Measurement of odour emissions using micrometeorological techniques following application of hog slurry to grass

M. S. Mkhabela[1]*, R. Gordon[2], E. Smith[2], A. Madani[2] and D. Burton[3]

*[1]Department of Soil Science, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada; [2]Department of Engineering, Nova Scotia Agricultural College, Truro, Nova Scotia B2N 5E3, Canada; and [3]Department of Environmental Science, Nova Scotia Agricultural College, Truro, Nova Scotia B2N 5E3, Canada. *Email: mkhabela@dal.ca.*

Mkhabela, M. S., Gordon, R., Smith, E., Madani, A. and Burton, D. 2008. **Measurement of odour emissions using micrometeorological techniques following application of hog slurry to grass**. Canadian Biosystems Engineering/Le génie des biosystèms au Canada **50**: 6.37–6.45. Odours emanating from livestock operations are a major concern to the non-farming public. Several field experiments were conducted to evaluate the magnitudes of odour emissions from hog slurry applied to grass and to identify management and meteorological factors that influence the rate of odour emissions. Management strategies evaluated included: slurry application rate, soil water status, slurry dilution, and simulated rainfall (irrigation) shortly after application. Results showed that doubling (120,000 L ha^{-1}) the application rate had no impact on odour emissions. Tripling (180,000 L ha^{-1}) the application rate, however, increased emissions on average by 28%, relative to the conventional (60,000 L ha^{-1}) application rate. On average, diluting slurry decreased odour emissions by 11%, while simulated rainfall immediately after slurry application increased odour emissions by 17%. Applying slurry to wet soils compared with dry soils produced variable results. Odour fluxes increased with higher wind speed, net radiation and evapotranspiration rates. Odour emissions can, therefore, be reduced by following proper application rates, but most importantly, by applying slurry during calm, cool days. However, such stable weather conditions may increase odour persistence due to lack of vertical mixing, reduced transfer rates and slow drying of the slurry. **Keywords:** livestock manure, manure spreading, odour emissions, hog slurry, olfactometry, micrometeorological techniques, theoretical profile shape method.

Les odeurs provenant des installations d'élevage représentent une préoccupation majeure pour les populations non agricoles. Plusieurs études sur le terrain ont été réalisées afin d'évaluer l'importance des odeurs émises lors de l'application au champ de lisier de porcs épandu sur des prairies et pour identifier les facteurs météorologiques et de gestion qui ont une influence sur l'émission de ces odeurs. Les stratégies de gestion évaluées comprenaient: le taux d'application du lisier, la teneur en eau du sol, la dilution du lisier et la pluie simulée (irrigation) survenant rapidement après l'épandage. Les résultats ont démontré qu'un taux d'épandage deux fois plus élevé (i.e. 120 000 L ha^{-1}) n'a pas affecté les émissions d'odeurs. Cependant un taux d'épandage trois fois plus élevé (i.e. 180 000 L ha^{-1}) a entraîné une augmentation des émissions d'odeurs de 28% en moyenne comparativement au taux d'épandage de référence (60 000 L ha^{-1}). La dilution du lisier a résulté en une diminution moyenne des émissions d'odeurs de 11% tandis qu'une précipitation de pluie simulée immédiatement après l'épandage augmentait les émissions d'odeurs de 17%. L'application du lisier sur des sols humides comparativement à des sols plus secs a produit des résultats variables au chapitre des émissions d'odeurs. Les flux d'odeurs ont augmenté avec la vitesse du vent ainsi qu'avec des taux plus élevés de radiation nette et d'évapotranspiration. Les émissions d'odeurs peuvent donc être réduites en limitant les taux d'application aux valeurs recommandées et, de façon plus particulière, en procédant aux épandages lors de journées calmes et fraîches. Cependant, de telles conditions météorologiques stables peuvent augmenter la persistance des odeurs en raison d'un mélange vertical de l'air insuffisant, de taux de transfert réduits et d'une durée de séchage du lisier accrue. **Mots clés:** fumier/lisier d'élevage, épandage, émissions d'odeurs, lisier de porcs, olfactométrie, techniques micrométéorologiques, méthode théorique de forme de profil.

INTRODUCTION

Malodours emanating from livestock operations are a major concern to the non-farming public. Odour is the perception of a complex mixture of many different compounds resulting from the anaerobic decomposition of manure (Zhang et al. 2002; Le et al. 2005). Some of these compounds may have negative effects on crops, animals and humans (Hobbs et al. 1999; Le et al. 2005; Schiffman et al. 2005). Land spreading of manure, in particular, draws more complaints about nuisance odour than any other aspect of livestock production (AAFC 1998b; Phillips et al. 1991). In Quebec, 70% of the complaints surrounding nuisance odour involved land spreading (AAFC 1998b). In Saskatchewan, Guo et al. (2005) observed that between May and October manure spreading contributed to increased odour occurrences.

Odour emissions from manure are generally affected by management practices and weather conditions. The major weather conditions include atmospheric stability, wind speed, temperature, relative humidity, solar radiation, and the mixing height (Guo et al. 2006; Zhang et al. 2007). High wind speeds increase odour transfer rate from manure to the air (Smith and Watts 1994b; Zhou and Zhang 2003), while higher temperatures stimulate the breakdown of odorous compounds (Le et al. 2005).

A significant amount of research has been devoted to quantifying odour emissions from livestock facilities and stored manure, with little focus on manure application (Jacobson et al. 1999; Edeogu et al. 2002; Zhou and Zhang 2003; Cicek et al. 2004; Agnew et al. 2006; Zhang et al. 2007). Moreover, the limited studies that measured odour emissions following manure application (Misselbrook et al. 1993; Rahman et al. 2001; Rahman et al. 2005; Agnew et al. 2006) have utilised enclosures or wind tunnels, which may provide unrealistic estimates due to their effect on the microclimate and controlled wind speeds.

Micrometeorological techniques are used to measure the turbulent transfer of gases and fluid particles between the surface and the atmosphere. These techniques typically measure fluxes over extensive areas thus minimising spatial variability (Baldocchi et al. 1988; Pain et al 1991). Among the various micrometeorological techniques, the Theoretical Profile Shape (TPS) method (Wilson et al. 1983) is one of the simplest in relation to physical monitoring. It has been extensively used to study ammonia (NH_3) flux from field applied manure (Wilson et al. 1983; Gordon et al. 1988, 2000, 2001). With the TPS method, both the gas concentration and wind speed are measured above the centre of the circular plot at a single height referred to as ZINST (Wilson et al. 1983; Gordon et al. 1988; Pain et al. 1991). Although this method has been extensively used for NH_3 volatilisation measurements, its application for quantifying odour emissions following field-spreading of manure has been quite limited (Pain et al. 1991; Smith et al. 2007).

The objectives of this study were therefore: (i) to evaluate the magnitude of odour emissions using the TPS method following the application of hog (*Sus scrofa*) slurry to grass, and (ii) to identify management and meteorological factors that influence the rate of odour emissions from surface applied slurry. The study specifically compared odour emissions from different slurry application rates, different initial soil water status, slurry dilution, and simulated rainfall immediately after slurry application.

MATERIALS and METHODS

Experimental location, site description and design

Several field experiments were conducted during the summers (June to October) of 2003 and 2004 on two acidic soils seeded to forage grass in Great Village, Nova Scotia (lat. 45°25'N, long. 63°36'W). The grass forage was a mixture of timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis*). In 2003, the soil used was an Acadia (Marshland) fine loam (Gleyed Regosol), and 2004 it was a Truro fine sandy loam (Orthic Humo-Ferric Podzol) (Webb et al. 1991; AAFC 1998a). Physical and chemical properties of both soils are shown in Table 1.

During both years, experiments were conducted in circular plots, 7-m in diameter and separated by 3-m spacing. To minimise cross contamination, plots were arranged in a straight line perpendicular to the direction of the prevailing wind. Treatments were randomly assigned to the plots. To obtain an even distribution, slurry was applied manually using buckets. Slurry used in all the experiments was collected from a nearby commercial hog operation with characteristics provided in Table 1. Before slurry application, the grass was mowed to a height of about 5 cm using a tractor-drawn mower. Experiments were always initiated when the weather forecast by Environment Canada showed that there would be no rainfall for the next 2–3 days.

Table 1. Chemical and physical characteristics of the soils (0-20 cm depth) and hog slurry used in the study.

	Soil		Slurry	
Characteristic	Acadia (2003)	Truro (2004)	2003	2004
pH	4.71*	6.05*	6.22	5.81
Total nitrogen (%)	0.33	ND	0.36	0.28
Carbon (%)	3.80	ND	1.41	1.06
C:N ratio	11.5	ND	3.92	3.79
NH_4^+-N (%)	ND	ND	0.24	0.20
NO_3^--N (mg kg^{-1})	2.2	14.3	ND	ND
Dry matter (%)	NA	NA	3.96	2.49
Porosity (%)	58.5	49.4	-	-
Bulk density (Mg m^{-3})	1.10	1.34	-	-

*pH 1:2 dry soil: de-ionised water, TN and C determined using CNS analyser.

Treatments tested

Four sets of experiments were conducted to evaluate the magnitudes of odour emissions from hog slurry and to identify management and meteorological factors that affect the rate of odour emissions. The four sets of experiments conducted included: (i) slurry application rate, (ii) soil water status, (iii) simulated rainfall, and (iv) slurry dilution. The slurry rate experiments compared a conventional (1 ×) rate (60 000 L ha^{-1}) versus either a 2 × rate (120 000 L ha^{-1}) or a 3 × rate (180 000 L ha^{-1}). The 1 × rate is a typical manure rate for forage grass in Nova Scotia. The soil water status experiments examined the effect of soil water content at the time of slurry spreading on odour emissions. Different soil water contents were achieved by applying water (i.e., 86 mm in the July 2003 experiment and 31 mm in the July 2004 experiment) using watering cans with spouts to a randomly selected plot prior to slurry application. The other plot received no water. Meanwhile, the simulated rainfall experiment examined the impact of rainfall (irrigation) after slurry application on odour emissions. Water (6 mm) was applied manually using watering cans with spouts on one plot immediately ($<$30 min) after slurry application. The other plot received no water. The dilution experiments evaluated the effect of slurry dilution on odour emissions. Slurry was diluted using 25, 50 or 100% water (vol/vol) and each of these was compared with undiluted slurry. Experiment start dates, duration of measurements, treatments, application rates and average meteorological conditions during each experiment are shown in Table 2.

Table 2. Summary of experiments, start dates, duration of measurement, treatments and average meteorological conditions i.e., air temperature (T_{air}), wind speed, net radiation (R_n), vapour pressure deficit (VPD), relative humidity (RH) and total rainfall during each experiment in 2003 and 2004.

				Meteorological conditions					
Type of experiment	Experiment start date	Duration of measurement (h)	Treatments	T_{air} (°C)	Wind speed (m s^{-1})	R_n (W m^{-2})	VPD (kPa)	RH (%)	Total rainfall (mm)
Application rate	6 June, 2003	42	60,000 vs. 120,000 L ha^{-1}	13.9	1.06	200	0.24	89.4	1.8
	20 June, 2003	42	60,000 vs. 120,000 L ha^{-1}	20.9	0.87	231	0.79	70.6	0.0
	3 July, 2003	48	60,000 vs. 180,000 L ha^{-1}	21.7	0.88	173	0.51	82.5	0.0
	12 Sep, 2003	48	60,000 vs. 120,000 L ha^{-1}	18.9	1.79	312	1.01	66.0	0.0
	7 June, 2004	71	60,000 vs. 120,000 L ha^{-1}	17.2	0.97	259	0.85	74.6	6.4
	18 Oct, 2004	72	60,000 vs. 180,000 L ha^{-1}	13.7	0.92	200	0.75	74.8	0.0
Soil water status	22 July, 2003	42	86 mm (wet) vs. No water	22.3	1.27	189	0.52	87.1	5.6
	28 July, 2004	42	31 mm (wet) vs. No water	21.0	0.68	285	0.64	83.4	6.4
Slurry dilution	25 Aug, 2003	48	25% water (volume)	17.5	1.56	268	1.14	61.5	1.8
	18 June, 2004	72	50% water (volume)	17.2	1.26	-	-	-	13.4
	21 Sep, 2004	72	100% water (volume)	12.2	1.26	315	0.80	63.2	4.8
Simulated rainfall	21 Sep, 2004	72	6 mm rainfall after slurry application vs. No rainfall	12.2	1.3	315	0.80	63.2	4.8

Air sample collection, analysis and flux calculations

Air samples for odour analysis were collected in 10-L Tedlar bags using micrometeorological techniques (Wilson et al. 1983; Gordon et al. 1988; Pain et al. 1991). Air samples were collected above the centre of each plot at 12.5-cm height (ZINST). This value of ZINST was determined by Gordon et al. (1988) for source plots of 3.5-m radius (i.e., 7-m diameter). At the start of each experiment, two samples were taken upwind from the experiment site for determination of background odour levels. Samples were collected using an AC'SCENT vacuum chamber (St Croix Sensory Inc., Stillwater, MN). During sampling, odour samples are directly drawn into the sample bags without coming into contact with the pump. This reduces chances of sample contamination by gases generated by the pump. The typical time to fill a bag was approximately 10 min. Before taking a sample, the bags were purged with sample air. Samples were generally collected at 0, 2, 4, 6, 18, 24, 30, and 48 h after slurry application. Soon after collection, samples were placed in plastic cooler containers and kept at room temperature (~20°C) until they were sent by courier to Agriculture and Agri-Food Canada (AAFC), Charlottetown, Prince Edward Island (PEI) for subsequent analysis. Odour samples were analysed following the guidelines of ASTM (1991) and recommendations provided by AC'SCENT (1999). Due to the high cost of analysing odour samples coupled with the limited number of samples (10-12 samples per session) that could be handled by the olfactometry laboratory, only one sample per treatment (no replication) was collected at each sampling time. Each odour analysis session lasted a maximum of 3 h. Panellist sensitivity drops noticeably after 3–4 h (Parker et al. 2003). Agnew et al. (2006) and Parker et al. (2003) describe some of the challenges with replication in odour studies using olfactometry.

Odour concentrations (OC) were determined using an AC'SCENT dynamic-dilution olfactometer (St Croix Sensory Inc., Stillwater, MN) together with an odour panel consisting of six trained panellists. The sensitivity of all panellists was measured using 50 ppb of n-butanol. The olfactometer mixes odour samples in specific ratios with odour-free air for presentation to the panel. The panellists were each presented with three samples via the olfactometer to test (i.e., sniff) and had to select the sample that contained odorous air. This approach is referred to as the triangular forced choice method (Zhang et al. 2002). The advantage with olfactometry is that it provides objective data on OC through the determination of threshold values (Pain et al. 1991). An OC is defined as the number of dilutions at which 50% of the panellist can detect an odour, and is expressed as odour units m^{-3} (OU m^{-3}) of air (Hobbs et al. 1995; Misselbrook et al. 1997; Trabue et al. 2006).

Table 3. Odour concentration (OC) range, mean OC (OU m^{-3}), total odour emission (OU m^{-2}) and% change for different experiments in 2003 and 2004.

Experiment start date	Treatments*	OC Range (OU m^{-3})	Mean OC (OU m^{-3})**	Total odour emissions $\times 10^6$ (OU m^{-2})‡	% change in emissions
6 June, 2003	1 ×	45–180	97 (17)	1.0	11
	2 ×	31–180	101 (22)	1.1	
20 June, 2003	1 ×	50–100	80 (7)	0.8	0
	2 ×	63–142	86 (8)	0.8	
3 July, 2003	1 ×	33–89	66 (7)	0.9	44
	3 ×	58–156	97 (13)	1.3	
12 Sep, 2003	1 ×	99–126	113 (5)	2.8	−11
	2 ×	62–126	104 (9)	2.5	
7 June, 2004	1 ×	25–79	46 (7)	0.9	11
	2 ×	25–89	51 (8)	1.0	
18 Oct, 2004	1 ×	50–89	65 (6)	1.5	11
	3 ×	67–135	80 (11)	1.6	
22 July, 2003	No water	40–89	65 (6)	0.9	0
	Water (86 mm)	35–135	69 (12)	0.9	
28 July, 2004	No water	44–203	101 (21)	1.2	−17
	Water (31 mm)	55–114	78 (10)	1.0	
25 Aug, 2003	Undiluted	44–126	82 (10)	1.1	0
	Diluted (25%)	40–113	79 (8)	1.1	
18 June 2004	Undiluted	56–142	83 (10)	2.0	−25
	Diluted (50%)	39–112	64 (23)	1.5	
21 Sep, 2004	Undiluted	50–112	68 (10)	1.2	−8
	Diluted (100%)	38–112	66 (7)	1.1	
21 Sep, 2004	No Rainfall	50–118	68 (10)	1.2	17
	Rainfall (6 mm)	37–118	77 (12)	1.4	

*1 ×, 2 × and 3 × represent 60,000, 120,000 and 180,000 L ha^{-1}, respectively.
**Numbers in brackets are standard errors.
‡Values have been rounded to the nearest tenth.

Using the theoretical profile shape (TPS) method, odour fluxes (OU m^{-2} s^{-1}) were calculated as follows (Wilson et al. 1983; Gordon et al. 1988; Pain et al. 1991):

$$F = \frac{\overline{SC}}{\left[\frac{\overline{SC}}{F}\right]} \tag{1}$$

where F is the odour flux (OU m^{-2} s^{-1}), $\overline{S}$ and $\overline{C}$ are the average wind speed (m s^{-1}) and OC (OU m^{-3}), respectively, both measured at a single sampling height ZINST (12.5 cm). The $[\overline{SC}/F]$ is a dimensionless ratio that has a value of 12 for 7-m-diameter plots (Gordon et al. 1988). Total odour emissions for the duration of an experiment are derived by integrating these flux measurements.

Wind speed for flux calculations was recorded at ZINST (12.5 cm) using an inverted cup anemometer (Met One 014A, Grants Pass, OR). From each plot, soil temperature at 10 cm depth was monitored using copper-constantan thermocouples, and soil water content at the 0-20 cm depth was recorded using time domain reflectometry (TDR). Additionally, several meteorological variables including net radiation (height 1.2 m), relative humidity (two heights; 0.5 and 1.5 m), air temperature (two heights; 0.5 and 1.5 m) soil heat flux (depth 5 cm) and rainfall (height 2 m) were measured using a Bowen Ratio Energy Balance (BREB) system (Radiation and Energy Balance System Inc, Seattle, WA). Evapotranspiration (ET) rates (mm day^{-1}) were calculated using latent heat (λE) flux data computed from the BREB (Oke 1996; Peacock and Hess 2004). Data were recorded at 60 s intervals and averaged over 15 min using CR10 and CR23X data-loggers (Campbell Scientific Corp., Logan, UT).

RESULTS and DISCUSSION

Odour concentration

Table 3 shows the mean OC, the ranges and the percent (%) change in odour emissions measured from each experiment in both 2003 and 2004. The mean OC were low (ranging from 46 to 113 OU m^{-3}) compared with other studies, even with the highest application rate. Using the TPS method, Pain et al. (1991) measured OC ranging from 34 to 1076 OU m^{-3} after applying pig or cattle slurry to grass. Rahman et al. (2001, 2005) recorded OC values ranging from 102 to 1053 OU m^{-3} after injecting slurry at different rates, while Mosley et al. (1998) observed an OC of 250 OU m^{-3} soon after surface application of pig slurry, but this declined to about 60 OU m^{-3} after 24 h. Our values were, however, similar to Smith et al. (2007), who recorded OC values ranging from 13 to 155 OU m^{-3} from field-applied swine manure in PEI using the TPS method. Misselbrook et al. (1993) reported that typical OC following pig slurry spreading would be 150 OU m^{-3} at source, while Mosley et al. (1998) suggested that OC for background (uncontaminated) air upwind of experiments should range from 50 to 150 OU m^{-3}. In the current study, background air samples collected before slurry spreading had OC ranging from 31 to 99 OU m^{-3}. Meanwhile, the Tedlar bags had an average background OC of 6 OU m^{-3}.

The lower OC in the current study may be attributed to different soil types, manure characteristics, soil and sward conditions, weather conditions, and measurement techniques. Another factor that may have caused the lower OC may have been due to off-gassing and or sorption of odour compounds to Tedlar bags during storage i.e., before analysis (Keener et al. 2002; Parker et al. 2003; Trabue et al. 2006). Trabue et al. (2006) found that storing odour samples in Tedlar bags for >0.5 h resulted in significantly reduced OC, and suggested that odour results from Tedlar bags must be interpreted with caution. Meanwhile, Parker et al. (2003) reported that background odour in Tedlar bags increased significantly with storage time. In the current study, it was not possible to analyse samples immediately after collection; samples were typically stored for >48 h before analysis, which may have lowered the OC. Nonetheless, Smith et al. (2007) also recorded low OC values (13 to 155 OU m^{-3}) from field applied swine manure even though their samples were analysed within 24 h after collection. It should be noted that Smith et al.'s samples were analysed by the same olfactometry laboratory as ours.

Odour fluxes

Odour fluxes were generally high shortly after slurry application and declined with time; however, treatment differences were not always discernable due to high variability and possibly low sensitivity of the olfactometer (Fig. 1). Large concentration differences (up to three times) between samples are often required for panellist to detect treatment differences (Smith et al. 2007). Overall, odour fluxes ranged from 1 to 30 OU m^{-2} s^{-1} in 2003, whereas in 2004, they ranged from 2 to 20 OU m^{-2} s^{-1}. Using the TPS method, Pain et al. (1991) observed similar odour emission patterns after applying cattle and pig slurry. Smith et al. (2007) using the TPS technique observed odour fluxes ranging from 2.2 to 13.8 OU m^{-2} s^{-1} after applying swine manure. Agnew et al. (2006) using a dynamic flux chamber recorded odour fluxes of 40 and 34 OU m^{-2} s^{-1} for surface applied and incorporated swine manure, respectively. Meanwhile, Rahman et al. (2005) using wind tunnels recorded higher odour emission rates (94 to 105 m^{-2} s^{-1}) after applying liquid swine manure at different rates. In Manitoba, odour emission rates from swine barns ranged from 12 to 38 OU m^{-2} s^{-1} (Zhou and Zhang 2003) and 8 to 23 OU m^{-2} s^{-1} (Zhang et al. 2007), while in Minnesota they ranged from 1 to 30 OU m^{-2} s^{-1} (Jacobson et al. 1999). Typical odour emission rates from field-applied pig slurry are summarised by Smith and Watts (1994a), and they range from 3 to 504 OU m^{-2} s^{-1}.

Total odour emissions

Total odour emissions (OU m^{-2}) and the percent (%) change in odour emissions for all experiments are shown in Table 3. These results show that in general, increasing slurry application rate resulted in higher odour emissions, particularly when the application rate increased to 3 ×. At this application rate, total odour emissions were on average 28% (range 11 to 44%) higher than the conventional (1 ×) rate. Smith et al. (2007) observed that odour emissions rates increased by 22 and 38% when manure application rates increased from 1 × to 2 × and 5 ×, respectively. Meanwhile, applying slurry on soils that had received water (wet) prior to application produced variable results. Such contrasting results were unexpected, and may have been caused by the fact that the soil water contents for the wet and dry plots were not very different at the start of the trials. Diluting slurry with water prior to application decreased emissions on average by 11% (range 0 to 25%). In a laboratory experiment, Le et al. (2005) found that increasing manure dilution from 0 to 100% decreased odour emissions by 50%. On the other hand, a 6-mm simulated rainfall after slurry application increased emissions by 17%, probably due to slow drying of the slurry. Watts et al. (1992) reported that odour emission rates from manure increased in the 2-day period following heavy rain and then declined rapidly as the manure dried. Moreover, a 6-mm rainfall may not be enough to suppress odour emissions. Smith et al. (2007) found that a 50-mm rainfall after manure application reduced odour emissions on average by only 14%.

Impact of meteorological variables on odour emissions

To establish possible relationships between meteorological variables (i.e., net radiation, latent heat flux, sensible heat flux, soil heat flux, relative humidity, vapour pressure deficit, wind speed, evapotranspiration and air and soil temperature) and odour emissions, the average odour fluxes (OU m^{-2} s^{-1}) for all conventional (1 ×) treatments in the 24 h following slurry application were used in the linear regression analysis. It is noteworthy that these meteorological variables are probably correlated with one another; however, performing simple linear regressions is sufficient to demonstrate the relationships that exist between odour emission rates and prevailing weather conditions. Out of the 10 meteorological variables tested, only three were correlated with odour flux during both years (Fig. 2). Fluxes increased with higher wind speed, net radiation and evapotranspiration. In 2003, the strongest correlation was with wind speed ($R^2 = 0.98$), whereas in 2004, it was with evapotranspiration ($R^2 = 0.97$). In 2004, the relationship with evapotranspiration was, however, weak, yielding an R^2 of

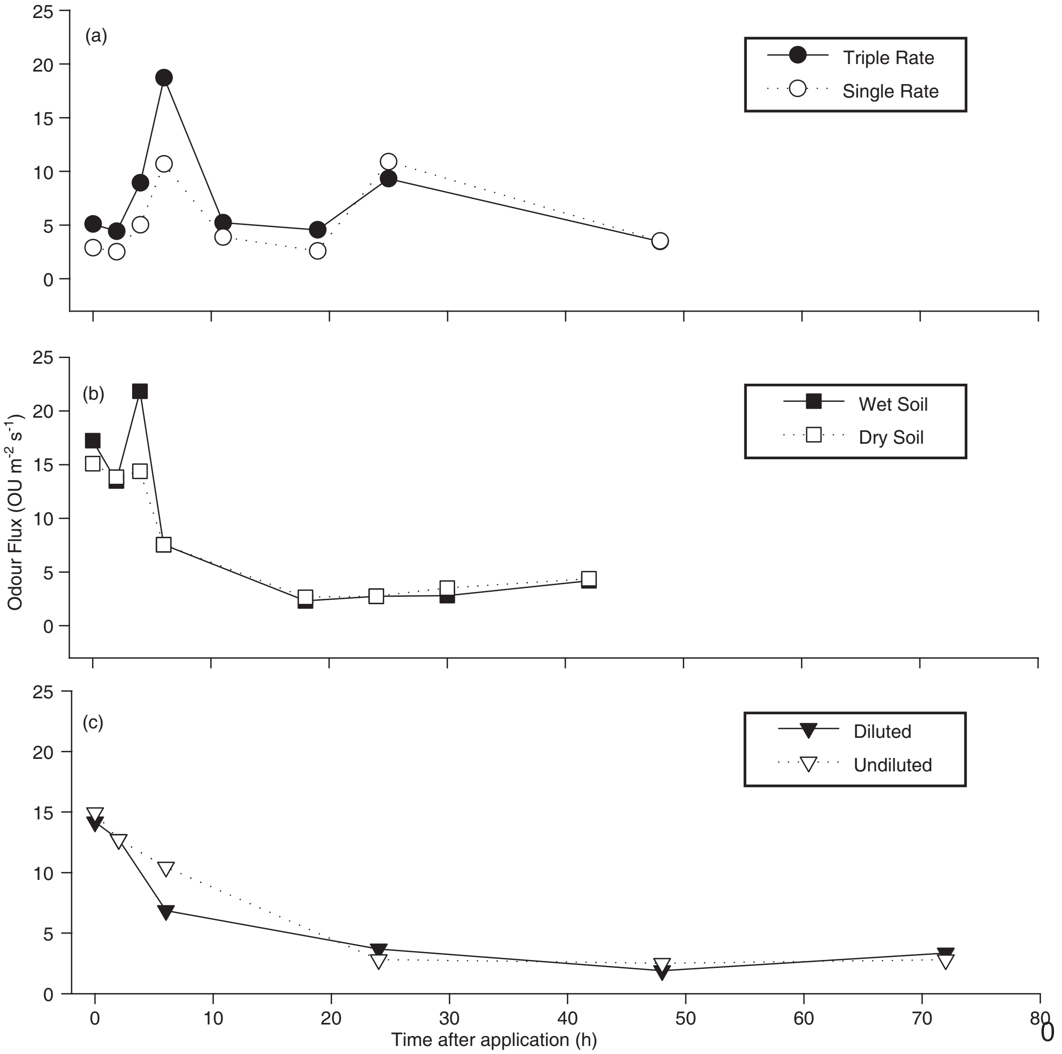

Fig. 1. Odour fluxes (OU m^{-2} s^{-1}) from selected experiments following application of hog slurry to grass showing a decreasing trend over time. Experiments were conducted on (a) 3–5 July, 2003 (single vs. triple rate), (b) 22–24 July, 2003 (wet vs. dry soil) and (c) 21–24 September, 2004 (undiluted vs. diluted slurry).

only 0.27. Using wind tunnels, Smith and Watts (1994b) and Schmidt et al. (1999) observed that odour emission rates from manure increased with wind speed. Meanwhile, Smith and Watts (1994b) suggested that evaporation of water from drying soil provides a guide to the likely process of odour emission.

Both air and soil temperature poorly correlated with odour flux. In a laboratory experiment, Le et al. (2005) found that raising temperature from 10 to 30°C increased odour emission by 216%. When studying odour emissions from swine barns, Zhou and Zhang (2003) reported that odour emission rates were not affected by outdoor air temperature in the range from 12 to 35°C. Zhang et al. (2007) found that odour emissions rates from swine barns increased as outdoor temperature increased from 10 to19°C and thereafter remained almost constant. In the current study, average air temperature during odour measurements was 19°C in 2003 and 16°C in 2004 (Table 2), which may partly explain the observed poor relationship between air temperature and odour emissions. Nonetheless, results suggest that odour emissions can be reduced by applying slurry when wind speed, net radiation and evapotranspiration rates are low. Incidentally, this will also reduce NH_3 volatilisation (Mkhabela 2007). Such weather conditions may, however, lead to increased odour persistence since there will be less dilution of odour (i.e., less vertical mixing) and transfer rates and slow drying of the slurry.

CONCLUSIONS

Odour fluxes were generally highest soon after slurry spreading and decreased with time. Compared with the conventional application rate (60,000 L ha^{-1}), doubling the slurry application rate had no effect on odour fluxes, but tripling the application rate increased odour fluxes and subsequently odour emissions. Applying slurry to wet soil produced somewhat variable results. Meanwhile, diluting slurry decreased odour emissions by an average 11%, while simulated rainfall after application increased

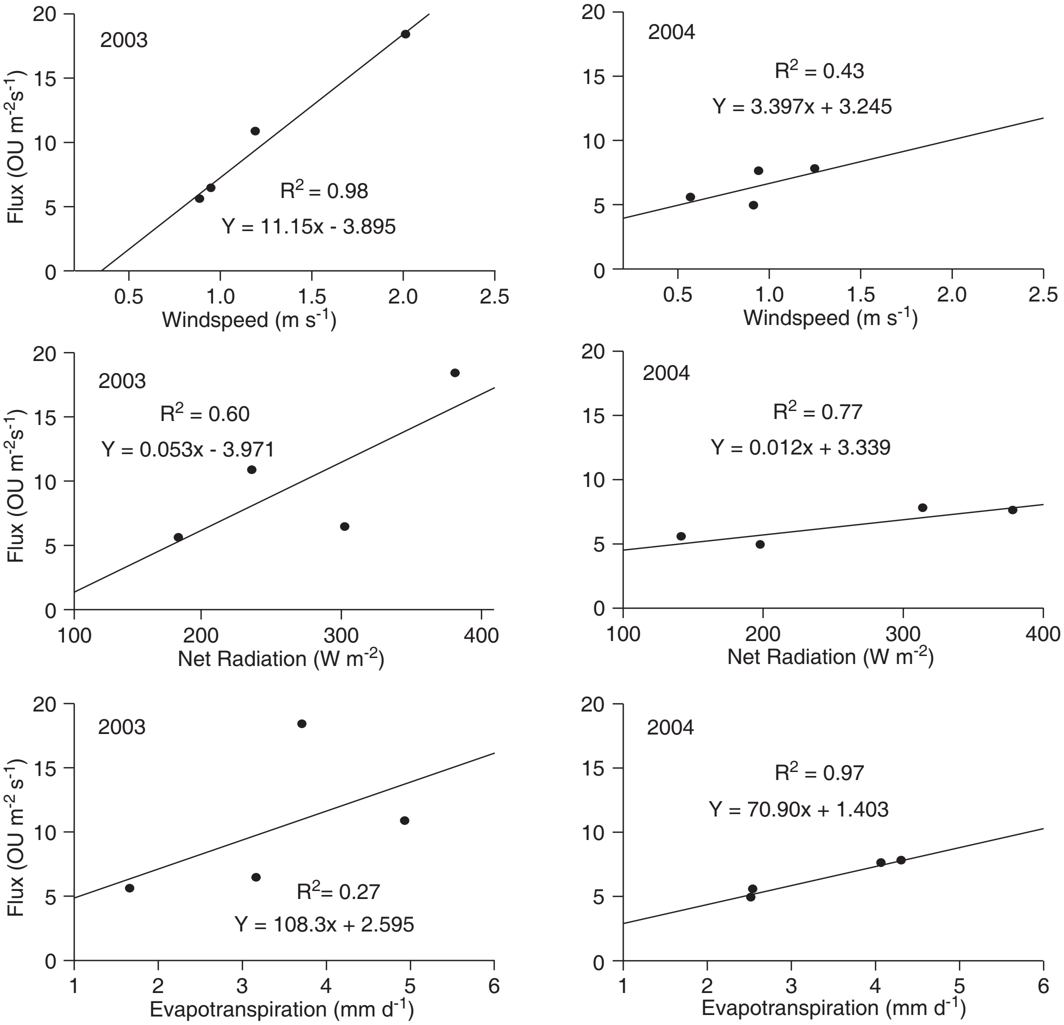

Fig. 2. Relationship between odour flux (OU m^{-2} s^{-1}) and meteorological variables (wind speed, net radiation and evapotranspiration) following application of hog slurry to grass in 2003 and 2004.

emissions by 17%. Odour fluxes increased with higher wind speed, net radiation and evapotranspiration. Thus, slurry spreading should be done during less windy, cool days (low evaporative demand) in order to reduce odour emissions; however, such weather conditions may increase odour persistence.

ACKNOWLEDGEMENTS

Funding for this study was provided by the Natural Science and Engineering Research Council (NSERC), Technology Development Program, Nova Scotia Department of Agriculture (NSDA), Agriculture and Agri-Food Canada (AAFC) and the Nova Scotia Agricultural College (NSAC). Thanks are also extended to the Bowers and Berfelo Family Farms.

REFERENCES

AAFC. 1998a. *The Canadian system of soil classification*. Publication 1646. Ottawa, ON: National Research Council, Research Press, Agriculture and Agri-Food Canada.

AAFC. 1998b. R*esearch strategy for hog manure management in Canada*. Ottawa, ON: Department of Supply and Services, Research Branch, Agriculture and Agri-Food Canada.

AC'SCENT. 1999. About AC'SCENT. International Olfactometer. http://www.fivesenses.com/accent/Aboutaccent.htm (2008/02/02)

Agnew, J., P. Loran, S. Karmakar and C. Lague. 2006. Greenhouse gas and odour emissions from land application of manure: A review of measurement methods. ASAE Paper No. MBSK 06-305. St Joseph, MI: ASABE.

ASTM. 1991. ASTM E 679-91. Standard practice for determination of odour and taste thresholds by forced-choice ascending concentration series method of limits. In 1991 *Annual Book of ASTM Standards*. Philadelphia, PA: American Society of Testing and Materials.

Baldocchi, D.D., B.B. Hicks and T.P. Meyers. 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology* 69: 1331–1340.

Cicek, N., X. Zhou, Q. Zhang and M. Tenuta. 2004. Impact of straw cover on greenhouse gas and odour emissions from manure storage lagoons using a flux hood. ASAE Paper No.04-4054. St. Joseph, MI: ASABE.

Edeogu, I., J.J.R. Feddes, R.N. Coleman and J. Leonard. 2002**.** Odour emission rates from manure treatment/storage systems. *Water Science and Technology* 44: 269–275.

Gordon, R., M. Leclerc, P. Schuepp and R. Brunke. 1988. Field estimates of ammonia volatilisation from swine manure by a simple micrometeorological technique. *Canadian Journal of Soil Science* 68: 369–380.

Gordon, R., G. Patterson, T. Harz, V. Rodd, and J. MacLeod. 2000. Soil aeration for dairy manure spreading on forage: Effects on ammonia volatilisation and yield. *Canadian Journal of Soil Science* 80: 319–326.

Gordon, R., R. Jamieson, V. Rodd, G. Patterson and T. Harz. 2001. Effects of surface manure application timing on ammonia volatilisation. *Canadian Journal of Soil Science* 81: 525–533.

Guo, H., W. Dehod, J. Feddes, C. Laque and I. Edeogu. 2005. Monitoring odour occurrence inthe vicinity of swine farms by resident observers-Part I: Odour occurrence profiles. *Canadian Biosystems Engineering* 47: 6.57–6.65.

Guo, H., J. Feddes, W. Dehod, C. Laque and I. Edeogu. 2006. Monitoring odour occurrence in the vicinity of swine farms by resident observers-Part II: Impact of weather conditions onoccurrence. *Canadian Biosystems Engineering* 48: 6.23–6.29.

Hobbs, P.J., T.H. Misselbrook and B.F. Pain. 1995. Assessment of odours from livestock wastes by photoionization detector, an electric nose, olfactometry and gas chromatograph-mass spectrometry. *Journal of Agricultural Engineering Research* 60: 137–144.

Hobbs, P.J., T.H. Misselbrook and T.R. Cumby. 1999. Production and emission of odours and gases from ageing pig waste. *Journal of Agricultural Engineering Research* 72: 291–298.

Jacobson, L.D., R.E. Paszek, R.E. Nicolai, D.R. Schimidt, B. Hetchler and J. Zhu. 1999. Odour and gas emissions from animal manure storage units and buildings. ASAE Paper No.99-4004. St. Joseph, MI: ASABE.

Keener, K.M., J. Zhang, R.W. Bottcher and R.D. Munilla. 2002. Quantification of odorants from Tedlar TM bags. ASAE Paper No.024165. St. Joseph, MI: ASABE.

Le, P.D., A.J.A. Aarnik, N.W.M. Ogink and M.W.A. Verstegen. 2005. Effects of environmentalfactors on odour emission from pig manure. *Transactions of the ASAE* 48: 757–765.

Misselbrook, T.H., C.R. Clarkson and B.F. Pain. 1993. Relationship between concentration and intensity of odours for pig slurry and broiler houses. *Journal of Agricultural Engineering Research* 55: 163–169.

Misselbrook, T.H., P.J. Hobbs and K.C. Persaud. 1997. Use of electronic nose to measure odour concentration following application of cattle slurry to grassland. *Journal of Agricultural Engineering Research* 66: 213–220.

Mkhabela, M.S. 2007. Gaseous nitrogen and odour emissions following manure application under grassland and cultivated systems. Unpublished Ph.D. thesis. Halifax, NS: Department of Biological Engineering, Dalhousie University.

Mosley, P.J., T.H. Misselbrook, B.F. Pain, R. Earl and R.J. Godwin. 1998. The effect of injector tine on odour and ammonia emissions following injection of biosolids into arable cropping. *Journal of Agricultural Engineering Research* 71: 385–394.

Oke, T.R. 1996. *Boundary Layer Climates*, 2nd edition. London, UK: Routledge.

Pain, B.F., C.R. Clarkson, V.R. Phillips, J.V. Klarenbeek, T.H. Misselbrook and M. Bruins. 1991. Odour emission arising from application of livestock slurries on land: Measurements following spreading using a micrometeorological technique and olfactometry. *Journal of Agricultural Engineering Research* 48: 101–110.

Parker, D.B., M.B. Rhoades, J. Koziel and J. Spinhirne. 2003. Background odours in Tedlar bags for CAFO odour sampling. ASAE Paper No.034144. St. Joseph, MI: ASABE.

Peacock, C.E. and T.M. Hess. 2004. Estimating evapotranspiration from a reed bed using the Bowen ratio energy balance method. *Hydrological Processes* 18: 247–260.

Phillips, V.R., B.F. Pain and J.V. Klarenbeek. 1991. Factors affecting odour and ammonia emissions during and after the land spreading of animal slurries. In *Odour and Ammonia Emissions from Livestock Farming,* eds. V.C. Nielsen, J.H Voorburg and P. L'Hermite, 98–106. London, UK: Elsevier.

Rahman, S., Y. Chen, Q. Zhang, S. Tessier and S. Biadoo 2001. Performance of a liquid manure injector in a soil bin and on established forages. *Canadian Biosystems Engineering* 43: 2.33–2.40.

Rahman, S., Y. Chen, Q. Zhang and D. Lobb. 2005. Evaluation methods on manure exposure from liquid manure injection tools. *Canadian Biosystems Engineering* 47: 6.9–6.16.

Schiffman, S.S., C.E. Stdwell, L.R. Landerman, K. Berman and J.S. Sundy. 2005. Symptomatic effects of exposure to diluted air sampled from swine confinement atmosphere on healthy human subjects. *Environmental Health Perspectives* 113: 567–576.

Schmidt, D.R., R.J. Bicudo and K.A. Janni. 1999. Determining odour emissions from manure surfaces using wind tunnels. ASAE Paper No.99-4033. St. Joseph, MI: ASABE.

Smith, E., R. Gordon, A. Campbell and C.P.A. Bourque. 2007. An assessment of odour emissions from land applied swine manure. *Canadian Biosystems Engineering* 49: 6.33–6.40.

Smith, R.J. and P.J. Watts. 1994a. Determination of odour emission rates from cattle feedlots: Part 1, A review. *Journal of Agricultural Engineering Research* 57: 145–155.

Smith, R.J. and P.J. Watts. 1994b. Determination of odour emission rates from cattle feedlots: Part 2, Evaluation of two wind tunnels of different size. *Journal of Agricultural Engineering Research* 58: 231–240.

Trabue, S.L., J.C. Anhalt and J.A. Zahn. 2006. Bias of Tedlar bags in the measurement of agricultural odorants. *Journal of Environmental Quality* 35: 1668–1677.

Watts, P.J., M. Jones, S.C. Lott, R.W. Tucker and R.J. Smith. 1992. Odour measurements at a Queensland feedlot. ASAE Paper No.92-4516. St Joseph, MI: ASABE.

Webb, K.T., R.L. Thompson, G.J. Beke and J.L. Nowland. 1991. Soils of Colchester county. NS. Report 19. Ottawa, ON: Nova Scotia Soil Survey, Research Branch, Agriculture Canada.

Wilson, J.D., V.R. Catchpoole, O.T. Denmead and G.W. Thurtell. 1983. Verification of a simple micrometeorological method for estimating the rate of gaseous mass transfer from the ground to the atmosphere. *Agricultural Meteorology* 29: 183–189.

Zhang, Q., J.J.R. Feddes, I.K. Edeogu and X.J. Zhou. 2002. Correlation between odour intensity assessed by human assessors and odour concentration measured with olfactometers. *Canadian Biosystems Engineering* 44: 6.27–6.32.

Zhang, Q., X.J. Zhou, N. Cicek and M. Tenuta. 2007. Measurement of odour and greenhouse gas emissions in two swine farrowing operations. *Canadian Biosystems Engineering* 49: 6.13–6.20.

Zhou, X. and Q. Zhang. 2003. Measurements of odour and hydrogen sulphide emissions from swine barns. *Canadian Biosystems Engineering* 45: 6.13–6.18.