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Nitrous Oxide Loss from Poultry Manure-Amended Soil after Rain

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ABSTRACT

Land application of poultry wastes in Kentucky will increase as the broiler industry grows. If poultry manure stimulates N_2O loss from soil it will reduce the fertilizer N value of this waste. In contrast, stimulated N_2O loss in grass filter strips receiving the runoff from manured fields could help reduce contamination of surface water by NO_3^-. Our objectives were to determine (i) if poultry manure stimulated N_2O loss in soil after rainfall and (ii) if there was an edge-of-field effect on N_2O loss in grass filters intercepting runoff from amended soil. Soil covers were used to measure N_2O loss from a well-drained, poultry manure-amended, silt loam soil immediately after simulated rainfall and were also used to measure N_2O loss from grass filters intercepting their surface runoff. Nitrous oxide loss from manure-amended soil was greater than from unamended controls and ranged from 5 to 13 mg N_2O-N m^{-2} h^{-1}. The maximum N_2O loss was equivalent to 3.2 kg N_2O-N ha^{-1} d^{-1}. Nitrous oxide loss from grass filters intercepting runoff ranged from 0.1 to 1.4 mg N_2O-N m^{-2} h^{-1} and was significantly greater than portions of the grass filters that did not intercept runoff. Nitrous oxide loss from poultry manure-amended soils was greater than N_2O loss typically measured from waste-amended agricultural soils. However, it only represented up to 0.7% of the total N in the applied manure.

BROILER PRODUCTION IN KENTUCKY has dramatically increased in recent years and by 1997 annual production is expected to exceed 250 million birds. Because approximately 1500 kg of waste is generated per 1000 birds in a 10-wk growing cycle, the waste generated by this industry's growth, both manure and litter, will be considerable (Edwards and Daniel, 1992).

Poultry wastes are typically land-applied in Kentucky, as in much of the southeastern USA, since this practice is cheap and convenient relative to processing methods such as composting. Crops can recover some of the N from the waste, which reduces the inorganic fertilizer N required to sustain high yields. However, compared with other animal wastes, relatively little is known about the environmental effects of poultry waste disposal (Edwards and Daniel, 1992).

One environmental consequence of poultry waste disposal may be stimulation of nitrous oxide (N_2O) loss from soil. Nitrous oxide contributes to global warming and ozone layer destruction (Davidson, 1991). However, in terms of N management, a more immediate interest is that it represents a largely irreversible loss of N from soil. Experiments employing poultry waste as a soil amendment have been conspicuously absent in studies of N_2O loss from agricultural soil (Eichner, 1990). More importantly, few of these field studies measured N_2O loss during periods when it was likely to be at its greatest— immediately after rain (Firestone and Tiedje, 1979).

Coyne et al. (1994) monitored N_2O loss after simulated rainfall on a well-drained silt loam soil amended with stored poultry manure and measured rates that averaged 0.18 kg N_2O-N ha^{-1} d^{-1}. However, up to 3 wk elapsed between the date of manure application and rainfall simulation. Furthermore, it was not obvious from this study whether poultry manure stimulated N_2O loss from soil relative to unamended soil. Evidence that recently incorporated fresh poultry manure stimulates N_2O loss from tilled soils immediately after rainfall still needs to be examined.

Although N_2O emission represents lost N from a nutrient management perspective, it would be beneficial in terms of reducing NO_3^- contamination of surface water and groundwater by runoff from manured fields. Grass filters are used as a best management practice to intercept surface runoff before it reaches waterways. Groffman et al. (1991) noted that grass filters had greater denitrification potential than control soils, although they did not demonstrate this effect by measuring N gas loss in field conditions. They suggested that adding readily available C, such as manure, might enhance denitrification in filter strips and remove some of the NO_3^- that infiltrated grass filters before it reached groundwater (Groffman et al., 1991). Nitrous oxide is an intermediate in denitrification and other microbial pathways that reduce NO_3^-; conse-

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quently, grass filters that trap runoff from manure-amended soil may have elevated N_2O loss and reflect increased denitrification activity.

Coyne et al. (1994) observed that N_2O loss from grass filters receiving runoff from poultry manure–amended soil was less than in the manure-amended soil itself. However, the edge-of-field effect was not examined by comparing N_2O loss from grass filters receiving runoff to suitable controls. Nitrous oxide loss may be stimulated in grass filters abutting manured plots and receiving their runoff compared with grass filters not similarly affected. If so, it represents a route by which N can be removed from surface runoff before it contributes to nonpoint-source pollution of adjoining waterways or infiltrates to groundwater.

In this article we report on the stimulation of N_2O loss from tilled soil amended with fresh, undercage layer manure immediately after a runoff-producing rain. We also report on the edge-of-field effect of runoff from manure-amended soil on N_2O loss in adjoining grass filters. Our objectives were to quantify N_2O loss immediately after rainfall in both cases and relate these measurements to the potential denitrification activity in both the manure-amended soil and grass filter strips.

MATERIALS AND METHODS

Site. We did the study at the University of Kentucky Agricultural Experiment Station in Lexington during June and July 1993 on plots that were previously used by Coyne et al. (1994) for rainfall simulation studies. The soil was a well-drained, Maury silt loam soil (fine, mixed, mesic Typic Paleudalf) with an average natural slope of 9% and soil permeability ranging from 5 to 15 cm h^{-1} (Blevins et al., 1990). Six individual tilled plots 4.6 m wide by 18.2 m long (Plots 1 and 2) or 13.7 m long (Plots 3, 4, and 5) were prepared (Fig. 1). An additional 18.2 m long plot was prepared but rendered unusable by storm damage during this study. A grass filter strip either 9.0 or 4.5 m in length abutted the downslope edge of each tilled strip as shown in Fig. 1. These grass filters were a mixed sod composed of tall fescue (*Festuca arundinacea* L.) and Kentucky bluegrass (*Poa pratensis* L.).

Site Treatment. Moore et al. (1983) previously described the rain simulator used in our study. Due to its size (five individual units, hooked in tandem, each with dimensions of 4.6 m by 6.1 m), the time necessary to prepare each plot for rain simulation, and the length of rain simulation on each plot, it was impractical to attempt more than one simulation per week. We minimized this temporal difference by strictly maintaining the same timing of manure application and rain simulation. Undercage poultry manure from a laying house was collected by 0900 h and uniformly spread over a tillage strip at 16.0 Mg ha^{-1} (wet wt.). The manure was incorporated into the tillage strip to a depth of 15 cm with a chisel plow as the only tillage practice. Tillage was in the direction of the slope and was completed by 1200 h. A border surrounding the manure-amended soil was tilled at the same time. We left the tillage strips uncovered after manure application unless rain was forecast. In that event, we covered the strips with black plastic tarps. We did not cover the grass filters. Meteorological conditions during the study are shown in Fig. 2.

The average nutrient composition of the manure was 2.8% total N, 2.9% total P, and 1.8% total K on a wet-weight basis. Average moisture content was 34%. The rate used was equivalent to an application of 448 kg N ha^{-1}, about three
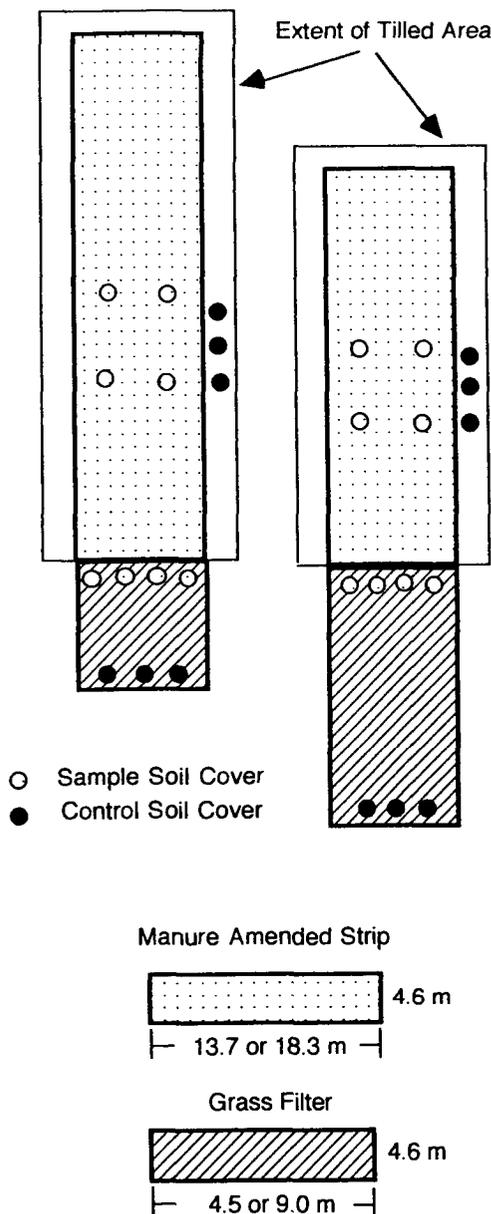

O Sample Soil Cover
● Control Soil Cover

Manure Amended Strip

4.6 m

├─ 13.7 or 18.3 m ─┤

Grass Filter

4.6 m

├─ 4.5 or 9.0 m ─┤

Fig. 1. Diagram of the research plots and location of the sample and control soil covers for N_2O–N loss measurements.

times the recommended N application rate for continuous corn (*Zea mays* L.) on this soil. The purpose of the high manure application rate was to simulate a worse-case scenario for surface runoff after rainfall.

We began rain simulation 48 h after manure application. The dates of rain simulation are in Table 1. Simulated rain was applied simultaneously to the entire length and width of each tillage strip and grass filter strip. This included the unamended but tilled border area. The rain simulation rate was 6.4 cm h^{-1}. The intensity of this rain approximates a 1-in-10-yr storm event in central Kentucky, but it was necessary to cause surface runoff onto the grass filters within a reasonable period.

We simulated rain until we obtained runoff from the bottom of the grass filters for at least 1 h. Since each tillage strip had different runoff characteristics, and the grass filters were of different lengths, the duration of simulated rain varied from
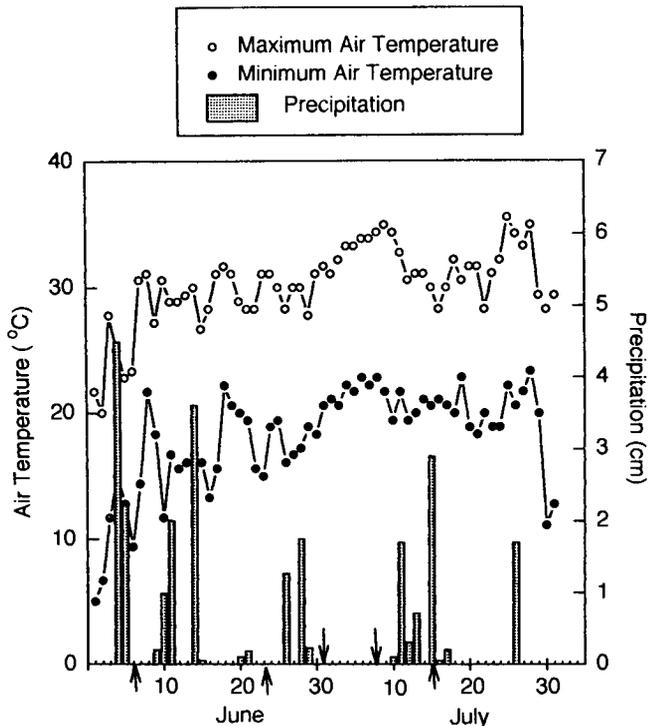
Fig. 2. Rain and air temperature during the study period. Arrows indicate dates of rainfall simulation.

plot to plot (Table 1). We usually observed surface runoff from the tillage strips 20 to 30 min after simulated rain began.

Soil Cover Measurements. We inserted soil covers to a depth of 2.5 cm in various locations in each plot to measure N_2O loss immediately after simulated rain ceased (Fig. 1). Four soil covers were placed in the middle of the tillage strips. Four soil covers were placed in the grass filters within 1 m of the tillage strips. This was where maximum sediment trapping took place during surface runoff. Three soil covers were placed in tilled but unamended soil adjacent to each manure-amended tillage strip (Fig. 1). An additional three soil covers were placed at the bottom of the grass filters approximately 4.0 or 8.5 m (depending on the filter strip length) from the interface with the tillage strips. These six soil covers were the controls against which we compared N_2O loss from manure-amended tillage strips and grass filters intercepting runoff.

The soil covers were coffee cans of 17.1 cm height and 15.6 cm diam. with the bottoms removed and a rubber septum penetrating the original plastic lid. The cans were not vented. Preliminary experiments indicated that the cans remained gas tight for the duration of field measurements. At 0, 15, 30, and 60 min, we removed 4.0-mL gas samples from the soil cover head space and stored them, until N_2O analysis, in pre-evacuated blood collection vials (vacutainers, Becton Dickinson, Rutherford, NJ). Though convenient, vacutainers have several drawbacks as storage containers: they are incompletely evacuated; they contain N_2O in excess of atmospheric background (0.31 μL L^{-1}); and N_2O leaks through the rubber stoppers (Mosier and Klemedtsson, 1994). We took into account sample dilution in incompletely evacuated tubes during calculation of N_2O flux and removed a time zero air sample for all flux measurements to correct for background N_2O in the vacutainers as recommended by Mosier and Klemedtsson (1994). A preliminary experiment indicated that N_2O loss from the vacutainers was <10% when samples were analyzed within 1 wk, as was the case in this study.

Table 1. Conditions during rainfall simulations.

Plot	Rain simulation date	Air temperature	Soil temperature† Tilled strip	Soil temperature† Filter strip	Minutes of rain
			°C		
1	6 June	28	23	22	110
2	23 June	28	24	23	92
3	1 July	30	26	24	115
4	8 July	34	29	27	205
5	15 July	29	26	24	175

† Mean of 10 measurements at the 0- to 15-cm soil depth recorded immediately after rain simulation stopped.

Gas Analysis. We measured N_2O with an electron capture detector (ECD) on a Varian 3700 gas chromatograph fitted with a 2 m Porapak Q column. Analysis conditions for the ECD were: detector temperature, 360°C; column temperature, 60°C; carrier gas, 95% argon, 5% methane; carrier gas flow 30 mL min^{-1}; and sample volume, 1.0 mL. Machine response to N_2O was measured and compared to N_2O standards of known concentration. Rates of N_2O–N evolution were calculated based on the formula given by Hutchinson and Mosier (1981).

Soil Analyses. Immediately before rain simulation in each plot, 10 soil cores at depths of 0 to 5 cm were randomly collected from the length of the tillage strip and from the grass filters. The soil cores were composited by location (tillage strip or grass filter), crumbled, mixed thoroughly, and stored at 4°C until rain simulations were completed. Subsamples were removed to determine gravimetric water content before storage. These soil samples were used for the following analyses:

For analysis of NO_3^- and NH_4^+ concentration in soil before rain simulation, subsamples were removed from the stored soil of each plot, uniformly mixed, extracted with a 1 M KCl (1:2, soil/extractant by weight), filtered to provide a soil-free supernatant, and analyzed using a Technicon Auto Analyzer System II.

We used the soil slurry method of Smith and Tiedje (1979) to measure potential denitrification activity in the stored soil samples of each plot. The soil slurry was prepared by combining 10 g soil (wet wt.) with 5 mL distilled water in a 125-mL erlenmeyer flask. The flask was sealed with a ported rubber stopper and made anaerobic by evacuating and flushing three times with oxygen-free N_2 gas. Reagent grade acetylene was added to the headspace of each flask to give a final concentration of 10%. One of three treatments was imposed on each flask: an unamended control; addition of 0.5 mg KNO_3 per flask; addition of 50 mg glucose per flask. Each treatment was replicated four times from which a mean value was determined and used for final statistical analysis. Chloramphenicol was not used to prevent denitrification enzyme synthesis because of the short duration of the assay (2 h) during which de novo synthesis of denitrification enzymes was assumed to be insignificant (Smith and Tiedje, 1979). The flasks were incubated in a shaking water bath at 30°C and 1-mL headspace samples were removed from each flask at 30-min intervals for immediate analysis by gas chromatography as previously described.

We determined the denitrifier most probable number (MPN) in the stored soil samples of each plot using the procedure outlined by Tiedje (1982). A 10-fold serial dilution of soil in physiological saline (8.5 g NaCl L^{-1} in distilled H_2O) was used to inoculate five replicate tubes per dilution. Growth media was 15 g L^{-1} Tryptic Soy Broth containing 1 g L^{-1} KNO_3. The tubes were sealed with rubber stoppers to facilitate development of denitrifying conditions and incubated 28 d at 26°C. Residual NO_3^- was detected with diphenylamine in con-

Table 2. The N_2O–N evolution from tilled strips and grass filters after simulated rainfall.

| Plot | Rain simulation date | Tilled strip | | Grass filter | |
		Manure amended[†]	Unamended control[‡]	Receiving runoff[†]	Control[‡]
		mg N_2O–N m^{-2} h^{-1}			
1	6 June	5.42 ± 4.04	5.62 ± 1.78	0.12 ± 0.03	0.01 ± 0.07
2	23 June	13.16 ± 0.22	2.43 ± 2.27	0.07 ± 0.13	0.43 ± 0.15
3	1 July	6.38 ± 3.02	2.00 ± 0.97	0.21 ± 0.16	0.09 ± 0.02
4	8 July	7.40 ± 3.99	2.45 ± 0.85	1.24 ± 0.27	0.33 ± 0.22
5	15 July	13.30 ± 2.68	0.46 ± 0.23	1.35 ± 0.47	0.15 ± 0.09

[†] Mean of four replicates ± 1 SD.
[‡] Mean of three replicates ± 1 SD.

Table 3. Soil NO_3^-–N and NH_4^+–N concentrations (oven dry weight soil basis) and gravimetric water content in the 0- to 5-cm soil depth immediately before simulated rainfall.

| Plot | Rain simulation date | Tilled strip | | | Grass filter | | |
		Percent moisture	NO_3^-–N	NH_4^+–N	Percent moisture	NO_3^-–N	NH_4^+–N
			mg kg^{-1}			mg kg^{-1}	
1[†]	6 June	12.4	25	166	13.0	3	3
2	23 June	8.4	55	177	11.6	4	5
3	1 July	14.0	54	126	17.9	4	8
4	8 July	14.3	19	67	11.8	4	8
5	15 July	12.8	21	99	15.7	10	9
Avg. (±1 SD)		12.4 (2.4)	35 (18)	127 (46)	14.0 (2.7)	5 (3)	7 (3)

[†] Samples in this plot were collected from the 0- to 15-cm soil depth.

centrated sulfuric acid. Published tables (Alexander, 1982) were used to convert the results of the MPN assays to an estimate of the mean denitrifier population per gram of dry soil for each location.

Statistical Analysis. The data for field N_2O loss were analyzed for statistical significance by one and two-way ANOVA using a completely randomized, replicated experiment design. Regression analysis was done using Microsoft Excel (Microsoft Corp., Redmond, WA). Potential denitrification activity in manure-amended tillage strips and grass filters was compared by means of t-tests.

RESULTS AND DISCUSSION

Our first objective was to determine the magnitude of N_2O loss from poultry manure–amended soil immediately after rain. There were significant differences in N_2O loss between plots ($P \leq 0.01$), so these results are reported on an individual plot basis (Table 2). Nitrous oxide loss ranged from 5.4 to 13.3 mg N_2O–N m^{-2} h^{-1} in the manure-amended soil. This is a conservative estimate. The soil covers were not vented and Hutchinson and Mosier (1981) showed that vented soil covers accumulate significantly more N_2O than nonvented covers. This reflects the combined effects of reduced N_2O diffusion from soil due to back pressure and the subsequent potential for further reduction of N_2O to N_2. The N_2O losses we measured would also account for only part of the N_2O formed under these conditions. Nitrous oxide is relatively soluble (0.54–0.47 mL N_2O per mL H_2O between 25 and 30°C) (Tiedje, 1982). Some of the N_2O produced after rainfall would not have been measured because it was undoubtedly dissolved in soil water.

The rates were not correlated with any obvious parameters. Regression analysis indicated that neither the date of rain simulation (Table 1), duration of rain (Table 1), water-filled pore space, initial soil moisture content before rainfall (Table 3), initial NO_3^- or NH_4^+ concentration (Table 3), nor potential denitrification activity were significantly correlated ($P \leq 0.05$) with N_2O loss from manure-amended soil. Spatial variability of N_2O loss in the plots may have obscured statistically significant relationships since the average coefficient of variability in manure-amended soil was 39%.

The N_2O emission we measured was equivalent to daily N_2O loss ranging from 1.3 to 3.2 kg N_2O–N ha^{-1} d^{-1}. Cates and Keeney (1987) measured total N_2O emission of 3.60 and 5.20 kg N_2O–N ha^{-1} yr^{-1} in manure-amended corn, whereas Goodroad and Keeney

(1985) measured N_2O emission of up to 10.31 kg N_2O–N ha^{-1} in a 151-d sample period in manure-amended tobacco (*Nicotiana tabacum* L.). Obviously, the short-term loss of N_2O–N from manured fields immediately after rainfall can be of the same or greater magnitude as estimates of N_2O–N loss extrapolated from periodic daily measurements over an extended period. Although we measured greater rates of N_2O loss than other studies have reported, we did not investigate whether these losses continued for an extended period. Consequently, the short-term measurements we conducted may not reflect N_2O loss, even a few hours after rain stops.

Eichner (1990) estimated that 2% of N fertilizer is lost as N_2O over a 1-yr period in fertilized and manured soils. The estimated N loss due to N_2O emission in our study represented between 0.3 and 0.7% of the total N applied in the poultry manure. The values we measured support Eichner's conclusion that N_2O emission accounts for a relatively small fraction of N fertilizer applied to agricultural soil (Eichner, 1990).

It is a tacit assumption on our part that the principal source of N_2O in this study came from denitrification. Although the intensity and duration of rain created conditions favorable for denitrification, we cannot rule out other microbial sources of N_2O. Nitrous oxide may be evolved during NO_3^- respiration (Smith and Zimmerman, 1981) and during autotrophic and heterotrophic nitrification (Robertson and Tiedje, 1987). Bremner and Blackmer (1981) reported that nitrification caused evolution of approximately 1.2 mg N_2O–N kg^{-1} soil d^{-1} from soil amended with poultry manure and incubated at 50% water holding capacity and 30°C.

We did not selectively inhibit nitrification. However, it is unlikely that nitrification was a major source of N_2O during our measurements. Oxygen diffusion limits this process when water-filled pore space begins to exceed 60% (Davidson, 1991). In manure-amended soil, the average gravimetric moisture content immediately after rainfall was 34.6% (SD ± 2.9%) and water-filled pore space ranged between 69 and 87% (avg., 76 ± 9 %). In grass filters the average gravimetric moisture content was 34.4% (SD ± 4.5%) and water-filled pore space ranged from 64 to 91% (avg., 76 ± 10 %). Soil moisture conditions were clearly unfavorable for nitrification and the most likely source of N_2O in our study was from denitrification.

To see whether poultry manure stimulated N_2O production, we compared N_2O loss in manure-amended and unamended soil that were subjected to the same rainfall conditions. Nitrous oxide loss was significantly greater ($P \leq 0.01$) in the manure-amended soil than the unamended soil. In contrast to the amended soil, N_2O loss in unamended soil was only 0.5 to 5.6 mg N_2O-N m^{-2} h^{-1} (Table 2). We didn't measure NO_3^- concentrations in unamended soil before rain simulations, but we assume that due to the short period between incorporation and simulation, nitrification would have contributed little to differences in soil NO_3^- between amended and unamended locations.

The N_2O losses we measured in the field were comparable to N_2O losses Rice et al. (1988) measured in cell waste-amended, acetylene blocked soil cores. They noted that organic wastes injected into soil stimulated denitrification by providing available C and N. Denitrification in most soils is C-limited and poultry manure represents the addition of potentially available C and N. The mean potential denitrification in glucose-amended, manure-treated soil (1.4 μg N_2O-N min^{-1} kg^{-1} soil) was only slightly greater than NO_3^--amended soil (0.9 μg N_2O-N min^{-1} kg^{-1} soil) or an unamended control (1.3 μg N_2O-N min^{-1} kg^{-1} soil) and the differences were not significant ($P = 0.05$). This suggests that after poultry manure amendment, although C may still have been limiting, there was sufficient C already present in the manure-treated plots to minimize the effect of NO_3^- and glucose addition.

Significant N_2O evolution from grass filters intercepting runoff from manure-amended soil (an edge-of-field effect) could indicate a route by which NO_3^- is removed from surface runoff before it contributes to nonpoint-source pollution. One of our objectives was to look for evidence that this occurred in field conditions.

Although the total sediment intercepted by the grass filters differed between plots (data not shown), there was not a significant difference ($P \leq 0.25$) between the length of tilled strips and the amount of soil that eroded from them onto the abutting grass filters. There was also not a significant difference ($P \leq 0.54$) between the length of tillage strip and N_2O loss from the grass filters, whether from those portions that received runoff or those that did not. Nitrous oxide loss, however, was significantly greater ($P \leq 0.01$) in parts of the grass filters that abutted the tillage strips compared with losses in downslope locations (Table 2).

We did not measure the runoff constituents, but Westerman et al. (1983) reported that runoff constituents from surface-applied poultry manure in a laboratory study under approximately similar conditions to ours (9% slope, 5 cm h^{-1} simulated rain, 27 Mg ha^{-1} application rate) were 19 mg L^{-1} NH_4^+-N and 1.3 mg L^{-1} NO_3-N. Chemical oxygen demand (COD) was 1875 mg L^{-1}. Groffman et al. (1991) proposed that addition of a C and N source (like manure) to a filter strip might increase its denitrification potential. Our results appear to support that conclusion, at least with respect to N_2O loss, although our study is not an absolute test of this hypothesis. Since every grass filter received runoff from manure-amended

soil, we cannot say definitively that increased N_2O loss was due to manure in runoff.

Nitrous oxide loss was significantly greater ($P \leq 0.01$) in manure-amended tillage strips than in grass filters intercepting their runoff (Table 2). Since average gravimetric water content immediately after rainfall was similar (34.6 vs. 34.4%) and average water-filled pore space was identical (76%), the difference is probably due to the initial soil NO_3^- concentration in both locations (Table 3).

It is possible that more N_2O was reduced to N_2 in grass filters than tillage strips. This would result in less measurable N_2O loss. When conditions were ideal for activity and N_2O reduction was inhibited by acetylene, denitrification in the potential denitrification enzyme assays was significantly greater ($P < 0.05$) in unamended soil from the grass filters (2.0 μg N_2O-N min^{-1} kg^{-1} soil) compared to unamended soil from the tillage strips (1.3 μg N_2O-N min^{-1} kg^{-1} soil). The N_2O production rates we observed were about half the rate reported by Smith and Tiedje (1979) for similar assays on a loam soil.

Nitrate addition alone did not increase denitrification in soil from the grass filters. The potential denitrification activity remained at 2.0 μg N_2O-N min^{-1} kg^{-1} soil. A much greater effect occurred when the grass filter soils were amended with glucose. The potential denitrification assays indicated that N_2O production significantly increased (to 4.2 μg N_2O-N min^{-1} kg^{-1} soil) when the soils were amended with glucose ($P < 0.05$). This suggests that grass filter soil was C-limited to a greater extent than was tillage strip soil.

These results did not correspond with the MPN denitrifiers enumerated for these soil samples. The mean tabulated value for MPN denitrifiers was greater in the tillage strip soil (7.3 × 10^5 cells g^{-1} soil) than the grass filter soil (5.5 × 10^5 cells g^{-1} soil). However, population estimates based on MPN are imprecise and small differences are not significant. The denitrifier numbers were statistically the same within the 95% confidence limit (± 3.3 × tabulated MPN).

CONCLUSION

Nitrous oxide evolution is a dynamic, microbially mediated process. We found that the average N_2O loss immediately after rain could exceed 13 mg N_2O-N m^{-2} h^{-1} in a well-drained silt loam soil amended with an available C and N source like poultry manure. The manure addition stimulated N_2O loss compared with controls; however, it accounted for <0.1% of the total N added in the manure. Although the potential denitrification activity in grass filters was greater than that in tilled soils, the N_2O loss immediately after rainfall was less, probably as a result of the available NO_3^- in soil in both locations. Grass filters intercepting runoff from poultry manure-amended soils produced significantly more N_2O than areas that did not intercept runoff. Consequently, there appears to be an edge-of-field effect for N_2O loss, which contributes to some NO_3^- removal from surface runoff of manure-treated soils.

ACKNOWLEDGMENTS

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