Effect of natural windbreaks on maximum odour dispersion distance (MODD)

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Lin, X.-J., Barrington, S., Nicell, J. and Choinière, D. 2007. **Effect of natural windbreaks on maximum odour dispersion distance (MODD)**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **49**: 6.21 - 6.32. Because of their frequency and intensity, livestock odour emissions are considered a nuisance often affecting the rural population. Although not extensively studied, windbreaks are said to improve odour dispersion. This paper therefore evaluates in the field, the effect of four natural windbreaks on maximum odour dispersion distance (MODD) and compares to a control site without a windbreak. Odour plumes were measured in the field by three groups of four trained panellists during the release of odours by a generator located 15, 30, and 60 m upwind from the windbreak. In the laboratory, the trained panellists were characterized by asking them to evaluate the hedonic tone (HT) of various n-butanol concentrations. Also in the laboratory, the trained panellists were asked to translate into odour concentration (OC) the HT of various odour samples to produce a regression equation converting field HT observations into OC. The panellists' translation of HT into OC for 72 odour samples produced a statistically significant exponential relationship (P=0.05). Using all and only the maximum OC points observed in the field, MODD for 1 and 2 OU/m^3 were obtained from regression and classification equations. The odour dispersion analyses show that the windbreaks with an optical porosity of 35% reduced MODD by 21 to 40% compared to the site without windbreak (P = 0.05). The best MODD reduction was obtained with a windbreak located 15 m downwind from the odour source, rather than 30 or 60 m and offering an optical porosity of 35 rather than 55%. Conifers were better at reducing MODD than poplars. Finally, higher temperatures and wind speeds favoured shorter MODD in the presence of a windbreak. **Keywords:** windbreak, odour dispersion, optical porosity, wind direction and speed, tree type, separation distance, MODD.

La gestion des fumiers provenant des élevages agricoles dégage souvent des odeurs d'une intensité élevée et nuisante. Quoique l'effet des brise-vent sur la dispersion des odeurs ait rarement fait l'objet d'études, ceux-ci sont fréquemment utilisés pour diluer plus rapidement dans l'atmosphère les odeurs provenant des opérations d'élevage. Le présent ouvrage a évalué au champ, l'effet des brise-vent naturels sur la dispersion des odeurs et sur la distance limite (DL) à respecter de la source d'odeur pour ne pas causer de nuisance. Des plumes de dispersion d'odeur ont été mesurées dans le champ par trois groupes de quatre panélistes d'expérience, lorsqu'une génératrice d'odeurs était en opération à 15, 30 et 60 m en amont de quatre différents brise-vent naturels. Au laboratoire, ces mêmes panélistes furent caractérisés en leur demandant d'évaluer le ton hédonique de différentes concentrations de n-butanol, à l'aide d'un olfactomètre à choix forcé. Ensuite, ces panélistes ont évalué le ton hédonique de diverses concentrations d'odeur pour pouvoir traduire leurs observations au champ en valeur de concentration d'odeur. Cette traduction de la valeur hédonique en valeur de concentration d'odeur a produit une équation de régression statistiquement significative (P = 0.05). En utilisant toutes les valeurs de ton hédonique mesurées dans le champ, ainsi que les plus hautes, des équations de régression et de classification furent produites pour évaluer la DL requise sous différentes conditions atmosphériques et pour les différents brise-vent. Ces équations ont indiquées que les brise-vent dont la porosité optique était de 35% dispersaient mieux les odeurs (MODD moindre) que ceux dont la porosité était de 55%. Une meilleure dispersion était obtenue lorsque la génératrice d'odeur se situait à 15 m en amont du brise-vent, comparativement à 30 et 60 m. Les brise-vent de conifères ont mieux performés que ceux constitués d'arbres toujours verts. Finalement, des températures et des vents élevés ont favorisé la dispersion des odeurs en présence de brise-vent naturels, comparativement à de basses valeurs.

INTRODUCTION

Air quality in rural communities could be greatly improved if practical methods were introduced to attenuate odour emissions from confinement livestock operations. These odours are mainly produced during the handling of manures, from building ventilation, from storages, and during land spreading. Since there are no technologies which can completely eliminate these odours, livestock operations and environmental authorities use air dilution as a remediation measure. The concept consists of distancing the livestock operation from neighbouring sites, such that ambient climatic conditions can dilute the emitted odours to an acceptable level before reaching critical points. Such distances separating the livestock building from neighbouring sites are called "set back" or "separation" distances. Most Canadian provinces, USA states, and European countries have adopted a method of calculating setback distances based on climatic conditions, topography, and practices used by local livestock operations. Among other options, this method allows for the introduction of correction factors accounting for the use of odour controlling technologies.

Known to affect air currents and improve air mixing, natural windbreaks can reduce separation or setback distances between livestock operations and their neighbours. Natural windbreaks are plantings of single or multiple rows of trees or shrubs used to reduce and redirect wind (Eimern et al. 1964). While diverting an approaching air mass upwards, windbreaks form a zone of lower air speed on their downwind side (Heisler and Dewalle 1988; McNaughton 1988). This function is widely used

Table 1. Experimental windbreak found on each site.

Description	Site			
	1	2	3	4
Tree type	poplar	mixed mature deciduous	conifers	conifers
Windbreak				
length (m)	2100	1050	405	380
height (m)	18.3	9.2	7.6	15.2
depth (m)		7		6
optical density (%)	55	35	55	35
Porosity at base (%)	70	30	70	40
Location*	Sherrington	St. Chrysostome	St. Amable	St. Charles

* All locations are located within 50 km of the Island of Montreal, Quebec in the southwest direction.

to provide many benefits such as snow control, sand drifting control, better wildlife habitat, and an enhanced farmstead environment. Most importantly, windbreaks have the potential to dilute odours (Bottcher et al. 2001; Leuty 2003, 2004; Tyndall and Collettii 2000). When planted around livestock facilities, a windbreak can dilute odours entering its leeward mixing zone where strong wind shearing forces are developed. Therefore, windbreaks can potentially reduce the setback or separation distance required to reduce odours to an acceptable level. The distance required to dilute odours below their threshold level is often referred to as the "maximum odour dispersion distance" (MODD).

The objective of this paper was to compare the MODD required for sites with and without natural windbreak and to measure the effect of various windbreak properties and climatic conditions on MODD. In calculating setback distances, the resulting analysis provides information pertaining to the value of the reduction factor applicable in the presence of windbreaks.

MATERIALS and METHODS

Sites and windbreaks

Four uniform single row windbreaks were selected at least 5 km from any livestock operation and free from the interference of odour sources. The four windbreaks offered different properties (Table 1). On sites 1 and 3, the windbreaks offered an optical porosity of 55% and on sites 2 and 4, the windbreaks offered an optical porosity of 35%. The porosity of each windbreak was optically evaluated by measuring the percentage of open surface visible through the windbreak (Guan et al. 2003; Heisler and Dewalle 1988).

Also, the four windbreaks consisted of different types of trees. Poplars and mixed mature deciduous trees were on sites 1 and 2 and evergreens on sites 3 and 4. Tree height varied among windbreaks. Sites 1 and 4 offered windbreaks with a height exceeding 15 m, compared to sites 2 and 3 offering windbreaks with a height under 10 m. A control site without windbreak was selected to also observe odour dispersion.

All sites were located on farm land southwest of Montreal, Quebec with a relatively flat and consistent slope of 0.1% and without trees or fences, where a cereal crop had been freshly harvested.

Experimental equipment

A mobile odour generator (Fig. 1) was used as a point odour source to carry out the tests away from any infrastructure capable of interfering with the results. During the tests, the odour generator was positioned upwind from the windbreak, at a distance of 15, 30, and 60 m (Fig. 2). Fully described by Lin et al. (2006), this odour generator used swine manure to generate the odorous air. At the start of each new day of testing, the odour generator tank was filled with fresh swine manure and therefore, the level of odour generation changed with test day. Because the odour emission dropped with time, morning testing never exceeded 2 h to limit to 30% the drop in odour emission. At 30-min intervals during each test, an air sample was collected from the outlet of the odour generator using Alinfan® sampling bags. The threshold dilution value of each air sample was determined in the laboratory using a forced choice dynamic olfactometer and the same 12 panellists who observed the field odour plume distribution. Odour threshold was defined as the largest number of dilutions causing half of the panellists to detect or recognize an odour (ASHRAE 2003). Odour concentration was expressed according to the European practices, as "odour units per cubic meter" (OU/m^3) (CEN 2001; Schaumberg et al. 2002; Zhang et al. 2002).

To measure wind speed and direction and air temperature without disturbance during each test, a weather station (Davis Weather Wizard III, Davis Inotek Instruments, Baltimore, MD) equipped with a portable PC as data logger was installed on a tower, 7.6 m in height, and some 200 m upwind from the windbreak. During the entire span of all tests, the temperature and wind direction and speed were recorded at one-minute intervals. The air stability conditions were obtained from the closest weather station, that of the Pierre Elliot Trudeau airport, in Dorval, Quebec.

Fig. 1. The experimental odour generator.

Fig. 2. The experimental windbreaks with the odour generator in position to run the tests.

The McGill University triangular forced-choice dynamic olfactometer used in this experiment was fully automated and capable of analyzing four contaminated air samples in 20 minutes, using two sets of six panellists (Choinière and Barrington 1998).

Panellists

Panellists were selected and trained for the field and laboratory olfactory work according to the European Odour Standard (CEN 2001). Before starting the experiment, a group of 20 panellists was selected by requiring them to detect n-butanol within a concentration of 20 to 80 ppb. Using the dynamic olfactometer, these panellists were then further selected by requiring them to correlate statistically (P=0.05) the hedonic tone and odour concentration of four odorous air samples presented at different concentrations (Fig. 3). The selection and training of 20 panellists, when only 12 were used during the field measurements, provided replacements to conduct the test during the experimental days.

For each test day, all 12 panellists were calibrated once more by measuring their individual n-butanol detection threshold, which had to respect 20 to 80 ppb (CEN 2001; Choinière and Barrington 1998; Edeogu et al. 2001). For the n-butanol calibration, a clean air sample with 32,905 ppb of n-butanol at 20°C, was prepared by injecting 5 µL of n-butanol into an Alinfan® bag previously filled with 40 L of air cleaned using an active carbon filter. Panellists were required to detect the n-butanol sample within a dilution factor of 411 to 1645 (80 to 20 ppb).

For the panellist field observations, hedonic tone (HT) was selected as odour sensation attribute because it refers to the degree of pleasant or unpleasant odour perception. The HT scale used in this project ranged from -10 to 0, where 0 to -2 was tolerable, -2 to -4 was unpleasant, -4 to -6 was very unpleasant, -6 to -8 was terrible and -8 to -10 was intolerable (Nimmermark 2006; Parker et al. 2005; Lim et al. 2001). In the laboratory and using the olfactometer, the selected panellists were further rated by being asked to subjectively assess HT of an n-butanol air sample (32,905 ppb of n-butanol at 20°C) presented at various dilution levels. Each level of n-butanol was randomly presented three times to each panellist (Table 2).

Test procedure

Odour plume evaluation was initiated some 15 min after starting the odour generator and the weather station recordings. Three groups of four (3×4=12) trained panellists detected the odour

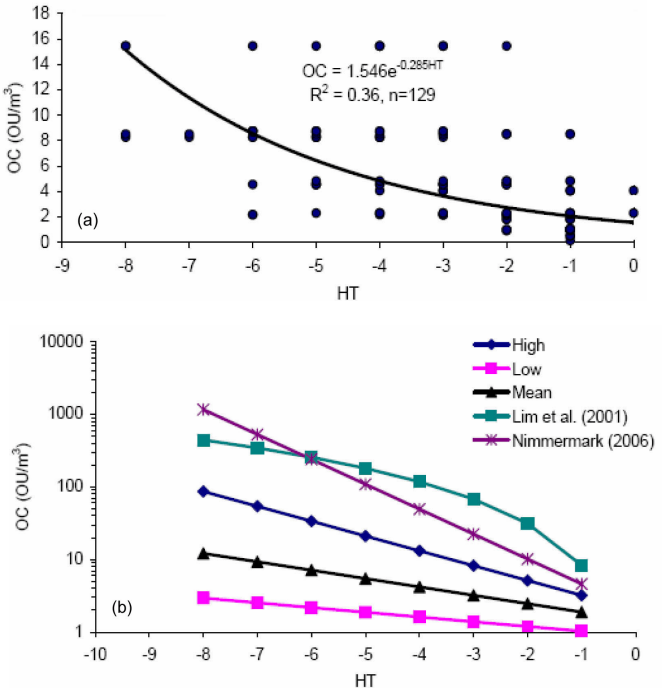

Fig. 3. Typical relationship between hedonic tone (HT) and odour concentration (OC) of an odorous air sample: (a) for a group of four panellists (tests 3 and 4); (b) data collected by Lim et al. (2001) and Nimmermark (2006) compared to that of the present project for the low, mean, and high curves.

plume developing downwind from a windbreak by moving about a random path predetermined from the wind direction and covering the odour plume zone. At each randomly designated observation station along this path, the group would stop walking, remove their carbon filter air masks, face the odour generator, and evaluate the odour hedonic tone during 60 s using the previously described scale of -10 to 0. Each field odour hedonic tone observation by individual panellists was recorded along with their GPS position and the actual time of reading. The odour hedonic tone observed at an odour reading station was the average of the four panellists' readings. The groups of panellists moved from one station to the next while wearing face masks.

At 30-min intervals, and while the panellists were observing each odour plume, a vacuum lung box was used to fill Alinfan® bags with 40 L of odorous air at the outlet of the odour generator, within a 3-min period. During each test day, the air velocity and therefore flow was also verified at eight points over the surface of the generator outlet using an Alnor anemometer (Alnor 8570, TSI Inc., Shoreview, MN).

After observing two field odour plumes during the morning of each test day, the 12 panellists went to the olfactometry laboratory in the afternoon to assess the odour concentration of each generator air sample according to the ASTM E679-91 Standard (ASTM 1997) and the CEN prEN13725 Standard (CEN 2000). The threshold dilution value of each odour sample was established by the 12 panellists exposed to a decreasing number of dilutions. The odour concentration of each air sample

Table 2. Panellist evaluation of hedonic tone versus n-butanol concentration.

Hedonic tone	Average n-butanol level (ppb)	Range of n-butanol level (ppb)
0	59	0 - 69
-1	80	69 - 93
-2	109	93 - 127
-3	149	127 - 174
-4	204	174 - 238
-5	278	238 - 325
-6	380	325 - 444
-7	519	444 - 607
-8	709	607 - 828
-9	968	828 - 1131
-10	1322	>1131

was calculated using the principle of geometric mean (ASTM 1990, 1997, 1998; CEN 1995a, 1995b, 2001).

Some 39 odour plumes were observed, generally two per morning, to evaluate the performance of the four windbreaks and the control site (without a windbreak). Some two to three tests were conducted for each of the three odour generator positions (15, 30, and 60 m upwind from the windbreak) and five windbreak sites including the control. These tests offered variable climatic conditions with high and low temperatures and wind speeds and with wind angles varying from 0 to 90° with respect to the windbreak (Table 3).

Standardizing the resulting odour plumes and computing MODD

During each test, the odour generator emitted a slowly decreasing odour level and, from one test to another, the odour level varied. Each odour plume was therefore standardized for purposes of comparison. Thus, the odour concentration measured at every station by each group of panellists, at a given period in time, was divided by the odour concentration of the generator at that time, and multiplied by the average odour level of 472 OU/m^3 calculated from all 39 tests.

The maximum odour dispersion distance (MODD) is impacted by criteria such as odour concentration, where a lower odour criterion will result in longer MODD. The criteria are generally determined by government regulations and, in the present paper, were set at 1 and 2 OU/m^3, where 1 OU/m^3 implies that half of the population can detect the odour.

Statistical analysis

Before conducting the statistical tests, a series of regression analyses were conducted to establish that the exponential function best described the relationship between the radial distance from the source and OC. This regression equation produced MODDs corresponding to 1 and 2 OU/m^3.

During all tests, the odour plume observed presented zones of high OC separated by zones of lower and sometimes no OC, rather than a uniform zone with a continuously descending OC with distance downwind from the source (Lin et al. 2006). Nevertheless, the OC of these maximum zones decreased with radial distance from the source. Therefore, for each odour plume, two regression equations and MODD values were produced, one obtained from all the data points representing an

Table 3. Test conditions for the sites.

Test number	Site	Date (2003)	Test conditions*					
			OG (m)	OE (OU/s)	WS (m/s)	Angle (°)	T (°C)	AS
1	1	Aug 29	15	621	6.4	90	19	B
2	1	Aug 29	30	760	6.0	90	20	D
3	1	Sept 2	30	859	2.5	50	17	C
4	1	Sept 2	60	551	2.5	50	20	C
5	2	Sept 3	30	1373	3.0	90	21	B
6	2	Sept 3	60	492	4.4	90	23	C
7	2	Sept 5	15	578	4.7	40	18	D
8	2	Sept 5	30	585	4.2	40	19	D
9	2	Sept 8	15	214	1.0	60	22	B
10	2	Sept 8	60	218	1.1	70	20	B
11	2	Sept 10	15	5360	1.2	30	22	C
12	2	Sept 10	30	1096	2.7	20	27	D
13	2	Sept 12	15	559	1.2	50	23	B
14	2	Sept 12	60	294	1.0	40	26	B
15	2	Sept 15	15	744	5.1	90	28	D
16	2	Sept 15	30	745	1.5	90	23	D
17	2	Sept 18	15	1879	1.5	40	24	C
18	2	Sept 18	60	13052	1.4	50	21	B
19	2	Sept 18	60	846	2.2	60	26	B
20	3	Sept 29	15	318	1.8	80	13	C
21	3	Sept 29	49	368	1.7	70	14	B
22	4	Dec 03	15	1339	4.1	60	-2	D
23	4	Dec 03	30	690	3.5	60	-4	D
24	4	Dec 03	60	208	2.6	50	-4	D
25	4	Dec 10	15	166	1.3	70	-2	D
26	4	Dec 10	15	148	1.9	70	-2	D
27	4	Dec 10	30	101	1.7	60	-2	D
28	4	Dec 13	30	111	0.0	60	-8	D
29	4	Dec 13	60	175	2.1	50	-6	D
30	4	Dec 13	60	79	1.4	50	-9	D
31	4	Dec 14	15	205	3.1	70	-8	D
32	4	Dec 14	30	394	3.3	60	-8	D
33	4	Dec 14	30	350	3.0	80	-8	D
34	2	Sept 09	197	166	1.2	0	18	C
35	4	Dec 09	191	102	0.3	57	-2	B
36	4	Dec 09	318	99	0.4	0	-3	C
37	5	Aug 21	NW	766	4.1	NW	28	C
38	5	Aug 21	NW	480	3.6	NW	26	C
39	5	Aug 22	NW	310	6.1	NW	26	D

* OG = odour generator distance upwind from the windbreak; OE = average odour emission during the test; WS = average wind speed; Angle = angle between the windbreak and the wind, 90° being perpendicular; T = average temperature measured during the test; AS = Pasquill-Gifford atmospheric stability condition; NW = no windbreak.

MODD computed from an average OC regression and one obtained from peak values representing an MODD computed from the maximum OC regression.

Based on the data available, two statistical tests were conducted. The first tested whether or not the windbreaks had a significant effect on MODD, as compared to the control site without a windbreak. The second verified the effect of the windbreak and climatic parameter on odour concentration (OC) with radial distance from the source, namely, the odour generator.

To determine the effect of the windbreak on MODD, sites 2 and 5 with a windbreak were compared to the control site without a windbreak. For each treatment, OC measured and its radial distance from the source were considered the two main factors. A covariance model (Eq. 1) was used to combine the regression and classification models (Cue 2006; SAS 2001).

$$\ln OC_{ij} = \mu + site_i + b_i x_{ij} + e_{ij} \quad (1)$$

where:

- OC_{ij} = OC at jth odour point for ith site (OU/m^3),
- i = 1 for site without a windbreak; and 2 for site with a windbreak,
- μ = effect of the overall mean,
- $site_i$ = fixed effect of ith site on OC,
- b_1 = regression effect of OC,
- x_{ij} = odour dispersion distance on jth odour point in ith site, and
- e_{ij} = random residual error of OC associated with jth odour point on ith site.

To measure the effect of windbreak properties (porosity and tree type) and climate (temperature, wind speed and velocity) on OC, case comparisons were conducted because of the difficulty in collecting, in the field, data related to specifically one factor. Therefore, similar tests were selected and all measured odour points were used to produce a regression equation comparing one factor. The sets of field conditions compared did not always provide conditions for an ideal comparison, but represented the best comparison possible, given all 39 field tests. For example, between sites compared, wind speed may be different, while all other parameters (temperature, wind direction, windbreak species and porosity) were similar but not equal.

RESULTS

The panellists used to conduct the experiment are described in Fig. 3 presenting a relationship between hedonic tone (HT) and odour concentration (OC), and in Table 2 presenting a relationship between n-butanol rating and HT.

Odour dispersion distance reflected by MODD is most likely affected by the presence of a windbreak, its porosity and tree species, the location of the odour generator, and ambient climatic conditions. These effects on MODDs are compared in Figs. 4 to 10 illustrating OC as a function of radial distance down wind from the source. In all cases, two regression equations are presented, both for all the data points and for the

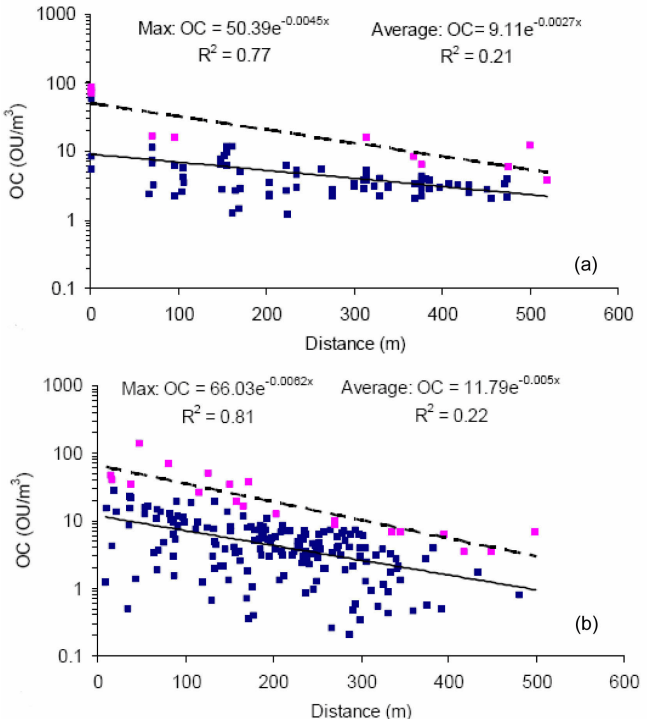

Fig. 4. Odour concentration with distance from the source, for sites: (a) without a windbreak (tests 37, 38 and 39); (b) with a windbreak (tests 5, 6, 8, 9, 10, 11, 13, 14, 15, 16, 17 and 19). The odour generator was located 15, 30 and 60 m upwind from the windbreak. The dotted line is the correlation for the maximum data (peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

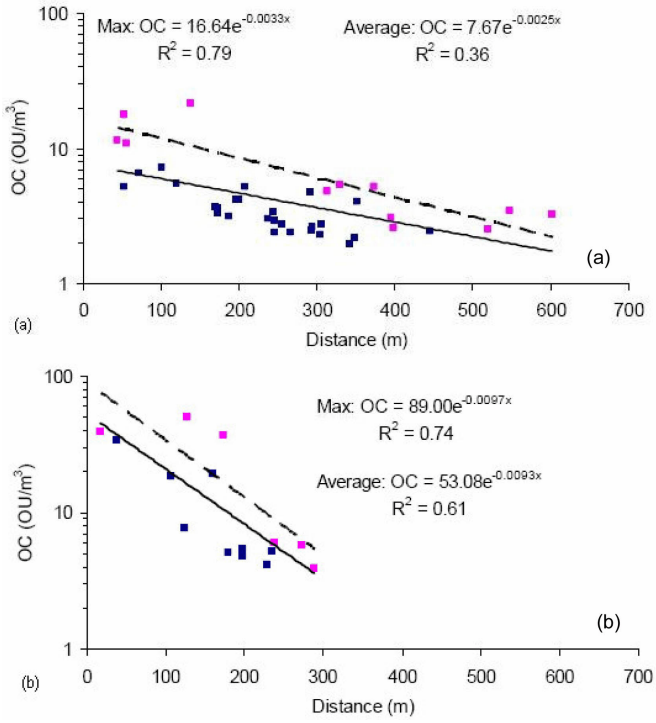

Fig. 5. Effect of windbreak porosity on odour dispersion with distance, for windbreak porosity of: (a) 55% (test 2 and 3); (b) 35% (test 16). In both cases, the odour generator is 30 m away from the windbreak. The dotted line is the correlation for the maximum data (the peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

maximum data points for MODD criteria of 1 and 2 OU/m^3 (Table 4). In Figs. 4 to 10 and despite low R^2 values especially for the average OC regression, both the average and maximum regression lines are presented because the equations are statistically significant (P = 0.05). For example, the R^2 of the average regression line in Fig. 9 is 0.14 (48 pairs of data), but the F-test interpreting OC drop with distance is statistically significant (P = 0.01).

Characterization of the panellists

The typical relationship between *HT* and *OC* for an odorous air sample, as perceived by one group of panellists (tests 3 and 4) is shown in Fig. 3a. A certain degree of variation was obtained despite the training and selection of the panellists.

For 129 comparisons conducted by all groups of panellists, the relationship obtained between *HT* and *OC* was:

$$OC = 1.546 \exp\left(-0.285 HT\right) \quad (2)$$

where *HT* ranges from 0 to -10. Equation 2 was found to be statistically significant (P = 0.01) meaning that HT can explain variation in *OC*.

The assessment of the 72 odour samples collected at the odour generator on the 18 different test days produced 54 regression lines in the form of Eq. 2. Each line represents the average assessment of a group of four panellists on a given test day. Out of 54, 51 lines produced a statistically significant regression equation (P=0.05); one group associated with tests 22, 23, and 24 did not produce a statistically significant regression equation at the P=0.05 level. Figure 3b shows the range of the 51 lines, where the low, high and average values are, respectively:

$$OC = 0.885 \exp\left(-0.150 HT\right) \quad \text{low} \quad (3)$$

$$OC = 2.008 \exp\left(-0.470 HT\right) \quad \text{high} \quad (4)$$

$$OC = 1.445 \exp\left(-0.266 HT\right) \quad \text{mean} \quad (5)$$

In Fig. 3b, the relationship between *HT* and *OC*, obtained in this project, is compared to that of other projects:

$$HT = -0.33 OC^{0.523} \quad \text{(Lim et al. 2001)} \quad (6)$$

$$HT = 0.933 - 2.91 \log_{10} OC \quad \text{(Nimmermark 2006)} \quad (7)$$

Because the lines obtained by Lim et al. (2001) and Nimmermark (2006) stand above those of the present work (Fig. 3), the panellists selected for the present field and laboratory work were found to be more sensitive to odours. In fact, Lim et al. (2001) report a panellist n-butanol detection threshold of 865 ppb which is 22 times higher than the CEN standard of 40 ppb. Nimmermark (2006) reports a panellist n-butanol detection threshold identical to that used in this project

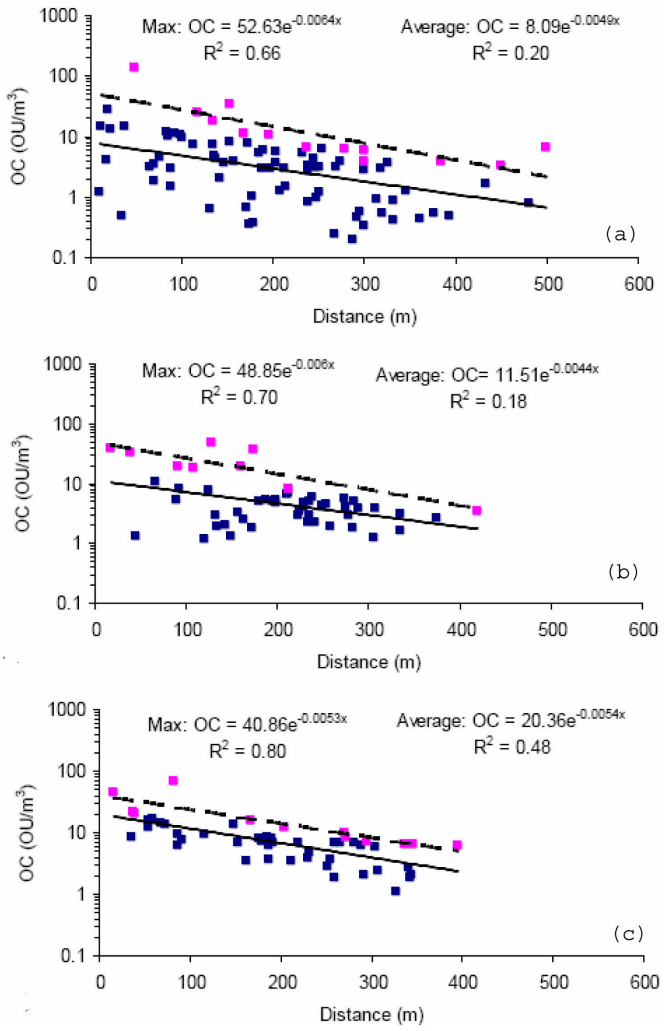

Fig. 6. Effect of odour generator location upwind from a windbreak: (a) 15m (test 9, 11, 13, 15, and 17); (b) 30m (test 5, 8, and 16), and; (c) 60m (tests 6, 10, 14 and 19). The dotted line is the correlation for the maximum data (the peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

(20 to 80 ppb detection threshold) but for OC above the threshold, the panellists used on the present experiment were more sensitive reporting a higher HT as compared to the panellists used by Nimmermark (2006). This increased sensitivity to odours may result from a more rigorous training method or the exposure of the panellists to a different every day cultural context.

Effect of the windbreak

The data measured on site 5 (tests 37, 38, and 39 - Table 3) with 84 odour points and on site 2 (tests 5, 6, 8, 9, 10, 11, 13, 14, 15, 16, 17, and 19 - Table 3) with 189 odour points were used in Eq. 1 to conduct an analysis of variance (Table 5). The F-test results for the model, the mean, the model over and above the mean, the sites and b_1 (Eq. 1) are significant at the 5% probability level. Therefore, the model does explain OC as a function of site (with and without windbreak) and distance. The

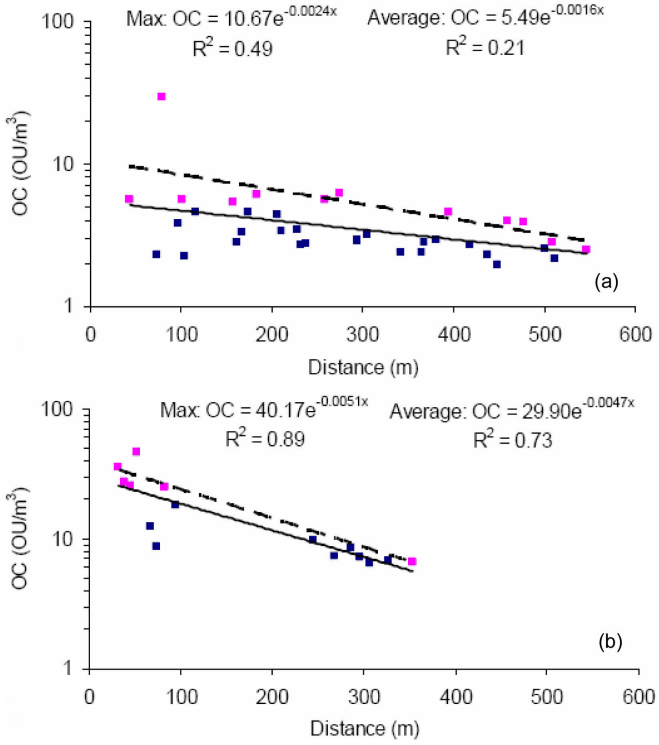

Fig. 7. Effect of tree species on odour dispersion: (a) site 1 with poplars (test 1); (b) site 3 with conifers (test 20). The odour generator is 15m away from windbreak. The dotted line is the correlation for the maximum data (the peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

F-test results also imply that the windbreaks (sites 2 and 5) had a significant impact on MODD, as compared to the control site without a windbreak.

For the windbreak and control sites (Figs. 4 and Table 4), the MODD obtained for 2 OU/m^3 were 564 and 717 m, respectively, when using the maximum values. When the OC criterion was set at 1 OU/m^3, the MODD were 676 and 871 m, respectively. In comparison and for the criterion of 2 OU/m^3, the windbreak on site 2 with an optical porosity of 35% produced MODD of 355 and 564 m for the average and maximum OC regressions; for 1 OU/m^3, the MODD were 493 and 676 m, respectively.

When considering all events measured in September 2003, for both the windbreak and control sites, the MODD produced by the windbreak were at least 21% shorter. Thus, windbreaks can effectively improve odour dispersion and this capability can likely be improved by selecting better performing windbreak parameters.

Effect of windbreak porosity

The impact on odour dispersion of windbreak porosity is illustrated in Fig. 5 for site 1 (tests 2 and 3) with an optical porosity of 55%, compared to that on site 2 (test 16) with an optical porosity of 35%. In both cases, the odour generator was located 30 m upwind from the windbreak, the wind speed was 4.2 and 1.5 m/s and the air temperature was 19 and 23 °C, respectively. The wind direction was 50 to 90° for tests 2 and 3 and 90° for test 16.

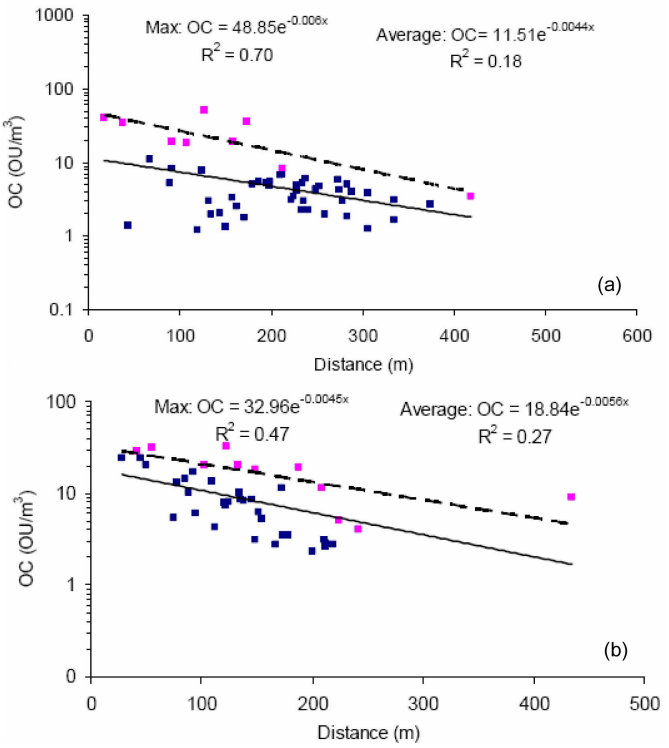

Fig. 8. Effect of air temperature on odour dispersion: (a) above 20°C for site 2 (test 5, 8 and 16); (b) below 0°C for site 4 (test 28, 32 and 33). The odour generator is located 30 m away from the windbreak. The dotted line is the correlation for the maximum data (the peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

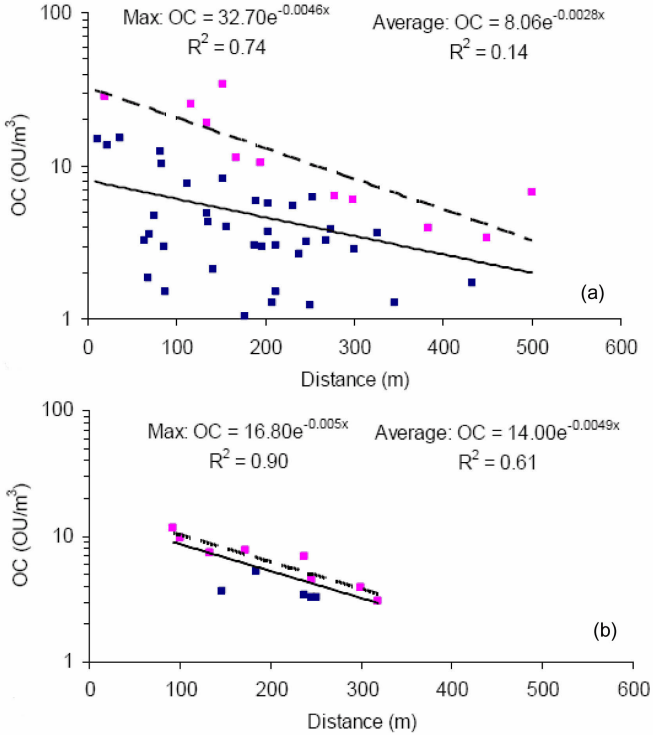

Fig. 9. Effect of wind speed on odour dispersion: (a) 1.2 m/s (tests 9, 11, 13 and 17): (b) 5.1 m/s (test 15). The odour generator is located 15m away from windbreak. The dotted line is the correlation for the maximum data (the peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

For 2 OU/m^3 and the maximum regression line, MODD reached 391 m for the denser windbreak, as compared to 642 m for the more porous windbreak, despite its greater height and exposure to higher wind velocities. For the same criterion but with the average OC regression, the predicted MODD was 353 m for the denser windbreak, compared to 538 m for the more porous windbreak. Using the criterion of 1 OU/m^3, the denser windbreak produced MODD of 463 and 427 m for the maximum and average regressions, respectively, compared to the more porous windbreak which produced MODD of 852 and 815 m under the same conditions. On the average, the denser windbreak reduced MODD by 42%, as compared to the more porous windbreak.

Improved odour dispersion indicates that a dense windbreak produced stronger turbulence and greater atmospheric mixing as compared to the porous windbreak. Therefore, conditions required to dilute odours are quite different from those of high porosity required to lower wind velocity downwind from the windbreak.

Effect of odour generator location

Effect of odour generator location on MODD was measured using the data from 12 tests measured on site 2 (Fig. 6). For the odour generator located 15 m upwind from the windbreak, the average wind speed and direction and the air temperature were 2 m/s, 58°, and 22°C, respectively; for that at 30 m, the average wind speed and direction and the air temperature were 3.2 m/s, 73°, and 21°C, respectively; and for that at 60 m, the average wind speed and direction and the air temperature were 2.2 m/s, 56°, and 24°C, respectively.

For the criterion of 2 OU/m^3 and the maximum OC regression, the odour generator produced MODD of 511, 533, and 569 m when positioning at 15, 30, and 60 m upwind from the windbreak, respectively. For the criterion of 1 OU/m^3 and the maximum OC regression, MODD of 619, 648, and 700 m were produced for the same respective locations. Thus, reducing the distance between the odour source and the windbreak had a significant effect on MODD. The 15-m position reduced MODD by 10 to 34% compared to the 60-m position.

A windbreak positioned closer to the odour source is therefore better able to trap odours on its downwind side, to disperse them thereafter. With the odour source located 60 m upwind from the windbreak, the odour is somewhat dispersed before reaching the windbreak, the odour trapping process is less effective, and the downwind dispersion is not as complete.

Effect of tree species

Odour dispersion was influenced by windbreak tree species (Figs. 7). The poplar windbreak (test 1 on site 1) with a height of 18 m was compared to that of conifers (test 20 on site 3) with a height of 7.6 m. Both windbreaks had an optical porosity of

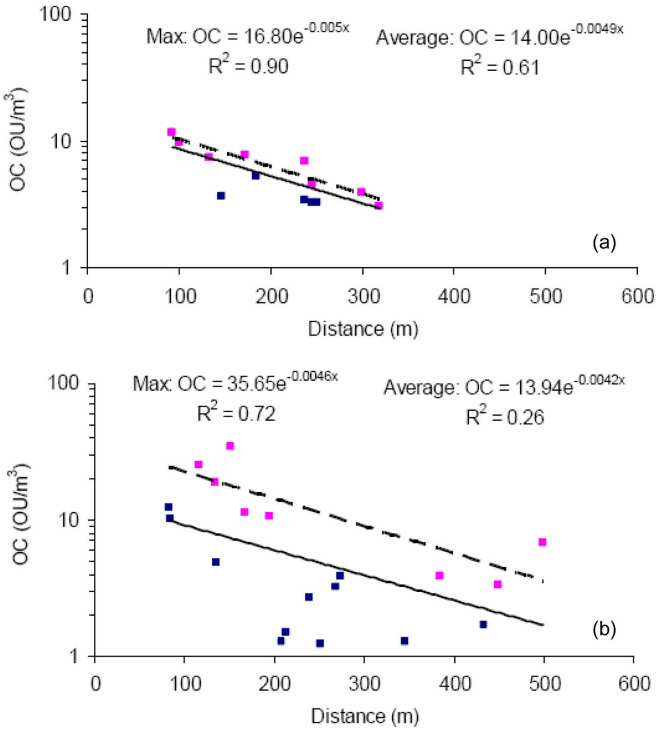

Fig. 10. Effect of wind direction on odour dispersion: (a) 90° (test 15); (b) 40° (test 17). The odour generator is located 15 m away from the windbreak. The dotted line is the correlation for the maximum data (the peak values are illustrated by pink squares), while the solid line is the correlation for all the data.

55%. In both cases, the odour generator was located 15 m upwind from the windbreak, the air temperature was 19 and 13°C, and the wind direction was 90 and 80°, respectively. Wind speed was nevertheless different, averaging 6.4 and 1.8 m/s, respectively.

For the criterion of 2 OU/m^3 and maximum and average OC regression for the conifer windbreak produced MODD of 588 and 575 m compared to MODD of 698 and 631 m for the taller poplar windbreak, despite higher wind velocities. Furthermore, for the criterion of 1 OU/m^3 and the maximum as well as average OC regressions, conifers produced MODD of 724 and 723 m compared to 987 and 1064 m for the poplar windbreak.

As compared to poplars, coniferous trees reduced MODD by 9 to 32%, likely because their stronger branches offered greater wind resistance for a more effective odour dispersion.

Effect of air temperature

The effect of air temperatures was compared under conditions of similar atmospheric stability (Figs. 8). Odour points from three tests (tests 5, 8, and 16) observed in September on site 2 with a deciduous windbreak were compared to those of tests 28, 32, and 33 conducted in December on site 4 with a coniferous windbreak. In both cases, the odour generator was located 30 m upwind from the windbreak; the optical porosity of both windbreaks was 35%; the wind velocity and direction averaged 3.2 and 2.4 m/s and 73° and 67°; and the average temperature was at 21 and -7°C, respectively. For both summer and winter conditions, the Pasquill-Gifford atmospheric stability condition was mostly D.

Warmer temperatures lead to shorter MODD compared to colder temperatures. For the criterion of 2 OU/m^3 and the maximum and average OC regressions, warm air temperatures produced MODD of 533 and 398 m compared to 623 and 401 m for cold air temperatures, despite the fact that conifers may be better at dispersing odours. For the criterion of 1 OU/m^3 and maximum and average OC regression, warm air temperatures produced MODD of 648 and 555 m compared to 777 and 524 m for the cold air temperatures.

Air viscosity increases with temperature and therefore produces more mixing on the downwind side of the windbreak. Therefore, odours will be transported over longer distances during the winter for the same OU production at the source.

Effect of wind speed and direction

Figure 9 compares the results of tests 9, 11, 13, and 17 (site 2 and wind direction ranging from 30 to 60°) with an averaged wind speed of 1.2 m/s, to those of test 15 (site 2 and wind direction of 90°) with an average wind speed of 5.1 m/s. In both cases, the odour generator was located 15 m upwind from the windbreak and the air temperature was 23 and 28°C, respectively.

For the criterion of 2 OU/m^3 and the maximum and average OC regressions, respectively, higher wind speeds produced MODD of 426 and 327 m as compared to 607 and 498 m for the lower wind speed. For the criterion of 1 OU/m^3 and the maximum and average OC regressions, respectively, higher wind speeds reduced MODD by 27% as compared to lower wind speed.

The greater dispersion associated with stronger wind speeds is consistent with the Gaussian odour dispersion model (Schnelle and Dey 2000) and the results of the Inpuff-2 model (Guo et al. 2001).

For site 2, Fig. 10 illustrates the effect of the wind direction where test 15 (average wind direction of 90°) is compared to test 17 (average wind direction of 40°). In both cases, the odour generator was located 15 m upwind from the windbreak; the wind speed was 5.1 and 1.5 m/s; and the air temperature was 28 and 24°C, respectively.

For the criterion of 2 OU/m^3 and the maximum and average OC regressions, the 90° wind angle produced MODD of 426 and 397 m compared to 626 and 462 m obtained with a smaller wind angle. For the criterion of 1 OU/m^3 and the maximum and average OC regressions, respectively, the 90° wind angle produced MODD of 564 and 539 m as compared to 777 and 627 m for the 40° wind angle.

Wind direction perpendicular to the wind windbreak can therefore reduce MODD by 15 to 30%, compared to a wind angle of 40°. This observation needs further verification as the wind speed for the 90° wind direction was quite different from that of the other case and may have interfered with the results.

Table 4. MODD values for the windbreak comparisons illustrated in Figs. 4 to 10.

Comparison	Figure	Condition	Test No.	MODD criterion			
				2 OU/m^3		1 OU/m^3	
				Max	Ave	Max	Ave
Windbreak presence	4	without	37, 38, 39	717	562	871	818
		with	5, 6, 8, 9, 10, 11, 13, 14, 15, 16, 17, 19	564	355	676	493
		reduction		21%	37%	22%	40%
Windbreak porosity	5	55%	2, 3	642	538	852	815
		35%	16	391	353	463	427
		reduction		39%	34%	46%	48%
Odour generator distance	6	15 m	9, 11, 13, 15, 17	511	285	619	427
		30 m	5, 8, 16	533	398	648	555
		60 m	6, 10, 14, 19	569	430	700	558
		reduction 1*		4%	28%	4%	23%
		reduction 2		10%	34%	12%	24%
		reduction 3		6%	7%	7%	1%
Tree type	7	deciduous	1	698	631	987	1064
		conifer	20	588	575	724	723
		reduction		16%	9%	27%	32%
Temperature	8	21°C	5, 8, 16	533	398	648	555
		-7°C	28, 32, 33	623	401	777	524
		reduction		14%	1%	17%	-6%
Wind speed	9	1.2 m/s	9, 11, 13, 17	607	498	758	745
		5.1 m/s	15	426	397	564	539
		reduction		30%	20%	26%	28%
Wind direction	10	90°angle	15	426	397	564	539
		40°angle	17	626	462	777	627
		reduction		32%	14%	27%	14%

* reduction 1: 15 m vs 30 m; reduction 2: 15 m vs 60 m; reduction 3: 30 m vs 60 m

Table 5. ANOVA for sites with and without windbreaks.

Source	Degrees of freedom	Sum of squares	Mean of the squares	F-ratio	F-tab at 5%	Test result
Total sum of squares	273	877.92				
Reduction sum of squares for model	3	647.81	215.94	253.38	2.638	significant
Correction factor for the mean	1	589.44	589.44	691.64	3.876	significant
Reduction sum of squares for model over and above the mean	2	58.37	29.19	34.25	3.029	significant
Reduction sum of squares for the site over the μ and b_1	1	4.24	4.24	4.97	3.876	significant
Reduction sum of squares for b_1 over μ and site	1	57.93	57.93	67.97	3.876	significant
Sum of squares of residual	270	230.10	0.852			

SUMMARY and CONCLUSIONS

Through field data regression and classification analysis, functions were obtained to relate odour concentration (OC) with radial distance from the source in the presence and absence of windbreak and for windbreaks of different types exposed to various climatic conditions. These functions also provided some basis for the statistical comparison of odour dispersion under different conditions. The analysis conducted in this project lead to the following conclusions.

1. The OC and hedonic tone (HT) of odorous air samples observed by trained panellists were found to be exponentially related (P=0.05).
2. Under variable climatic conditions, windbreaks can improve odour dispersion and reduce MODD by at least 21%, especially when offering an optical porosity of 35%, as compared to a site without a windbreak.
3. For the same optical porosity, conifers were better at dispersing odours than poplars.
4. Odour dispersion was optimized with a windbreak of limited optical porosity (35% as compared to 55%); therefore, a porous windbreak designed to reduce wind speed over a long distance on its downwind side, is not designed to disperse odour.
5. Windbreaks are more effective in dispersing odours when close to the source; as compared to a distance of 15 m, distances of 30 and 60 m increased MODD by 6 and 12%, respectively. For livestock shelters using natural ventilation, a 30 m distance is preferred to allow for some air movement about the inlets and outlets.
6. Climatic conditions such as air temperature and wind speed and direction have an impact on the odour dispersion efficiency of windbreaks. Higher temperatures and wind speeds improve odour trapping on the downwind side for a more extensive dispersion.

Despite the fact that these conclusions were based on 39 field tests, each comparison was not perfect as all factors could not be controlled. For an effective comparison, the air mixing performance of windbreaks should be reproduced by modelling.

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