COMMUN. SOIL SCI. PLANT ANAL., 29(1&2), 121–139 (1998)

Seasonal Trends in Soil Nitrogen from Injected or Surface-Incorporated Sewage Sludge Applied to Corn

Juliet M. Cartron and Ray R. Weil

Department of Agronomy, H.J. Patterson Hall, University of Maryland, College Park, MD 20742

ABSTRACT

Use of sewage sludge on cropland may contribute to nitrate leaching or runoff from fields if mineralization of organic nitrogen (N) is not in synchrony with crop N uptake. Differences in sludge application method may influence sludge N use efficiency. A two-year field experiment was conducted to determine how method of applying lime-stabilized digested sewage sludge in the spring affected seasonal patterns of soil mineral N. Sludge rate was such as to supply 157 kg ha^{-1} plant available N as determined by State of Maryland regulations. Corn (*Zea mays*) yield in year 2 and corn earleaf N at tasseling in both years were significantly lower for surface-incorporated sludge than for injected sludge, although equivalent N was applied to both. Vertical distribution of soil ammonium-N and nitrate-N within the surface 30 cm of soil in year 2 suggested that, compared to injected sludge, surface-incorporated sludge lost more nitrate by leaching before the period of rapid plant N uptake. Release of nitrate was delayed by at least one month with injected as compared to surface-incorporated sludge. In both years, soil pH and electrical conductivity measured about one month after sludge application were sufficiently high to inhibit nitrification in the injected sludge band. Residual mineral soil N remaining in the upper 30 cm of soil after plant N uptake ceased in fall was greatest with injected sludge in both years. Delayed nitrification in the injected band should be considered in planning method and timing of sludge applications to cropland.

INTRODUCTION

Organic N sources, such as sludge, used in field crop production may contaminate surface and ground water with N if mineralization of organic N occurs before crop N uptake begins, or if it continues after crop N uptake has ceased. Non-point sources of N contamination are a high priority for nutrient management in the Chesapeake Bay Watershed. Most leaching in the Eastern United States occurs during groundwater recharge between September and May, and NO_3^--N remaining in the soil profile after crop N uptake ceases in fall is susceptible to leaching (Chichester, 1977; Meisinger et al., 1991). The period between sludge application and the onset of rapid crop N uptake is another period of potential N leaching. Losses of N from sludge during both periods has not been sufficiently investigated.

Organic N applied to soils in sewage sludge is subject to a variety of biological transformations which are sensitive to pH, moisture, temperature, and other soil environmental parameters. Depending on conditions in the soil, N released from sludge is either incorporated into plant tissue and soil organic matter or lost from the system through volatilization, denitrification, runoff, or leaching. Sewage sludge has been shown to be an effective substitute for fertilizer in supplying N to corn (Cripps et al., 1992; Magdoff and Amadon, 1980), however, little is known about effects of sludge application methods with respect to potential N loss by leaching or runoff.

Application of municipal sewage sludge to cropland is regulated using standard mineralization factors to determine the amount of N expected to be plant available in one growing season. The USEPA (1983) guidelines for sludge application to cropland define the amount of plant available N (PAN) in sludge by the following equation:

$$\text{mg kg}^{-1}\ \text{PAN} = [(\text{mg kg}^{-1}\ NH_4^+\text{-N})(k) + \text{mg kg}^{-1}\ NO_3^-\text{-N} + (\text{mg kg}^{-1}\ NO_{Org})(F)]$$

where F is a mineralization factor, k is a volatilization factor and NO_{Org} is the organic N in the sludge. The k is assigned a value of 0.5 for surface-applied liquid sludge (unincorporated) and 1.0 for all other sludges. The mineralization factor (F) is the proportion of organic N expected to be mineralized within one growing season and is assigned a value of 0.1 for composted sludge, 0.2 for anaerobically digested sludge, 0.3 for aerobically digested sludge, and 0.4 for unstabilized sludge. These guidelines were based predominantly on laboratory incubations and limited field research (USEPA, 1983). The Maryland Department of Environment (1989) uses a mineralization factor of 0.3 for lime stabilized sludges. Limited field research has reported mineralization rates for digested sludge close to 0.50 for the first growing season after application (Cripps et al., 1992; Kelling et al., 1977; Magdoff and Amadon, 1980). This value contrasts with the 0.30 value used in regulations and estimated by incubation studies (Sommers et al., 1981; Serna and Pomares, 1992). Higher rate of N mineralization in the field may be the result of freeze/thaw and wet/dry cycles as well as the extended period of potential N mineralization which occurs in the field. Several researchers have reported application of sludge at current regulatory rates increases corn grain yields, compared to equivalent rates (based on regulatory calculations) of commercial fertilizer (Cripps et al.,1992; Menelik et al.,1991). It was not clear, however, whether increased yields from sludge compared to fertilizer are due to improvement in N availability or to under estimation of N mineralization in the field.

Sludge is typically applied either in concentrated subsurface injected bands or spread on the soil surface and incorporated. Cripps et al. (1992) reported higher corn yields with injected sludge compared to surface applied sludge and attribute the difference to higher volatilization loss of N from the latter. Differences in sludge application method may influence N plant availability and susceptibility to leaching, but research comparing application methods has been conducted mostly with liquid animal manures, not sewage sludges. Compared to surface incorporation, application of liquid manures in concentrated bands below the soil surface may delay inorganic N release to crops due to inhibition of nitrification or ammonification by ammonia toxicity (Sawyer and Hoeft, 1990), anaerobic conditions (Motavalli et al., 1985; Walker, 1975; Godwin, 1985; Sawyer and Hoeft, 1990; Schmitt et al., 1992), or low soil to waste contact (Schmitt et al., 1995). Lime stabilization is a sludge treatment process which is utilized in over one third of the wastewater treatment plants in Maryland. Factors which could affect N mineralization rate such as salinity (electrical conductivity >9 dS m^{-1}) and pH (pH 12) are markedly different for lime-stabilized digested sludge than for sludge produced by digestion processes alone. However, current regulations apply the same mineralization rate to digested sludge, whether lime-stabilized or not.

In this study, aerobically-digested and lime-stabilized sewage sludge was applied each spring to corn by subsurface injection or by surface-incorporation in a two-year field experiment. Our objectives were to compare the effects of injected sewage sludge, surface-incorporated sewage sludge or a split application of urea ammonium nitrate fertilizer on 1) seasonal dynamics of soil inorganic N within the 0 to 30 cm soil profile, 2) interrelationships between N availability and potentially leachable residual soil N in fall, and 3) spatial distribution of inorganic N and soluble salts in the upper 30 cm of soil.

MATERIALS AND METHODS

Site Description

A field experiment was conducted in 1994 and 1995 at the Chesapeake Bay Foundation's Clagett Farm in Upper Marlboro, MD, on soils predominately Westphalia fine sandy loam (coarse-loamy, siliceous, mesic, Ochreptic Hapludults). At the start of the experiment, soil tests for available phosphorus (P), potassium (K), and magnesium (Mg) levels in the 0 to 15 cm soil layer were in the high to very high range, soil organic matter was 17.5 g kg^{-1} soil , CEC was 7.0 $cmol^{+}$ kg^{-1} and pH was 5.9 (1:2 soil:water). The sand, silt, and clay contents were 687, 194, 118 g kg^{-1}, respectively, for the top 30 cm of soil.

Experimental Design and Layout

The experimental design was a randomized complete block with three N sources as treatments. The experiment was replicated five times in 1994. Only three of these replications were continued in 1995. Two replications used 0.03 ha (10x30 m) plots. The remaining replicates used 0.06 ha (14x45 m) plots. The MGLH (multiple general linear model) procedure of SYSTAT (Wilkinson, 1990) was used for analysis of variance of the data for each sampling date to test the effect of N source on total soil NO_3^--N and NH_4^+-N, corn yield and corn N contents. Mean separations among treatments were determined by Fisher's-protected LSD. A distance weighted regression was used to generate two dimensional contour plots of vertical and horizontal N distribution.

Treatments

Treatments consisted of the following three N sources: injected sewage sludge (INJ), surface-incorporated sewage sludge (SUR), and commercial fertilizer (FER). Sewage sludge application rates were based on standard Maryland Department of Environment sludge application guidelines (MDE, 1989) to provide 157 kg plant available N ha^{-1}. To serve as a check for N availability on the site, 0 kg N ha^{-1} check plots (4 m x 6.09 m) were established between the larger treatment plots.

On 24 April, 1994, sludge was applied at a rate of 9.13 Mg dry sludge ha^{-1} to provide an estimated 156 kg PAN ha^{-1} for the 1994 growing season. On 21 or 27 May, 1995, sludge was applied at a rate of 11.0 Mg dry sludge ha^{-1} (148 kg PAN ha^{-1}). The sludge applied in 1994 was estimated to contribute an additional 71 kg N ha^{-1} to the 1995 PAN according to the second mineralization rate of 0.15 in the MDE guidelines (MDE, 1989). The total PAN in the sludge treated plots in 1995 was therefore 219 (148+71) kg ha^{-1}, or 62 kg ha^{-1} in excess of the desired PAN for the year. This over-application was unavoidable because it occurred with the application vehicle set to the lowest rate of which it was capable.

The application vehicle (Ag-chem, Minneapolis, MN, model 2505), with vertical injection tines spaced 60 cm apart, injected liquid sludge 15 to 25 cm deep in a concentrated band, approximately 8 cm outside diameter. For the SUR treatment the injection tines were raised 1.5 m above the soil surface so as to splash liquid sludge on the soil, and the sludge was then mixed into the top 7.5 cm by discing in two directions. All treatments received the same disk tillage. The vertical injection tines of the application vehicle have an effect similar to chisel plow tillage, and were used without sludge in the SUR and FER plots to provide equivalent soil loosening as in the INJ treatment. In 1994 tillage occurred within 1 to 2 hr of sludge application and in 1995 tillage occurred within 8 to 10 hr of sludge application.

The FER plots received split applications of fertilizer N for a total of 160 and 157 kg N ha^{-1} in 1994 and 1995, respectively. On 24 April 1994 and 21 or 27 May 1995, 45 kg N ha^{-1} starter fertilizer was broadcast as NH_4NO_3 for the FER treatment plots. In 1994, urea ammonium nitrate solution (UAN) was broadcast on 11 May at 54 kg N ha^{-1} and dribbled between corn rows on 16 June at 60 kg N ha^{-1}. On 16 June 1995, UAN was dribbled on at 112 kg N ha^{-1}.

Crop Management

To kill existing grass sod, 1683 g.a.i. ha^{-1} glyphosate [N-(phosphonomethyl) glycine] was applied 19 through 24 April 1994. For weed control 1670, 1354, and 1262 g.a.i. ha^{-1} of metalochlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2methoxy-1-methylethyl) acetamide], atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine], and glyphosate [N-(phosphonomethyl) gylcine] were applied, respectively, on 10 May 1994. Only 1670 g.a.i. ha^{-1} of metolachlor [2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2methoxy-1-methylethyl) acetamide] and 1354 g.a.i. ha^{-1} of atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2,4-diamine] were applied on 22 May in 1995.

On 24 April 1994 and 21 or 27 May 1995, all treatments received the same tillage consisting of chisel-plow tillage 25 cm deep with the injection vehicle tines and light disc tillage in two directions, leaving an average percent residue cover of 42%. On 9 May 1994 and 22 or 27 May 1995 (Pioneer 3394) was planted at 50,161 kernels ha^{-1}, in 96 cm rows. Growing degree units (GDU°C) (Figure 1) were calculated and corn growth stage evaluated in the field to estimate periods of rapid corn N uptake.

Chemical Analyses

Sludge was sampled for analysis as applied to fields in 1994 and 1995 (Table 1). Solids content was determined by oven drying at 60°C to constant weight. Total N was determined on oven dried sludge using a CHN Analyzer (CHN-600, Leco Corp., St. Joseph, MI). Sludge samples (5.0 mL) were shaken with 20 mL 0.1M K_2SO_4 for 15 min and analyzed for NH_4^+-N by ammonia-sensitive electrode (Orion Model 95-12; Banwart et al., 1972) and for NO_3^--N by the salicylic acid

TABLE 1. Chemical and physical analysis of sludge as applied to field plots.

Year	pH	solids	Organic C	Organic N	NH_4^+-N	NO_3^--N	Total P
		%	----------	----------	g kg^{-1}	----------	
1994	11.3 (0.13)†	15.4 (0.14)	320 (0.81)	52 (0.33)	1.4 (0.055)	0.11(0.034)	18 (0.21)
1995	12.4 (0.04)	16.5 (0.22)	250 (3.3)	41 (0.41)	1.0 (0.048)	0.11 (0.02)	nd‡

†Values in parentheses are standard error of the mean.
‡Not determined.

method (Cataldo et al., 1975). The pH of the sludge was measured directly using a combination glass electrode.

Field Measurements and Plant Tissue Sampling

For the SUR and FER treatments, 8 randomly-located soil cores 2 cm in diameter, were taken to a depth of 30 cm. These cores were then divided into 6 cm increments and composited by depth. In the INJ plots nine cores were taken, three directly through the injected sludge band, three 12 cm from the injected band, and three 24 cm from the injected band. Sludge bands were centered 60 cm apart.

Soil Chemical Analyses

Soil samples were put on ice for transport to the laboratory where they were rapidly fan-dried at room temperature, ground, and sieved <2 mm. Dry 10.0 g soil samples were extracted with 20 mL 0.1M K_2SO_4 for 15 min and analyzed for NH_4^+-N by ammonia-sensitive electrode (Orion Model 95-12; Banwart et al., 1972) and for NO_3^--N by the salicylic acid method (Cataldo et al., 1975).

Electrical conductivity was measured on saturated paste extracts of selected soil samples using an electrical conductivity meter and dip cell. Soil pH measurements were performed *in situ* on the moist wall of shallow soils pits, including directly in the injected sludge band for the INJ plots, using a flat surface combination glass electrode. Because of the high salinity within the sludge bands, these pH values are reported as pH_{salt}. Values of pH_{water} for these measurements were calculated from a linear regression (r^2=0.94) determined previously for this soil: pH_{water}=0.707+1.07*pH_{salt}. Soil NH_3 concentrations were calculated from the following equilibrium equation:

$$NH_4^+ \; NH_3 + H^+ \; .... \; K = 10^{-9.41} \text{ at } 20°C$$

$$pKa=10.05-0.032 * (\text{temperature}°C) \text{ (Ferrara and Dimino, 1985)}$$

using soil NH_4^+-N concentrations measured on air-dried samples, H^+ activity determined by pH_{water} and soil temperature measured in the field. Soil NH_4^+-N and NO_3^--N concentrations (mg kg^{-1}) were adjusted for bulk density of each 6 cm soil layer and summed over all depths to calculate kg N ha^{-1} for the 0-30 cm layer. Bulk densities measured at the conclusion of the study were 1.25, 1.44, 1.49, 1.48, and 1.55 g cm^{-3} for the first five 6-cm increments of soil. A mean bulk density of 1.04 g cm^{-3} was used for the 6-cm soil core increments containing the injected sludge band. Based on the observed width of the sludge bands and associated zone of extremely high N concentrations, N concentration values for cores taken directly through a sludge band were weighted to represent 0.16 of the soil volume between adjacent injection bands, while the other cores were weighted to represent the remaining 0.84 of the soil volume. This weighting avoided over-estimation of N due to very high values in soil cores containing the injected sludge.

TABLE 2. Effect of N source on above-ground dry matter, N contents and N concentration for corn at harvest in 1994 and 1995.

N Source	PAN§	n†	Dry Matter		Nitrogen				
			Grain	Stover	Grain	Stover	Grain	Stover	Earleaf
			kg ha^{-1}				%		
					1994				
INJ	156	5	8946a††	nd‡	131a	nd	1.476a	nd	3.45a
SUR	156	5	9070a	nd	129a	nd	1.430a	nd	3.28b
FER	160	5	9104a	nd	131a	nd	1.454a	nd	3.25b
F 0*	0	4	4991	nd	62	nd	1.175	nd	2.87
					1995				
INJ	219‡‡	3	9872a	16030a	137a	91.6 ab	1.39a	0.79ab	3.31a
SUR	219‡‡	3	7999b	16667a	108b	98.7 a	1.35a	0.80a	3.10b
FER	157	3	9262ab	13710a	125ab	79.1 ab	1.35a	0.76ab	3.15ab
F 0	0	2	3822	6619	39	nd	0.98	0.49	nd

†Sample size.
††Means followed by the same letter within a column are not significantly different at the 0.10 probability level by Fisher's least significant difference.
‡ Not determined.
‡‡160 kg N ha^{-1} applied in 1995 plus 71 kg N ha^{-1} estimated PAN from 1994 sludge application, as per MDE guidelines.
§Plant available nitrogen.
*No nitrogen added control.

Plant Sampling and Analyses

Grain in 1994 and both grain and stover in 1995 were hand harvested in four 4.57 m rows in the larger plots, in three 4.57 m rows in each smaller plot and in two 4.57 m rows in the no-N control plot. In 1995, grain and stover were hand-harvested in four 10 m rows in all plots. At tasseling, ear leaves from eight corn plants in each plot were collected. Grain, stover, and earleaf samples were dried at 65°C to constant weight, ground in a Wiley mill to pass a 1 mm sieve, and a 0.1 g subsample was analyzed for total N using a CHN Analyzer (CHN-600, Leco Corp., St. Joseph, MI).

RESULTS AND DISCUSSION

Plant Nitrogen Uptake

Except for the no-N controls, there were no significant (P=0.10) treatment effects on N in grain (kg ha^{-1}) in 1994 or N in grain plus stover in 1995, despite the high estimated PAN for the INJ and SUR treatments in 1995 (Table 2). The lack of differences suggests all treatments had sufficient N and corn removed similar amounts of N from the rooting zone in SUR, INJ, and FER in both years. Low rainfall in August of both years (Figure 1) may have limited late-season corn N uptake and grain fill. Grain yield in 1995 and earleaf N content in both years were significantly higher (P=0.10) for INJ compared to SUR treatment, suggesting higher N availability to corn in the INJ treatment plots, especially after tasseling (Table 2). Cripps et al. (1992) reported a similar corn yield advantage for injected over surface-applied sewage sludge.

Soil Inorganic Nitrogen

In both years, the SUR and INJ treatments provided a large pool of soil inorganic N before the corn reached the 6-leaf stage in late June (Figures 2A and 3A). On 22 May 1994 there was no significant difference between SUR and INJ in total inorganic N in the 0-30 cm layer of soil, however on 15 June and 23 August 1994 total soil inorganic N was significantly higher for INJ. Compared to SUR, INJ had significantly higher NH_4^+ on 22 May and significantly lower NO_3^-, suggesting a delay in nitrification, but not in ammonification (Figure 2B and 2C) in INJ. The NO_3^- content in the injected band of sludge increased dramatically from 22 May to 15 June 1994, suggesting the oxidation of NH_4^+ or NO_2^- had recovered by 15 June (Figures 2B and 2C).

During mid June 1994, corn plants in SUR plots were visibly greener than in INJ plots, indicating greater early-season availability of N in the SUR compared to the INJ treatment. In 1994, the trend of inorganic N for SUR (Figure 2A) between May and September suggests that inorganic N content may have peaked for that treatment application at the first sample date on 22 May. Vertical

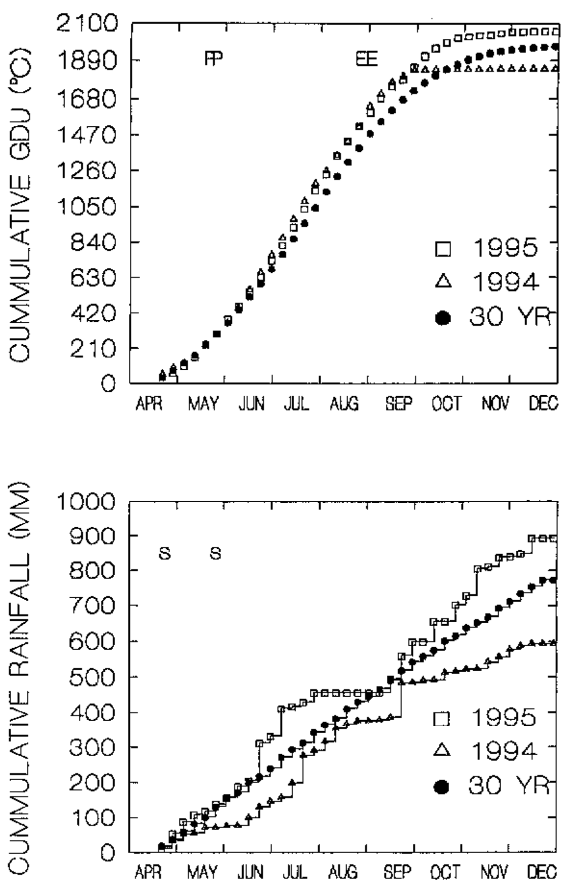

FIGURE 1. Weekly rainfall and growing degree units (°C) for April 22 to December 31, for 1994, 1995, and the 30-year average for Upper Marlboro, Maryland. (S), (P), and (E) indicate the dates of sludge application, planting, and end of plant N uptake determined growing degree units for 1994 (earlier dates) and 1995 (later dates), respectively.

distribution of N (Figure 4) shows both NH_4^+ and NO_3^- in the upper 6 cm of soil were similar for SUR and FER and that NO_3^- became available later and deeper in INJ plots. Denitrification or volatilization are other potential N loss pathways which could account for N loss from the SUR treatment. Volatilization from the SUR treatment is less likely due to the high degree of sludge incorporation into the soil.

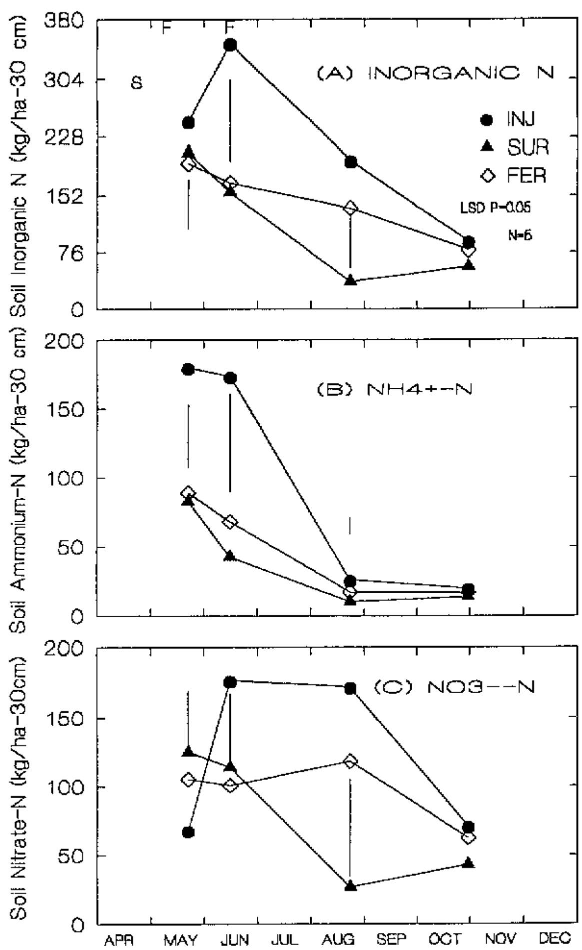

FIGURE 2. Effects of four nitrogen treatments on inorganic nitrogen in the upper 30 cm of soil during 1994. Least squares means for total inorganic N (A), ammonium-N (B), and nitrate-N (C). Vertical bars indicate Fisher's LSD (P=0.05). (S) and (F) indicate dates of sludge and fertilizer application, respectively.

On the first three sampling dates after sludge application 1995 the amount of inorganic N ha^{-1} in the 0 to 30 cm soil depth was not significantly different for INJ and SUR (Figure 3A). However, there were significant differences between these treatments in NH_4^+ and NO_3^- (Figures 3B and 3C). As in 1994, a delay in NH_4^+ oxidation was observed in INJ in 1995 (Figure 3B). In both years late-season NO_3^- was higher in INJ.

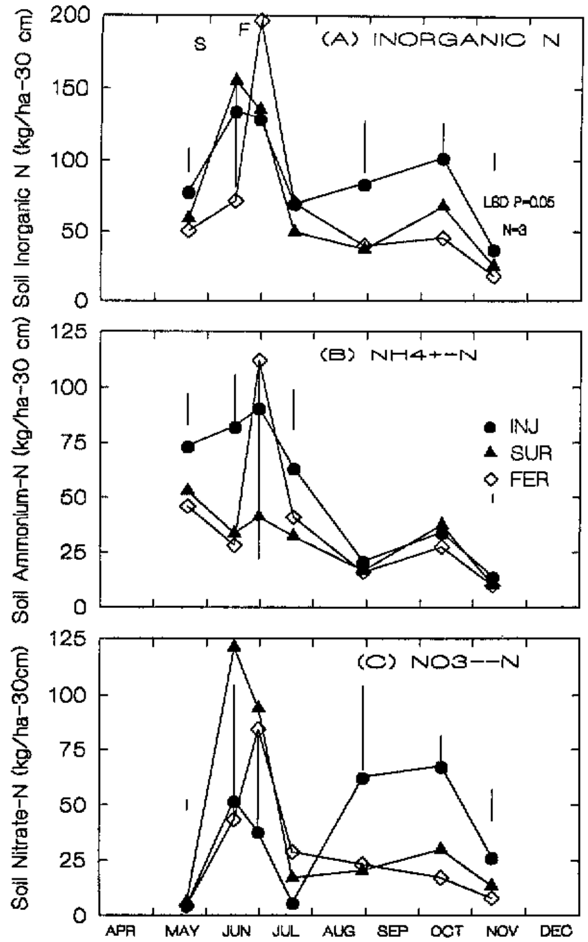

FIGURE 3. Effects of four nitrogen treatments on inorganic nitrogen in the upper 30 cm of soil during 1995. Least squares means for total inorganic N (A), ammonium-N (B), and nitrate-N (C). Vertical bars indicate Fisher's LSD (P=0.05). (S) and (F) indicate dates of sludge and fertilizer application, respectively.

On the first two sampling dates after sludge application in 1995, NO_3^- levels were higher at all soils depths for SUR compared to INJ (Figures 5B and 5D). Increased NO_3^- at 24 and 30 cm in SUR between 15 and 30 June suggest rapid NO_3^- leaching in SUR plots. This apparent early season loss of NO_3^- from SUR plots by leaching was confirmed by NO_3^- concentrations in the shallow unconfined

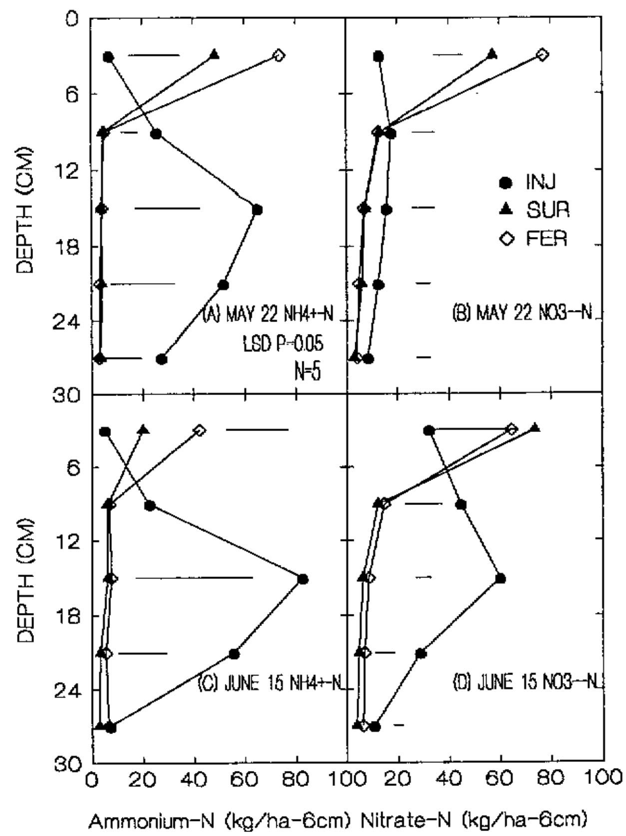

FIGURE 4. The effect of nitrogen source on ammonium-N and nitrate-N distribution (kg ha^{-1}-6 cm) with depth in the upper 30 cm of soil on May 22 and June 15, 1994. Data points are least squares means and horizontal bars indicate on $LSD_{0.05}$ for each depth sampled.

groundwater aquifer as reported by Cornwell (1996). During August in both years, NO_3^- was higher in INJ than in SUR (Figures 2 and 3) in the 0 to 30 cm root zone. In 1995, 423-mm of rainfall were recorded from 1 May through 29 July (compared with 273 mm for this period in 1994), so soluble NO_3^- could have leached below the corn rooting zone in SUR plots before rapid corn N uptake began in 1995 (Figure 1). Denitrification or volatilization are other pathways which could potentially account for N loss from SUR plots. Although not measured in this study, volatilization of NH_3 from SUR plots is unlikely because only about

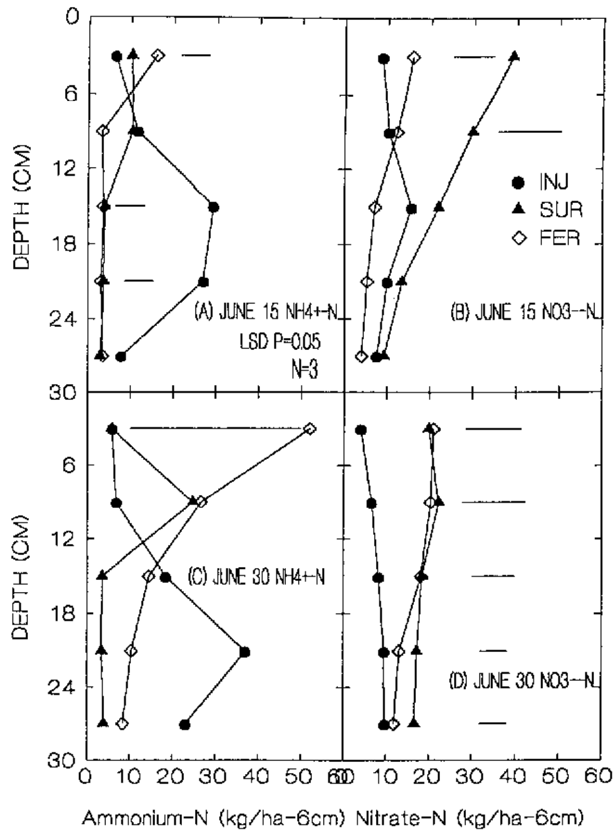

FIGURE 5. The effect of nitrogen source on ammonium-N and nitrate-N distribution (kg ha^{-1}-6 cm) with depth in the upper 30 cm of soil on June 15 and June 30, 1995. Data points are least squares means and horizontal bars indicate one $LSD_{0.05}$ for each depth sampled.

2% of the sludge total N was in the NH_4^+ form, the sludge was well incorporated into the soils, the soil pH was <5.8 and no extended drying periods occurred. The leaf N and yield data (Table 2) support the hypothesis that the inorganic N within SUR was lost from the 0 to 30 cm root zone sooner than within INJ in both years, and that INJ had greater late-season N availability than SUR.

Inhibition of Nitrification

Electrical conductivity, NH_4^+ and *in situ* pH measurements made in the injected sludge bands within two months of sludge application (Table 3) suggest nitrification

TABLE 3. Selected soil parameters measured in the zone of highest sludge concentration.

Date m/d/y	Treatment	Days†	NO_3^--N mg kg^{-1}	NH_4^+-N mg kg^{-1}	in situ§ pH_{salt}	pH_{water}‡	pKa	NH_3-N†† mg kg^{-1}	EC‡‡ dS m^{-1}
5/22/94	INJ	28	46	513	8.00	9.27	9.54	275	3.98
6/15/94	INJ	52	164	537	8.00	9.27	9.42	380	3.50
6/15/95	INJ	26	19	240	7.91	9.17	9.42	135	4.04
6/30/95	INJ	40	20	342	8.09	9.36	9.42	298	3.50
5/22/94	SUR	28	80	63	5.37	6.45	9.54	0.05	1.49
6/15/94	SUR	52	98	30	5.78	6.89	9.42	0.09	1.40
6/15/95	SUR	26	55	14	6.85	8.03	9.42	0.57	1.45
6/30/95	SUR	40	26	8	6.72	7.89	9.42	0.23	1.75

†Days after sludge application.

§Salt pH measured on fresh samples in field.

‡Calculated from relationship (r^2 = 0.94) between pH_{salt} and pH_{water}:pH_{water}=0.707+ 1.07*pH_{salt}.

††Value calculated from NH_3-N_g=α*NH_3-N where $\alpha=1/(1+10^{(pKa-pH)})$ and pKa=10.05-0.032*(Temp.°C) (Ferrara and Dimino, 1985).

‡‡Saturated paste extracts.

was temporarily inhibited in the sludge band by high NH_3-N concentrations (>275 mg kg^{-1} soil) and high pH. A delay in NO_3^- release in both years indicates inhibition of nitrification in INJ plots. Comparable conditions that could have inhibited nitrification were not observed in SUR plots, even in the zones of highest sludge concentration.

Inhibition of NO_2^- oxidation in pure cultures has been reported to occur when pH is near 8.0 and NH_4^+-N is >12 mM (Gee et al., 1990; Stojanovic and Alexander, 1958; Aleem and Alexander, 1960). Nitrification inhibition has been reported when sewage sludge or other organic wastes are applied at rates that generate high NH_4^+ concentrations at high pH. Premi and Cornfield (1969) observed that nitrification was inhibited for four weeks with 228 to 457 kg NH_4^+-N ha^{-1}. Ryan et al. (1973) reported a two-week nitrification inhibition during laboratory incubations of digested sludge with 940 and 1880 mg NH_4^+-N L^{-1}. Ammonia toxicity inhibited *Nitrobacter* spp. in dairy manure injected in a concentrated band with concentrations of 1200 to 2000 mg NH_4^+-N kg^{-1} and high pH values of 7.5 to 8.5 for 21 days (Sawyer and Hoeft, 1990). Measurements in the present study made 28 days after sludge application show extremely high NH_4^+ concentrations centered locally in the injected sludge band (at about 15 to 20 cm deep) and the lack of a zone of correspondingly high NO_3^- concentrations at that time (Figure 6). Our data indicate that nitrification inhibition by NH_3 toxicity delayed NO_3^- release from injected lime stabilized sewage sludge. It is also possible that low oxygen levels (not measured) resulting from saturated conditions and rapid ammonification in our sludge bands could have contributed to the delay in nitrification. Significant denitrification losses would be unlikely during the period of nitrification inhibition because of low levels of available nitrate.

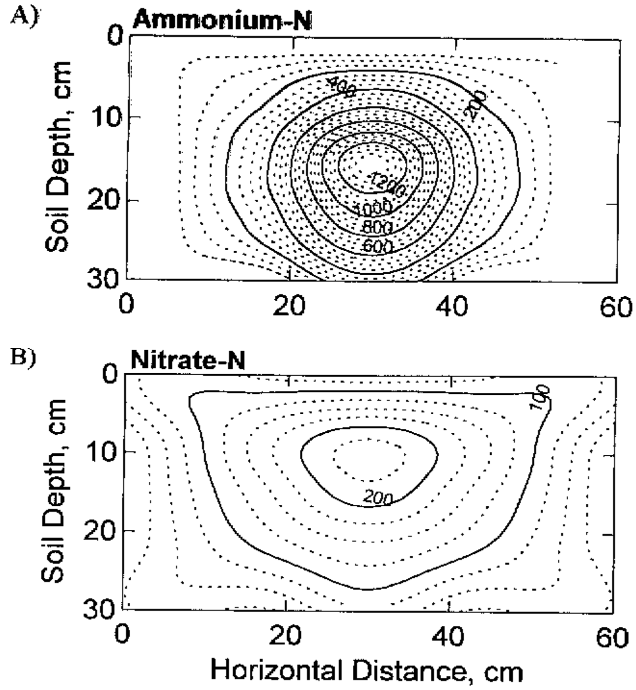

FIGURE 6. A two-dimensional depiction of (A) soil ammonium-N and (B) soil nitrate-N (μg cm^{-3}) on May 22, 1994, 28 days after sludge application for the injected sludge treatment.

Residual Soil Nitrogen

In both years cumulative growing degree units (GDU°C) exceeded 1550 by the late August sample date, indicating that N uptake by the corn crop would have essentially ceased by that time (Karlen et al., 1988). Nitrate accumulating in the soil after this point can be considered as potentially leachable. High soil NO_3^- after crop harvest has been associated with NO_3^- leaching losses between fall and spring (Bergstrom and Brink, 1986; Wiesler and Horst, 1993). In both years of the present study more NO_3^- was present in the upper 30 cm of soil in INJ than in SUR during the period following crop N uptake (Figures 2 and 3) .

CONCLUSIONS

Both subsurface-injected and surface-incorporated sewage sludge provided a large pool of inorganic N by the time corn had reached the 6-leaf stage. Although sludge was applied at the same rate and on the same date for both treatments, NO_3^- was released later in the season from the INJ than from the SUR treatment. Early in the growing season for both years INJ was higher in NH_4^+ and significantly lower in NO_3^- than SUR. A delay in NO_3^- release, most likely due to nitrification inhibition within the injected band of sludge, resulted in higher N availability later in the season for INJ compared to SUR. Vertical distribution of N in the upper 30 cm of soil also indicated less N leaching in spring with the INJ than with the SUR application. This research suggests that injecting sewage sludge results in a delay in NO_3^- release and subsequent enhancement of late-season corn N uptake compared to surface-incorporating sludge when sludge is applied shortly before planting. In the SUR treatment the rapid formation of NO_3^- resulted in substantial early season losses of nitrogen by leaching, runoff and/or denitrification.

From a management standpoint, this study suggests that subsurface injection is the preferred method for earlier application of sludge on cropland in the United States mid-Atlantic region. When sludge must be applied months before corn planting, sludge subsurface injection may increase total N uptake, by synchronizing N release with maximum corn N uptake compared to surface incorporation. Surface incorporation of sludge is more suitable when application of sludge is to occur close to planting.

The high levels of residual N observed in this study, despite higher than expected corn yields, indicate that the 30% mineralization factor used to calculate sludge application rates may be too low. Further research should focus on field rates of N mineralization and nitrate movement with respect to different methods of sludge application to cropland.

ACKNOWLEDGMENTS

This research was partially funded by the Chesapeake Bay Foundation. Sludge application and permitting was provided by Wheelabrator-BioGro, Inc. of Annapolis, MD. Special thanks go to Lisa Williams who coordinated sludge application, to Michael Heller and William Addison, Jr. who coordinated farm operations, and to Susannah Watson who conducted preliminary work with sludge on the site.

REFERENCES

Aleem, M.I.H. and M. Alexander. 1960. Nutrition and physiology of *Nitrobacter agilis*. Appl. Microbiol. 8:80-84.

Banwart, W.L., M.A. Tabatabai, and J.M. Brenner. 1972. Determination of ammonium ion in soil extracts and water samples by ammonia electrodes. Commun. Soil Sci. Plant Anal. 3:160-163.

Bergstrom, L. and N. Brink. 1986. Effects of differentiated applications of fertilizer N on leaching losses and distribution of inorganic N in the soil. Plant Soil 93:333-345.

Cataldo, D.A., M. Haroon, L.E. Schrader, and V.L. Young. 1975. Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Commun. Soil Sci. Plant Anal. 6(1):71-80.

Chichester, F.W. 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. J. Environ. Qual. 6:211-217.

Cornwell, C.K. 1996. Impacts of types and placement of organic nitrogen sources on groundwater quality. M.S. Thesis, University of Maryland, College Park, MD.

Cripps, R.W., S.K. Winfree, and J.L. Reagan. 1992. Effect of sewage sludge application method on corn production. Commun. Soil Sci. Plant Anal. 23:1705-1715.

Ferrara, R.A. and M.A. Dimino. 1985. A case study analysis for seasonal nitrification: economic efficiency and water quality preservation. J. Water Pollut. Control Fed. 57:763-769.

Gee, C.S., M.T. Suidan, and J.T. Pfeffer. 1990. Modeling of nitrification under substrate-inhibiting conditions. J. Environ. Eng. 116:18-31.

Godwin, R.J., N.L. Warner, and J.E. Hall. 1985. Soil injection of liquid wastes. Agricultural waste utilization and management. Proceedings of the 5th International Symposium on Agricultural Wastes, 16-17 December 1985, Chicago, IL. American Society for Agricultural Engineers, St. Joseph, MI.

Karlen, D.L., R.L. Flannery, and E.J. Sadler. 1988. Aerial accumulation and partitioning of nutrients by corn. Agron J. 80:232-242.

Kelling, K.A., L.M. Walsh, D.R. Keeney, J.A. Ryan, and A.E. Peterson. 1977. A field study of the agricultural use of sewage sludge: II. Effect on soil N and P. J. Environ. Qual. 6:345-352.

Magdoff, F.R. and J.F. Amadon. 1980. Nitrogen availability from sewage sludge. J. Environ. Qual. 9:451-455.

Maryland Department of Environment. 1989. Title 26: Department of Environment, Subtitle 04, Regulation of water supply, sewage disposal, and solid waste, Chapter 06, Sewage sludge management, Environmental Article, Title 9, Subtitle 2, annotated Code of Maryland, Regulation 09. Amended effective December 11, 1989 (16:24 Md. R. 2621).

Meisinger, J.J., W.L. Hargrove, R.L. Mekkelson, J.R. Williams, and J.W. Benson. 1991. Effects of cover crops on groundwater quality. pp. 57-68. In: W.L. Hargrove (ed.), Cover Crops for Clean Water. Proceedings, International Conference, April 9-11, 1991, West Tennessee Experiment Station, Jackson, TN.

Menelik, G., R.B. Reneau, Jr., D.C. Martens, and T.W. Simpson. 1991. Yield and elemental composition of wheat grain as influenced by source and rate of nitrogen. J. Plant Nutr. 14(2):205-217.

Motavalli, P.P., S.D. Comfort, K.A. Kelling, and J.C. Converse. 1985. Changes in soil profile N, P, and K from injected liquid dairy manure or fertilizer. pp. 200-210. In: Proceedings of the 5th Agricultural Waste Utilization and Management. International Symposium on Agricultural Wastes, 16-17 December, Chicago, IL. American Society of Agricultural Engineers, St. Joseph, MI.

Premi, P.R. and A.H. Cornfield. 1969. Incubation study of nitrification of digested sewage sludge added to soil. Soil Biol. Biochem. 1:1-4.

Ryan, J.A., D.R. Keeney, and L.M. Walsh. 1973. Nitrogen transformations and availability of an anaerobically digested sewage sludge in soil. J. Environ. Qual. 2:489-492.

Sawyer, J.E. and R.G. Hoeft. 1990. Effect of injected liquid beef manure on soil chemical properties and corn root distribution. J. Prod. Agric. 3:50-55.

Schmitt, M.A., J.E. Sawyer, and R.G. Hoeft. 1992. Incubation of injected liquid beef manure. Effect of time and manure rate. Agron. J. 84:224-228.

Schmitt, M.A., S.D. Evans, and G.W. Randall. 1995. Effect of liquid manure application methods on soil nitrogen and corn grain yields. J. Prod. Agric. 8:186-189.

Serna, M.D. and F. Pomares. 1992. Nitrogen mineralization of sludge-amended soil. Bioresource Tech. 39:285-290.

Sommers, L.E., C.F. Parker, and G.J. Meyers. 1981. Volatilization, plant uptake and mineralization of nitrogen in soils treated with sewage sludge. Water Resources Research Center Purdue University, Technical Report No. 133:1-64.

Stojanovic, B.J. and M. Alexander. 1958. Effect of inorganic nitrogen on nitrification. Soil Sci. 86:208-215.

USEPA. 1983. Land Application of Municipal Sludge: Process Design Manual. EPA-625/1-83-015. Environmental Protection Agency, Cincinnati, OH.

Walker, J.M., W.D. Burge, R.L. Chaney, E. Epstein, and J.D. Menzies. 1975. Trench incorporation of sewage sludges in marginal agricultural land. USEPA Rep. 600/2-75-034. US Government Printing Office, Washington, DC.

Weisler, F. and W.J. Horst. 1993. Differences among maize cultivars in the utilization of soil nitrate and the related losses of nitrate through leaching. Plant Soil 151:193-203.

Wilkinson, L. 1990. SYSTAT: The System for Statistics. SYSTAT, Inc., Evanston, IL.