

Ammonia volatilization and soil nitrogen dynamics following fall application of pig slurry on canola crop residues

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Rochette, P., Chantigny, M. H., Angers, D. A., Bertrand, N. and Côté, D. 2001. **Ammonia volatilization and soil nitrogen dynamics following fall application of pig slurry on canola crop residue.** *Can. J. Soil Sci.* **81**: 515–523. Land application of liquid manures is a major source of atmospheric ammonia. The presence of crop residues on the soil surface usually increases emissions by retarding slurry infiltration, whereas incorporation of slurry into soil reduces emissions. Our objective was to quantify the relative reduction in NH_3 volatilization resulting from the soil incorporation of pig slurry (PS) applied on canola (*Brassica napus*) residues under fall conditions in Quebec, Canada. Pig slurry was applied at 7.4 L m^{-2} on six plots covered by canola crop residues. Slurry and residues were incorporated in the top 5 cm of soil (INCORP) in half of the plots, while the other half were left untouched (SURF). Ammonia volatilization was measured following application for 10 d using wind tunnels. Soil NH_4^+ and NO_3^- contents, pH, moisture and temperature were also monitored to explain variations in NH_3 fluxes. Soil NH_4^+ -N in the surface soil was lower than expected shortly after slurry application, maybe as a result of fixation by clays or interception by crop residues. The volatilization of NH_3 was higher ($P < 0.05$) on SURF plots than on INCORP plots in 20 of the 26 measuring periods, with total NH_3 losses being five times greater in the former. Cumulated emissions during the first 11 h accounted for the 60 and 53% of total NH_3 emissions for the SURF and INCORP plots, respectively. Our results confirm that a large fraction of the NH_3 volatilization from slurry application on canola residues can be greatly reduced if the slurry and crop residues are incorporated into the soil immediately after slurry application. Despite significant reduction (80%) of NH_3 volatilization in INCORP compared with SURF plots, no difference was found in soil mineral N between treatments, suggesting that other processes such as N mineralization or denitrification were more active in INCORP plots.

Key Words: Ammonium, nitrate, nitrogen cycle, organic amendments

Rochette, P., Chantigny, M. H., Angers, D. A., Bertrand, N. et Côté, D. 2001. **Volatilisation d'ammoniac et dynamique de l'azote du sol suivant une application automnale de lisier de porc sur résidus des cultures de canola.** *Can. J. Soil Sci.* **81**: 515–523. L'épandage de lisiers sur les sols agricoles est une source importante de NH_3 atmosphérique. La présence de résidues à la surface du sol augmente habituellement ces émissions en retardant l'infiltration du lisier alors que l'incorporation du lisier diminue ces émissions. Notre objectif était de quantifier la réduction relative de la volatilisation d'ammoniac résultant de l'incorporation du lisier appliqué sur des résidus du canola (*Brassica napus*) à l'automne sous les conditions fraîches et humides du Québec. Du lisier de porc a été appliqué à un taux de 7.4 L m^{-2} sur six parcelles. Les résidus et le lisier ont été incorporés dans la couche 0–5 cm du sol sur trois des parcelles (INCORP) alors que les trois autres étaient laissées intactes (SURF). Après l'application du lisier, la volatilisation du NH_3 a été mesurée pendant 10 jours à l'aide de tunnels ventilés. Certains paramètres du sol, tel que la teneur en NH_4^+ and NO_3^- , le pH, l'humidité et la température du sol ont également été suivis pour expliquer les variations d'émissions de NH_3 . La teneur du sol de surface en NH_4^+ a été plus faible qu'anticipée, probablement en raison de l'interception par les résidus de récolte et de la fixation sur les argiles. Nous n'avons pas mesuré de différences de teneur du sol en azote minéral entre les traitements malgré de nettes différences dans les pertes de NH_3 par volatilisation. La volatilisation de l'ammoniac a été plus grande ($P < 0.05$) sur les parcelles SURF que sur les parcelles INCORP durant 20 des 26 périodes de mesure résultant en des pertes totales de NH_3 cinq fois plus élevées. Les pertes cumulées durant les onze premières heures suivant l'épandage ont représenté respectivement 60 et 53% des pertes totales durant l'expérience dans les parcelles SURF et INCORP. Nos résultats confirment qu'une grande partie du NH_3 qui est volatilisé lorsque le lisier est appliqué sur des résidus du culture peut être conservé si les résidus et le lisier sont rapidement incorporés dans le sol.

Mots clés: Ammonium, nitrate, cycle de l'azote, amendements organiques

Application of ammonium-based mineral fertilizers and livestock manure to agricultural land results in significant losses of ammonia (NH_3) to the atmosphere (McGinn and Janzen 1998). In Europe, it has been estimated that agriculture is responsible for about 90% of total anthropogenic sources of

NH_3 (Van Der Hoek 1998). Among agricultural sources of NH_3 , livestock manure is by far the most important with 80% of the emissions (Van Der Hoek 1998). In addition to the economic losses related to the inefficient use of N fertilizer, NH_3 volatilization has adverse effects on the environment. In

the atmosphere, NH_3 reacts with hydroxyl radicals to form N oxides and with acids to form NH_4^+ salts. Subsequent deposition of NH_3 and NH_3 -derived products can have significant impacts on natural ecosystems such as soil acidification (van Breemen et al. 1982), eutrophication (Hutchinson and Viets 1969), plant toxicity (Pearson and Stewart 1993) and decline in biodiversity (van Dam et al. 1986).

In the province of Québec, Canada, the hog industry produces more than 9 million Mg of slurry (27 000 Mg $\text{NH}_4^+\text{-N}$) annually (Trudelle 1996). Most of this slurry is applied to agricultural land and adequate management must be identified to ensure minimal impacts on air quality. Canola production is increasing rapidly in Québec and its nutrient requirements could be at least in part satisfied by a fall application of PS. There is a short window of time between the average harvest date of canola (15 September) and the latest date for PS fall application to land (1 October) in Québec. This means that slurry is usually applied on recently harvested crop residues, which may slow down the infiltration of slurry into the soil and lead to greater NH_3 volatilization losses than when slurry is applied on a bare soil (Parsons et al. 1990). Rapid incorporation of slurry following application has been shown to reduce volatilization of ammonia (Brunke et al. 1988). However, the efficiency of incorporation has been shown to vary with local soil, slurry and meteorological conditions, resulting in reductions varying from 22% (Hoff et al. 1981) to 98% (Frost 1994) compared with slurry left on the soil surface. Our objective was to quantify the impacts of soil incorporation of pig slurry applied on canola crop residues on NH_3 volatilization and soil nitrogen dynamics.

MATERIALS AND METHODS

The study was carried out from 23 September to 4 October 1999 at the St-Lambert Research Farm of the Institut de recherche et de développement en agronenvironnement near Québec city, Canada (latitude $46^\circ 05'$, longitude $71^\circ 02'$, altitude 110 m). The soil was a Le Bras loam (Orthic Gleysol) with 0.31 g of sand, 0.42 g of silt and 0.27 g of clay per g of soil. In 1999, canola (*Brassica napus*) was seeded at 9 kg ha^{-1} on 7 May and harvested on 7 September with 530 (± 72) g m^{-2} of straw residues returned to the soil surface.

Ammonia volatilization was measured using six wind tunnels built according to Lockyer (1984). The tunnels consisted of an inverted U-shape acrylic plastic device (thickness = 3.15 mm) covering an area of 1 m^2 (0.5×2 m) connected to a steel duct housing a fan. Air temperature and velocity were measured using a hot wire sensor (Model KM 4007, Comark Limited, Hertfordshire, UK) immediately downflow from a flange reducing the internal diameter of the steel duct (Lockyer 1984). The NH_3 volatilization rate (F_{NH_3} , mg N m^{-2} h^{-1}) was calculated as:

$$F_{\text{NH}_3} = \frac{f}{A_s} (c_o - c_i)$$

where f is the air flow rate (270 m^3 h^{-1}) through the tunnel and A_s is the enclosed surface area (1 m^2) and c_o and c_i are

Table 1. Pig slurry description

pH	Dry matter	Total C	$\text{NH}_4^+\text{-N}$	$\text{NO}_3^-\text{-N}$	Total N
8.2	15.8	5.06	2.03	0	2.52

the NH_3 concentration of the air leaving and entering the tunnel, respectively (mg $\text{NH}_3\text{-N}$ m^{-3}). Values of c_o and c_i were obtained by trapping NH_3 in 100 mL of 0.005 M H_3PO_4 at an air flow rate of 3 L min^{-1} .

The slurry used in our study came from a commercial hog and sow operation and its composition is given in Table 1. Pig slurry was applied at a rate of 7.4 L m^{-2} on six parallel adjacent plots (0.5 m by 2 m) between 0940 and 1010 h on 23 September. Slurry and canola residues were immediately incorporated into the top 5 cm of soil using manual tools in three plots (INCORP) while the other three were left untouched (SURF). The tunnels were then rapidly installed. For each plot, the elapsed time between PS application and the start of NH_3 volatilization measurement was ≤ 3 min. Tunnels were operated continuously for the next 10 d except during two rainfall periods when the tunnels were removed and replaced at the same location after the rain (Table 2).

Slurry was also applied on six additional plots (4×4 m) reproducing the same treatments and located 15 m away from the tunnels within the same canola field. Three soil sub-samples were taken from the 0- to 5-cm and 5- to 10-cm soil layers just before PS application and daily following application except for days 8 and 9. Sub-samples were pooled into one composite sample per plot and per soil layer which were brought to the laboratory and extracted within 4 h with 2 M KCl (10 g field-moist soil in 40 mL KCl). The extracts were frozen until analysis for $\text{NO}_3^-\text{-N}$ using an ion chromatograph (Model 4000i, Dionex, Sunnyvale, CA) and $\text{NH}_4^+\text{-N}$ by colorimetry (Nkonge and Ballance 1982). Soil pH was determined on 10 g of field-moist soil in 20 mL of distilled water. Values of pH- H_2O , although not reflecting the real pH of soil-slurry mixture, were used as an indication of temporal changes in soil pH.

Soil temperature at 1 cm below the surface inside and outside each tunnel, and air temperature inside tunnels (in the shade) were measured using copper-constantan thermocouples. Thermocouples were read every 2 min and averaged hourly by means of a datalogger (CR-10, Campbell Scientific Inc, Logan, UT). Three-bar time-domain reflectometry probes were inserted vertically in the top 15 cm of each tunnel and read once a day to measure soil moisture (1502B Cable Tester, Tektonix Inc, Beaverton, OR). Rainfall was measured daily with standard rain gauges at the St-Lambert Research Farm weather site located 50 m from the experimental plots. The effects of treatments were analysed at each date using a two-way analysis of variance (SAS Institute, Inc. 1989).

RESULTS AND DISCUSSION

Mean air temperature inside the tunnels during the experiment was 11.7°C (extremes of 1.1 and 24.7°C) (Fig. 1a) and a total of 26.2 mm of rain was received (Fig. 1c). These val-

Table 2. Experimental schedule

Period #	Start ²		End ²		Duration (h)	Time since ³ application (h)
	Date	Time (h: min)	Date	Time (h: min)		
1	23 Sept.	9:54	23 Sept.	10:54	1.0	0.5
2	23 Sept.	10:57	23 Sept.	11:57	1.0	1.5
3	23 Sept.	11:59	23 Sept.	13:53	1.9	3.0
4	23 Sept.	13:55	23 Sept.	17:06	3.2	5.6
5	23 Sept.	17:08	23 Sept.	21:05	4.0	9.2
6	23 Sept.	21:08	24 Sept.	7:15	10.1	16.3
Rain ³	24 Sept.	7:16	24 Sept.	8:34	1.3	22.0
7	24 Sept.	8:35	24 Sept.	12:05	3.5	24.4
8	24 Sept.	12:07	24 Sept.	17:04	5.0	28.6
9	24 Sept.	17:05	25 Sept.	7:12	14.1	38.1
10	25 Sept.	7:16	25 Sept.	12:04	4.8	47.5
11	25 Sept.	12:07	26 Sept.	17:04	5.0	52.5
12	26 Sept.	17:07	26 Sept.	7:16	14.2	62.0
13	26 Sept.	7:19	26 Sept.	12:07	4.8	71.5
14	26 Sept.	12:10	26 Sept.	17:07	5.0	76.4
15	26 Sept.	17:10	27 Sept.	7:04	13.9	85.8
16	27 Sept.	7:06	27 Sept.	12:06	5.0	95.3
17	27 Sept.	12:08	27 Sept.	17:09	5.0	100.3
18	27 Sept.	17:12	28 Sept.	7:06	13.9	109.8
19	28 Sept.	7:08	28 Sept.	17:10	10.0	121.7
20	28 Sept.	17:12	29 Sept.	6:24	13.2	133.3
21	29 Sept.	6:26	29 Sept.	16:51	10.4	145.1
22	29 Sept.	16:52	30 Sept.	8:53	16.0	158.4
Rain ³	30 Sept.	8:54	1 Oct.	9:37	24.7	178.8
23	1 Oct.	9:38	1 Oct.	17:37	8.0	195.1
24	1 Oct.	17:40	2 Oct.	8:07	14.5	206.3
25	2 Oct.	8:09	3 Oct.	11:34	27.4	227.3
26	3 Oct.	11:36	4 Oct.	12:41	25.1	253.6

²Refer to the average starting and ending time of the six tunnels.

³Refer to mid-point time.

⁴No measurements were made during rainfall.

ues are approximately 2°C above and 8 mm below the 30-yr normals at the Quebec city airport (20 km from the site) for that 10-d period (Environment Canada 1991). Soil temperature at 1 cm in the SURF plots ranged between 6.2 to 20.7°C with an average of 13.1°C (Fig 1a). The thermal insulation provided by the canola residues maintained mean soil temperature in the SURF plots 0.3°C warmer than in the INCORP plots (Fig. 1b). Soil temperature differences between the inside and outside of tunnels averaged 0.1 and -0.39°C in SURF and INCORP plots, respectively (Fig. 2). Amplitude of the diurnal variations was greater in INCORP than in SURF plots, as expected. Soil moisture in both treatments was high after slurry application and first rainfall, decreased between these two dates due to evaporation and increased during the last 3 d following the second rainfall (Fig. 1c). The slightly higher soil moisture in INCORP than in SURF plots were probably due to water interception by the canola residues.

Ammonia Volatilization

The volatilization of NH₃ was higher ($P < 0.05$) on SURF plots than in INCORP plots during 20 of the 26 measuring periods (Fig. 3a) Among the six periods during which incorporation did not reduce emissions, five occurred after rainfalls [period #7 after rain on 24 September and periods #23, 24, 25 and 26 after rain on 1 October (Table 2)]. Rainfall on

wet soil usually decreases volatilization by (1) diluting surface-NH₄⁺, thereby reducing NH₃ partial pressure, and (2) transporting NH₄⁺ deeper into the soil, thereby increasing resistance to volatilization (Whitehead and Raistrick 1991). The other period (#18, Table 2) corresponded to the fifth night following application when emissions were already greatly reduced (Fig. 3a). The effectiveness of incorporation on the reduction of NH₃ volatilization decreased linearly with time following PS application (Fig. 3c), with a maximum of 80% during the first day. The decreasing trend probably reflected the increasing resistance to NH₃ diffusion as the NH₄⁺ concentration decreased near soil surface and as the relative contribution of deeper soil layers to volatilization increased (Van der Molen et al. 1990). This effect was likely more pronounced in the SURF plots where most of slurry is located near the surface than in the INCORP plots where slurry was more evenly distributed into the top 5 cm. Incorporation remained effective in reducing volatilization during 6 d after PS application when NH₃ losses were still 60% lower in INCORP than in SURF plots (Fig. 3c). These values are in the mid-upper end of the range of reported reduction rates which vary from 22% (Hoff et al. 1981) to nearly 100% (Frost 1994). Our results confirm that a large fraction of the NH₃ volatilization occurring when slurry is applied to crop residues can be avoided if the slurry and residues are immediately incorporated into the soil.

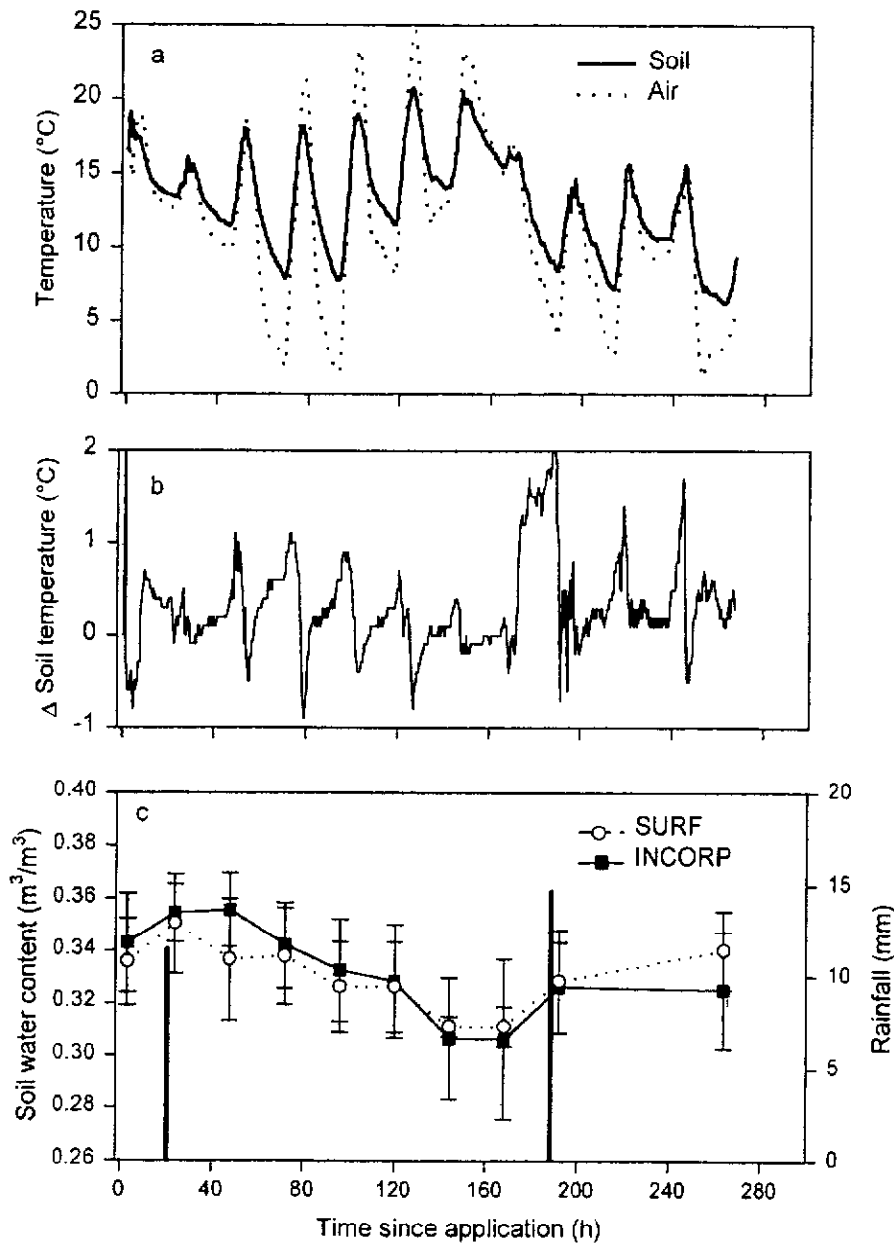


Fig. 1. Temporal variations of (a) soil temperature at 1 cm in the SURF plots and air temperature, (b) soil temperature (1 cm) difference between SURF and INCORP plots, (c) rainfall and soil moisture in the top 15 cm in SURF and INCORP plots (SURF = slurry was left on the soil surface; INCORP = slurry was incorporated).

In both experiments, ammonia volatilization rates were highest during the first 6 h following PS application (Fig. 3a). High emissions immediately after application are typical of mature slurries (Gordon et al. 1988; Sharpe and Harper, 1997; Générmont et al. 1998), which contain a large proportion of their N in the ammonium form (Sommer et al. 1992). These emissions reflected the greater availability of $\text{NH}_4^+\text{-N}$ at the surface of the SURF plots than of the INCORP plots. As more of the surface N is lost to the atmosphere, the volatilization process increasingly involves upward diffusion of NH_4^+ from the soil layers below the surface and volatilization rates slow down (Générmont and

Cellier 1997). Volatilization was very low following the second rainfall 175 h after PS application (Figs. 1c and 3a). The reducing effect of rainfall on NH_3 volatilization has been well documented (Klarensbeek and Bruins 1991; Moal et al. 1995).

Cumulative emissions during the first 6 h accounted for 60 and 53% of total NH_3 emissions during the 10-d experiment in the SURF and INCORP plots, respectively (Fig. 3b). Similar values have been reported for pig slurry [80% after 2 d, Lockyer et al. (1989); >50% after 6 h, Sommer et al. (1991)] and other slurries [50% after 4 h, Frost (1994); 45% after 24 h, Thompson et al. (1990); 60% after 1 d,

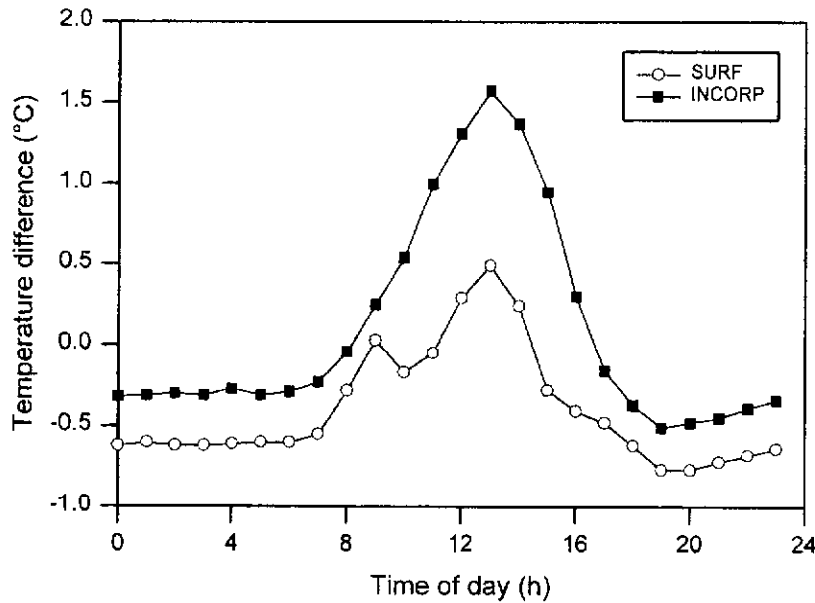


Fig. 2. Mean diurnal pattern of soil temperature (1 cm) difference between the inside and the outside of the tunnels during the 10-d experiment (SURF = slurry was left on the soil surface; INCORP = slurry was incorporated).

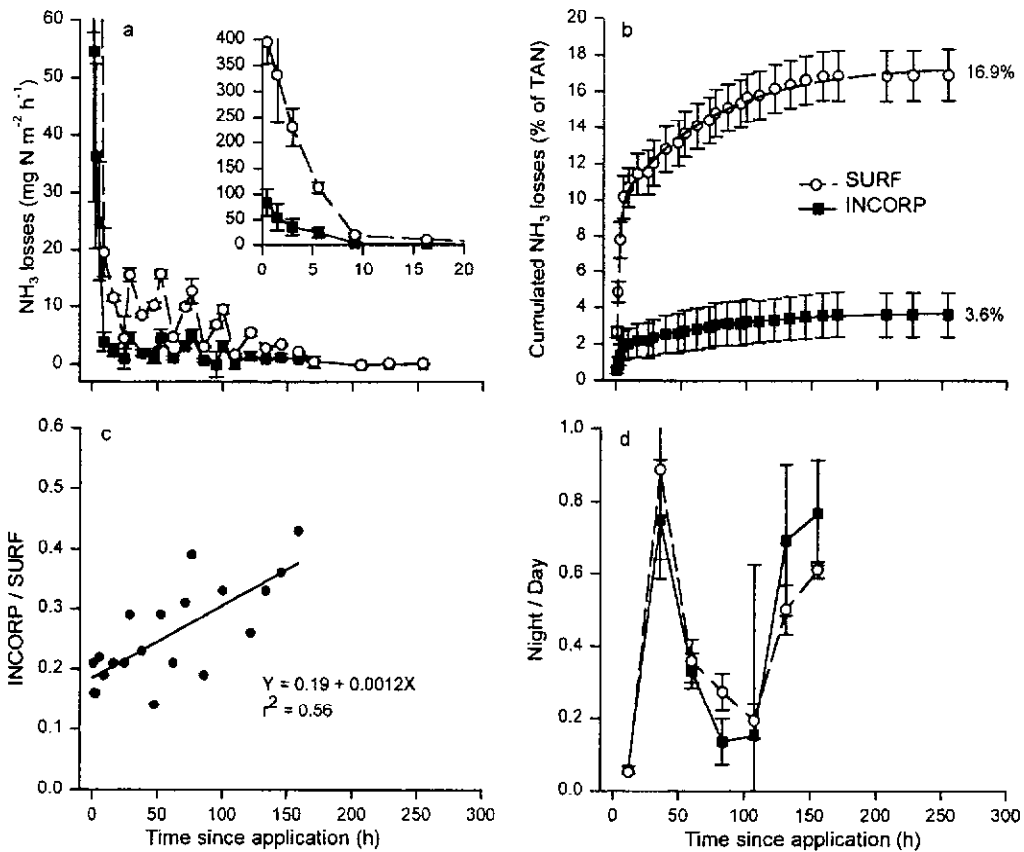


Fig. 3. Temporal variations in (a) ammonia volatilization and (b) cumulative ammonia losses expressed as a percentage of total slurry ammonium nitrogen (TAN) after pig slurry was either left on the soil surface or incorporated in the soil. Double exponential equations (Table 3) were fitted to the cumulative NH₃ losses. (c) Temporal variations of the ratio of ammonia emissions incorporated over broadcasted plots and (d) the ratio of ammonia emissions during the night over emissions during the day. Ratios after 160 h were highly variable because of very low emissions rates and are not presented (SURF = slurry was left on the soil surface; INCORP = slurry was incorporated).

Table 3. Statistics of the double exponential equations fitted to the accumulated NH_3 emissions [Y, cumulated emissions (% of total slurry ammonium nitrogen (TAN)); t, time since slurry application (h)] [$Y = a(1 - e^{-bt}) + c(1 - e^{-dt})$]

	a (% TAN)	b (h^{-1})	c (% TAN)	d (h^{-1})	r^2
Surface	9.70	0.500	7.73	0.0138	0.99
Incorporated	1.77	0.517	2.00	0.0127	0.99

Bussink et al. (1994)]. Cumulative emissions of NH_3 following addition of $\text{NH}_4^+\text{-N}$ to soil have been described using a single logistic or exponential equation under relatively constant environmental conditions (Sommer and Ersbøll 1994; Demeyer et al. 1995; Petersen et al. 1998). Our data were fitted by a double rather than a single exponential equation (Fig. 3b). In this equation, the first and second exponentials referred to before and after the first rainfall, respectively (Table 2), indicating that this event had a strong impact on the availability of $\text{NH}_4^+\text{-N}$ for volatilization. The relative impact of rain on volatilization has been similar on both treatments as suggested by the similar curvature coefficients (b and d) in both equations (Table 3). The high emission rates immediately after application emphasized the importance of avoiding delays between PS application and incorporation into the soil.

During the first 7 d following PS application, emission rates were higher during the day than during the night (Figs. 3a, d). The relative decrease in volatilization during the night was greater than 60% during the first 5 d, except during the second day when rainfall depressed emissions in both treatments (Fig. 3a, b). These values agree with reductions between 50 and 85% reported by Vertregt and Rutgers (1988). Such a diurnal pattern has been described by McGarity and Rajatnam (1973) and Thompson et al. (1990) and has been related to temporal variations in evaporation rates at the soil surface (Molloy and Tunney 1983; Bussink et al. 1994). The small but measurable bias in soil temperature induced by tunnels (Fig. 2) as well as condensation on the tunnel walls at night may have increased the amplitude of the diurnal pattern of NH_3 volatilization (Fig. 3a).

Soil pH and Nitrogen

Soil mineral N contents (NH_4^+ and NO_3^-) were very low prior to the PS application (Fig. 4a-d). During the first 50 h following PS application, soil pH and NH_4^+ in the top 5 cm increased strongly, while NO_3^- remained low. Despite the marked increase in soil NH_4^+ content in the hours following slurry application, between 40 and 50% of the slurry NH_4^+ was unaccounted for by soil NH_4^+ . This low recovery of slurry NH_4^+ in soil could be the result of several factors. Crop residues have likely absorbed a significant amount of slurry at the time of application. Difficulties in including the long canola straws in relatively smaller soil cores might have led to an underestimation of total soil NH_4^+ . As a result, the increase in soil NH_4^+ between the 6th and 40th h after slurry application (Fig. 4a) could be explained by the release of NH_4^+ initially absorbed by canola residues following precipitation (22th h, Table 2). Ammonium could also have

been rapidly fixed by clays and not extracted during soil analysis. Finally, leaching of NH_4^+ below 10 cm cannot be ruled out but appears unlikely since little ammonium has reached the 5- to 10-cm layer during the first day (Fig. 4b).

Even though volatilization was about five times lower in INCORP than SURF plots, there were no significant differences in soil mineral N between these treatments during the initial phase of the experiment. Soil water content was high during that period (Fig. 1c). High denitrification in wet slurry-amended soils has been reported (Dendooven et al. 1998b) and greater denitrification losses in INCORP than in SURF plots may partially explain the absence of differences in soil mineral N between treatments. However, the amount of $\text{N}_2\text{O} + \text{N}_2$ produced by denitrification is usually much smaller than the NH_3 losses (Dendooven et al. 1998b) and other mechanisms have likely been involved to explain this apparent loss of mineral N in the INCORP plots. An increase in nitrogen immobilization in the first days following incorporation of crop residues (Parker 1962) may also have partly counteracted the greater NH_3 volatilization in SURF than in INCORP plots.

Values of pH- H_2O decreased by one unit as acidifying reactions (volatilization and nitrification) took place (Fig. 4e, f). This decrease in pH may have contributed to limit NH_3 volatilization by favouring the NH_4^+ form in the soil solution. Significant NO_3^- production and accumulation started 50 h after PS application (Figs. 4c, d). Such a delay between NH_4^+ addition and nitrification has been reported in other studies (LePham et al. 1984; Morvan et al. 1996; Dendooven et al. 1998a) and could be attributed to NH_3 toxicity (Stojanovic and Alexander 1958), a rise in electrical conductivity and salt effect (Laura 1977; Malhi and McGill 1982) or simply to the period required for the growth of the nitrifier population necessary for enzyme expression (Malhi and McGill 1982; Grant 1994). Whitehead and Raistrick (1993) observed a negative correlation between the extent of NH_3 volatilization and soil nitrification activity. However, it is unlikely that nitrification competed with volatilization for available NH_4^+ in this study because volatilization was already considerably reduced when NO_3^- started to accumulate in the soil (Fig. 4c).

During the period of active nitrification (50 to 150 h), net $\text{NH}_4^+\text{-N}$ disappearance was about twice the net $\text{NO}_3^-\text{-N}$ accumulation, indicating that other processes affecting NH_4^+ dynamics were of significant importance. In our case, NH_3 volatilization is to be discarded because it was considerably reduced as NO_3^- started to accumulate in soil (Fig. 4c). Nitrogen immobilization is another possibility, especially during the initial phase of the crop residue decomposition (Green et al. 1995; Recous et al. 1995). Denitrification of NO_3^- is also plausible in this fine-textured soil because soil water content was generally high during the experiment and PS provided large amounts of water, C and N. Finally, nitrate leaching to lower soil depths may also have contributed to the apparent imbalance between NH_4^+ disappearance and NO_3^- production.

The last period of the experiment (>150 h after PS application) was characterized by a rapid decline in nitrification activity, stabilization of soil pH and very low

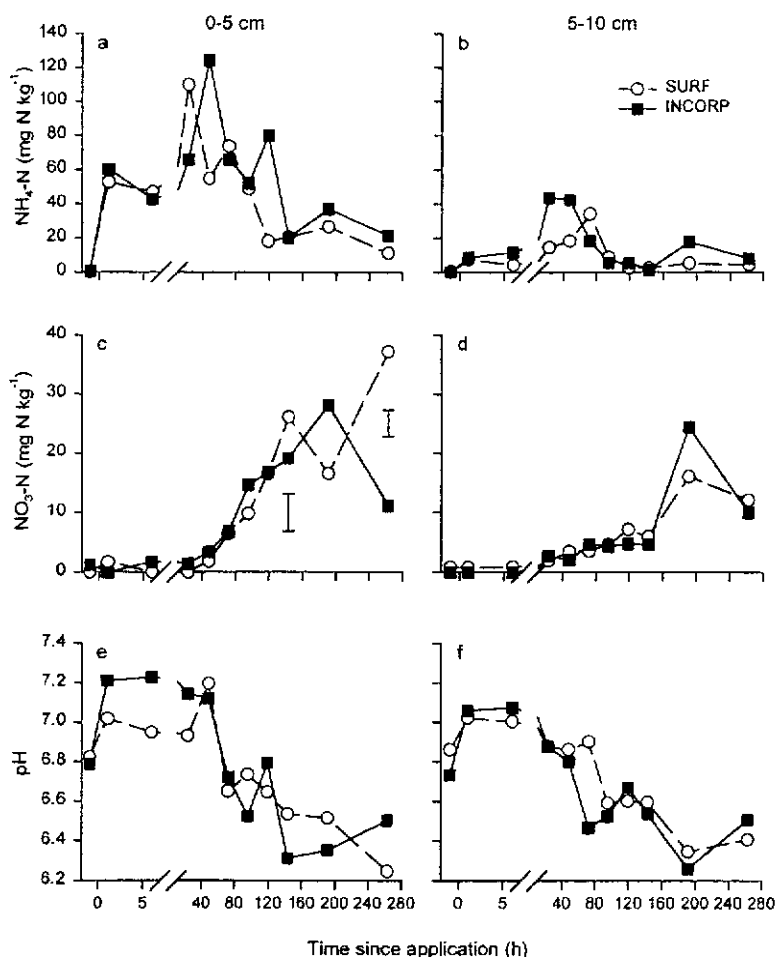


Fig. 4. Temporal variations in soil $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$ and pH in the 0- to 5-cm and 5- to 10-cm layers after pig slurry was either left on the soil surface (SURF) or incorporated (INCORP) into the soil.

NH_3 volatilization. The decrease in nitrification activity is likely the result of a lower NH_4^+ availability, but may also have been affected by a decreased soil aeration following the second rainfall (Fig. 1c). The marked increase in soil NO_3^- content in the 5- to 10-cm soil layer between 150 and 180 h suggests that the infiltrating rain water caused nitrate migration to lower soil depths (Fig. 4d), which contributed to the levelling-off of soil NO_3^- content in the 0- to 5-cm layer.

CONCLUSION

In summary, incorporating pig slurry into a soil covered with canola crop residues had little effects on the bulk mineral nitrogen dynamics of the 0- to 5-cm and 5- to 10-cm soil layers compared with broadcasting the slurry. On both treatments, nitrification followed a sigmoidal curve with enhanced activity taking place between 50 and 150 h after slurry application. The absence of treatment effects on bulk soil N dynamics contrasted with the large reduction in NH_3 volatilization in the INCORP plots compared with the SURF plots. The most likely explanation is that other

processes such as N immobilization and denitrification were more active in INCORP than in SURF plots. The reduction in NH_3 emissions induced by PS incorporation was maximum (80%) during the first 11 h following slurry application and decreased linearly to approximately 60% after 160 h. Rainfall periods 22 and 180 h after slurry application strongly decreased NH_3 emissions, likely by favouring infiltration of ammonium-N deeper in the soil. Our results indicate that a shallow and rapid incorporation of PS is an efficient measure for minimizing losses of ammonia in Quebec when slurry is applied in early fall on recently harvested canola residues.

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