Determining Sludge Fertilization Rates for Forests from Nitrate-N in Leachate and Groundwater[1]

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ABSTRACT

Municipal and papermill wastewater sludges were applied to conifer and hardwood forests growing on sand soils (Entic Haplorthods, Spodic Udipsamments, and Alfic Haplorthods), In northwestern Lower Michigan where annual precipitation averaged 765 mm/y, to Investigate the Impact of sludge on nitrate-N concentntlons In soil water and groundwater. During the first growing season after treatment, all forms of N in groundwater and soil water remained near background levels except under aspen (*Populus grandidentata* Mlchx.) plots treated with 46 dry Mg munldpal sludge/ha. Following the first spring snowmelt period after sludge was applied (spring 1977), nitrate-N concentrations exceeded the 10 mg/L potable water standard In groundwater under plots treated with 16 or more dry Mg/ha an-digested papermill sludge. Soil leachate exceeded 10 mg/L under pine plantations receiving 19.3 dry Mg/ha and aspen sprout stands receiving 23 dry Mg/ha or more anaerobically digested munldpal sludge.

Sludge application rates which would not degrade water quality In water-table aquifers were estimated by regression analysis of nitrate (NO_3^-) concentrations In relation to dry solids loading. Applying raw papermill sludge at rates not exceeding 9.5 dry Mg/ha (670 kg total N/ha) to a red pine (*Pinus resinosa* Ait.) plantation was found to be consistent with levels that met the 10 mg/L potability standard In groundwater. These analyses showed anaerobically digested municipal sludge could be applied to a red pine and white pine (*Pinus strobus* L.) plantation at 16.5 dry Mg/ha (YYO kg total N/ha) or less and to aspen sprouts at rates up to 19 dry Mg/ha (1140 kg total N/ha) wlth the same water quality limits.

Additional Index Words: Pinus resinosa, Pinus strobus, Populus grandidentata, soil water, nitrate leaching.

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To meet Federal secondary treatment standards for wastewater discharge, states in the Great Lakes Region must dispose of increasing volumes of sludge in a manner that will not degrade environmental quality nor endanger public health. Applying these residual wastes to land has been identified as a major, cost-effective solution to this problem (Forster et al., 1977).

In recent years, application of sludge to farm land has come to be highly regarded as an effective means of using wastewater sludge nutrients. Many northern communities that do not have enough cropland for sludge recycling sites are surrounded by large areas of forest land capable of assimilating the nutrients (particularly N) in sludges.

Although chemical fertilization of forests is common in many regions of the world, including southern and northwestern United States, it may not be economically practical in the northcentral and northeastern regions. Growth rates in these regions are moderate lo low, and fertilization is too expensive on all but the most productive sites. If the costs of fertilization can be absorbed as a least-cost alternative method of sludge utilizatlon by a municipality or an industry, many sites may be made more productive (Urie et al., 1978).

A potential hazard of forest fertilization with wastewater sludge is contamination of groundwater with nitrate-N (NO_3^--N). Groundwater provides most drinking water in the Great Lakes Region. Because well water is often used without treatment, its chemical and microbiological purity must be maintained. Fertilization beyond the ecosystem's capacity to assimilate nutrients can degrade the usually high quality water of forest watersheds (Sopper, 1975). Although forests vary widely in their vulnerability to excessive NO_3^- leaching, experiments with mineral fertilizers have illustrated the problem. The 10 mg/L NO_3^- potable water standard was exceeded following N fertilization of Scotch pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L.) at rates of 300–400 kg/ha (Kreutzer & Weigner, 1974). Coarse-textured soils with low organic matter content were also vulnerable to NO_3^- leaching following fertilization in British Columbia forests (Otchere-Boateng & Ballard, 1978). Digested sludge applied to conifers in Germany at rates exceeding 300 kg N/ha resulted in peak NO_3^--N concentrations as high as 160 mg/L in soil percolate (Huser, 1977).

But many researchers contend that high N dosage rates do not always enrich the NO_3^- in soil percolate. Cole et al. (1975) found no substantial NO_3^- leaching under second-growth Douglas-fir (*Pseudotsuga menziessii*) growing on gravelly, sandy loam, outwash fertilized with 448 kg N/ha. Tamm (1975) reported similar results when ammonium nitrate (NH_4NO_3) and urea [$(NH_2)_2CO$] were applied to a recently clearcut she. Nitrogen applied in wastewater sludge at a rate of 300 kg/ha to a hardwood forest growing on acidic loamy soil in Germany did not significantly enrich soil percolate (Keller & Beda-Puta, 1976).

BACKGROUND AND OBJECTIVES

Previous research on spodosol soils similar to those in our study has shown that excess N from sludge-enriched groundwater and soil water with NO_3^--N (Urie, 1979; Urie et al., 1978). Forest applications of sludge in Pennsylvania (Sidle & Kardos, 1979), New Hampshire (Koterba et al., 1977; Hornbeck et al., 1979), and the Pacific Northwest (Riekerk & Zasoski, 1979; Stednick & Wooldrldge, lY79) have resulted in similar flushes of NO_3^-. Sidle and Kardos (1979) have shown that downward movement of excess NO_3^- may be partially related to the hydrologic budget expressed In pore volumes of soil water transfer from the soil surface to the point of soil water measurement.

This study was conducted to identify sludge application rates acceptable for soil-plant systems typical of forest land In northern Michigan. The maximum 10 mg/L NO_3^- limit for drinking water was selected as being consistent with the normally high quality of groundwater found in the forest environment. Sludges were applied to sandy forest soils on three northwestern Lower Michigan sites. These plots were then analyzed to relate sludge application rates to NO_3^- concentrations In soil water and groundwater. This report interprets these

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relationships and prescribes sludge application rates for use in similar forest environments.

MATERIALS AND METHODS

Study Areas

Wastewater sludge fertilization tests were conducted on the Udell and Pine River Experimental Units of the Manistee National Forest in northwestern Lower Michigan (44°15′N 86°W). Undigested papermill sludge was applied to a pole-sired, 40-year-old red pine (*Pinus resinosa* Ait.) plantation on the Udell Experimental Forest. Anaerobically digested municipal sludge was applied to a pole-sized, 36-year-old red and white pine (*Pinus strobus* L.) plantation and to a recently clearcut and roller-chopped stand of bigtooth aspen (*Populus grandidentata* Michx.) sprouts on the Pine River Experimental Forest.

soils

Soils on the Udell Experimental Forest developed upon sandy moraines and medium altitude (230–335 m) outwash plains of stratified, unconsolidated deposits. Rubicon and Croswell series (Entic Haplorthods) predominated upon the nearly level site. These soils are little used for nonirrigated agriculture because of low fertility. Depth to groundwater was 2.5-3.5 m.

Soils on the Pine River Experimental Forest were developed from sandy moraines, outwash plains, and old lacustrine plains. An intergrade of Grayling series (Spodic Udiient) and Menominee series (Alfic Haplorthod) occurs on the gently rolling-to-nearly level site. Grayling sand is well-drained, rapidly permeable, droughty, low in native fertility, and used little for agriculture. Menominee sand is well- to moderately well-drained, rapidly to moderately permeable, low to medium in native fertility, and marginally suited to agriculture. The Menominee soils have moderate water capacity in contrast with the droughty Grayling portions. Depth to groundwater was in excess of 25 m as determined from on-site drilling. Local wells indicate a regional water depth between 30 and 50 m.

Vegetation

The Udell plantation was thinned to a basal area of about 23 m^2/ha by removing two adjacent rows of trees from every four in May 1976. The pine plantation on the Pine River Experimental Forest was thinned the same way to 16.9 m^2/ha for red pine and 18.3 m^2/ha for white pine in June 1976. The bigtooth aspen stand on the Pine River Expermental Forest was clearcut in 1971 and roller-chopped in 1975.

Understory vegetation on the Udell site included *Pteridium, Comptonia, Vaccinium, Carex,* several grasses, mosses, lichens, and many seedlings and suppressed saplings of *Quercus, Prunus,* and *Acer.* On the Pine River sites were *Pteridium, Comptonia, Vaccinium, Carex,* a variety of grass, mosses, and lichens, along with a vigorous understory of *Populus, Quercus, Prunus, Acer, Fraxinus* and *Sassafras* seedlings, *Rubus,* and lilies (*Liliaceae* L.)

Experimental Design

Three replications of five sludge treatment levels were assigned to completely randomized plots on the Udell site. Each 8 1.4 m by 20.4 m rectangular plot was oriented with its long axis parallel to the direction of groundwater flow. Groundwata samples were removed at the downslope end of each plot from a drive-point well, located with its screen section covering the seasonal range of water table depths.

Six replications of four sludge treatment levels wae arranged in a randomized complete block design in the pine plantation on the Pine River Experimental Forest. Three replications were in red pine and three in white pine plots. Because the depth to water table exceeded 25 m, precludii direct analysis of groundwater, ceramic cup suction lysimeters wae used to sample percolating soil water at 1.2 m beneath each 36.6-m diameter circular plot. Two lysimeters per plot were installed 9.2 m north and south of each plot center.

Four replications of four sludge treatment levels were arranged in a randomized complete block design in the aspen sprouts on the Pine River Experimental Forest. Soil water percolating beneath each 15.2-m diameter circular plot was sampled at the 1.2-m depth using four suction lysimeters systematically located in the quadrants of each plot.

Sludge Application

Sludge treatments consisted of single applications of liquid sprayed over the forest floor. Undigested papermill sludge from the wastewater treatment plant at the Packaging Corporation of America in Filer City, Mich., was applied in June 1976 to the Udell site at rates of 4, 8, 16, and 32 dry Mg/ha (17, 34, 68, and 136 m^3/plot, liquid) using an all-terrain liquid sludge spreading truck. Thii sludge had received centrifugation to concentrate the dry solids content, but no digestion. Muncipal sludge that had been anaerobically digested for about 90 d at the Wastewater Treatment Facility in Cadillac, Mich., was applied to the Pine River pine plantation in July 1976 at rates of 4.8, 9.7, and 19.3 dry Mg/ha (7.5, 15, and 30 m^3/plot, liquid) using a portable pipeline and fire hose. Replicated control plots were delineated and evaluated at each study site.

Sludge samples were obtained directly from spray nozzles during treatment. Samples were preserved with concentrated sulfuric acid (H_2SO_4) (2 mL/L) and stored at 4°C. Nitrite-N (NO_2^--N) and nitrate-N were measured by automated Cd reduction, and NH, was measured with a specific ion electrode (Milham et al,. 1970). Total Kjeldahl N was analyzed in the liquid sludge samples (APHA, 1971). and total solids content was measured by the gravimetric method, drying to constant weight at 85°C.

Total N concentrations were 7% in the papermill sludge and 6% in the municipal sludge (Table 1). Most of the N in both sludges was in the organic form. The percentage of total N present as NH_4^+ varied from 6% in the papermill sludge to 28% in the municipal sludge. Nitrate comprised < 2% of the total N. Total N application rates ranged from 282 to 2260 kg/ha on the Udell site, from 287 to 1160 kg/ha on the Pine River red pine and white pine site, and from 689 to 2760 kg/ha *on* the aspen site. Carbon-to-nitrogen ratios were 9:1 for the papermill sludge and 13:1 for the municipal sludge. These values were close to the 12: 1 optimum ratio for humus mineralization in the forest environment. Both sludges contained 5.5% total solids.

Water Sampling and Analysis

Groundwater samples were collected monthly from March 1977 through November 1980 by pumping to remove three casing volumes of water before collecting the sample. Mid-winter and prethaw sets of groundwater samples were also collected. Soil water was sampled weekly during the spring and fall periods of recharge, then monthly during the growing season whenever soil water was available at the 1.2-m depth. During winter, snow cover and frozen access lines limited collections.

Groundwater and soil water samples were placed in polyethylene bottles, preserved with $HgCl_2$ (40 mg/L), and stored at 4°C. AU water samples were analyzed for total Kjeldahl N, NH_4^+-N, NO_3^--N, and NO,--N using standard automated methods (Technicon Industrial Method, 1967). Nitrate-N analyses from 1978 to 1979 were conducted with a selective ion electrode, with correction for Cl^- interference (Miiham et al., 1970).

Nitrate- plus nitrate-N concentrations in soil water and groundwater were statistically analyzed using a log (x + 1) transformation to normalize typically skewed data. Samples collected ova a month or longer were combined to group sufficient samples for statistical analysis, especially during dry periods when only a small proportion of the suction lysimeters yield leachate samples. Differences between treatment means were tested for significance using a "t" test for unpaired data on two populations with unknown variance.

RESULTS AND DISCUSSION

Nitrate Leaching

During 1976, the first growing season after treatment, groundwater and soil water NO_3^--N concentrations beneath the two pine plantations remained. near background levels. However, elevated NO,‘-N concentrations were measured during December 1976 in soil water percolating at 1.2 m under the aspen plots treated with 46 dry Mg of sludge/ha. During snowmelt in March–May 1977, elevated NO_3^--N concentrations appeared in

Table 1-Nitrogen concentration and application rates for municipal and papermill wastewater sludges, 1976.

Element	Raw papermill sludge applied to red pine					Anaerobically digested municipal sludge applied to red pine, white pine. and aspen						
		Appliccation rate (Mg/ha)					Application rate (Mg/ha)					
	Concentration	4	8	16	32	Concentration	4.8	9.7	19.3	11.5	23.0	46.0
	mg/kg	kg/ha				mg/kg	kg/ha					
NO_3^--N	1 150	4.4	8.8	17.6	35.2	24	0.1	0.2	0.4	0.3	0.5	1.1
NH_4^+-N	4 440	17.8	35.5	71.0	142	16 600	79.5	160.0	320	191	381	762
Total N	70 600	282	565	1130	2 260	60000	237	578	1160	689	1380	2760

Table 2a—Mean NO_2 + NO_3^--N concentration in soil leachate: aspen sprouts fertilized with digested municipal sludge.

Date	Sludge treatment rate (Mg/ha)			
	0	11.5	23	46
	Mean NO_2 + NO_3^-- concentration			
	mg/L			
May 1976	0.62 a*	1.54 a	0.41 a	0.72 a
June 1976	0.55 a	1.34 a	0.45 a	0.96 a
July 1976	0.32 a	0.32 a	ND‡	ND
August 1976	0.65 a	6.24 b	1.20 a	ND
October 1976	1.20 a	1.67 a	5.29 a	ND
November 1976	0.93 a	1.86 a	8.01 a	1.41 a
March 1977	0.43 a	6.23 b	17.0 bc	41.5 c
April 1977	0.28 a	6.26 b	14.8 bc	27.5 c
May 1977	0.16 a	1.49 a	22.4 b	29.6 b
July 1977	0.30 a	4.52 a	ND	34.5 b
August 1977	0.34 a	ND	ND	ND
September-November 1977	<0.03 a†	0.03 a	0.88 b	40.6 c
January-March 1978	0.37 a	0.12 a	2.88 a	7.00 b
September-November 1978	0.14 a	0.25 a	0.14 a	0.95 a
May 1979	<0.05 a	CO.49 a	<0.38 a	<0.05 a

• Means in the same line with different fetters are significantly different ($P < 0.05$).
† Mean includes one or more samples below detection limit.
‡ No samples available in period.

Table 2b—Mean NO_2 + NO_3^--N concentration in soil leachate: white and red pine plantation fertilized with digested municipal sludge.

Data	Sludge treatment rate (Mg/ha)			
	0	4.8	9.7	19.3
	Mean NO_2 + NO_3^--N concentration			
	mg/L			
1976	ND†	ND	ND	ND
March-April 1977	0.88 a	0.53 a	0.42 a	8.16 b
May 1977	0.26 a	0.88 a	0.23 a	9.20 b
July 1977	1.62 a	1.98 a	0.02 a	12.8 b
August 1977	1.66 a	2.00 a	5.80 a	15.2 b
September-November 1977	0.58 a	0.57 a	1.56 a	15.0 b
January-March 1978	0.87 a	0.38 a	0.48 a	4.58 b
May-June 1978	0.33 a	0.09 a	0.28 a	2.35 b
July-August 1978	0.24 a	0.16 a	2.39 a	3.32 b
September 1978	0.12 a	0.18 a	1.09 ab	1.40 b
November 1978	<0.10 a*	<0.10 a	0.40 a	0.39 a
May 1979	0.08 a	<0.04 a	0.39 a	0.43 a

* Means includes one or more sample below the detection limit. Means on same line with different letters are significantly different ($P < 0.05$).
† No samples available in period.

Table 2c—Mean NO_2 + NO_3^--N concentration in ground water: red pine plantation fertilized with undigested papermill sludge.

Data	Sludge treatment rate (Mg/ha)				
	0	4	8	16	32
	Mean NO_2 + NO_3^--N concentration				
	mg/L				
1976	<0.05 a*†	<0.05 a	<0.05 a	CO.41 a	<0.05 a
March 1977	0.50 a	0.02 a	3.4 a	12.3 a	13.7 a
May 1977	0.02 a	0.18 a	1.8 ab	8.9 b	5.6 b
July 1977	0.19 a	0.10 a	0.5 b	8.4 b	16.7 b
August 1977	0.01 a	0.16 a	0.4 a	8.6 a	6.9 a
September 1977	0.02 a	0.24 a	0.6 b	13.2 bc	23.1 c
March 1978	0.01 a	0.34 a	4.6 ab	5.8 b	46.6 b
May 1978	1.28 a	1.76 a	1.0 a	10.0 ab	26.2 b
June 1978	0.04 a	0.30 a	1.6 b	16.8 c	28.7 c
July 1978	0.01 a	0.09 a	1.3 a	5.9 b	10.2 b
September 1978	0.03 a	0.54 a	0.56 a	24.2 b	19.3 b
December 1978	0.40 a	0.74 a	1.2 a	13.6 b	27.8 b
February-April 1979	0.81 a	0.66 a	1.5 a	11.9 b	30.6 b
October 1979	x0.05 a	<0.05 a	<0.05 a	7.0 b	12.3 b
1980—all	<0.08 a	<0.16 a	<0.16 a	2.5 b	7.7 b
1981—all	<0.10 a	<0.10 a	<0.15 a	1.0 b	4.7 b

* Means in the same line with different letters are significantly different ($P < 0.05$).
† Mean includes one or more sample below the detection limit.

water samples collected from sludge-treated plots on all three sites. Nitrate movement below the rooting zone primarily occurred during spring and fall periods of recharge identified using the method of Thornthwaite and Mather (1957). Nitrogen forms other than NO_3^- rarely exceeded background levels in groundwater and soil water.

ASPEN-SOIL LEACHATE

Sludge was applied to the aspen sprout test area during April 1976. By August, significant increases in the NO_3^- concentration in leachate samples were detected under the lightest dosage (11.5 Mg/ha). Mean concentrations were related to dosage for the remainder of the season. However, due to high variability within treatment, the differences were not significant at the 95% level of probability (Table 2a).

During 1977, mean NO_3^- concentrations were generally correlated with the sludge dosage rates. Under the lightest dosage rate, the treatment effect had effectively disappeared by the end of the 1977 growing season. Significantly elevated NO_3^- concentrations were evident under the two higher sludge rates during the spring of 1979.

RED AND WHITE PINE PLANTATIONS-SOIL LEACHATE

Suction lysimetry was installed in the pine plantation treated with digested municipal sludge after the sludge was applied in July 1976. Soil water samples were not obtained until the following spring snowmelt period. At that time, significantly elevated NO_3^- concentrations were measured under the highest sludge rate (19.3 Mg/ha). By late fall of 1978, these increases were C 1 mg/L NO_3^--N. Samples collected in the spring of 1979 did not show significant treatment effects (Table 2b). Only the 19.3-Mg rate resulted in NO_3^--N concentrations in excess of the 10 mg/L limit.

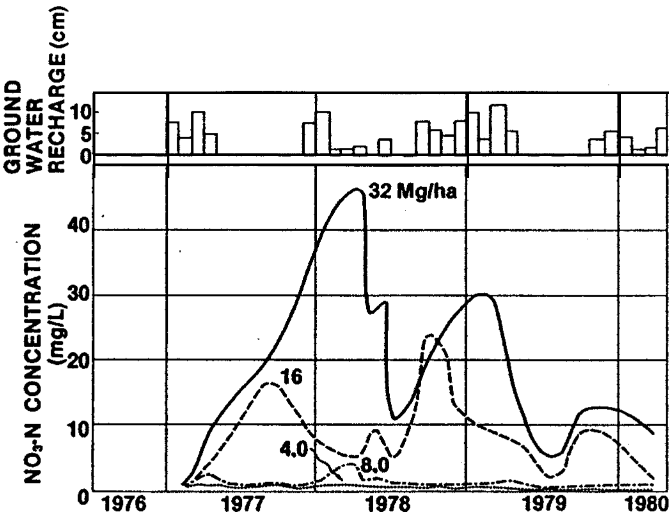

Fig. 1—Mean NO_2 + NO_3^--N concentrations in groundwater at 3-m depth under red pine treated with papermill sludge.

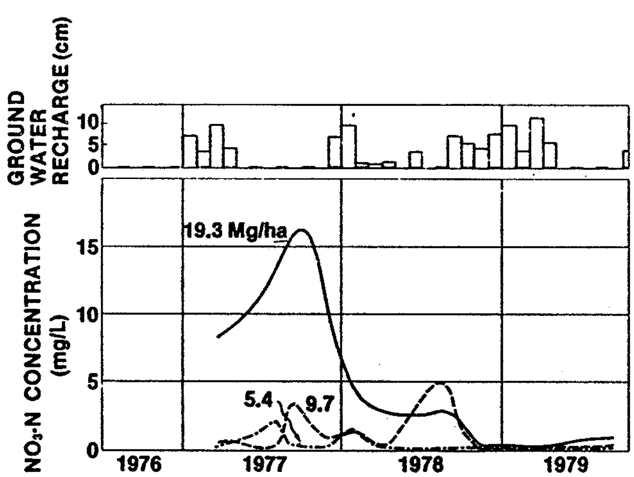

Fig. 2-Mean NO_2 + NO_3^--N concentrations in soil water at 1.2-m depth under red pine and white pine treated with municipal sludge.

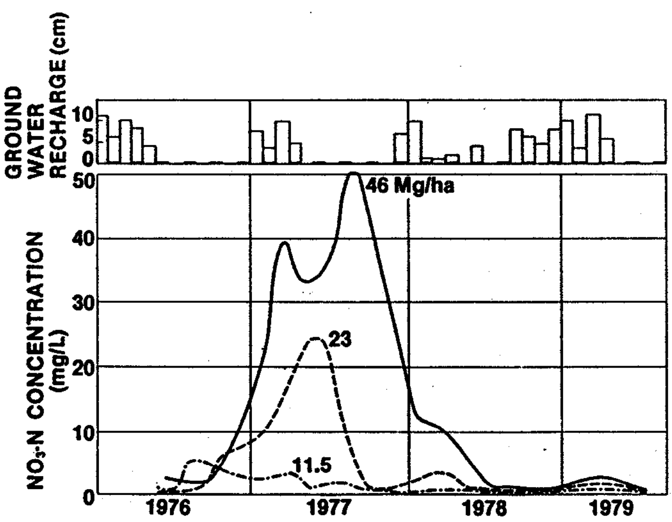

Fig. 3—Mean NO_2 + NO_3^--N concentrations in soil water at 1.2-m depth under aspen treated with municipal sludge.

RED PINE-GROUNDWATER

Significant changes in groundwater concentrations of NO_3^- appeared following snowmelt under the red pine plantation treated with undigested papermill sludge (Table 2c). The peak concentrations occurred 6-12 months later than those measured in soil leachate under the municipal sludge treatments. The treatment effects were also longer lasting, with annual mean concentrations still above background levels in 1981 under the plots receiving the two highest sludge dosage rates.

Nitrate-N concentrations in groundwater under the Udell plantation exceeded 10 mg/L in early April (Fig. 1). Mean groundwater NO_3^--N concentrations were elevated during every major period of groundwater recharge under plots treated with 32 Mg sludge/ha. The highest NO_3^--N concentration measured in a single groundwater sample was 49 mg/L occurring in March 1978. Lower sludge application rates produced lower NO_3^--N leachate concentrations. Untreated paper sludge additions of 16 and 32 Mg/ha resulted in elevated groundwater NO_3-N concentrations that exceeded 10 mg/L for a 2-y period that began about 12 months after application.

Measurements taken in the saturated zone were influenced by seasonal fluctuation of the water table. Changes in the height of the water table in relation to the screened section of well point altered the proportion of water sample that represented recent leachate. Despite this source of variation, groundwater NO_3^--N concentrations at the 3-m depth at the Udell site were closely correlated to sludge application rates.

Nitrate-N concentrations in soil water under the red pine and white pine plantation fertilized with 19.3 Mg/ha of anaerobically digested municipal sludge exceeded 10 mg/L after snowmelt in May 1977 (Fig. 2). Mean soil water NO_3^--N concentrations of 16 mg/L were found in September 1977. Peak soil water NO_3^- levels in individual samples as high as 68 mg/L were found during the growing season of 1977. By April 1978, mean NO_3^--N concentrations decreased to $<$ 10 mg/L. Plots receiving 9.7 Mg/ha or less of sludge produced mean soil water NO_3^--N levels $<$ 5 mg/L throughout the study.

Soil water under aspen sprouts treated with 46 Mg municipal sludge/ha in April 1976 contained NO_3^--N concentrations exceeding 10 mg/L by fall the same year (Fig. 3). After the 1977 snowmelt in March, soil water NO_3^--N concentrations varied in relation to sludge fertilization rates. Mean soil water NO_3^--N concentrations reached 40-50 mg/L under plots receiving 46 Mg sludge/ha and exceeded 10 mg/L during the first 2 after treatment. Peak NO_3^--N levels in individual samples approached 95 mg/L. Plots treated with 23 Mg/ha of sludge produced soil water with average NO_3^--N values exceeding 20 mg/L during the period May-July 1977. Under aspen sprouts treated with sludge at the 11.5 Mg/ha rate, soil water NO_3^--N levels remained $<$ 5 mg/L throughout the study. By August 1978 NO_3^--N concentrations in soil water percolating beneath all sludge-treated aspen plots had decreased to background levels.

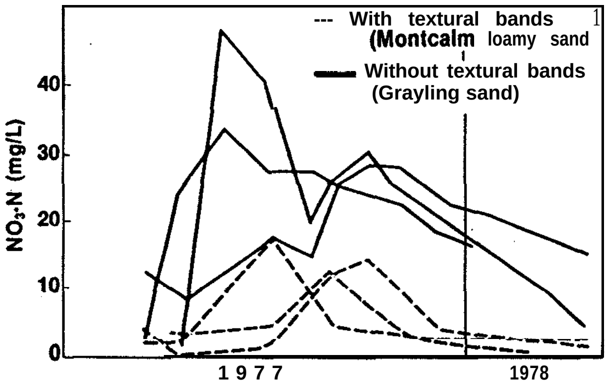

Fig. 4—Concentrations of NO_3 + NO_2^--N in soil water under pine plantations treated **with** 19.3 **Mg/ha** of digested municipal sludge on July 1976 in Montcalm vs. **Grayling soil** profiles.

The NO_3^--N levels vary in groundwater and particularly in soil water because of dilution from precipitation, concentration from evaporation, and seasonal mineralization of organic N. Sludge treatments on aspen plots in May 1976 resulted in peak NO_3-N levels in August and September 1977, by which time approximately 35 cm of percolation water had passed the 1.2-m sampling depth since sludge was applied, according to a Thornihwaite approximation of the water budget. Pine plots fertilized during **July** 1976 produced peak NO_3^--N levels at 1.2 m in October 1977 after a soil water flux estimated at 30 cm. The delayed NO_3^--N peak under pines could be related to the difference in treatment dates, but it probably stems from the longer period of evapotranspirational drain by the conifers, delaying downward movement of soil moisture. The lack of available soil water 1.2 m under both pines and aspen was shown by the lack of water in samplers during the late summer of 1977.

In the Pine River pine plantation, NO_3^--N concentrations in soil water samples varied between individual sampler locations under the 19.3 Mg sludge application rate. Nitrate-N concentrations were measured in plots where no discernible capillary discontinuity occurred in the upper 1.5 m of soil. Characteristic NO_3^--N patterns for the two groups of soils are shown for three example suction lysimeters in Fig. 4. These soil profiles would be classified as Montcalm loamy sand as they contained loamy sand, sandy loam, or sandy clay loam horizons within the upper 1.5 m of soil. Soil water NO_3^--N concentrations were consistently lower in these sites, and the NO_3^--N concentrations declined more. rapidly toward background levels. The presence of temporary zones of saturation in and above the finer-textured layers **suggested** the presence of anaerobic zones after heavy rainfall. Brighter chromacolors were also characteristic. Denitrification in subsoil horizons of this type has been demonstrated during periods of temporary saturation (Lund et al., 1974).

Determining Sludge Fertilization Rates

Nitrate **concentration** over 10 **mg/L** measured in soil percolate does not indicate a similarly high **concentration** in groundwater. Soil water NO_3^- levels may be reduced by denitrification during passage through the unsaturated zone and further reduced through dilution after entering the saturated zone. Thus, NO_3^--N concentrations > 10 **mg/L** measured at the 1.2-m depth do **not** equate to levels in excess of potable groundwater standards. Denitrification in temporarily saturated soil layers has been shown to limit the downward movement of N in soils in California (Lund et al., 1974) and in Wisconsin (Olsen et al., 1970). Dilution effects occurring below 1.2 m must also be considered (Kreutzer & Weigner, 1974). Richardson (1979) found **that** N fertilization practices in the agricultural areas, 100 km north of the forest study sites reported here, resulted in NO_3^--N concentrations of **20–40 mg/L** in water table aquifers. However, because forest land is expected to produce high-quality groundwater, a conservative approach to sludge fertilization was indicated.

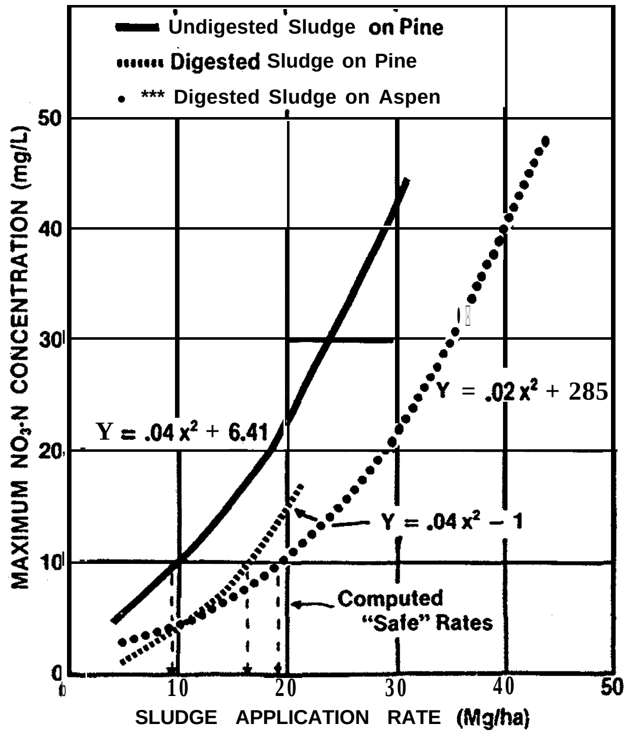

Fig. 5-Recommended **sludge application** rates as **related** to **soil** water and groundwater NO_3^--N concentrations.

Regression analysis was used to correlate sludge dosage to the highest average monthly NO_3^--N levels **measured** in soil water during major recharge periods and the **maximum** mean groundwater at any time during the test (Fig. 5). A second-degree polynomial was **fitted** to the maximum NO,--N concentration measured under each sludge dosage for the three tests. Figure **5 illustrates** the estimated maximum "safe" rates of sludge application as read from the abscissa of each concentration curve at the **10-mg/L** level. Estimated safe rates of undigested papermill sludge from these' analyses were 9.5 dry **Mg/ha** (670 kg total N/ha) or less in the red pine plantation. The red pine and white pine plantation could be treated with anaerobically digested municipal sludge at rates up to 16.5 dry **mg/ha** (990 kg total N/ha) without producing peak soil water NO_3^--N concentrations > 10 mg/L during major recharge periods. Municipal sludge applications up to 19.0 dry Mg/ha (1140 kg total N/ha) were determined to be safe initial dosage rates for the stand of aspen sprouts.

Recommended sludge fertilization rates for forest land depend on sludge characteristics, soil properties, water table depth, hydrologic conditions, vegetation type, and age. The maximum recommended single-dose application in pine plantations for undigested papermill sludge (9.5 Mg/ha) is lower than for digested municipal sludge (16.5 Mg/ha) because the undigested papermill sludge decomposes more rapidly, resulting in faster N mineralization. A direct measure of this difference was obtained from NO_3^--N concentrations in leachate from 1.2-m soil columns treated with the two sludges at 11 .5 Mg/ha. The average peak concentration ratio was 3.1: 1 (± significant at 0.05 level) during the first year after treatment. Only minor differences existed in the two plant communities present in the two pine plantation sites. The higher recommended digested sludge application rate (19 Mg/ha) for aspen was primarily a function of plant community type and age. The sprouts represented a young ecosystem with rapidly growing plants in both the understory and the overstory. This plant community was capable of greater rates of N uptake than the pine plantations. Application of the highest sludge dosages to the most vigorously growing forest ecosystems appears to be a sound management strategy on which to base forest nutrient additions while also protecting groundwater quality.

SUMMARY

Applying wastewater sludge to pine plantations and aspen sprout stands growing on coarse-textured soils resulted in elevated groundwater and soil water NO_3^--N concentrations. Mean NO_3^--N levels increased to near 50 mg/L, while peak concentrations approached 95 mg/L during major recharge periods. Sludge application rates that would not elevate groundwater or soil water NO_3^--N levels above the 10 mg/L potable water standard were recommended as 9.5 dry Mg of undigested sludge/ha of red pine plantation, 16.5 dry Mg of digested sludge/ha of red pine and white pine plantation, and 19 dry Mg of digested sludge/ha of aspen sprout stand. These rates differ because of the faster N mineralization rate in undigested sludge and the greater nutrient uptake rate in the young aspen stand. For sound fertilization and water quality management, sludge application rates should be adjusted to the characteristics of the forest site and the properties of the sludge.

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