	1083
Farm A*	4410	2757	1766	1400	1003	755

Farm A*: assuming Farm A had the same building emission as Farm B (12,9267 OU/s)

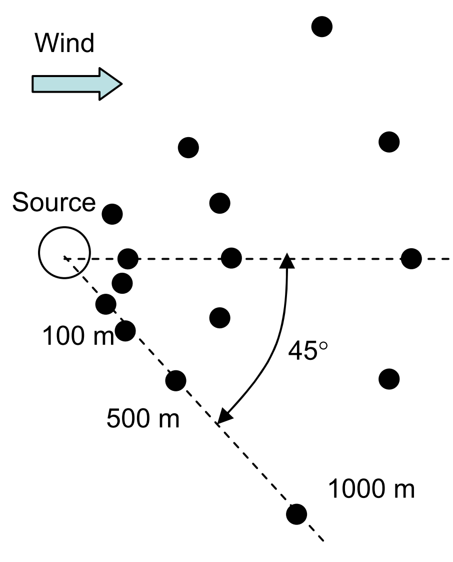


Fig. 1. Field grid (locations) for downwind odour sniffing.

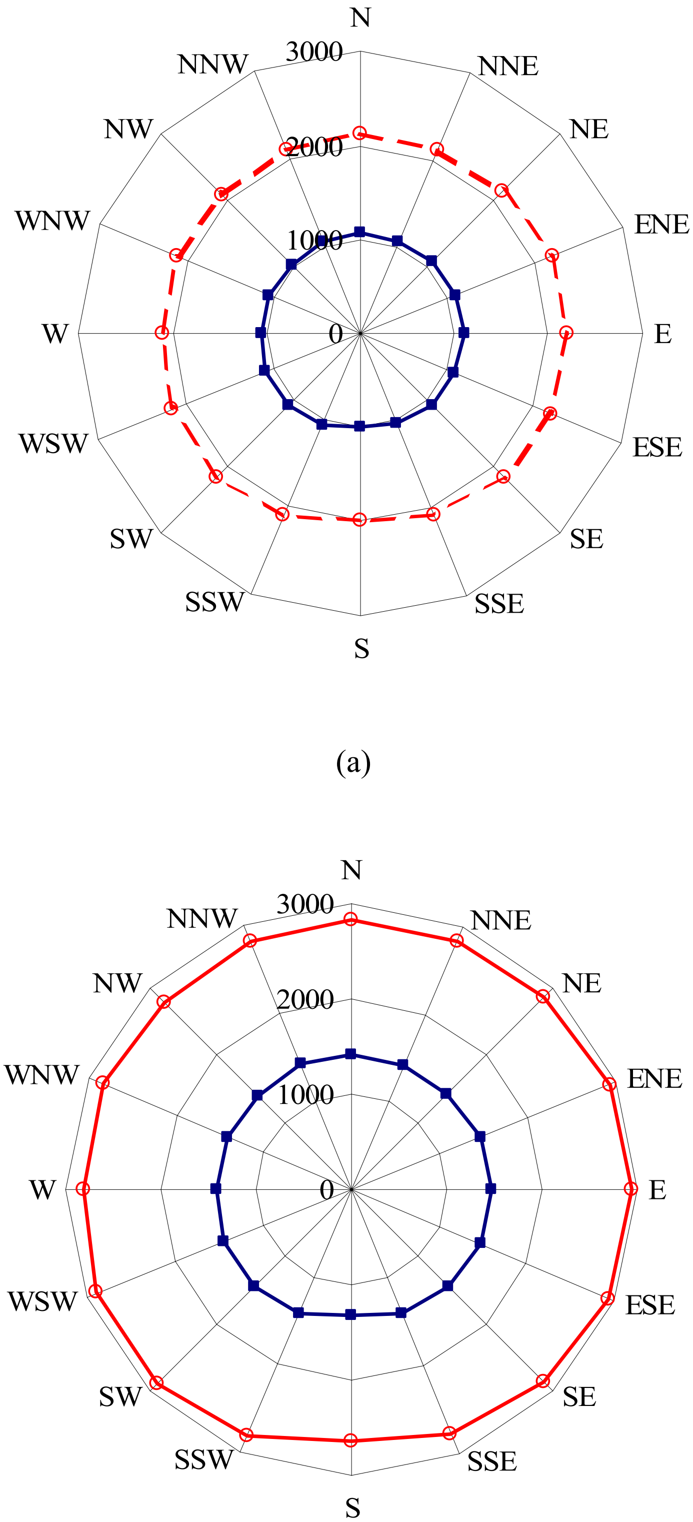


Fig. 2. The closest and the farthest setback distances determined by Purdue model: (a) Farm A; (b) Farm B; —■—, closest distance, m; —O—, farthest distance, m

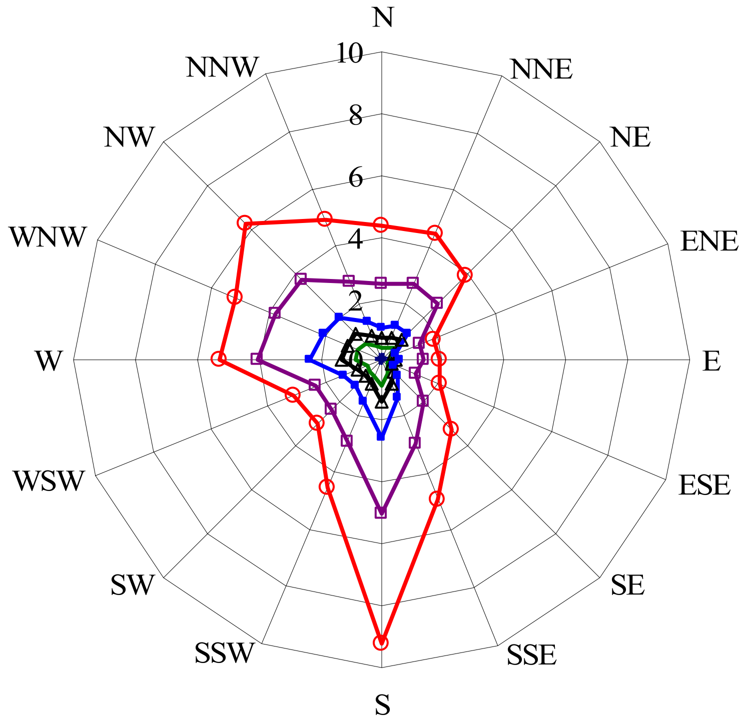
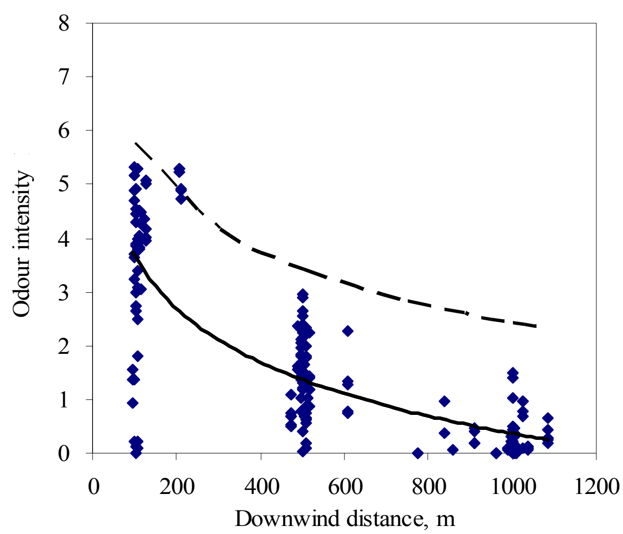
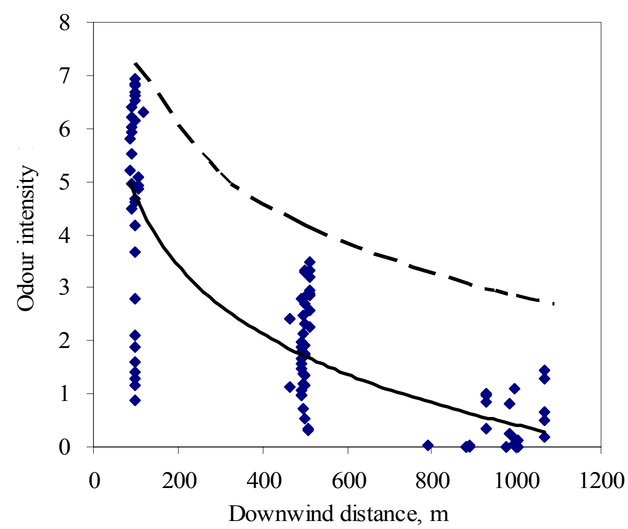


Fig. 3. Windstar of Winnipeg from 1988-2002: ——, W2; —Δ—, W3; —■—, W4; —□—, W5; —O—, W6; frequencies for W1 were close to zero



(a)



(b)

Fig. 4. Variation of odour intensity with downwind distance on two farms: (a) Farm A; (b) Farm B; ♦, measured data; —, regression line; ---, PL 95% line