Field Olfactometry Assessment of Dairy Manure Land Application Methods

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Surface application of manure in reduced tillage systems generates nuisance odors, but their management is hindered by a lack of standardized field quantification methods. An investigation was undertaken to evaluate odor emissions associated with various technologies that incorporate manure with minimal soil disturbance. Dairy manure slurry was applied by five methods in a 3.5-m swath to grassland in 61-m-inside-diameter rings. Nasal Ranger Field Olfactometer (NRO) instruments were used to collect dilutions-to-threshold (D/T) observations from the center of each ring using a panel of four odor assessors taking four readings each over a 10-min period. The Best Estimate Threshold D/T (BET_{10}) was calculated for each application method and an untreated control based on preapplication and <1 h, 2 to 4 h, and ~24 h after spreading. Whole-air samples were simultaneously collected for laboratory dynamic olfactometer evaluation using the triangular forced-choice (TFC) method. The BET_{10} of NRO data composited for all measurement times showed D/T decreased in the following order (α = 0.05): surface broadcast > aeration infiltration > surface + chisel incorporation > direct ground injection ≈ shallow disk injection > control, which closely followed laboratory TFC odor panel results (r = 0.83). At 24 h, odor reduction benefits relative to broadcasting persisted for all methods except aeration infiltration, and odors associated with direct ground injection were not different from the untreated control. Shallow disk injection provided substantial odor reduction with familiar toolbar equipment that is well adapted to regional soil conditions and conservation tillage operations.

As livestock production has evolved to more intensive and larger units, odors complaints have increased. Land application of livestock manures is one activity where odors are particularly intense, and manure spreading typically produces more annoying odor than the livestock facility itself (Noren, 1986). Besides the possibility of nuisance complaints, spreading equipment and methods have far-reaching implications for a farmer, affecting operating costs and fertilizer requirements.

Volatilization of odorous gases from surface-applied livestock manures is influenced by many factors such as temperature and wind speed, manure pH and moisture content, and the extent of contact between the manure and soil (Sommer and Olesen, 1991; Morken and Sakshaug, 1998). Manure incorporation is a well-documented method for mitigating odors and reducing nuisance complaints. Manure incorporation is often adopted as a best management practice for maximizing nutrient availability to crops and reducing potential runoff of nutrients to surface waters. Incorporation of manure can increase crop yields (Chen et al., 2001; Hanna et al., 2000) and reduce runoff nutrient losses (Kleinman and Sharpley, 2003). However, pastures and cropland under reduced tillage account for a substantial portion of land in North America. Manure in such systems is typically surface applied and not incorporated. Significant effort is underway to develop technologies that facilitate incorporation of liquid manures while minimizing soil and residue cover disturbance.

Incorporation of manure typically reduces odors compared with broadcast application. Hanna et al. (2000) found that several incorporation methods reduced odor levels by 20 to 90% compared with broadcast application of swine slurry. Chen et al. (2001) reported that ammonia volatilization after application of liquid swine manure followed the order: surface banding with a dribble bar > incorporation using an aerator > injection. Lau et al. (2003) found the swine manure odor emission rate with subsurface deposition was reduced 8 to 38% compared with conventional splash-plate application.

Quantifying odor is difficult because agricultural emissions are complex and transient. More than 290 odorous compounds have been identified in manure or the surrounding air (Yin-Cheung

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Abbreviations: BET_{10}, odor panel best estimate threshold for field observations collected over 10-min period; DGI, direct ground injection; DT, detection threshold; D/T, dilutions to threshold; ITE, individual threshold estimate; NRO, Nasal Ranger Field Olfactometer; RT, recognition threshold; TA, test administrator; TFC, triangular forced-choice olfactometry.

et al., 2008), and reduction of odor offensiveness may not be directly correlated with efforts to suppress individual components such as ammonia or hydrogen sulfide. Thus, direct sensory methods (olfactometry) using the human nose are still considered the most reliable means of quantifying odors (Miner, 1995). But human odor evaluation can be influenced by anxiety, distraction, personal comfort, and visual cues. For outdoor environments, local weather conditions also play an important role in odor release and transport. Despite limitations, olfactometry has the ultimate benefit of capturing the "total effect" human experience (Gostelow et al., 2003).

Laboratory-based triangular forced-choice olfactometry (TFC) measurement is presently considered to be the best available technology for odor quantification (USEPA, 1996; Zang et al., 2002). In 2003, the Comité Européen de Normalisation published a standard, EN13725 (CEN, 2003), which has been adopted by the European Union and received widespread acceptance for threshold olfactometry evaluation (St. Croix Sensory, 2005). This document provides standards for equipment, calibration, sampling, as well as odor panel selection, qualification, and size. Calculation of detection threshold (DT) from panel responses is also detailed.

Field-based olfactometry dilutions-to-threshold (D/T) observations are generally more convenient and less costly than laboratory TFC measurements (Miner, 1995; McGinley and McGinley, 2003). Field olfactometry is currently used as a regulatory tool in some states to verify complaints and determine compliance at property lines or in neighboring communities (McGinley and McGinley, 2003). Currently, eight U.S. states (Colorado, Connecticut, Illinois, Kentucky, Missouri, Nevada, North Dakota, Wyoming) use field olfactometry limits of 7 to 15 D/T for defining odor nuisance conditions (Maine Department of Environmental Protection, 2009). Thus, field olfactometry is used to monitor routine operations, document specific events or odor-release episodes, and to investigate the effectiveness of control practices. A recent study by Brandt et al. (2007) found that the Nasal Ranger Field Olfactometer (NRO; St. Croix Sensory, Inc., Lake Elmo, MN) can be a very useful management tool to aid producers and agricultural advisers in decision-making processes involving odor potential of production practices and odor reduction strategies. These researchers note that meaningful results are contingent on strict methodological protocols and recommend Best-Estimate Dilution Threshold (ASTM E679-04) data evaluation.

Because field olfactometry is increasingly used to quantify and regulate odor emissions from agricultural operations, it is important to define how this technique can be used to obtain meaningful measurements. Thus, a study objective was to investigate the use of field olfactometry for quantifying odors associated with five methods for dairy manure slurry application to grassland. Critical to the experiment was the design of a protocol that would minimize odor sampling variability. It was also important to understand how field olfactometry measurements compared with data collected via the internationally accepted TFC methodology. In addition to identifying effective land application strategies for manure odor mitigation, we hoped to understand how field olfactometry should be conducted to yield results with sufficient sensitivity to discriminate among the various methods evaluated.

Materials and Methods

Manure Characterization

Manure was obtained from a local dairy farm (200 lactating dairy cows) in October 2007 where it was scraped daily from freestall housing into a reception pit and then pumped (bottom-loaded) into an open-top Slurrystore manure storage tank (Slurrystore Systems, DeKalb, IL). While anoxic manure conditions typically dominate in such storage facilities, the tank was not managed as an anaerobic treatment unit. A small amount of barnyard runoff was added to facilitate unloading and field application twice per year. Table 1 shows the manure characteristics, which are typical for Pennsylvania dairy operations. Stored manure was loaded into a tractor-drawn manure-tanker unit equipped to accommodate various interchangeable field spreading implements.

Manure Application

To minimize the influence of variable wind direction and source distance, dairy manure slurry was applied at a uniform rate of 56,100 L ha^{-1} in a 3.5-m swath to sod, in 61-m-inside-diameter rings. An untreated area (control) was also established where odor observations were made in the absence of manure. To avoid cross-contamination among treatments, manure rings were carefully located considering local prevailing winds, and separated by 200 to 400 m. Due to the relatively small manure footprint of each manure ring, odors rapidly dissipated below detection downwind of treatments, but maximum topographic separation among rings was still employed to the greatest extent possible.

Odor emissions were measured for five methods of manure application, which are illustrated in Fig. 1:

1. *Surface broadcasting:* Manure was broadcast from a toolbar with six outlets placed above splash plates. Outlets were spaced 65 cm apart and were operated approximately 1 m above the ground.
2. *Surface plus chiseling:* Manure was broadcast and plots were chisel plowed (~20 cm deep) and culti-mulched approximately 1 h after manure application.

Table 1. Manure characteristics.†

Parameter	g kg^{-1} (dry basis)
pH (pH units)	8.01
Solids (%)	7.71
Total nitrogen	45.78
Ammonium N	16.93
Calculated organic N	28.85
Total phosphate (as P_2O_5)	14.27
Total potash (as K_2O)	43.77
Total calcium	23.74
Total magnesium	8.75
Total sulfur	4.47
Total copper	0.26
Total zinc	0.39
Total manganese	0.26
Total iron	1.56
Total sodium	7.78
Total aluminum	0.91

† Penn State Agricultural Analytical Services Laboratory using standard methods.

3. *Aeration infiltration:* An Aerway aerator (Holland Equipment Limited, Norwich, ON, Canada) was used for this treatment. The Aerway unit had 18 sets of rotating, spiked disk tines (four tines) spaced 0.2 m apart to create cavities in the soil. Manure was applied in a band (0.05-m width) on the soil surface behind each set of aeration tines so that some of the manure infiltrated into the 0.06-m-deep aeration cavities. The tine angle was set at 0 degrees.
4. *Shallow disk injection:* Six shallow disk injection assemblies (Yetter Avenger, Colchester, IL) were mounted on a toolbar and spaced 0.75 m apart. Each injector unit included a 0.6-m-diameter cutting disk, behind which was placed the manure drop tube. The cutting disk was set to create a 0.1-m-deep slot. Two disc sealers trailed the cutting disk/drop tube assembly to close the slot.
5. *Direct ground injection (DGI)*: The DGI system (Moi A/S, Orre, Norway) employed a pump to pressurize (0.6 to 0.8 MPa) slurry through injection nozzles that open and close during application. Nozzles were spaced 20 cm apart and located on skis that slide over the soil surface. Slurry was pulsed from nozzles with sufficient force to inject the slurry into the ground, forming 0.05- to 0.1 m-deep discontinuous cavities.
6. *Control:* An unmanured grassed plot served as the control treatment.

Field Olfactometry Measurements

Odor panel observations were made of the six treatments at 0 h (preapplication), 1 h, 2 to 4 h, and ~24 h following manure application. At each location, four qualified odor assessors (CEN, 2003) were positioned in the center of the manure ring and equipped with individual NRO units, which were used to determine the odor D/T (low dilution dial) value of the treatment. For each sampling event, field D/T observations were collected over a 10-min period under the supervision of a test administrator (TA), who ensured protocol compliance and recorded all observations.

Odor panelists wore half-face carbon-filter respirators to prevent odor desensitization. At each observation location, assessors were placed as close together as possible (shoulder-to-shoulder), facing the prevailing wind direction. The TA set each NRO unit to a blank setting (100% carbon-filtered air), and signaled panelists to simultaneously remove their respirators and begin D/T observations without inhaling (smelling) ambient air during the exchange. Assessors each operated their own NRO units, at their own pace. When an assessor noted a *detect* reading, the NRO unit was removed and the respirator replaced. Assessors then waited until other panelists completed their current observation (typically <1–2 min). When all assessors were finished, the TA recorded the NRO dilution dial D/T setting on each unit and then reset the dial to another blank position (as appropriate), and the process was repeated. In all, four sequential D/T readings were obtained by each of the four panelists, resulting in 16 individual measurements over the 10-min observation period. Care was taken to ensure that odor panelists were unaware of the D/T level on any units.

Odor assessors had no knowledge of the manure application methods and were prevented from inspecting the manure-treated areas. Wind speed and prevailing direction were recorded at each observation location, along with odor characterization (odor wheel descriptors by St. Croix Sensory, 2003). Weather data (temperature, relative humidity, barometric pressure, cloud cover, and precipitation) were also recorded.

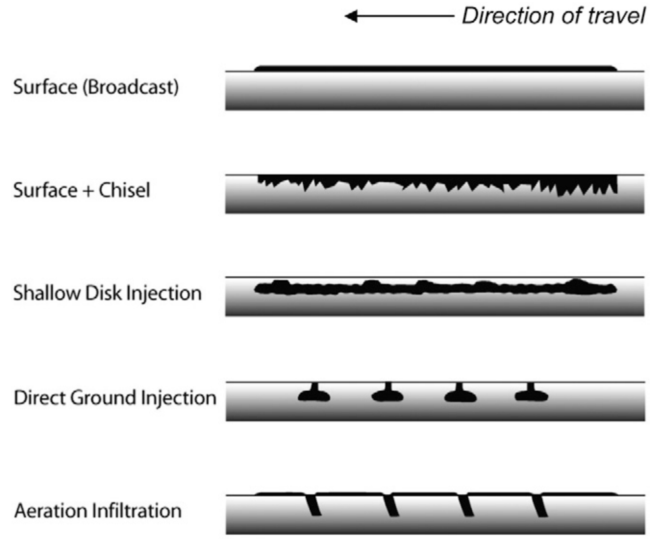

Fig. 1. Schematic of manure distribution for the various field application methods.

Laboratory-based Triangular Forced-choice Olfactometry

During the 2- to 4-h observation period, whole-air samples were collected for each treatment in preconditioned 10-L Tedlar bags (Smith Air Sample Supply Co., Hillsborough, NC). Preconditioning consisted of (i) inflating bags with odorless nitrogen (N_2) gas and expelling several times; (ii) baking half-inflated bags in a laboratory oven at 100°C overnight; (iii) expelling gas from the baked bag; and (iv) reinflating baked bags with fresh N_2 gas and expelling to vacate the bag (repeated as necessary until no bag odor was detectable). Sample bags were then inflated with odorless N_2 gas until use, typically within 48 h. In the field, N_2 was exhausted from the sample bag, which was then filled with the air sample of interest. This first fill was exhausted before refilling with the actual sample for evaluation. All field air samples were obtained at face level (~1.5 m) immediately adjacent to assessors using a suitcase vacuum chamber unit employing the lung principle. Approximately 8 L of whole air was collected during each panel observation set, representing a composite sample for each 10-min sampling event. In all, six whole-air samples were secured and preserved (room temperature, dark) for odor panel evaluation the following day. Laboratory TFC DT and recognition threshold (RT) levels were determined with an Ac'Scent International Dynamic Olfactometer within 24 h of sample collection.

Data Treatment

Field olfactometry data were processed to determine a Best Estimate Threshold (BET) odor D/T value for each panel data set (16 observations). In this method (ASTM E679-04), the geometric mean of the last nondetect dilution ratio and the detectable dilution ratio is determined for each assessor [known as the Individual Threshold Estimate (ITE)]. The overall panel BET was then determined as the geometric mean of all ITE values. Since this method was applied to field olfactometry observations collected during a 10-min period, we introduce the term "BET_{10}" to distinguish this calculated value apart from lab-based olfactometry results reported elsewhere in the literature.

Laboratory TFC odor panel results were evaluated in accordance with EN13725:2003 calculation and retrospective screening procedures. In this study, TFC odor panel threshold results are identified as $Z_{ITE,pan}$ following CEN (2003) terminology. Basic statistics (mean, median, mode, standard deviation, coefficient of variation, and minimum and maximum values) were determined using log-transformed data.

Statistical evaluations were performed to assess the effect of manure application methods on odor emission using SAS (SAS Institute, 2003). The effect and interaction of application method, time of measurement, and odor quantification method (NRO vs. TFC) were analyzed using the PROC MIXED covariance test. Least significant differences were determined when the effect of application method on odor panel results was found to be significant ($\alpha = 0.05$). Relationships with environmental variables were assessed using Pearson correlation and stepwise regression analyses. The Shapiro–Wilk test (SAS Institute, 2003) showed that log BET_{10} data were normally distributed. Variance analyses were performed on odor panel data from the Ac'Scent instrument (TFC) and NRO field observations, which were found to be normally distributed ($P < 0.0001$).

Results and Discussion

Influence of Manure Application Method

Table 2 shows the log BET_{10} values for application methods and sampling times. For comparison, individual and composited arithmetic BET_{10} values are plotted in Fig. 2. Correlation analysis of weather data indicated that none of the measured climatic factors were significantly related to log BET_{10} for any of the treatments. Time 0 (Table 2 and Fig. 2) readings were collected at all sites before manure application. With one exception, the log BET_{10} values at Time 0 were identical, and four of five application sites had background D/T odor levels not statistically different from the control site. The Time 0 log BET_{10} value for aeration infiltration method site was statistically higher. All other ring sites were surrounded by open grassland, while the aeration infiltration treatment ring was located ~30 m from the edge of a normally downwind wooded area. During background measurement, the wind direction shifted so that natural emissions from the woodlot were detected and described as "earthy" by assessors.

As expected, readings from the untreated control location were significantly lower than those for any of the application sites. For the DGI method, the odor D/T level had dissipated by 24 h to the point that it was no longer statistically greater than the untreated control, indicating the greater effectiveness of this technique for controlling odors.

The log BET_{10} D/T values for the three postapplication sampling times and the composite values (Table 2 and Fig. 2) have some features in common. At all sampling times, the surface broadcast application had the highest log BET_{10} values. Others have documented lower odor emissions using methods that incorporate or mix manure into the soil (Pain et al., 1991; Moseley et al., 1998; Hanna et al., 2000; Chen et al., 2001). However, in our study, broadcast application was not always statistically higher than every other application method. For example, at the <1-h and 24-h observation times, the aeration infiltration method exhibited statistically similar odor levels. And at the 2- to 4-h time period, the effect of chiseling following surface application did not produce statistically lower odors compared with surface broadcasting. However, all incorporation methods resulted in lower odor production than surface broadcasting for at least one observation time.

Noteworthy was the relative inability of the aeration infiltration device to significantly mitigate manure odors. This device consists of rotating knives which cut the soil surface, followed by manure spreading which fills the cuts in the soil. For two time periods (<1 h and 24 h) aeration infiltration had odor D/T levels statistically similar to surface broadcasting. As represented in Fig. 1, aeration infiltration is a partial incorporation method. In work conducted at the USDA Forage Research Center, Johnson (2007) found ammonia emissions for different application methods followed the order: surface broadcast > aeration device > injection. However, Bonnefoy (2001) found no difference in odor concentrations between surface application and an aerator device using a dynamic olfactometer with the TFC method. Lau et al. (2003) found statistically lower odor strength 0.5 h after application of swine manure for an aeration infiltration spreading device compared with conventional splash-plate surface application. At later observation times (1.5 and 2.5 h) the gap between the measured odor for the two methods decreased. Our <1-h observations (Table 2) are consistent with the results of Chen et al. (2001) who found that odor concentrations immediately after manure application were

Table 2. Field olfactometry odor panel dilutions-to-threshold (D/T) log BET_{10}† (mean ± standard deviation) sorted by application method and time.

Method	Time			
	0 h (preapplication)	<1 h	2–4 h	24 h
Direct ground injection	0.151 ± 0.0b‡	0.633 ± 0.133b	0.406 ± 0.275b	0.226 ± 0.135bc
Aeration infiltration	0.438 ± 0.31a	0.942 ± 0.197a	0.430 ± 0.133b	0.622 ± 0.290a
Shallow disk injection	0.151 ± 0.0b	0.678 ± 0.429b	0.224 ± 0.168c	0.280 ± 0.185b
Surface broadcast	0.151 ± 0.04b	1.113 ± 0.215a	0.784 ± 0.3214a	0.690 ± 0.204a
Surface + chisel	0.151 ± 0.0b	0.549 ± 0.252b	0.692 ± 0.250a	0.335 ± 0.209b
Control	0.151 ± 0.0b	0.151 ± 0.0c	0.181 ± 0.103c	0.151 ± 0.0c

† BET_{10} = Odor panel best estimate threshold (ASTM E669) for field observations collected over 10-min period.

‡ Values followed by the same letter are not significantly different ($\alpha = 0.05$).

not statistically different for aerator incorporation and surface banding with a dribble bar.

The data do not permit an unequivocal assessment of the effect of surface chiseling on odor generation. Odor levels at the <1- and 24-h times were significantly different from the broadcast application. However, the 2- to 4-h data (both field and laboratory olfactometry) indicated that chiseling following surface spreading did not reduce odors. Pain et al. (1991) reported odor emission during the first hour after spreading were similar for plowing with a rigid-tine instrument vs. simple surface application.

Two application methods (shallow disk injection and DGI) consistently generated lower odors than did the surface broadcast method. Both methods result in a significant proportion of the manure being covered by soil (Fig. 1). With DGI, the manure is injected in pulses to form discontinuous cavities beneath the soil surface (Morken and Sakshaug, 1998). This method would presumably involve the least amount of slurry–atmosphere contact following application. In a related unpublished study using exactly the same equipment at Penn State University, C. Dell (personal communication, 2010) found that DGI application resulted in 32% less manure on the surface compared with surface broadcasting. This technique has been shown to result in lower ammonia emissions relative to surface broadcasting and band spreading (Morken and Sakshaug, 1998). In our study, the DGI had the lowest overall odor potential according to composited field olfactometry data (Fig. 2) and laboratory dynamic olfactometer DT results (Table 3). Except for the <1-h observations, the shallow disk was equal to, or better than, the DGI in reducing odors compared with surface broadcasting. C. Dell (personal communication, 2010) found that shallow disk application had 56% less manure surface exposure compared with broadcast application, which helps to explain why shallow disk injection was so effective.

Figure 3 shows the effect of time on odor release for each treatment. These results are consistent with the expectation that odor potential is greatest immediately after application and then decreases with time. For example, ammonia emissions are highest right after manure application (Johnson, 2007). Lau et al. (2003) found odor strength from pig manure spreading on grassland consistently decreased from 0.5 to 2.5 h after application. Hanna et al. (2000) reported that odors measured 1 d after swine manure application (various methods) were comparable to odors from untreated soil. Our results for dairy manure do not support such a conclusion (Fig. 2 and Table 2), with a single exception. The log BET_{10} values for the DGI method were similar to the control plots at the 24-h observation time (Table 2).

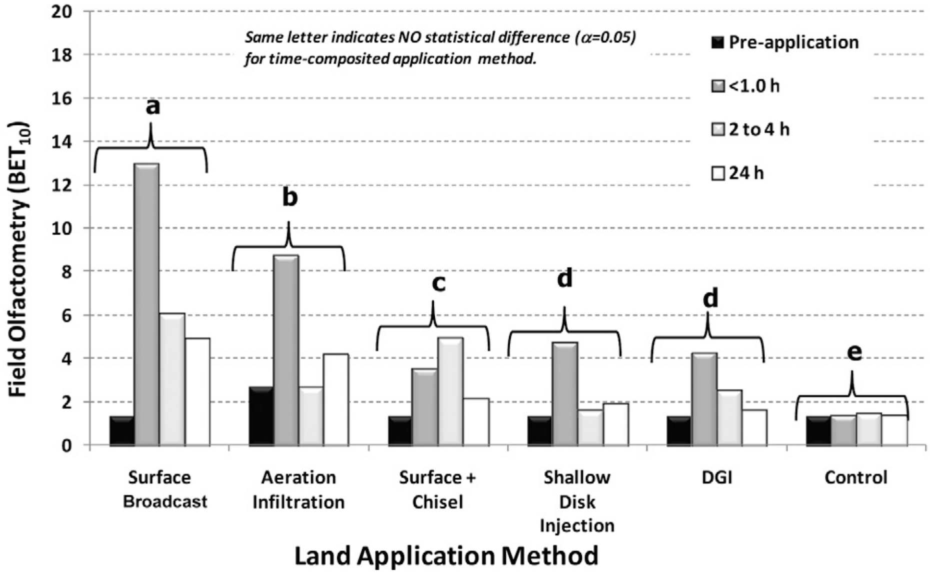

Fig. 2. Average field olfactometry pooled values (arithmetic BET_{10}) for all observation times. Methods designated by the same letter were not statistically different at α = 0.05. BET_{10}, odor panel best estimate threshold (ASTM E669) for field observations collected over 10-min period; DGI, direct ground injection.

Comparison of Field vs. Laboratory-based Olfactometry Results

Tables 2 and 3 allow comparison of laboratory TFC olfactometry log $Z_{ITE,PAN}$ (log DT and log RT) results with the field BET_{10} (log D/T) findings for the 2- to 4-h observation period. Laboratory DT and NRO BET_{10} were highly correlated (r = 0.83). Noteworthy is the discrepancy between laboratory log DT and field log D/T odor panel values, which in most cases are more than an order of magnitude different. Newby and McGinley (2004) likewise found laboratory TFC odor panel levels to be much higher than field olfactometry readings and concluded that a laboratory DT of 110 was approximately equivalent to a field olfactometry D/T level of 7:1. Though differences were not as pronounced, Bokowa (2008) reported that the NRO device gives significantly (2× to 3×) lower odor detection threshold values than ambient air sampling with laboratory assessment. Bokowa (2008) attributes the discrepancy to three factors: (i) inadequate removal of selected odorants (e.g., sulfur compounds, dimethylamine, trimethylamine) by

Table 3. Mean laboratory olfactometry log detection threshold (DT) and log recognition (RT) results for whole-air samples collected 2 to 4 h following manure application.

Method	Laboratory olfactometry odor panel (log $Z_{ITE,pan}$)†	
	Detection threshold (log DT)	Recognition threshold (log RT)
Direct ground injection	1.62 ± 0.11b‡	1.32 ± 0.11c
Aeration infiltration	2.11 ± 0.36a	1.80 ± 0.25a
Shallow disk injection	1.84 ± 0.15b	1.58 ± 0.14b
Surface broadcast	2.23 ± 0.30a	1.89 ± 0.28a
Surface + chiseling	2.23 ± 0.30a	1.86 ± 0.25a
Control	1.35 ± 0.00c	1.05 ± 0.00d

† $Z_{ITE,pan}$ = Odor panel dilution factor (CEN, 2003).

‡ Log DT and log RT standard deviation values followed by the same letter are not significantly different (α = 0.05).

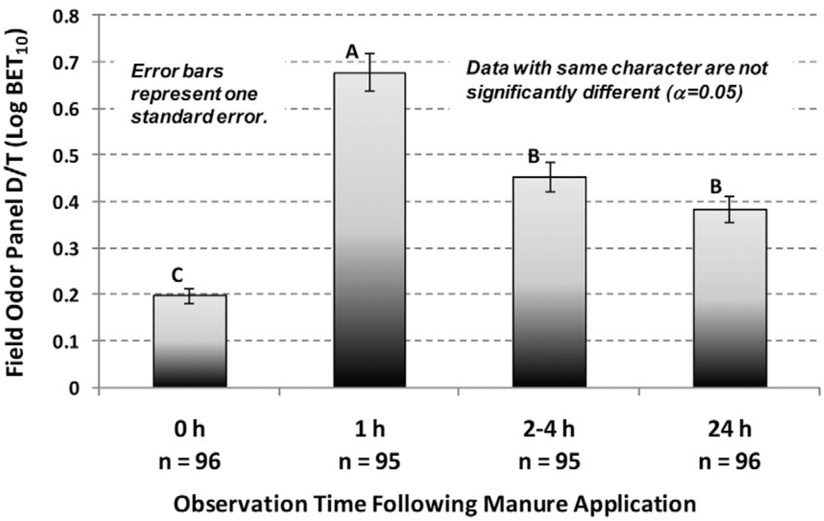

Fig. 3. Field olfactometry log BET_{10} D/T values for all sampling periods and field application methods combined. Error bars were computed as 1 SE. Average field odor panel log BET_{10} values followed by the same letter were not significantly different at α = 0.05. BET_{10}, odor panel best estimate threshold (ASTM E669) for field observations collected over 10-min period; D/T, dilutions-to-threshold.

the NRO carbon filters; (ii) single-person field measurements; and/or (iii) NRO assessor odor fatigue over time.

Factors cited by Bokowa (2008) likely played a minor role in our study. All NRO assessors wore carbon-filter respirators when in the vicinity of manure emissions and switched to NRO units without breathing unfiltered air. Thus, assessors were exposed to manure odors during D/T observations, and then only when observing a threshold *detect* reading. At the conclusion of each observation set, assessors were instructed to remove their masks and characterize the unfiltered whole air. Panelists never detected odors while wearing the respirator or the NRO unit when set at a blank position (100% carbon-filtered air). Moreover, assessors often commented that they were surprised with the strong odor intensity of ambient air during initial observations after manure spreading. At least 30 min elapsed between exposures to full-strength malodorous air, providing ample time for nasal sensitivity recovery. Based on assessor feedback, the respirator and NRO unit filter cartridges effectively removed odorants below detection. Because we used multiple assessors, Bokowa's (2008) single-observer rationale is inapplicable. Detailed statistical analysis of the NRO field data collected throughout the experiment revealed no trends in reported D/T levels that would suggest desensitization of odor assessors. While we believe it unlikely, it is possible that low-level odors (below detection) may have passed through the carbon filter units and induced odor desensitization.

Other possible explanations for greater laboratory olfactometry odor panel DT levels relative to field NRO odor panel results include (i) the use of TFC (lab) vs. Yes/No (field) odor panel methodologies; (ii) ultra-clean odor-free laboratory environment vs. inherently tainted field conditions; (iii) temperature differences between field (12°C) and laboratory (21°C) environments; and (iv) adulteration of whole-air samples related to Tedlar bag containers and holding time (~24 h). It is also noteworthy that many people who use the NRO will not register a detect (*Yes*) response until they notice some character of the odor. Such a response is more appropriately identified as the RT, which is typically about half of the DT level in laboratory olfactometry. This would account for much of the discrepancy between lab and field olfactometry thresholds noted by Bokowa (2008), but alone cannot explain the magnitude of difference in our work, which is more similar to the findings of Newby and McGinley (2004).

Despite the numerical differences between lab and field values, it is noteworthy that the odor emission trend for the various land application technologies is similar (Tables 2 and 3). Because laboratory TFC olfactometry is considered the standard for threshold olfactometry, we conclude that the NRO field protocol employed in this study was effective. Indeed, one may argue that the NRO technique presented here may be more effective than the laboratory TFC method for quantifying low-threshold odor emissions. For example, statistical analyses of field olfactometry BET_{10} results for various application methods, composited over time, enabled discrimination of five statistically different odor emission categories (Fig. 2). This was made possible, at least in part, by the number of observations collected in the field. Laboratory TFC measurements were limited to only one composite air sample for each treatment (six samples total) for the 2- to 4-h event, due to logistical constraints and cost. In the laboratory, 12 individual odor panelist observations for each sample were performed per CEN (2003). As a result, laboratory odor panel DT and RT results provided only three statistically different odor emission categories, respectively.

Conclusions

Increasing frequency of odor complaints and lawsuits are linked to population migration to rural agricultural communities. Some states are adopting odor guidelines which include limits based on field olfactometry. We analyzed odors associated with different dairy manure application methods to identify effective odor reduction techniques and refine protocols for field olfactometry observations.

Because field observations are influenced by changing conditions (e.g., wind direction and distance from source), a circular ring configuration is useful for investigating odor differences among manure application methods. Pooled field olfactometry log BET_{10} data found odor D/T levels decreased as follows (α = 0.05): surface broadcast > aeration infiltration > surface + chisel incorporation > direct ground injection ≈ shallow disk injection > control, which closely followed visual estimates of manure remaining on the surface. Field olfactometry findings were highly correlated with laboratory TFC olfactometry (r = 0.83) 2 to 4 h following application, providing added confidence in the manure-ring technique. Shallow disk injection provided substantial odor reduction using familiar toolbar equipment well adapted to regional soil conditions and conservation tillage management.

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