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ENVIRONMENTAL AND PLANT EFFECTS OF SEWAGE SLUDGE APPLICATION TO FORESTS AND PASTURES[1]

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ABSTRACT

Digested sewage sludge was applied to pastures and tree plantations at 19 to 44 Mg/ha (dry weight) as part of a municipal sludge disposal program. The sludge had low concentrations of heavy metals and traces of ^{137}Cs and ^{60}Co. Monitoring of soils, soil solutions, and runoff indicated that N, P, heavy metals, and radionuclides were largely retained in the upper 15cm of the soil. Soil solutions had elevated NO_3^- concentrations often >100 mg/L, but no significant increases in groundwater NO_3^- were found during the first year. Runoff from active sites had elevated concentrations of NO_3^- (20-30 mg/L), soluble P (1 mg/L), BOD_5 (5-30 mg/L), and fecal coliform (up to 14,000 colonies per 100 ml), not unlike runoff from pastures with cattle.

Enrichment of organic N (2 times), available (inorganic) N (5 to 10 times), and Bray-P in the upper soils persisted for several years following sludge application. Sludge increased vegetation N concentrations from 1.5% to 2.3% and P concentrations from 0.16% to 0.31%. With the exception of Zn, heavy metals did not accumulate substantially in the vegetation. The sludge addition increased the survival and growth of sycamore (<u>Platanus</u> <u>occidentalis</u> L.). For a loblolly pine (<u>Pinus</u> <u>taeda</u> L.) plantation future growth improvements are expected based on elevated foliar N concentrations.

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INTRODUCTION

Land application of sewage sludge is an economical method of waste disposal with the potential to improve soil fertility and plant growth, especially on poorer soils. However, sludge often contains metals, microorganisms, and organic chemicals that may pose potential environmental and public health risks (Bitton et al., 1980). Several studies have shown the beneficial effects of sludge on the production of agricultural crops (e.g., Sopper and Kardos, 1973) and, more recently, on tree productivity (e.g., Sopper and Kerr, 1979; Cole et al., 1986). Forest applications have received increasing attention because of the greater capacity of forest ecosystems to retain sludge constituents (Sopper and Kerr, 1979) and because potentially toxic metals that may accumulate in the vegetation generally do not enter the human food chain. However, there are limits for annual and total loading rates to a particular site dictated by possible contamination of the water resources with sludge constituents (e.g., N, P, heavy metals) via leaching or overland flow (EPA, 1983).

Unlike some investigations that address constituent movement with extreme sludge addition rates (e.g., Riekerk, 1981), this study was conducted in conjunction with an ongoing sludge disposal operation. Therefore, the observed fate of sludge constituents should better reflect realistic conditions [i.e., a typical application regime following current U.S. Environmental Protection Agency (EPA) guidelines].

Beginning in 1983, the City of Oak Ridge has disposed of anaerobically digested sewage sludge by land application on the U.S. Department of Energy's (DOE's) Oak Ridge Reservation in East Tennessee. Early in the application program, Oak Ridge sludge was contaminated with ^{137}Cs and ^{60}Co at concentrations many times greater than in typical municipal sludge. In this paper we will discuss the monitoring results from several years of land application to pasture sites and forest plantations. The main objectives are to evaluate (1) the environmental effects of the sludge additions, that is, the extent of soil retention and off-site movement of the major potential contaminants (such as radionuclides, regulated heavy metals, N, and P) into the groundwater and through surface runoff and (2) the sludge effect on site fertility, nutrient accumulation by the vegetation, and plant growth.

MATERIALS AND METHODS

Land application sites

Anaerobically digested sewage sludge was transported almost daily between November 1983 and May 1989 from the City of Oak Ridge wastewater treatment plant to the DOE's Oak Ridge reservation where it was applied either to pasturelands or to a pine plantation. The sludge was applied as a liquid with a solids content of 2 to 4%. At the McCoy pasture site, an average of 44 Mg/ha of sludge was applied to a 22-ha area by subsurface injection (1983-1986). At the Rogers pasture site, a 12-ha area received a total of 43 Mg/ha of sludge either through subsurface injection or surface application (1986-1988). A total of 19 Mg/ha of sludge was applied by over-canopy spraying to a 4-year-old plantation of loblolly pine (*Pinus taeda* L.) by using a spray gun mounted on the delivery vehicle (1988-1989).

The soils in the pasture sites had a silt loam texture in the surface horizons and silty loam subsoils and were classified as either Typic Paleudults or Typic Hapludalfs (various soil series). The soil underlying the pine plantation was classified as a Typic Paleudult (Fullerton series) and had a cherty silt loam texture. Slopes ranged from 5% to 25% in the pasture sites and between 5% and 45% in the pine plantation. During extremely wet weather, when trafficability in the sites was a problem, operations were temporarily shifted to a more level pasture site not included in the monitoring system.

In 1978 a single treatment of dewatered-digested sludge corresponding to a total N load of about 1500 kg/ha N was applied to an approximately 0.5 ha plot. Following application the sludge was disked-in and a plantation of sycamore (*Platanus occidentalis* L.) was established. The soil had a silt loam to cherty silt loam texture and was classified as a Typic Paleudult (Clarksville series). Soils, vegetation, and soil solutions on this site were sampled during 1987 and 1988. At each of the four treatment areas, measurements were made at adjacent untreated sites to provide data for reference conditions.

Measurements and observations

Solution sampling

Soil solution chemistry was monitored through lysimetry in the treatment and reference areas of the McCoy, Rogers, and pine sites. In the treatment areas a total of six (McCoy) to nine (Rogers, pine) ceramic-cup tube lysimeters (5-cm diameter, 90-cm length) were placed to a depth of approximately 50 cm at three topographic classes: upslopes, midslopes, and bottoms. Six lysimeters (two replicates per slope position) were installed in the corresponding reference areas. The lysimeters were sealed, evacuated to 60-80 kPa once a month prior to a precipitation event, and solutions collected a few days later. Soil solution monitoring was started in March 1987 (during sludge application) at the Rogers site, in December 1987 (after termination of the sludge additions) at the McCoy site, and in April 1988 (prior to sludge application) at the pine site.

Soil water samples were routinely analyzed for pH, alkalinity, conductivity, NH_4, NO_3, total N and total P (Lachat autoanalyzer), and total metal concentration [inductively coupled plasma spectroscopy (ICP)]. Selected soil water samples were also analyzed for concentrations of Cd, Pb, and Hg (atomic absorption), and of radionuclides (gamma spectrometry).

To monitor the influence of the sludge application on the water quality of a small stream traversing the McCoy site, grab samples were collected monthly during precipitation events in the wet season (i.e., when overland flow was apparent) upstream and downstream of the application site. A Coshocton wheel mechanical flow-proportional sampler was placed downstream of the application area to provide an integrated flow sample. Flow was typically collected for 8 to 12 hours for the composite samples. No perennial surface waters were located near the Rogers or pine sites. At these sites Coshocton wheel proportional flow samplers were placed in the treatment and reference areas to intercept overland flow during precipitation events. Grab samples and composite samples were collected monthly during a single precipitation event.

Chemical analysis of runoff samples included parameters determined for soil water samples and, in addition, total suspended solids, biological oxygen demand (BOD), and total and fecal coliform. Samples were filtered through Whatman GF/F filters and analyzed for molybdate reactive P (Lachat autoanalyzer), Cd and Pb (graphite furnace atomic absorption), and Hg (cold vapor atomic absorption).

At the pine site five RCRA-type groundwater wells (EPA, 1986) were installed prior to sludge application. The Karst geology (abundant solution cavities) in this area makes groundwater sampling difficult. Three downgradient wells were located in the sludge application area, at the downgradient edge of the area and about 200 m further downgradient of the area; each well was 7 to 8 m deep to intercept the first major soil-rock interface were solution flow was likely to occur. Two wells were located upgradient of the application area, the first at 7 m at the first soil-rock interface, and a second at 57 m, at the major bedrock level. Water samples were collected monthly and analyzed for pH, alkalinity, conductivity, and NO_3^-. Intermittently, samples were also analyzed for radionuclides, total N, total P, and metals.

Soil sampling

After sludge application ended, six to ten soil cores were collected at each topographic area to 15-cm depth at the McCoy site and from 0- to 15-cm and from 15- to 30-cm depth at the Rogers pasture site. The samples were pooled per slope position prior to chemical analysis, yielding one or two samples per slope position per depth for the Rogers reference and treatment area, respectively, and three samples per slope position at the McCoy site. All samples were air-dried and analyzed for total N, for total and extractable metal concentration (by ICP), and for Bray P (McCoy).

Nitrogen availability was evaluated as soil NH_4-N and NO_3-N concentrations determined by extraction with 100 ml 2$\underline{N}$ KCl of 10 g field-moist soil (0-10 cm) taken in July 1988 along topographic transects in the McCoy and Rogers treatment areas (20 replicates) and the control area (15 replicates). At the pine plantation three 20-m by 30-m plots (one per slope position) were set out in the reference area and nine in the sludge application area (three per slope position), six of which received additional treatments not discussed in this paper. Soil samples to 15-cm depth were taken quarterly following sludge application at three random points of each treatment plot (total nine replicates per treatment) for NH_4 and NO_3 analysis. At the sycamore site total and mineral N contents were determined on five random samples taken at 0- to 20-cm and 20- to 40-cm depth in the treated and the adjacent control area.

Radionuclides

In early 1984 shortly after application began on the McCoy site, it was determined that the sludge was contaminated with radionuclides (primarily ^{137}Cs and ^{60}Co). A total of 117 soil cores were collected, separated into three depths, and analyzed for gamma activity. Water and sediment samples were taken from a creek traversing the application area and analyzed for radionuclides. Soils (0- to 15-cm depth) from the treated and reference areas of the McCoy site were again sampled after sludge application ended in September 1986. During 1987 and 1988, stream water upstream and downstream of the McCoy site and soil solutions from treatment and reference areas were analyzed. Similarly, on the Rogers sites soil solutions and surface runoff samples were analyzed during and following application.

Vegetation sampling

Posttreatment weed samples were taken from the three slope positions in reference and treated areas of the Rogers site, pooled to one (control) or two (sludge) replicates per slope position, and analyzed for the macronutrients and micronutrients. In the pine plantation, needles (all age classes) were taken quarterly from ten pine seedlings along a diagonal transect in each treatment plot, washed with distilled water to remove residual sludge caked to the fascicles, pooled per plot, and analyzed as above. In addition, height and basal diameter were measured on all loblolly pine seedlings in two or three rows per plot at the end of the dormant season before sludge application was started and one year later.

RESULTS AND DISCUSSION

Characteristics of Oak Ridge sludge

The characteristics of Oak Ridge sludge during application on the McCoy site (1983-1986) and application on the Rogers and pine sites (1987-1988) are presented in Table 1. Compared to the composition of many other municipal sludges (Doty et al., 1977; Sommers, 1977; Chaney, 1980), Oak Ridge sludge is rich in macronutrients, particularly N and P, but relatively low in heavy metals. Sludge Hg concentrations (~ 15 mg/kg dry weight) were higher than for most municipal sludges (Sommers, 1977). The concentrations of ^{137}Cs and ^{60}Co in the sludge were about 85 and 245 pCi/g dry weight during 1984

Table 1. Concentrations (dry weight basis) of selected constituents in digested sewage sludge from the City of Oak Ridge, Tennessee, during 1983-1986 and 1987-1988 (n = number of samples analyzed).

		1983-1986		1987-1988	
Constituent	Mean	Mean	n	Range	n
Solids (%)	2.4	3.1	126	1.8- 2.8	44
N (%)	8.1	5	2	6.0- 10	8
P	2.8	3	2	2.3- 3.5	10
K	0.7	0.6	2	0.4- 1.1	8
S	1.6			1.4- 1.7	2
Fe	1.7			1.4- 2.0	3
Al	1.9			1.7- 2.1	5
Ca	3.7			3.3- 3.9	4
Mg	0.6			0.5- 0.7	4
Na	0.2			0.2- 0.3	3
Ag (mg/kg)	123			110- 140	3
Au	1.4			-	1
As	5.6	4.8	8	-	1
Ba	790			720- 851	3
Be	3.2			3.2	2
Cd	10	14	126	7- 17	10
Co	17			-	1
Cr	255	630	126	131- 552	10
Cu	612	825	126	512- 828	9
Hg	15	14	7	12- 17	3
Mn	773			360-1197	5
Mo	48			37- 60	2
Ni	64	143	126	31- 88	8
Pb	171	220	126	130- 215	8
Zn	2170	2720	126	1720-3530	9

(C. S. Gist, Pers. Comm.). These concentrations had decreased to about 2.2 and 5.2 pCi/g for ^{137}Cs and ^{60}Co, respectively, by 1988.

Environmental effects of sludge application

Results of the chemical analysis for all the sites will not be reported in this paper. Rather, we will use the data from the different sites in a complementary fashion to address key concerns regarding the contamination and fertilization potential of land application of Oak Ridge sludge. We will indicate, however, when strikingly different results were found among the sites.

Radionuclides

Soil sampling at the McCoy site indicated that essentially all the activity of ^{137}Cs had been retained in the upper 7.5 cm of soil. Similarly for ^{60}Co, only about 17% of the soil samples from below 7.5 cm were above background (Oakes et al., 1984). At that time no ^{137}Cs and ^{60}Co could be detected in the stream water. The relative enrichment of the topsoil reflects the retentiveness of soils and sludge for these metals (Lagerwerff et al., 1976b).

After treatment ended ^{137}Cs and ^{60}Co were 3.5 and 0.45 pCi/g dry soil in the treatment and reference area, respectively (K. L. Daniels, 1986, Pers. Comm.). The resulting effective total body dose for continuous occupancy at the McCoy site was well below 100 mrem/year. Cobalt-60 provides the majority of the dose; because it has a relatively short half-life (5.3 years), the potential exposure will decrease rapidly. Soil water and stream water sampling after application ended showed no increased activity of ^{137}Cs or ^{60}Co.

Heavy (trace) metals

Posttreatment soil samples (upper 15 cm) collected from the McCoy site (three topographic regions) showed increases in Cd, Cu, Hg, Ni, Pb, and Zn compared with soils in the reference area (K. L. Daniels, 1986, Pers. Comm.). The average soil Cd concentration was 0.84 mg/kg, significantly greater than in the unamended soil (<0.45 mg/kg). However, this was well below the concentration that could result from the 10-kg/ha total Cd loading rate allowed by the State of Tennessee. Soil Hg was significantly elevated in the treatment area (0.44 mg/kg vs. 0.073 mg/kg); however, concentrations of Hg and most other metals (except Cd) were still within the range typically observed in soils (Chang et al., 1986). Furthermore, a comparison of measured and expected soil concentrations for these elements (based on concentrations in the sludge and sludge loading rates) suggested that most of the added metals were retained in the upper soils (i.e., the mass of a metal added with the sludge could be accounted for in the increase in mass of that metal on treatment compared with control soils, suggesting that much of the added mass had been retained).

Results from posttreatment soil analysis for the Rogers site are summarized in Table 2. Slope position did not affect soil

Table 2. Average nutrient and metal concentrations (mg/kg dry soil) in post treatment soil samples taken in May 1988 at the Rogers site (mean with standard deviation in parentheses, followed by significance of difference between treated and untreated soils at a given depth: *, p = 0.05; **, p = 0.01).

Constituent (mg/kg soil)	0-15 cm		15-30 cm	
	Control	Treated	Control	Treated
N	2800(1100)*	1200(700)	800(700)	1000(600)
P	1150(180)**	270(130)	380(95)	270(100)
K	960(690)*	640(530)	500(390)	760(290)
Ca	4350(2680)*	1350(140)	1960(1020)	1150(270)
Mg	1260(450)*	990(470)	910(380)	830(110)
Na	44(21)*	20(17)	27(10)	16(4)
Fe	16500(8400)	24000(9500)*	17900(7400)	24500(6100)*
Al	15200(2600)	14700(5400)	13400(600)	17700(2100)
Mn	2480(310)**	1170(890)	2220(820)*	1350(690)
B	6(4)	6(3)	5(3)	7(2)
Cd	tr	tr	tr	tr
Cu	16(7)	11(10)	1(2)	3(6)
Cr	31(10)	32(12)	27(8)	36(13)*
Mo	88(17)	94(30)	82(9)	85(4)
Ni	13(3)*	8(4)	22(30)	7(4)
Pb	55(23)**	41(5)	50(15)	40(5)
Zn	82(17)*	27(1)	31(7)	25(5)

concentrations (based on a two-way analysis of variance), and averages were calculated across all slopes. Concentrations of Mn, Ni, Pb, and Zn were significantly higher in soils in the treated area but, for the most part, were within the normal range observed in soils (Chang et al., 1986). Soil Cd levels were below detection limits both in reference and treatment areas. For the metals of regulatory concern, the calculated cumulative loadings at this site were 0.4 kg/ha for Cd, 21 kg/ha for Cu, 2.4 kg/ha for Ni, 6 kg/ha for Pb, 80 kg/ha for Zn, and 8 kg/ha for Cr, which were well below the recommended cumulative metal loadings for soils of this textural class or for agricultural use of the site even at the lowest cation exchange capacity (Chang et al., 1986; State of Tennessee, 1987).

For the 15- to 30-cm soil depth, except for Mn, no differences between treatment and reference areas were found, indicating limited downward movement of metals. This was further substantiated by the analysis of the soil water samples: Cd solution concentrations were always <1 μg/L, Pb concentrations ranged between <1 and 6 μg/L in both treatment and reference areas, and Hg ranged up to 0.38 μg/L and was slightly greater for the reference area than the application area. Zasoski (1981) earlier observed that even one year after a single sludge dose was applied to an acid forest soil, little Cd, Pb, or Ni had moved out of the sludge layer into the soil. He suggested that the elevated metal concentrations in the upper soil were due to physical movement of sludge particles rather than to solution leaching. Lagerwerff et al. (1976a) also found low water extractability of heavy metals, particularly Pb and Cu, from sludge.

Concentrations of regulated metals (As, Cd, Pb, and Hg) in the soluble fraction of stream water downstream of the McCoy site were usually below detection limits and always below EPA drinking water standards for runoff from both treatment and reference areas (e.g., Cd < 2 μg/L; Pb < 6 μg/L; Hg < 1 μg/L). Concentrations of Ni, Cr, Zn, and Mo in filtered samples of runoff from the Rogers site were also low and were similar for treated and reference areas. Concentrations of Ca, Mg, and occasionally Zn were greater in samples from the treatment areas than from the reference areas. Occasional differences in Fe, Al, and other metals between unfiltered samples from treatment and reference areas usually related to the amount of sediment in the sample. The above observations suggest that there is little concern regarding off-site movement of heavy metals and water contamination with this type of land application. However, site disturbances that trigger or accelerate soil erosion may lead to subsequent export of the sludge constituents currently retained on the soil particles.

BOD and fecal coliform bacteria

Surface runoff from the Rogers and pine application areas were sampled for BOD_5 and fecal coliform during the period of daily sludge application. Surface runoff was less common on the vegetated pine site than the Rogers pasture site where sludge injection had disturbed the vegetative cover. Increased concentrations of sludge constituents in surface runoff from disturbed soils have been reported by Mostaghimi et al. (1988). Fecal coliform bacteria reached levels of about 600 and about 14,000 colonies per 100 ml for the Rogers site and the pine site, respectively. However, fecal coliform typically ranged from about 2 to 600 colonies per 100 ml, which was similar to runoff from the reference areas. Sampling of surface runoff (Rogers site) and stream flow (McCoy site) during the year after sludge application ended still revealed occasionally high levels of fecal coliform bacteria (>1200 colonies per 100 ml). Overall these concentrations of fecal coliform bacteria are not uncommon in surface runoff or stream flow from agricultural areas during precipitation events (H. L. Boston, unpublished data).

BOD_5 in surface runoff from the pine site and the Rogers sites during the application period reached maximum concentrations of 17.5 and 26 mg/L, respectively. Runoff from reference areas never exceeded 8 mg/L BOD_5. On most sampling dates BOD_5 was similar for treatment and reference areas. Stream water collected upstream and downstream of the McCoy application site during storm events in the year after application ended always had similar BOD_5 values. These data were similar to other reports for runoff from watersheds receiving sludge (Shelton and Lessman, 1978).

Nitrogen and phosphorus

As shown in Tables 2 and 3, sludge additions significantly increased total soil P and N levels in the treatment areas, especially in the upper part of the soil profile. Estimates of total soil N content indicated that the bulk of the added N was retained in the upper 10 to 15 cm of the soil mostly in organic form (based on the increase in the mass of soil-N in the upper soils on treated sites vs. reference sites). At the Rogers site, the estimated differences in total soil N and P content (0-30 cm) between treatment and control areas were respectively 3150 and 2250 kg/ha, which were in the range of estimated total loadings (~2200 kg/ha for N and ~1200 kg/ha for P). Eight years following sludge addition to the sycamore site, total soil N content (0-40 cm) was 7000 kg/ha in the treatment area vs. 3500 kg/ha in the control plots; greatest differences were still observed at 0- to 20-cm depth.

The addition of organic sludge N had an almost immediate (within 1-4 months after application started; e.g., pine site) and long-lasting (8 years after application; e.g., sycamore site) stimulatory effect on mineralization and nitrification, as indicated by the significantly higher extractable NH_4^+ and NO_3^- levels in all treated soils (Table 3). Because of the mobile nature of NO_3^- (Kinjo and Pratt, 1971; Johnson and Cole, 1980), water moving through the sludge-amended soil was significantly enriched in NO_3^- compared with the control plot values (Fig. 1). Nitrate solution concentrations during sludge application (Rogers and pine sites) often exceeded 100 mg/L, while they ranged between 0 and 7 mg/L in the reference area. Selected samples collected at approximately 150-cm depth in the Rogers treatment area had NO_3^- levels on the order of 70-100 mg/L, indicating that NO_3^- leaching persisted deeper in the soil profile.

Table 3. Total nitrogen and KCl-extractable NH_4-N and NO_3-N concentrations in the sludge-treated and reference soils of the McCoy and Rogers pastures, and the pine and sycamore plantations (mean with standard deviation in parentheses, followed by significance of difference between treated and untreated soils at a given depth: *, p = 0.05; **, p = 0.01).

Site Depth (cm)	Sampling Date	Total N Treatment	Total N Control	NO_3-N Treatment	NO_3-N Control	NH_4-N Treatment	NH_4-N Control
		------------%	------------	---------------------mg/kg			-------------------
Sycamore							
0-20	(2/87)	0.18 (0.05)**	0.07 (0.01)	3.4 (0.9)**	0.2 (0.2)	4.4 (2.0)*	1.8(0.6)
20-40	(2/87)	0.05 (0.01)*	0.04 (0.01)	2.4 (0.7)**	0.14 (0.08)	2.1 (0.7)*	1.3(0.5)
McCoy							
0-15	(9/86)***	0.22 (0.05)*	0.10 (0.01)				
0-10	(7/88)	0.27 (0.06)*	0.19 (0.02)	15 (25)*	0.4 (0.6)	6.1 (3.3)**	3.8(1.3)
Rogers							
0-10	(7/88)	0.46 (0.12)**	0.19 (0.03)	257 (173)**	2.9 (1.9)	39 (31)**	4.9(2.8)
0-15	(5/88)	0.28 (0.11)*	0.12 (0.07)	--	--	--	--
15-30	(5/88)	0.08 (0.07)	0.10 (0.06)	--	--	--	--
Pine							
0-15	(7/88)	--	--	2.1 (1.7)	1.2 (1.7)	36 (17)**	2.7(1.4)
0-15	(10/88)	--	--	95 (31)**	2.9 (1.5)	37 (14)**	2.9(5.1)

***From Daniels, 1986.

Figure 1. Average NO_3^- concentration (mg/L) of soil leachates collected at 50-cm depth between March 1987 and April 1989 in active (___) and inactive (.....) sludge treatment areas and in untreated reference areas at the Oak Ridge Reservation, Tennessee.

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SOIL SOLUTION NO_3 CONCENTRATIONS

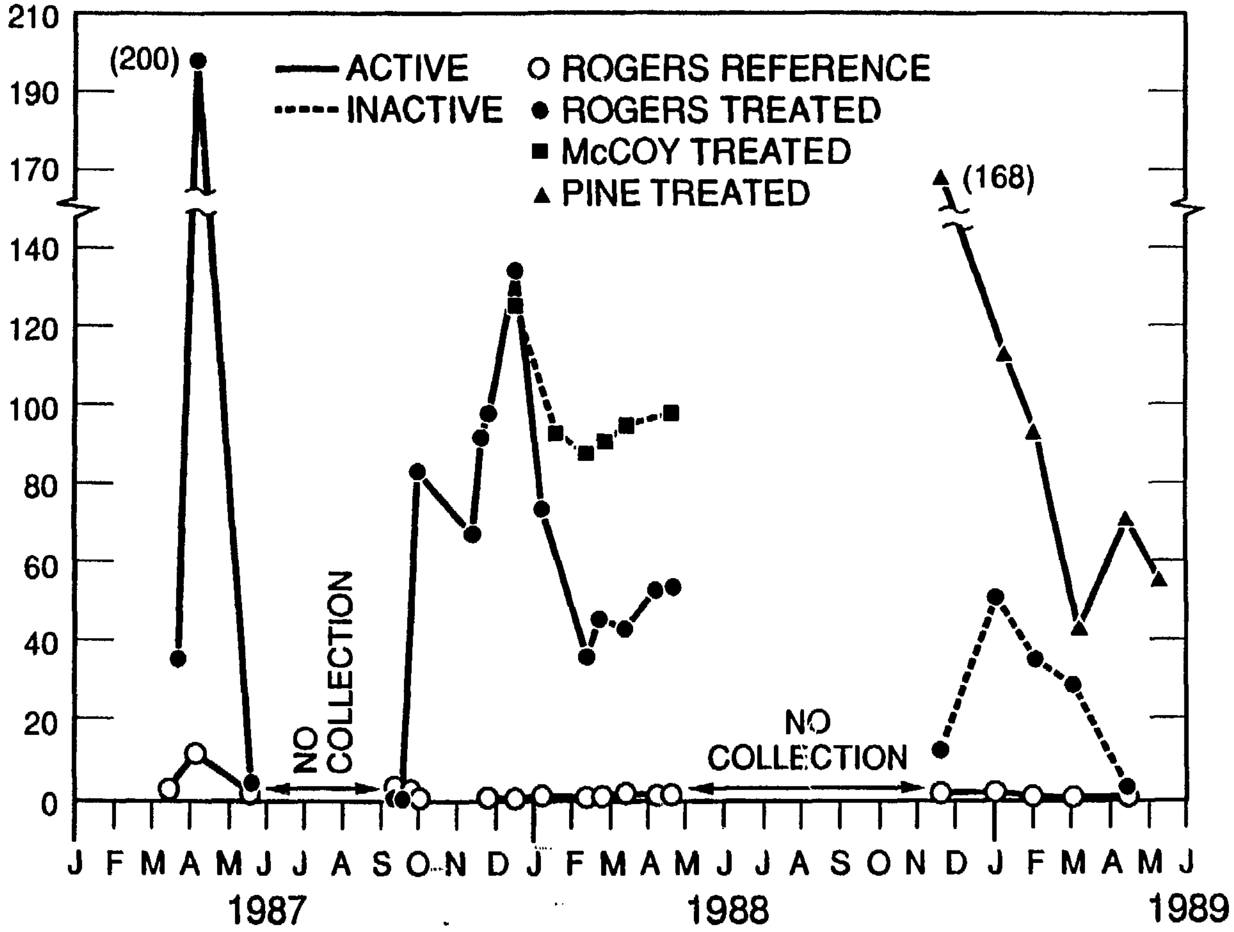

Figure 2. Average NO_3^- concentration (mg/L) in runoff samples from active (____) and inactive (.....) sludge treatment areas and from the corresponding untreated references areas.

Figure 3. Average soluble P concentration (mg/L) in runoff samples from active (____) and inactive (....) sludge treatment areas and from the corresponding untreated references areas.

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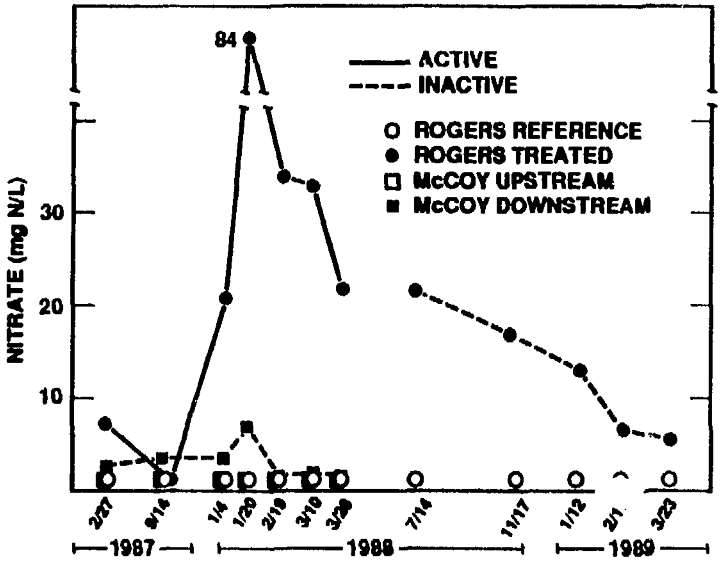

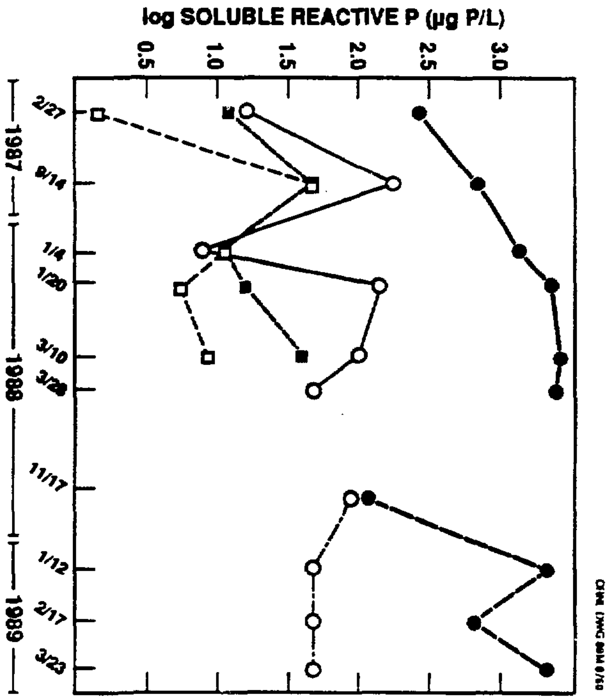
log SOLUBLE REACTIVE P (µg P/L)
0.5
1.0
1.5
2.0
2.5
3.0
2/27
9/14
1/4
1/20
3/10
3/28
11/17
1/12
2/17
3/23
1987
1988
1989

Solution NO_3^- concentrations were highest in winter and generally lowest in spring, probably a reflection of increased vegetation uptake. Concentrations decreased to <50 mg/L after application stopped at the Rogers site but were higher at the McCoy site (88-126 mg/L in the treated vs. 0-1 mg/L in the reference area). Since we have no solution data during application for the latter site, we do not know if these posttreatment values represent a decline in NO_3^- leaching. Wells et al. (1986) report similar declines in soil solution NO_3^- concentration 18 months to 3 years after sludge application ended. Accelerated NO_3^- leaching following sludge application to forests or croplands has been widely documented, but the extent and persistence of the NO_3^- pulse appear to differ substantially with the sludge application rate, vegetation cover, and soil properties (e.g., King and Morris, 1972; Koterba et al., 1979; Riekerk, 1981; various references in Sopper and Kardos, 1973; Sopper and Kerr, 1979; Cole et al., 1986).

Water samples from two of the three wells downslope from the sludge treatment in the pine plantation had NO_3^- concentrations that remained consistently below 1 mg/L throughout the first collection year. The NO_3^- concentrations in third well were somewhat higher, ranging from 0.4 to 5.3 mg/L, but showed no tendency for further enrichment over time. This suggests that within the first year of sludge application, minimal amounts of NO_3^- had been transported into the groundwater. Brockway (1988) and Riekerk (1981) reported a 1- to 2-year delay following sludge application before nitrate reached the groundwater above well-drained soils. However, at similar N loading rates as were used here, Brockway and Urie (1983) and Brockway (1988) found that groundwater NO_3^- levels were always significantly diluted compared with the soil solution concentrations.

Phosphorus retention appeared more complete compared with N, as little soluble P was moving through the soil profile, irrespective of treatment. Soil solution P concentrations in the Rogers treatment area ranged from 0.01 to 1.5 mg/L but were for the most part <0.2 mg/L vs. <0.1 mg/L in the reference area (Table 4). Phosphate mobility is generally restricted by adsorption and/or precipitation reactions (Wiklander, 1976; Johnson and Cole, 1980), making soils effective chemical filters for the P added with sludge or wastewater (e.g., Sopper and Kardos, 1973; Sopper and Kerr, 1979).

During sludge application, runoff samples from the pasture sites were significantly enriched in NO_3^-, with maximum values up to 84 mg/L, but typically had concentrations of about 20 to 30 mg N/L. Soluble P concentrations in runoff ranged between 2.4 and 3.4 mg/L for the treatment fields compared with 0.8 to 2.4 mg/L for the reference area (Figs. 2 and 3). These concentrations are in the range reported for runoff from agricultural areas with livestock use (Omernik, 1977). Concentrations of NO_3^- in runoff decreased significantly soon after application ended.

Table 4. Average total P concentration (mg/L) of soil leachates collected between March 1887 and February 1988 in the Rogers treatment and reference area (n indicates the number of lysimeters sampled per collection period).

Collection	Treated			Control		
Date	Average	Range	n	Average	Range	n
3-20-87	0.09	0.06 - 0.12	2	0.02	0.004 - 0.03	2
4-7-87	0.03	0.01 - 0.05	4	0.01	0.01 - 0.04	4
9-10-87	0.94	0.94	1	0.03	0 - 0.05	3
9-14-87	1.09	1.09	1			
9-30-87	0.24	0.24	1			
11-17-87	0.14	0.14	1			
1-5-88	0.60	0.2 - 1.5	4	0.14	0.11 - 0.16	4
2-22-88	0.16	0 - 0.52	7	0.02	0.01 - 0.03	5

Table 5. Average nutrient and metal concentration in posttreatment weed samples taken in April 1988 from the Rogers treatment and reference area (mean with standard deviation in parentheses, followed by significance of the difference between treated and control samples: *, p = 0.05; **, p = 0.01; n.s. = not significant).

Element	Treated	Control	Sign.
N (%)	2.36 (0.19)	1.40 (0.15)	**
P (%)	0.31 (0.05)	0.16 (0.05)	*
K (%)	2.90 (0.47)	1.50 (0.26)	**
Ca (%)	0.50 (0.14)	0.32 (0.05)	n.s.
Mg (%)	0.26 (0.04)	0.16 (0.02)	*
Na (μg/g)	456 (391)	64.3 (24.8)	n.s.
Al (μg/g)	111 (66)	91 (62)	n.s.
B (μg/g)	11.6 (6.2)	11.3 (1.6)	n.s.
Cu (μg/g)	39.6 (41.7)	15.3 (0.3)	n.s.
Fe (μg/g)	156 (67)	104 (53)	n.s.
Mn (μg/g)	82.4 (21.6)	82.3 (24.8)	n.s.
Pb (μg/g)	12.0 (7.9)	15.4 (13.4)	n.s.
Zn (μg/g)	48.9 (16.7)	21.6 (9.3)	n.s.

Plant effects of sludge application

Soil fertility changes

Soil N and P often limit tree productivity in the southeastern United States (e.g., Lea and Ballard, 1982; McNeil et al, 1988; Pritchett and Comerford, 1982). As indicated in the previous section, sludge application resulted in a significant increase in total soil N and P (Tables 2 and 3). Although we found that most of the added N remained in organic form, the sludge-treated soils had significantly higher extractable NH_4 and NO_3, especially in the upper soils (Table 3), even several years after the treatment had ended (e.g., sycamore site). A separate N mineralization study at the pasture sites also indicated higher mineralization rates in the treated areas (Van Miegroet et al., 1989), resulting in an overall increase in N availability. The long-term increase in soil total N and available N following sludge application contrasts with the short-term (1-2 years) increase in soil N following fertilization with inorganic N (Johnson and Todd, 1988).

Bray-extractable P, an indicator for P availability in soils, ranged between 390 and 1300 mg/kg in the McCoy treatment soils and between 25 and 100 mg/kg in the reference soils (K. L. Daniels, 1986, Pers. Comm.), suggesting that the sludge application had effectively increased available P levels by at least an order of magnitude. Because of the typically low P mobility in soils (Wiklander, 1976), positive tree growth responses to P applications may last as long as 20 to 25 years (e.g., Pritchett and Comerford, 1982).

Plant nutrient and metal concentrations

Posttreatment weed samples at the Rogers site showed an increase in N concentration (i.e., from 1.4% in the reference area to 2.4% in the treated area, in response to a significant improvement in soil N status (Tables 2, 3, and 5). Sludge N added to the loblolly pine plantation was rapidly taken up and resulted in an increase in needle N concentration from 1.35% to 1.7% within 1 month. Four months later, needle concentrations in the treatment plots had increased to 2.3% compared with 1.5% in the reference plots (Table 6), and the needles were darker green in color.

Tissue P concentrations at the Rogers and pine sites were about doubled following sludge addition (Tables 5 and 6). Other macronutrients that were elevated in the sludge-amended soils (i.e., K, Ca, and Mg) were generally found in higher concentrations in plant tissue samples.

No significant metal accumulation was measured in the weeds growing on the Rogers sludge area compared with those from the reference area (Table 5), even though soil Mn, Pb, and Zn levels were significantly increased by sludge application (Table 2). This likely reflected the low total metal loading at this site and the limited

Table 6. Average nutrient and metal concentration in posttreatment pine needles sampled in July and October 1988 from the treatment and reference area in the pine plantation (mean with standard deviation in parentheses, followed by significance of the difference between treated and control samples: *, p = 0.05).

	July 1988		October 1988	
Element	Treated	Control	Treated	Control
N (%)	1.66 (0.07)*	1.34 (0.06)	2.26 (0.29)*	1.46 (0.01)
P(%)	0.30 (0.01)	0.25 (0.02)	0.32 (0.08)*	0.16 (0.02)
K (%)	0.81 (0.06)	0.78 (0.06)	0.83 (0.03)*	0.73 (0.07)
Ca (%)	0.43 (0.05)*	0.24 (0.03)	0.48 (0.08)*	0.27 (0.03)
Mg (%)	0.15 (0.02)*	0.11 (0.02)	0.15 (0.02)*	0.11 (0.01)
Na (%)	0.05 (0.02)	0.03 (0.01)	0.02 (0) *	0.01 (0)
Al (μg/g)	817 (40)*	293 (32)	1667 (569) *	410 (46)
B (μg/g)	20 (1)	16 (2)	29 (4) *	18 (4)
Cu (μg/g)	39 (5)	6 (1)	58 (36)	4 (1)
Fe (μg/g)	677 (502)	527 (6)	1280 (420) *	62 (7)
Mn (μg/g)	204 (41)	202 (41)	229 (11)	253 (121)
Zn (μg/g)	173 (12)	33 (3)	193 (51)	38 (3)

Table 7. Seedling height and diameter increment (cm) by slope position in the first year following treatment application at the loblolly pine plantation (mean with standard deviation in parantheses; means followed by a different letter or * are significantly different at p = 0.05).

Slope Position	Height Increment		Diameter Increment	
	Treated	Control	Treated	Control
Upslope	53(14) bc	63(14) ab	1.7(0.4) a	1.7(0.4)
Midslope	50(18) c	73(21) a	1.2(0.4) b	1.2(0.5) b
Bottom	62(16) b	56(21) bc	1.7(0.4) a	1.7(0.5) a
All slopes	55(17)	65(21) *	1.6(0.5)	1.5(0.5)

mobility of these metals in organically rich (sludge) substrate (Zasoski, 1981). There was four- to fivefold increase in Al and Zn concentrations in the loblolly pine needles. Such increases are not problematic, however, in view of the fact that loblolly pine readily accumulates Al (Boyer and South, 1985) and tolerates high Al solution concentrations without negative growth effects (Raynal et al., 1989). A small but significant increase in the foliar concentration of the micronutrients B and Fe was also measured in the treated plots.

Growth responses

Height and basal diameter growth of the loblolly pine seedlings measured during the first year of sludge application were generally not different between treatment and reference plots at the same slope position (Table 7). The topographic location of the plots seemed to have a greater impact on growth than the different treatments, possibly as a result of different soil moisture regimes associated with the slope positions. Needle N concentrations on the control plots were in a range where a growth response to N addition would be expected (Lea and Ballard, 1982; Comerford and Fisher, 1984). The lack of treatment effect was not entirely unexpected, however, since sludge was not added until well into the growing season, and potential stimulatory effects were confounded by a prolonged drought. Richter et al. (1982) and McKee et al. (1986) reported increased loblolly pine growth with sludge application over a 4-year period. The positive growth response appeared highly correlated with tree age, and sludge application was generally more effective in younger plantations, although 3-year-old seedlings showed no growth response, primarily due to weed competition (McKee et al., 1986). On our plots the trees were more than 170 cm and had overtopped the weeds.

The beneficial effects of sludge were also illustrated in the sycamore plantation. Actual growth rates between treated and untreated areas could not be compared, as most all of the trees in the control plot had died by 1988, whereas the sludge-amended plot supported a fully stocked plantation. The available data do not allow us to conclude to what extent this dramatic difference in seedling survival was caused by an improvement in nutrient status or in water retention capacity of soils with the addition of sludge (organic matter), or what other site characteristics contributed to these differences.

CONCLUSIONS

Sludge application on pastures and tree plantations caused a significant and prolonged increase in soil total and plant-available N and P, which may increase tree growth and biomass production. The change in soil nutrient status was reflected by a significant increase in plant macronutrient and micronutrient content. Potentially toxic metals (Cd, Cu, Pb, Zn, etc.) contained in the sludge were largely retained in the upper soil layers. These metals were not found to be moving in soil solutions or surface runoff, suggesting that there was little potential for the contamination of nearby groundwater or surface water resources. Vegetation on application sites had higher concentrations of several metals (e.g., Ni, Pd, Zn) compared with vegetation on reference sites; however, the tissue concentrations were not considered problematic for plant growth or consumption. Radionuclides (^{137}Cs and ^{60}Co) in the sludge were similarly immobilized in the upper soil layers and were not elevated in vegetation, soil water, or runoff. During sludge application, surface runoff following storm events was enriched with NO_3^-, soluble reactive P, BOD, and fecal coliform bacteria. Concentrations of these constituents were similar to those in runoff from livestock areas. The quality of surface runoff from treatment fields improved substantially shortly after application ended. Nitrate was the only sludge constituent found to be substantially elevated in soil solutions. Preliminary results from direct groundwater monitoring suggest that NO_3^- contamination of groundwater resources is not occurring. However, additional monitoring will be required.

These results suggest that sludge application in accordance with current EPA guidelines substantially improves site fertility with minimal environmental degradation. Additional efforts will be required to improve the quality of surface runoff and to be sure that groundwater resources are protected.

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