Enhancing Soil Infiltration Reduces Gaseous Emissions and Improves N Uptake from Applied Dairy Slurry

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Rapid infiltration of liquid manure into the soil reduces emissions of ammonia (NH_3) into the atmosphere. This study was undertaken to assess the effects of two low-cost methods of assisting infiltration of applied dairy slurry on emissions of NH_3, nitrous oxide (N_2O), and on crop N uptake. The two methods were removing of solids by settling-decantation to make the manure less viscous and mechanically aerating the soil. Ammonia emissions were measured with wind tunnels as percentage of applied total ammoniacal nitrogen (TAN) while emissions of N_2O were measured with vented chambers. Mechanically aerating the soil before manure application significantly reduced emissions of NH_3 relative to the nonaerated soil in spring (38.6 to 20.3% of applied TAN), summer (41.1 to 26.4% of applied TAN) and fall (27.7 to 13.6% of applied TAN) trials. Decantation of manure had no effect on NH_3 emissions in spring, tended to increase emissions in summer and significantly decreased emissions in fall (30.3 to 11.1% of applied TAN). Combining the two abatement techniques reduced NH_3 emission by 82% in fall, under cool weather conditions typical of manure spreading. The two abatement techniques generally did not significantly affect N_2O emissions. Uptake of applied N by Italian ryegrass (*Lolium multiflorum* Lam.) was generally significantly greater with decanted than from whole manure but the effect of aeration was generally small and not significant. The study shows that low cost methods that assist manure infiltration into the soil may be used to greatly reduce ammonia loss without increasing N_2O emissions, but efficacy of abatement methods is affected by weather conditions.

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Animal manures are known to contain important plant nutrients beneficial for crop production. Manure application in soil can lead to large N losses to the environment, especially the atmosphere (Neeteson, 2000). Atmospheric emission of gaseous N reduces efficacy of manure N and contributes to environmental pollution through N deposition and acidification, formation of particulates, and global warming. In Canada, land application of manure causes approximately 9.5% of the N_2O emission from agricultural soils (Environment Canada, 2006). For the dairy industry in Canada, about 40% of the loss of NH_3 to the atmosphere occurs in land spreading of liquid manure (S.C. Sheppard and S. Bittman, unpublished data, 2008). Sustainable agriculture must aim at making optimal use of the applied manure nutrients.

Emissions of NH_3 and N_2O are influenced by many factors as well as interactions among these factors (Jarvis and Pain, 1994; Amon et al., 2006), requiring a multifaceted approach to reduce emissions of these gases. It is important that controlling emissions of one pollutant does not inadvertently enhance the emission of other pollutants. Low-cost manure application technologies are needed to reduce emissions of both NH_3 and N_2O from field applied manure. New manure application technologies need to be carefully assessed to provide appropriate emission factors for national NH_3 and N_2O inventories and also to ensure that costs can be justified. Incorporation and injection of manure into the soil reduce NH_3 emission but these techniques are costly and often problematic due to stones, hard soils, etc. (e.g., Malgeryd, 1998; Rodhe and Etana, 2005). Lower cost methods such as surface banding (Huijsmans et al., 2004; Bittman et al., 1999) and shallow incorporation (Rochette et al., 2001; Rodhe and Etana, 2005) have been shown to reduce emissions and improve crop uptake of N. Bittman et al. (2005) proposed a method to assist infiltration of slurry manure by banding manure over aeration slots made by rolling tines. These methods reduce NH_3 loss by reducing surface and time exposure of manure with the air and bring it more in contact with the soil (Sommer and Hutchings, 2001). In some cases, techniques used to reduce am-

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Abbreviations: DM, dry matter content; MAI, mechanically assisted infiltration; SWC, soil water content; TAN, total ammoniacal nitrogen; WFPS, water-filled pore space.

monia emissions result in greater N_2O emissions compared with surface spreading (Dosch and Gutser, 1995).

Decreasing the dry matter content of liquid manure is known to reduce ammonia emission (Sommer et al., 2006) by reducing viscosity of manure, which facilitates soil infiltration (Stevens and Laughlin, 1997). This reduction in NH_3 volatilization has been found to increase uptake of swine (*Sus scrofa*) manure N by perennial forages (Chantigny et al., 2007). Removing solids has the added benefit of lowering concentration of nutrients, especially P (Chantigny et al., 2007), allowing greater application volumes, which reduces hauling distances.

Few studies have examined the efficacy of practical techniques for abating ammonia loss from land-applied manure while assessing the effects of these techniques on emissions of N_2O. The goal of this study was to test the efficacy of two simple low-cost methods of assisting manure infiltration into the soil, solids removal by settling and decantation, and surface banding liquid manure over aeration pockets (Bittman et al., 2005), on emissions of NH_3 and N_2O emission and crop N uptake.

Materials and Methods

Field trials were conducted in 2005 and 2006 at the Pacific Agri-Food Research Centre, located at Agassiz in south coastal British Columbia (BC). The soil at the experimental site is silty to sandy loam belonging to the Monroe series, described as Typic Dystrudept of moderately good drainage derived from medium texture stone-free Fraser river deposits (Luttmerding, 1981). The soil (0–15 cm depth) has an organic matter content of 60 g kg^{-1} (23 g kg^{-1} soil carbon) and bulk density of 1.09 g cm^{-3}. The land was fallow with no crop cover on it. The experiments were arranged in randomized complete block designs with four or five treatments and four replicates. The plot size was 6 by 6 m. Different plots were used for each of the six trials though they were located at close proximity (<80 m apart) and had similar soil type. Within each plot, areas were dedicated for measurement of NH_3 (0.5 by 2 m), N_2O (0.6 by 0.6 m), herbage yield (1 by 2 m) and soil sampling (2 by 2 m). The wind tunnels for measuring NH_3 emissions and chambers for measuring N_2O were installed on bare land.

The dairy slurry manure used for the trial was collected in each fall before the trials from typical commercial dairy farms using sawdust bedding in free-stall barns with frequent scraping. The slurry was stored undisturbed over winter in two identical 2.5-m deep tanks. In spring, the surface crust was removed from one tank and the upper 0.6 m of the liquid was decanted. Whole manure was collected from the second tank after agitation. The two manure products (whole and decanted liquid) were stored in sealed tanks for use in each trial. There were four manure treatment combinations: all combinations of decanted and whole manures applied by surface broadcasting (surface) or mechanically assisted infiltration (MAI). The latter was performed by manually banding the slurry over aeration slots (aerated) formed with the AerWay (Holland Canada, Norwich ON) implement (set at 5° offset angle) to simulate the AerWay SSD applicator (Bittman et al., 2005). The four manure treatments were: decanted surface, decanted MAI, whole surface, and whole MAI. A control (no manure) treatment was also used for N_2O and crop N uptake measurements.

Six trials were conducted in the spring, summer, and fall seasons of 2005 and 2006. The start dates of the trials are presented in Table 1. The decanted and whole manures were analyzed for total ammoniacal nitrogen (TAN), total N, dry matter (DM), and pH. The total N in the manure was determined by Kjeldahl method and ammonium was determined by steam distillation, followed by titration (McGill and Figueiredo, 1993). Dry matter content of the manure was determined after oven drying at 60°C for 24 h and pH was measured using pH meter (Model 810, Fisher Scientific, Ottawa). Total P was determined by inductively coupled plasma (ICP) spectrophotometry after nitric acid digestion. Manure properties and application rates are presented in Table 2. Target application rate was set at 125 kg ha^{-1} TAN. A lower rate of TAN was applied in fall 2006 so that the volume applied did not exceed 125 m^3 ha^{-1}. A greater volume would have resulted in the liquid running off the plots. The study area is extremely flat and where necessary small dikes were formed so runoff from plot areas was minimal.

Ammonia Emissions

Ammonia volatilization was measured in each trial using the wind tunnel technique of Lockyer (1984) with one tunnel per treatment. Sampling periods are shown on Table 1. The tunnel (0.5 by 2 m by 0.45 m high) consisted of an inverted U-shaped transparent polycarbonate sheet (3.15 mm thick) connected to a steel duct housing an electrically powered fan which drew air through the tunnel and into a tapered 15-cm diam. orifice. Air velocity (maintained at 1 m s^{-1}) was monitored continuously with a rotary anemometer connected to a CR10 data logger (Campbell Scientific Inc., Logan, UT). An air sample was drawn from both ends of the tunnel through Teflon coated tygon tubing at 5 L min^{-1} to determine increase in NH_3 emission within the tunnel due to manure. The cumulative sample air flow was measured with Gallus 2000 gas flow meters (Norgas Controls, Inc., Burlington, KY). The air samples were bubbled through a 100-mL solution of orthophosphoric acid (0.005 mol L^{-1}) to trap the emitted NH_3. On the first sampling day, when the rate of NH_3 volatilization was anticipated to be the highest, acid-traps were changed (shifts) 1, 2, and 5 h following manure application. Thereafter, traps were changed at approximately 12-h intervals for 8 d, and 24-h interval for the remainder of the measurement period. The anemometers and gas flow meters were frequently tested and data were cross referenced.

Acid traps were stored at 5°C then brought to a 120 mL volume with distilled water before analysis. Samples were analyzed for NH_4 with a flow injection analyzer (FIA Star 5000, FOSS Analytical AB, Hoganas, Sweden). The NH_3 emission rate in the tunnel was calculated using the ratio of tunnel airflow rate to the subsample airflow rate:

$$E = (C_o - C_i)\, V R$$

where, E is NH_3 emission rate; C_o is concentration of NH_3 at fan intake in mg L^{-1}; C_i is concentration of NH_3 at tunnel intake in mg L^{-1}; V is volume of acid trap solution in mL; R

Table 1. Dates of manure application, gas emission measurement periods, grass harvest dates, soil water content, soil temperature, and air temperatures for spring, summer, and fall trials in 2005 and 2006 at Agassiz, BC.

	Spring		Summer		Fall	
	2005	2006	2005	2006	2005	2006
Treatment application date	12 May 2005	30 May 2006	25 July 2005	11 July 2006	20 Oct 2005	24 Oct. 2006
N_2O measurement period	13 May 2005 to 15 Feb. 2006	31 May 2006 to 8 Mar. 2007	27 July 2005 to 21 Feb. 2006	12 July 2005 to 19 Mar. 2007	21 Oct. 2005 to 22 Mar. 2006	25 Oct. 2006 to 19 June 2007
NH_3 measurement period	12 to 26 May 2005	30 May to 11 June 2006	25 July to 9 Aug. 2005	11 to 24 July 2006	20 Oct. to 3 Nov. 2005	24 Oct. to 5 Nov. 2006
Herbage cut date	21 July 2005	11 Oct. 2006	26 Oct. 2005	11 Oct. 2006	20 June 2006	21 May 2007
Soil water content, g kg^{-1}†	311	357	328	261	374	330
Soil temperature, °C†	20.6	23.6	22.8	19.7	13.9	7.0
Air temperature, °C†	15.3	15.0	18.8	17.4	10.8	7.6
Soil NH_4–N, kg ha^{-1}	10.1	13.2	10.0	12.4	10.6	9.8
Soil NO_3–N, kg ha^{-1}	11.0	10.0	6.9	22.2	10.9	43.2

† Values as measured on Day 1 of the respective trials.

Table 2. Properties and application rates of the dairy cattle liquid manure in spring, summer, and fall trials in 2005 and 2006 at Agassiz, BC.

Trials	Manure type	TAN†	TN†	DM†	pH	P	Application volume	Application rate
			g kg^{-1}			mg kg^{-1}	m^3 ha^{-1}	kg NH_4–N ha^{-1}
Spring 2005	Decanted	1.2	1.8	28	7.0	21	120	144
	Whole	1.3	2.4	68	6.8	45	100	130
Summer 2005	Decanted	1.1	1.5	22	7.4	16	126	139
	Whole	1.2	2.4	72	6.8	41	104	125
Fall 2005	Decanted	1.0	1.2	13	8.1	6	133	133
	Whole	1.1	2.5	70	7.5	52	109	120
Spring 2006	Decanted	0.9	1.7	28	–	34	124	114
	Whole	1.0	2.1	60	–	48	115	115
Summer 2006	Decanted	0.9	1.3	2	–	19	141	124
	Whole	1.0	2.0	57	–	56	120	124
Fall 2006	Decanted	0.6	1.0	13	–	14	127	80
	Whole	1.0	2.0	46	–	50	70	67

† TAN, total ammoniacal nitrogen; TN, total nitrogen; DM, dry matter content.

is the ratio of tunnel airflow rate to the sample airflow rate. The ratio of flow rates was calculated as $v\ A/Q$; v is rotary anemometer wind speed in m s^{-1}, A is tunnel cross-sectional area in m^2 and Q is the sample flow rate in m^3 s^{-1}.

Nitrous Oxide Measurement

During the first week of each trial, N_2O emissions were measured on alternate days to capture major changes in N_2O fluxes. Frequency of N_2O measurements decreased as the fluxes approached background levels. Nitrous oxide was measured using one square vented aluminum chamber (0.60 by 0.60 m) per plot. The chamber collar (height 12 cm) remained installed in the soil throughout the trial period at approximate depth of 5 to 6 cm. On each sampling day, a vented lid (height 5 cm) was placed on the collar (water channel seal) and 20-mL gas samples from inside the chamber were drawn at 0, 30, 45, and 60 min after closing of the chamber with a 30-mL syringe and transferred to 12 mL-evacuated vials (soda glass flat bottomed vials; 101 × 15.5 mm in size). At the end of each sampling period the lid was removed from the base. Measurements were made consistently between 0900 and 1200 h.

The gas samples collected in the vials were analyzed using a Varian CP-3800 gas chromatograph equipped with a ^{63}Ni-electron capture detector (Lemke et al., 1998). Nitrous oxide flux was calculated by multiplying the number of moles of air in the chamber by the slope of the change in N_2O concentration in the chamber as sampling time progressed. Moles of air in the chamber were calculated using ideal gas law (n = PV/RT; where n = number of moles of air, P = atmospheric pressure, T = temperature in Kelvin, R = molar gas constant and V = volume of chamber in liters) and slope of the N_2O produced in the chamber was calculated from the change in N_2O concentration in the chamber over the sampling period by assuming a steady-state increase of N_2O from the soil. The flux values were then converted to grams N_2O-N ha^{-1} d^{-1}. Cumulative N_2O emission was then approximated by linearly interpolating data points and integrating the underlying area assuming that the measurements made between 0900 and 1200 h were good estimations of average daily N_2O emission. The method and reference gases were calibrated across several Canadian laboratories.

Soil Sampling and Analysis

Four soil cores (0–15 cm depth; 2.5 cm diam.) were collected on each N_2O gas sampling day and mixed to make one composite sample per plot. Gravimetric soil water content (SWC) was measured as the mass loss of a subsample (approximately 50 g) after oven-drying at 105°C until constant weight. The remainder of the composite soil sample was air dried and crushed to <2 mm for N measurements. Mineral N was extracted from the dried soil with 2 mol L^{-1} KCl solution by shaking for 1 h (1:10 soil/solution ratio). The extracts were analyzed for NO_3 and NH_4 by standard colorimetric methods on the flow injection analyzer described above for analysis of NH_4 in acid traps.

The SWC and soil N contents were converted to soil volume basis by multiplying the content with the soil bulk density. Soil bulk density was measured using core method immediately before the commencement of the trial. Four replicates of undisturbed soil cores (9.7cm in diameter) were collected from each plot. Water-filled pore space (WFPS) was calculated as the ratio of the volumetric SWC to the total pore space which was calculated as follows:

Total pore space = 1 – (Soil bulk density/Soil particle density)

where, soil particle density was 2.56 g cm^{-3} as determined by the suspension method (Blake and Hartge, 1986).

Soil temperature at 7.5 cm soil depth was measured with a Digi-Sense thermocouple thermometer (Cole-Parmer Canada Inc., Montreal, QC, Canada) along with N_2O measurements. The SWC and the soil and air temperatures at the beginning of the trials are presented in Table 1. Air temperature (hourly) was measured at a weather station located <500 m from the study site. Water-filled pore space and soil temperature distribution during the measurement period for each trial are presented in Fig. 1 and 2, respectively.

Herbage Yield

Italian ryegrass was sown in each trial, after applying the manure, in the area within each plot marked for herbage yield production. The herbage harvest dates for each trial are presented in Table 1. The herbage samples were cut to a height of 2 to 3 cm above the ground and after measuring the fresh weight they were dried at 60°C to constant weight to determine DM yield. Concentration of N in herbage was determined with an automated dry-ash instrument (FP-428 Nitrogen Analyzer, LECO Corp., St. Joseph, MI). Uptake of N by crop was determined by multiplying N concentration with herbage DM yield. Uptake values were standardized for application rates of TAN and of total N by dividing the N uptake by the herbage with the total TAN or TN applied through manure.

Statistical Analysis

Gaseous N emission data for individual sampling dates and cumulative values were subjected to analysis of variance using SAS Proc GLM (SAS Institute, 2004). Interaction between the manure type and application method was also calculated. Treatment means were compared using Fishers protected least significant difference (LSD). Statistical significance was set a priori to the 5% confidence level. As NH_3 emission from soil is influenced mainly by the TAN applied and N_2O emissions as well as N uptake by the plants is more affected by the total N present, thus in this paper results for NH_3 emissions are expressed as percent of TAN and those of N_2O emission and plant N uptake are expressed as percent of total N added from the manure application.

Results and Discussion

Ammonia Emissions

For whole slurry manure applied on the soil surface, which is standard practice on dairy farms in Canada (Statistics Canada, personal communication, 2006) loss of NH_3 was fairly similar across all trials, ranging from 36.7 to 41.9% of applied TAN (Table 3). Emission values previously reported for similar dairy slurry at the same site, using micrometeorological method, ranged from 37 to 64% of applied TAN (Bittman et al., 2005). Measurements made using the micrometeorological technique are often higher than wind tunnel measurements (Søgaard et al., 2002). The EMEP (2007) attributes an emission coefficient of 55% of applied TAN for broadcasted dairy slurry. Our emission measurements for surface-applied whole manure are consistent with values (44% of applied TAN) simulated for similar conditions by the ALFAM model (Søgaard et al., 2002). Mechanically assisted infiltration reduced NH_3 emissions from both manure types by 32 to 66% (average of 42% across all treatments and trials), relative to broadcasting (Table 3). The MAI effect was always statistically significant; where there was significant interaction between manure type and method of application, the reduction with MAI was greater for manure type with the highest NH_3 emission (decanted manure in summer 2005; whole manure in fall 2006). The reductions in NH_3 emissions reported here (32–39%) for whole manure (except in fall 2006) are generally lower than reductions attributed to open or shallow injection systems, but comparable to reductions attributed to surface banding systems (e.g., Søgaard et al., 2002) although many factors can affect abatement. The reductions in this study (except fall 2006) are more typical of reports on surface banding than partial or shallow injection systems, but in European studies manure was often applied at much lower rates, typically 25 to 30 m^3 (e.g., Huijsmans et al., 2004, Rodhe and Etana, 2005, Hansen et al., 2003) which is less than one-third the volumes applied in these trials. The greater benefit of MAI for whole manure in the fall 2006 compared to fall 2005 trial may be due to lower application volume (70– vs. 100–120 m^3 ha^{-1}), so that little manure remained on the soil surface after application. Sagoo et al. (2007) showed that the benefit of shallow (open slot) injection over broadcasting in reducing NH_3 emissions is greater when cattle slurry is applied at 50 to 65 than at 80 m^3 ha^{-1}.

The effect of solids removal on NH_3 emission varied with season (Table 3). In spring of both years there was little difference in NH_3 emissions between manure types and no interaction with method of application. In summer of 2005, decanted manure emitted more NH_3 than whole manure under both application methods, with the greater difference for surface applied manure (significant interaction). Manure type had no effect on NH_3 emissions in summer of 2006. In contrast to spring and summer, emissions in fall were greatly reduced by solids removal in both 2005 (59% reduction) and 2006 (69% reduction); the effect was greater for surface application than MAI (interaction was significant in 2006 and the same trend was found in 2005 [$P = 0.08$]).

The relationship between air temperature and soil moisture on the effectiveness of the two mitigation techniques can be seen in Fig. 3. Removing solids to produce thinner manure reduced ammonia loss in cool weather which is consistent with Stevens and Laughlin (1997). However, in warm weather de-

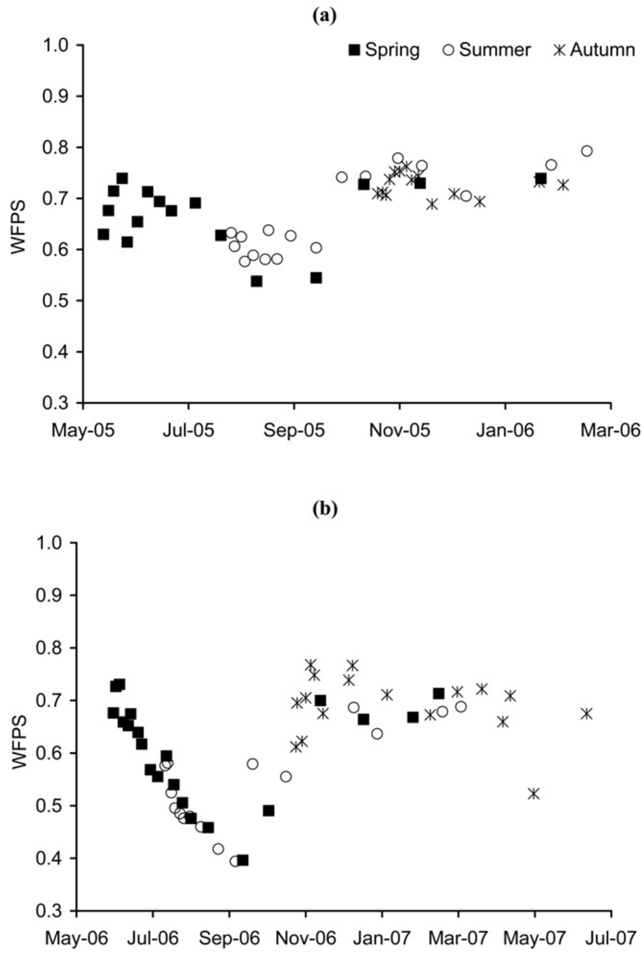

Fig. 1. Soil water filled pore space (WFPS) in spring, summer, and fall of (a) 2005 and (b) 2006.

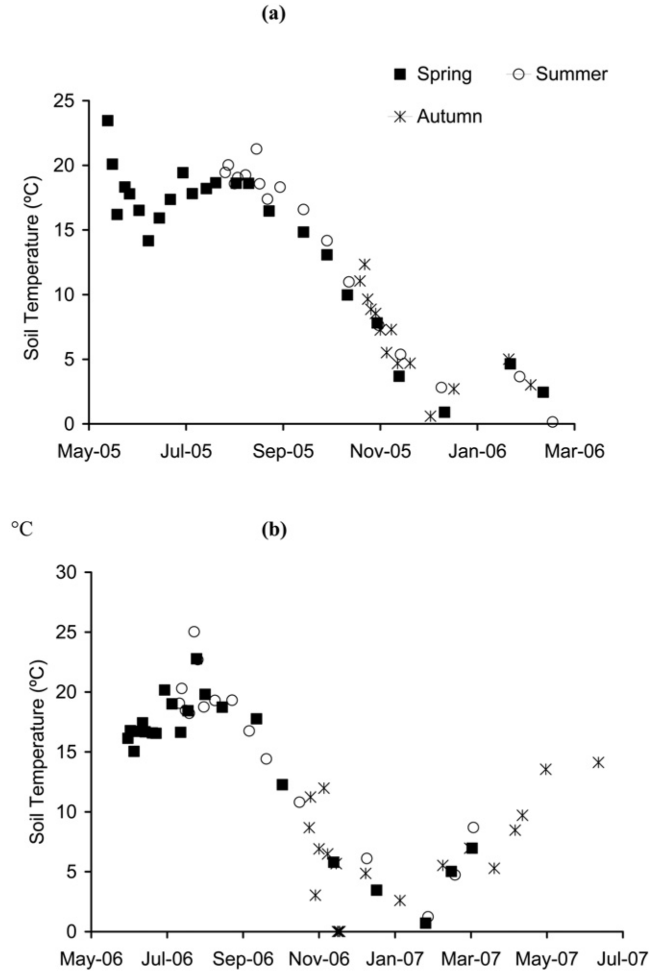

Fig. 2. Soil temperature in spring, summer, and fall of (a) 2005 and (b) 2006.

cantation tended to have no effect or to stimulate emissions. This may be due to quick surface drying or crusting on the whole but not the watery decanted manure in hot sunny weather. The crust may act as a barrier against NH_3 diffusion to the atmosphere. Effectiveness of MAI was also greater in cooler (65% reduction at 7.5°C) than in warmer (30–40% reductions at 11–19°C) air temperatures (Fig. 3). Combining manure decantation with MAI showed a very strong temperature relationship, ranging from about 20% reduction at 18°C, to almost 60% at 15°C and around 80% at the coolest temperatures (Fig. 3). These data suggest a stronger temperature relationship than represented in the ALFAM model which is a statistical analysis of many experiments conducted in Europe (Søgaard et al., 2002). In Canada, well over half the slurry manure on dairy farms is applied during the October–November and March–May periods (S.C. Sheppard and S. Bittman, unpublished data, 2006); average daily temperatures are less than 12°C in May and under 8°C during the other months. That soil moisture did not appear to be closely associated with the effectiveness of either abatement technique (Fig. 3) perhaps reflects the high application rates which overwhelmed the ability of soil to rapidly absorb manure for the first few hours. Lower application volumes may be recommended to producers under warm conditions which favor rapid volatilization, while larger volumes may be acceptable under cool conditions. It would be reasonable to conclude that decanted manure could be applied safely at low volumes on dry soils.

In these trials the maximum reduction in NH_3 emissions occurred when decanted manure was applied with MAI in the fall; the combined effect of these two techniques reduced emissions by 72% in 2005 and 88% in 2006. This substantial benefit from the two simple techniques needs to be further validated over additional years and locations. Under summertime conditions which favor volatilization but not abatement techniques tested, other techniques may need to be invoked. On grassland, there may be an opportunity to apply manure under the plant canopy (Sommer et al., 1997). On arable land, a shallow incorporation may be helpful, but this must be done almost immediately to obtain the most benefit (Rochette et al., 2001). Of the total NH_3 emission losses measured, 27 to 69% occurred on the day manure was applied depending on treatments and seasons (Table 4). Emission rates of 5 to 8% applied TAN h^{-1} were observed during the summer, whereas lower peak hourly rates, 3 to 5 and 1.5 to 3% applied TAN h^{-1} were measured in spring and fall trials, respectively (Fig.

Table 3. Effect of manure type and application method on cumulative emission of NH_3–N as percentage of added total ammoniacal nitrogen (TAN) from dairy slurry manure in spring, summer, and fall of 2005 and 2006 at Agassiz, BC.

	Manure type	Application method: Surface	MAI†	Mean	Interaction‡
Spring 2005	Whole	37.5 A§	24.6 AB	31.1 a	
	Decanted	39.2 A	14.9 B	27.1 a	0.36 (22.3)
	Mean	38.4 a	19.6 b	15.8§	
Spring 2006	Whole	39.3 A	24.1 B	31.7 a	
	Decanted	38.0 A	17.9 B	28.0 a	0.43 (11.9)
	Mean	38.7 a	21.0 b	8.4§	
Mean- spring		38.6	20.3		
Summer 2005	Whole	36.7 B	25.1 C	30.9 b	
	Decanted	51.0 A	28.2 C	39.6 a	0.03 (7.9)
	Mean	43.9 a	26.7 b	5.6§	
Summer 2006	Whole	37.4 A	23.5 B	30.5 a	
	Decanted	39.1 A	28.6 AB	33.9 a	0.69 (13.9)
	Mean	38.3 a	26.1 b	9.9¶	
Mean- summer		41.1	26.4		
Fall 2005	Whole	39.1 A	25.4 B	32.3 a	
	Decanted	16.3 C	10.0 D	13.2 b	0.08 (6.38)
	Mean	27.7 a	17.7 b	4.5§	
Fall 2006	Whole	41.9 A	14.7 B	28.3 a	
	Decanted	13.4 B	4.3 C	8.9 b	0.01(4.74)
	Mean	27.7 a	9.5 b	3.4§	
Mean- fall		27.7	13.6		
Overall mean		35.8	20.1		

† MAI, mechanically assisted infiltration.

‡ Significance level [and LSD (0.05)] for interaction term (manure type × application method).

§ Within a trial, simple effect values followed by same uppercase letters, or main effects values followed by the same lowercase are not significantly different at $P < 0.05$ according to Fishers protected LSD.

¶ LSD for main effects.

4–6). Soil aeration consistently decreased the amount of NH_3 emitted, which was likely due to the reduction of NH_4 concentration at the soil surface. Incorporation would be most useful for surface applied manure (and of some value even for MAI applied manure) provided that it is performed immediately after spreading.

Nitrous Oxide Emission

Emission of N_2O from the conventional treatment (surface applied, whole manure) ranged from 0.05 to 0.49% of total N applied in all trials (Table 5). These values are less than half of IPCC default value of 1.0% (IPCC, 2006), and lower than previous published reports on manure (Amon et al., 2006; Petersen et al., 2006). Lowest rates were observed in summer and fall of 2006 when soils were relatively dry or cool (Table 5) with less WFPS (Fig. 2). In summer trials, greatest N_2O emissions took place right after manure application, but emissions were delayed for several days or weeks in spring and fall (Fig. 7–9). In the fall of 2006, a small secondary peak was measured in late December, which was attributed to a freeze–thaw cycle (Koponen et al., 2006; Morkved et al., 2006). In most cases temporal patterns of N_2O emissions were similar among treatments, though the rates differed.

Averaged over all trials, MAI reduced N_2O emission rates as proportion of total N from 0.26 to 0.20% (Table 5). In both

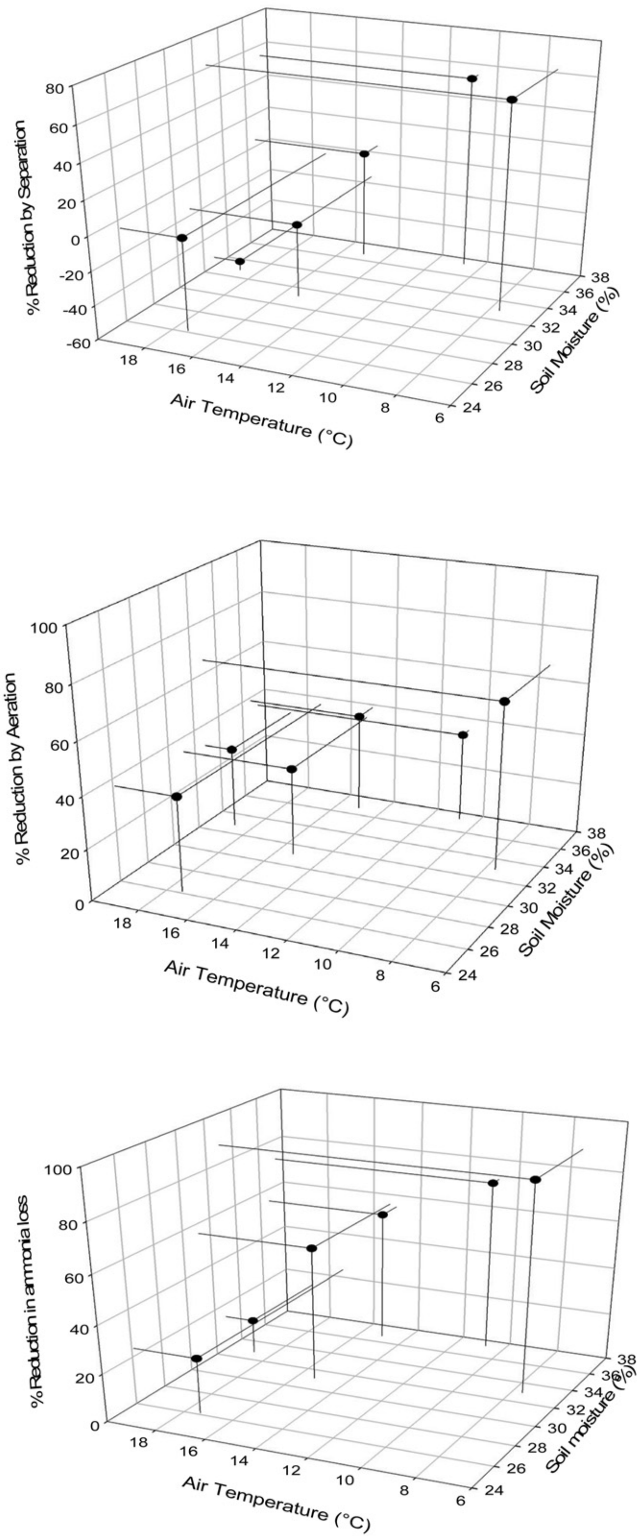

Fig. 3. Reduction of NH_3 loss by methods intended to assist manure infiltration: solids removal (top), soil aeration (middle), and both techniques (bottom), as affected by air temperature (mean daily for the first 24 h after spreading) and soil water content at start of experiment.

spring trials, MAI significantly reduced emissions, whereas in summer of 2006 MAI caused a small but significant increase.

Table 4. Percent of total NH_3 emission measured in the first day after manure application for spring, summer, and fall in 2005 and 2006 at Agassiz, BC.

Treatments	2005			2006		
	Spring	Summer	Fall	Spring	Summer	Fall
Whole surface	55.4a†	69.3a	58.7a	47.8a	60.3ab	47.8a
Whole MAI‡	54.4a	58.9b	55.9a	44.8a	63.1a	39.2a
Decanted surface	47.0b	68.2a	56.6a	58.6a	55.8ab	40.6a
Decanted MAI	29.7c	58.8b	45.4b	54.8a	48.4b	26.9b
$LSD_{0.05}$	7.2	3.9	7.5	22.9	14.4	9.7

† Values followed by the same letter in each trial (within columns) are not significantly different at $P < 0.05$.

‡ MAI, mechanically assisted infiltration.

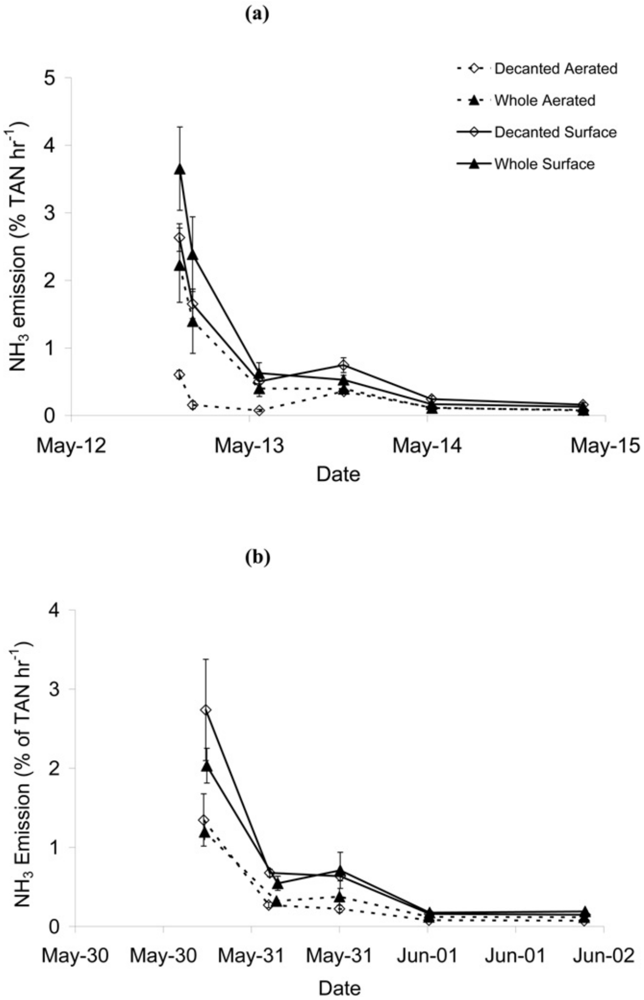

Fig. 4. Hourly NH_3 emission (as percentage of the added total ammoniacal N from application of dairy manure in spring of (a) 2005 and (b) 2006.

The effect of MAI in the other three trials was not significant. The trend to reduced N_2O emissions with MAI was unexpected because less N was lost as NH_3 (Table 3); when subtracting N loss through NH_3 emissions, about 25% more N remained in the soil with MAI than with surface-applied manure. Stevens and Laughlin (1997) suggested that the reduction in NH_3 volatilization may stimulate N_2O production through denitrification as more N is retained in the soil. In agreement, greater emissions have been reported for incorporated manure compared to surface application (Flessa and Beese, 2000; Vallejo et al., 2005). In the present study, lower emissions of N_2O with MAI, could be because of the aeration effect, which generally reduces denitrification.

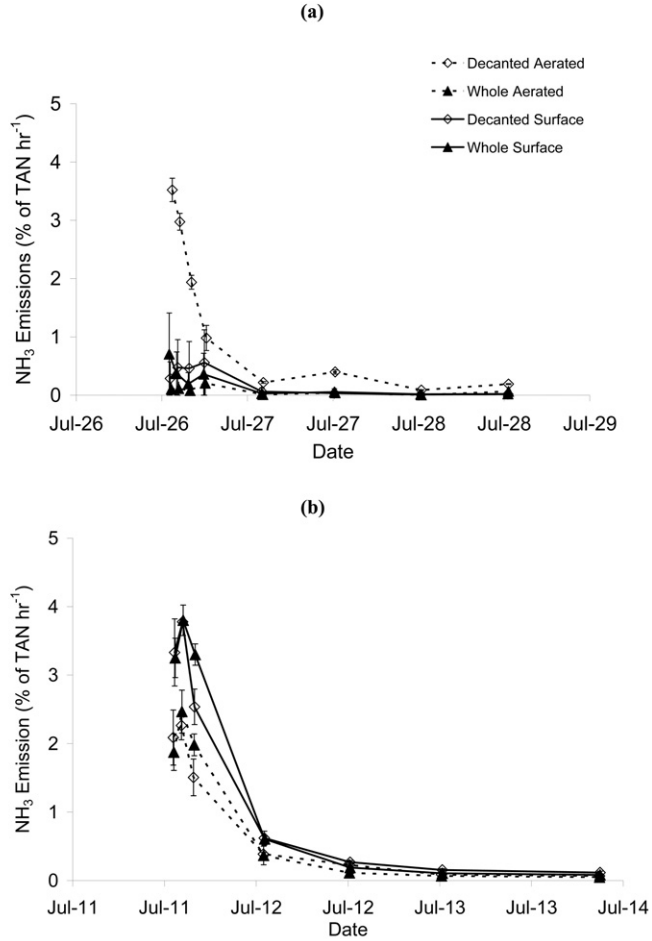

Fig. 5. Hourly NH_3 emission (expressed as percentage of the added total ammoniacal N) from application of dairy manure in summer of (a) 2005 and (b) 2006.

The comparison of N_2O emissions between decanted and whole manure in the present study is complex since the manures were applied based on equivalent rates of TAN. As a higher proportion of manure total N was present as TAN in the decanted than in the whole manure (Table 2), more total N was applied with the whole manure. Based on the total N applied, the N_2O emission coefficients were generally similar between decanted and whole manure, except in summer 2005 for surface application and in fall 2005 for MAI when the decanted manure induced larger N_2O emissions than the whole manure (Table 5). Similar N_2O emissions have previously been reported in the field between whole and mechanically separated manure for dairy cattle (*Bos taurus*) (Clemens et al., 1997) and hog (*Sus scrofa*) manure (Chantigny et al., 2007). This would indicate that decantation of manure before field application of the liquid fraction generally does not influence N_2O emissions in the field.

If crops can be furnished with lower total N as decanted manure, compared to whole manure, then what would be the effect

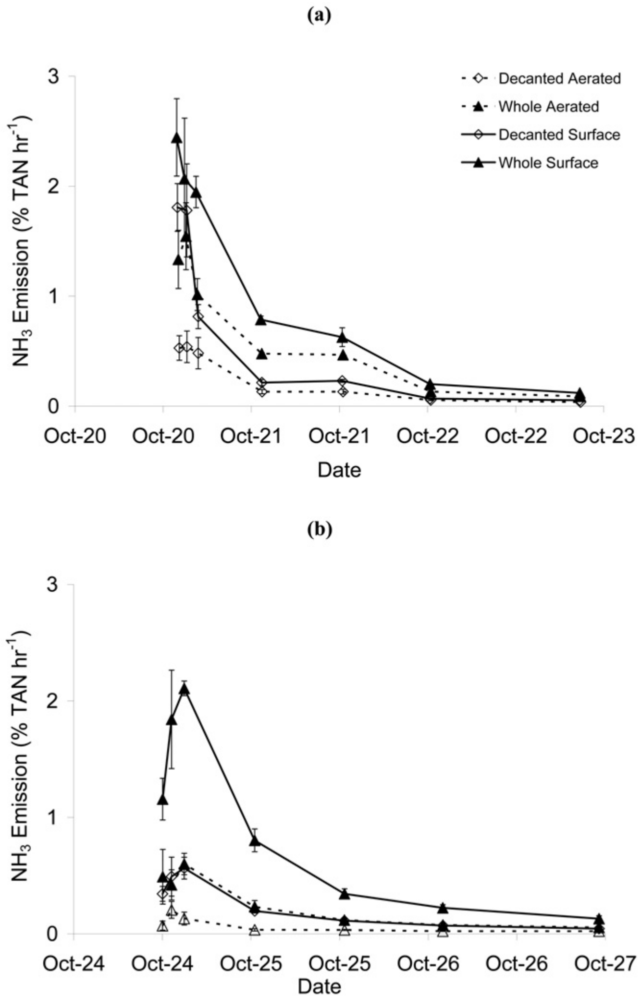

Fig. 6. Hourly NH_3 emission (expressed as percentage of the added total ammoniacal N) from application of dairy manure in fall of (a) 2005 and (b) 2006.

on emissions of N_2O? The rate of emissions based on the rates of applied TAN averaged 0.49% for whole manure vs. 0.34% for decanted manure (not shown). The pattern was consistent across all trials but statistically significant only in summer 2006 and fall 2005. While higher emissions from the whole manure plots is not surprising since these plots received greater rates of total N, the lower N_2O emissions for equivalent rates of available N (TAN) would seem to enhance the value of manure separation, provided that less total (organic) N is applied. However, in comparing the emissions from decanted and whole manure types, final use of the solid fraction also needs to be taken into account. The solid fraction might be a source of N_2O emission while it is stored or applied to the soil (Sørensen and Thomsen, 2005).

Crop Nitrogen Uptake

Despite consistent reductions in NH_3 loss using MAI (average 18.3 kg N ha^{-1}), significant increases in crop N uptake were observed only for decanted manure in summer of 2005 and 2006 (Table 6). In spring and summer trials, an average of 20.9 kg NH_3-N ha^{-1} was conserved in the soil with MAI, but MAI increased crop N uptake by only 9.6 kg ha^{-1} during the same period.

Table 5. Effect of manure type and application method on N_2O emission coefficients as percentage of added total N from dairy slurry manure in spring, summer, and fall of 2005 and 2006 at Agassiz, BC.

		Application method					
	Manure type	Surface		MAI†		Mean	Interaction‡
Spring 2005 Control		0.33 kg ha^{-1}					
	Whole	0.63	A§	0.40	B	0.52 a	
	Decanted	0.52	AB	0.36	B	0.44 a	0.62 (0.22)
	Mean	0.58	a	0.38	b	0.15§	
Spring 2006 Control		0.41 kg ha^{-1}					
	Whole	0.60	A	0.46	A	0.53 a	
	Decanted	0.72	A	0.42	A	0.57 a	0.49 (0.34)
	Mean	0.66	a	0.44	a	0.24§	
Mean (spring)		0.62		0.41			
Summer 2005 Control		0.13 kg ha^{-1}					
	Whole	0.21	B	0.28	AB	0.25 a	
	Decanted	0.37	A	0.25	AB	0.31 a	0.10 (0.16)
	Mean	0.29	a	0.27	a	0.11§	
Summer 2006 Control		0.13 kg ha^{-1}					
	Whole	0.12	B	0.16	AB	0.14 a	
	Decanted	0.14	AB	0.17	A	0.16 a	0.77 (0.039)
	Mean	0.13	b	0.17	a	0.028§	
Mean (summer)		0.21		0.22			
Fall 2005 Control		0.48 kg ha^{-1}					
	Whole	0.67	AB	0.41	B	0.54 a	
	Decanted	0.46	B	0.76	A	0.61 a	0.01 (0.28)
	Mean	0.57	a	0.59	a	0.20§	
Fall 2006 Control		0.31 kg ha^{-1}					
	Whole	0.28	A	0.29	A	0.29 a	
	Decanted	0.27	A	0.30	A	0.29 a	0.92 (0.16)
	Mean	0.28	a	0.30	a	0.11¶	
Mean (fall)		0.42		0.44			
Overall mean		0.41		0.36			

† MAI, mechanically assisted infiltration.

‡ Significance level [and LSD (0.05)] for interaction term (manure type × application method).

§ Within a trial, simple effect values followed by same uppercase letters, or main effects values followed by the same lowercase are not significantly different at $P < 0.05$ according to Fishers protected LSD.

¶ LSD for main effects.

There was a tendency for a greater effect on N uptake when MAI was combined with decanted manure than with whole manure. We found no evidence of an increase in recovery of fall applied N in spring herbage due to MAI despite about 13 kg N ha^{-1} being conserved in the soil. Bittman et al. (2005) reported that the MAI was generally but not always associated with higher yield or crop N uptake by perennial grasses. It may be that the growth of the new grass stand in this trial was insufficiently advanced to take advantage of the additional N before it was lost over winter, so earlier planting may be needed. On average, the apparent manure N recovery (determined in three trials) was only 3 to 14%. Previous studies have shown yield improvements with manure separation (Rubaek et al., 1996; Mattila et al., 2003; Chantigny et al., 2007) and better application methods but the benefits may be less clear with slow growing crops (new grass stand) and fall applied manure in a high rainfall environment. Improved N uptake is important to justify economically the use of more costly application technol-

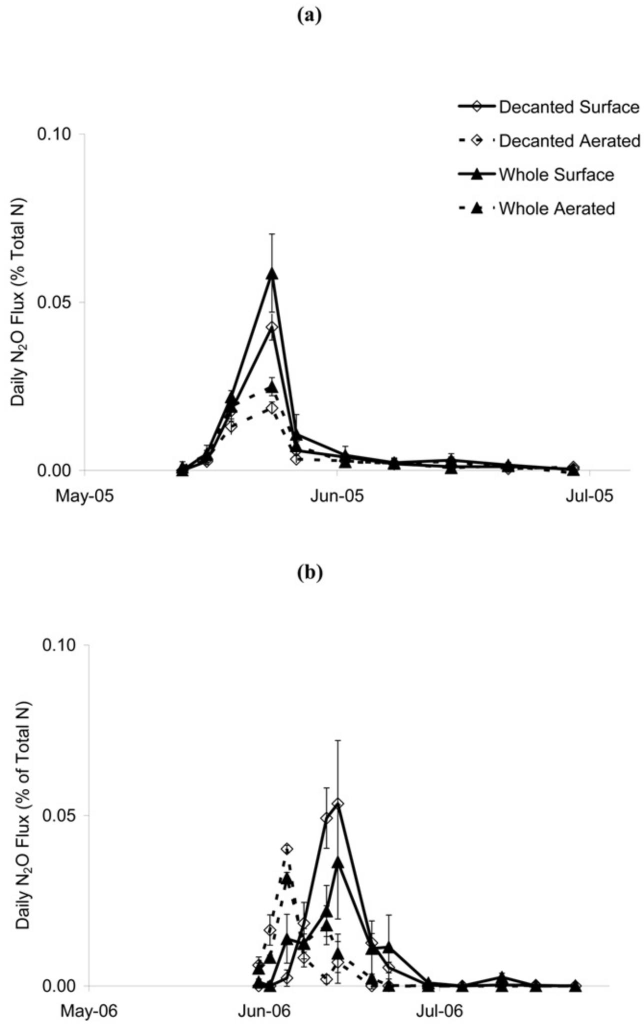

Fig. 7. Daily nitrous oxide (N_2O) emission as percentage of the total N from application of dairy manure in spring of (a) 2005 and (b) 2006.

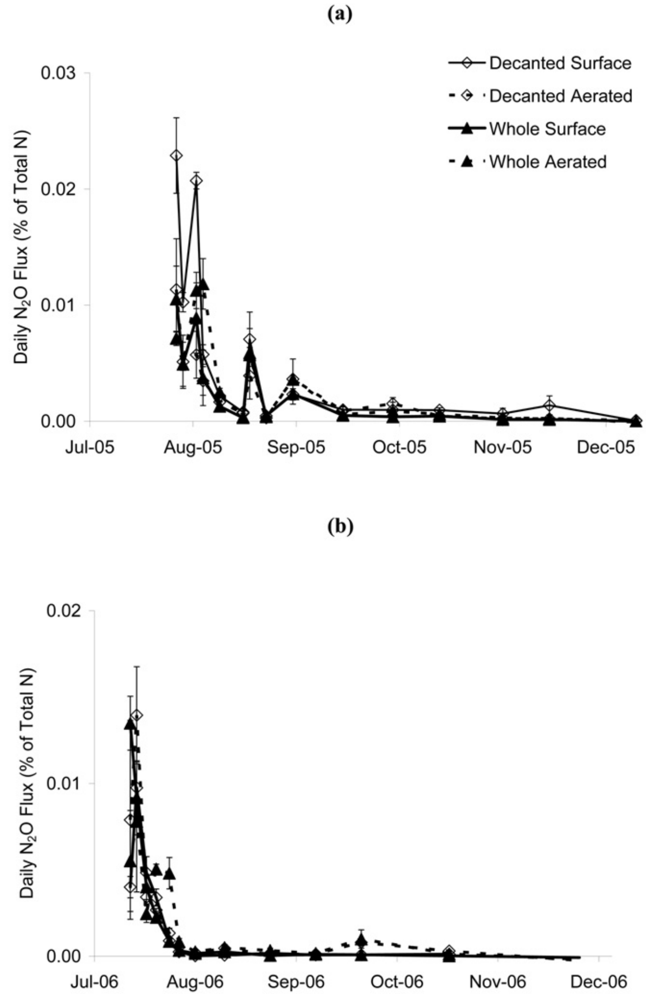

Fig. 8. Daily nitrous oxide (N_2O) emission as percentage of total N from application of dairy manure in summer of (a) 2005 and (b) 2006.

ogy. Also, conserving N without additional crop removal may lead to other environmental contamination such as N leaching and runoff and N_2O emission from increased denitrification.

Comparison of N uptake from whole and separated manure was complicated by slightly different application rates of TAN and somewhat larger differences based on total N. Prorated for equivalent rates of applied TAN, there was significantly more N uptake for decanted than whole manure in spring of 2005 and for whole than decated manure in summer and fall of 2005 (data not shown). When adjusting for equivalent rates of total N applied, uptake from decanted manure was significantly greater than from whole manure in spring 2005, summer of 2005 and 2006, and fall of 2005, and numerically greater in the other two trials (Table 6). Prorated for equivalent application rate of total N (220 kg ha^{-1}), there would be 17.5 kg ha^{-1} more N taken up from decanted than from whole manure. This is due to relatively higher N availability in decanted (68% of total N as TAN) than in whole manure (49% of total N as TAN). Rubaek et al. (1996) reported increased plant N uptake only where treated manure resulted in lower NH_3 losses than raw manure. The greater crop N uptake with treated than with raw manure could be due both to the reduction in NH_3 loss and to lower C content of the treated manure (Chantigny et al., 2007).

Some of the manure organic N would be mineralized during the grass growth period but most would not (Bittman et al., 2007). Note that the difference in crop N uptake was the smallest in spring 2006 when the proportions of organic N in whole (52.5%) and decanted (46.0%) manure were relatively close (Tables 2 and 6). Applying decanted manure will produce equivalent or greater grass yield with less accumulation of soil nutrients such as P and N that would eventually be prone to loss. These results suggest that in the long term, application of decanted dairy cattle manure with soil aeration is more sustainable than current practices, but that the long-term release of applied organic N needs to be investigated. Long-term uptake of manure total N applied to grass by surface banding was 37 to 42% depending on application rate with 21 to 25% of applied N remaining in the soil as organic N (Bittman et al., 2007). Multi-year trials are needed to assess the long-term economic and environmental benefits of applying manure using improved infiltration strategies that reduce losses and accumulation of N and P.

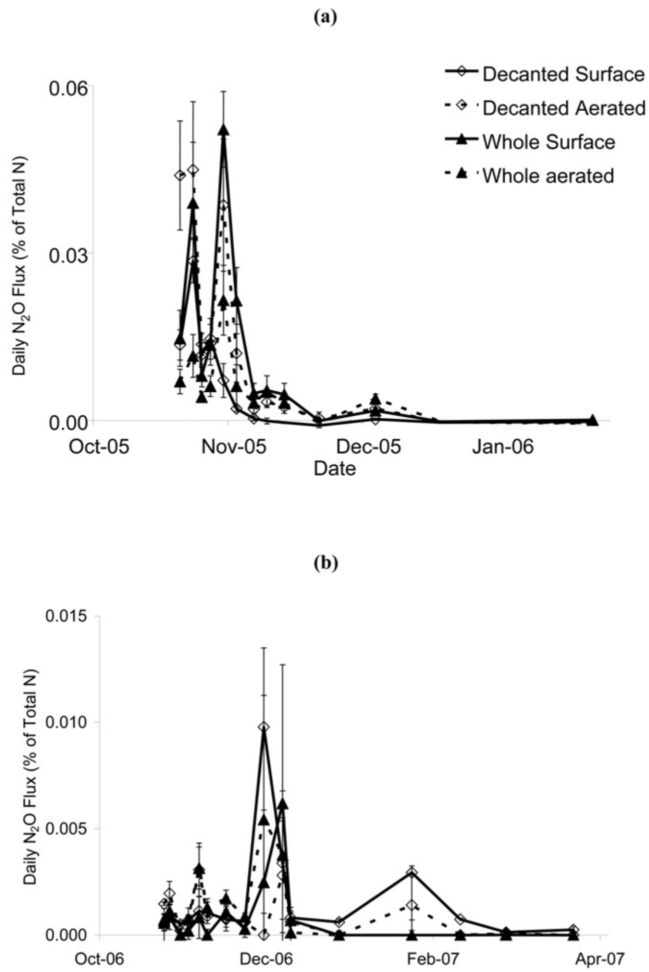

Fig. 9. Daily nitrous oxide (N_2O) emission as percentage of total N from application of dairy manure in fall of (a) 2005 and (b) 2006.

Conclusion

The concept of facilitating infiltration of manure into the soil to reduce NH_3 loss was generally supported in this study. Significant emission reductions were achieved by combining manure decantation with mechanically assisted infiltration, particularly in cool weather, which is when most manure is spread (i.e., early spring and fall). This gives a practical and inexpensive strategy to farmers, especially when injection or incorporation is difficult. The ineffectiveness of decanted manure to reduce NH_3 emissions under warm summer conditions means that this technique is not appropriate for application of manure on grass in summer. Our study found no evidence of pollution swapping; conservation of NH_3 with decanted manure and mechanically assisted infiltration did not increase emissions of N_2O even though more N was retained in the soil. Long-term studies are needed to fully assess the effect of the treatments on N_2O emissions. The effect of MAI on N uptake was inconclusive in this study despite substantially lower NH_3 losses. This is important because conserved NH_3–N not used by the crop may leak out of the system through other detrimental ways (e.g., leaching, runoff, or N_2O). And since manure application rates are often near the plateau of the N response curve in many contemporary dairy farms, there is not likely be economical advantage in employing NH_3–conserving methods. Moreover, on high density dairy farms, increasing N concentration in feed crops may contribute to excessive protein consumption, which may be deleterious to cattle health and may also lead to high N excretion rates. Decanted manure was advantageous because it contributed less total N to soil at similar or greater N uptake. Compared to decanted manure, the additional slowly available organic N (and P) applied with whole manure relative to decanted may lead to soil N build up (Bittman et al., 2007), but may eventually be degraded and lost when soils are cultivated. In complete assessments of manure separation, the benefits and impact of the solid fraction that has been removed must also be taken into account.

Table 6. Effect of manure type and application method on N uptake as percentage of added total N by Italian ryegrass fertilized with dairy slurry manure in spring, summer, and fall of 2005 and 2006 at Agassiz, BC.

		Application method			
	Manure type	Surface	MAI†	Mean	Interaction‡
Spring 2005					
	Whole	31.1 B§	35.2 B	33.2 b	
	Decanted	43.8 A	49.6 A	46.7 a	0.72 (7.9)
	Mean	37.5 a	42.4 a	***5.6***§	
Spring 2006					
	Whole	18.6 A	19.1 A	18.9 a	0.87 (9.3)
	Decanted	19.7 A	21.1 A	20.4 a	
	Mean	19.2 a	20.1 a	6.6§	
Mean (spring)		28.3	31.3		
Summer 2005					
	Whole	29.6 B	30.7 B	30.2 b	0.12 (8.4)
	Decanted	31.2 B	41.3 A	36.3 a	
	Mean	30.4 a	36.0 a	6.0§	
Summer 2006					
	Whole	21.1 B	29.5 B	25.3 b	0.43 (10.2)
	Decanted	29.1 B	42.8 A	36.0 a	
	Mean	25.1 b	36.2 a	7.2§	
Mean (summer)		27.8	36.1		
Fall 2005					
	Whole	37.2 A	24.0 B	30.6 b	0.009 (9.4)
	Decanted	39.7 A	45.7 A	42.7 a	
	Mean	38.5 a	34.9 a	6.6¶	
Fall 2006					
	Whole	21.8 A	21.8 A	21.8 a	0.95 (11.1)
	Decanted	25.8 A	25.3 A	25.6 a	
	Mean	23.8 a	23.5 a	7.9§	
Mean (fall)		31.2	29.2		
Overall mean		29.1	37.4		

† MAI, mechanically assisted infiltration.

‡ Significance level [and LSD (0.05)] for interaction term (manure type × application method).

§ Within a trial, simple effect values followed by same uppercase letters, or main effects values followed by the same lowercase are not significantly different at $P < 0.05$ according to Fishers protected LSD.

¶ LSD for main effects.

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