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J. C. Corey, M. W. Lower, C. E. Davis

E. I. du Pont de Nemours and Company
Savannah River Laboratory
Aiken, South Carolina 29808

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ABSTRACT

Since 1980 a research program has been conducted at the Savannah River Plant to evaluate the use of domestic sewage sludge to enhance forest productivity. The objective of the program has been to determine the environmental impact of using sewage sludge as a soil conditioner and slow-release fertilizer. The potential impacts of sludge application on nutrient cycling, organic carbon budgets, and biomass production have been studied. Soil, soil water, groundwater, and stand biomass samples have been analyzed to monitor the availability and movement of nutrients and metals.

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INTRODUCTION

Studies have been under way at the Savannah River Plant (SRP) in southwestern South Carolina since 1980 to evaluate the environmental effects of applying sewage sludge for forest productivity. The Savannah River Plant, encompassing 77,701 hectares (ha) (192,000 acres), is a Department of Energy installation in southwestern South Carolina which produces fissionable nuclear materials for national defense weapons programs. Currently some 70,882 ha of SRP lands are classified as suitable for growing pine and/or hardwood trees. Over 107 million pine trees, largely longleaf and loblolly pine, have been planted at the site since 1952. Presently, about 500 million board feet of sawtimber and one million chords of pulpwood exist onsite with an inventory value exceeding 53 million dollars.

Forests at the SRP are ideally suited for evaluating sewage sludge management based on the following considerations: (1) the diversity of soils that are representative of the coastal plain area; (2) extensive and protected forests at the 77,701 ha SRP site with only limited public access; and (3) SRP forests are primarily managed for sustained yield timber production which provides a variety of stand age classes and conditions ideal for forest research purposes.

The implementation of environmentally sound waste management technologies for the disposition of sewage sludges was mandated under the Federal Water Pollution Act Amendments of 1972 and the

Clean Water Act Amendment of 1977. As a consequence of improved wastewater treatment, the quantities of sewage sludge generated and required for disposal have increased. Disposition of most sewage sludges is accomplished in landfills and lagoons, by incineration and dumping in the ocean, and by application to land.

Program Organization

The forestry management expertise provided by the U.S. Forest Service (USFS) at SRP, the Southeastern Forest Experimental Station (SEFES) of Charleston, South Carolina and Research Triangle Park, North Carolina, the Savannah River Ecology Laboratory (SREL), and the Savannah River Laboratory (SRL) organizations was beneficial to programmatic design and implementation. The organizational roles of the integrated study effort under way since 1980 have been:

Organization	Primary Roles
SRL	Research coordination and administration
	Site preparation
	Plot sampling
	Groundwater monitoring
	Biomass estimations and assessment correlations
USFS	Oversight and consultation
	Pine forest management
	Site preparation

SEFES	Experimental design
	Sample collection and analysis
	Interpretation of results
SREL	Nutrient cycling: stemflow, throughfall, litterfall, understory
	Wildlife habitat

Sludge Characteristics

The sludge used in the forest productivity research came from two offsite sources, the Horse Creek Pollution Control Facility located in North Augusta, South Carolina and the Augusta Wastewater Treatment Plant in Augusta, Georgia. Because the two plants treat wastewater differently, the resultant sludge product provided a range in nutrient and heavy metal composition. A compilation of average concentrations and application rates for both the Horse Creek and Augusta sludges is given in Table 1. Analyses of the Horse Creek sludge indicated lower nitrogen levels and higher heavy metals concentrations as compared to the Augusta sludge (Table 1). These differences in nutrient and metals compositions were attributed to different treatment processes and influent compositions at the two treatment facilities, respectively. Both sludges had comparable pH ranges of 7.3 to 7.4. Prior to land application, analyses of both sludges were performed on a routine basis for nutrients and metals.

TABLE 1

Average Concentrations and Application Rates for Augusta and Horse Creek Sludge

	Augusta	Horse Creek	Augusta	Horse Creek	Augusta Low	Augusta High	Horse Creek Low
pH	7.32	7.37				kg/ha	
	g/100 g						
Oven dry	2.48	55.72			5,555	11,100	49,925
	g/100 g O.D.						
Ash	46.02	36.11			2,556	5,113	18,027
	µg/g wet		µg/g O.D.				
Kjeldahl-N	1,795	7,066	72,374	12,676	402	804	632
NH_4-N	753	134	30,361	240	169	338	12
NO_3-N	3.7	0	149	0	0.82	1.64	0
P	402	4,206	16,209	7,546	90	180	377
K	66	170	2,661	305	15	30	15
Ca	361	11,649	14,556	20,898	81	162	1,043
Mg	61	1,943	2,460	3,486	14	28	174
Na	519	1,638	20,926	2,939	116	232	147
Mn	3.4	167	137	300	0.76	1.52	15
Zn	33	1,203	1,330	2,158	7.39	14.78	108
Cu	7.9	696.0	318	1,249	0.77	1.54	62
Pb	5.9	98.0	238	176	1.32	2.64	8.79
Ni	1.1	23.9	44	43	0.24	0.48	2.15
Cd	1.1	3.3	44	6	0.24	0.48	0.29
S	148	2,031	5,967	3,644	33	66	181
Fe	2,525	23,662	10,808	42,449	565	1,130	2,119
B	6.3	149.5	254	268	1.41	2.82	13
Cr*	4.3	772.0	173	1,386	0.96	1.92	69
Sb*	0.2	0.9	8	2	0.04	0.08	0.09
Se*	2.0	42.3	81	76	0.45	0.90	3.79
As*	2.6	19.5	105	35	0.58	1.16	1.74
Sn*	2.5	22.3	101	40	0.56	1.12	2.00
Co*	0.2	4.6	8	8	0.04	0.08	0.39
Hg*	0.1	17.2	4	31	0.02	0.04	1.55

* Analyzed by inductive coupled argon plasma spectrophotometer

O.D. = oven dry

The Horse Creek Pollution Control Facility receives 80 percent of its wastewater from industrial sources, primarily textile mills. Sewage is aerobically digested and solids are heated for 0.3 hr at 375°C under 250 psi. The heat treated sludge is then dewatered and contains 30 percent solids. These processes condition and stabilize the sludge and destroy pathogenic organisms without extensive chemical use. The Augusta Wastewater Treatment Plant receives 80 percent of its influent wastewater from domestic sources. Sewage treatment is by both conventional aerobic and anaerobic processes producing a "liquid" sludge with a 2 to 3 percent solid suspension.

The Horse Creek sludge was broadcast on pine forest experimental sites with a manure spreader at a rate equivalent to 632 kg/ha. The Augusta sludge was sprayed on the forest floor with a pressurized tanker. Application rates for the Augusta sludge were equivalent to 402 and 804 kg/ha, respectively. Control plots were established at all forestry research sites. Control plots received no sludge amendments so that biomass production and environmental impacts could be compared to experimental sites receiving sludge amendments.

Objectives

The principal objective of the forest productivity program has been to evaluate optimum methods and alternative techniques for the land disposal of sewage sludge which will result in increased biomass production of the pine forests without environmental degradation. This objective was accomplished by examining:

- The growth and/or survival responses of pine trees at various ages following sludge amendments at different rates on both sandy and sandy clay soils;
- The necessary management decisions to minimize the potential for adverse environmental and health impacts following application of sewage sludge as a soil conditioner and slow release fertilizer;
- The cycling and fate of nutrients and heavy metals in sewage sludges applied to varying soil systems and resultant impacts on biomass and understory associated with loblolly pine stands;
- The responses of pine plantations amended with sewage sludge to inorganic fertilizers and/or herbicides;

During 1980-1981, 45 acres of experiment plots 0.2 ha in size in four different age loblolly pine stands on two soil types were installed, and all background information on the physical and chemical characteristics of the trees and the soils at these experimental plots were determined. Following the single sludge amendment at these sites, the monitoring program, continuing today, was initiated for evaluating environment impacts and modifications of nutrient and elemental cycling on the treated plots.

Seven experimental loblolly pine sites were selected at five different locations at SRP. The pine plantations on these sites have planting dates of 1953, 1973, 1978, and 1981. The ages of the stands were selected on the basis of stage of growth representing times of near maximum stemwood formation, crown closure, maximum

hardwood competition, and seedling establishment. The 1953, 1973, and 1978 plantings amended with sewage sludge reside on two different soil classes, a sandy soil and a heavier sandy clay.

Lucy Site

The Lucy Site is a loblolly pine forest located in northwestern SRP typified by thick loamy sands known as the Fuquay Series. Trees at this site were planted in 1953. This experimental site received a single sludge amendment in 1981 of both the solid (Horse Creek) and liquid (Augusta) sludges. This site was selected for research so that the effects of sludge amendments on low fertility sandy soils might be evaluated and to determine whether the organic matter in the sludges would improve soil moisture holding properties, thus enhancing biomass production by the retention of nutrients.

For practical purposes, the Lucy sand is part of the Fuquay Series, with 46 to 76 cm of sand over sandy clay subsoils. The soil is considered highly permeable, acid and infertile by agronomic standards. The experimental research design consisted of randomized gross plots 0.2 ha in size, with rows eight feet apart. Plots measured about 44 m by 46 m. Liquid sludge was applied in 1981 at rates of zero, 233,000, and 466,000 L/ha (equivalent to zero, 402, and 804 kg N/ha, respectively). Solid sludge was applied at rates of zero and 89,668 wet kg/ha (equivalent to zero and 632 kg N/ha, respectively).

Stands at the Lucy Site had been periodically thinned by the U.S. Forest Service at SRP. Understory vegetation at the time of sludge application was minimal.

Baseline stand measurements of pine diameter at breast height (dbh) at specific plots within the gross plots were collected in 1981 prior to the sludge amendment. Soil, soil water, litterfall, throughfall, stemflow, and groundwater samples have been collected and analyzed periodically since the sludge amendment to monitor the effects upon nutrient and heavy metal cycling.

Orangeburg Site

The Orangeburg Site is located in central SRP and encompasses about eight acres of loblolly pine stands planted in 1953. Sludge amendments at this site were performed in 1981 similar to the regime performed at the Lucy Site; soils at the Orangeburg Site, however, were a heavier sandy-clay.

The study at the Orangeburg Site entailed the design of three randomized blocks with three replications at the site. Gross plots measured 0.2 ha in size. Liquid and solid sludges from Augusta and Horse Creek, respectively, were applied at rates equivalent to 0, 402, and 804 kg N/ha for the liquid and 0 and 632 kg N/ha for the solid material.

Prior to sludge application, tree identification and dbh measurements were performed for baseline purposes. Incidence of fusiform rust disease was documented. Following the sludge amendment, soil, soil water, litterfall, and groundwater samples were

collected periodically to ascertain environmental effects. Biomass production measurements, stem measurements, and stem analyses were made in 1984.

Road F Site

The Road F Site is a loblolly pine plantation located in northwestern SRP. Loblolly pines, planted in 1973, were grown on both a sandy soil and heavier sandy clay. Soils at the Road F Site received a sewage sludge amendment in 1980 to determine the cycling and assimilation of nutrients and heavy metals.

Sewage sludge from the Augusta Wastewater Treatment Plant was sprayed in a liquid form at three levels equal to 0, 402, and 804 kg N/ha at the Road F pine forest. The treatment design involved three replications of the three treatments imposed in a block design on the Wagram-Lucy (sand) and Fuquay-Dothan (sandy clay) soils.

Tree spacing at this site was about 1.8 m by 3 m. Prior to sludge application, the stand had an average height of 5.61 m and dbh of 9.1 cm. Control of competition, both hardwood and herbaceous species, was not of concern since pines at the Road F Site represent crown closure and have overtopped the hardwoods.

Gross plots were designed for an area of 46-m square (0.2 ha). Each gross plot contained 15 rows of trees about 46 m in length. Measurement plots were established within gross plots of 34 m by 34 m or 0.11 ha.

Soil water, groundwater, litterfall, and biomass samples were periodically collected and analyzed.

Lower Kato Road Site

The Lower Kato Road Site is a 20-ha plantation of loblolly pines planted in 1978 on two soils, a sandy (>90%) soil (Lucy) and a heavier sandy clay (10 to 20% clay in surface horizons, Orangeburg). Sludge amendments were imposed on three-year-old loblolly pine stands in 1981. Liquid and solid sludges were applied at rates equivalent to 0, 402, and 804 kg N/ha for the liquid sludge and 0 and 632 kg N/ha for the solid sludge.

The experimental design consisted of a randomized block design with three replications installed on the two soils. Competing vegetation of a variety of hardwood and herbaceous species existed at this site. Split plot treatment application of granular Velpar was applied to reduce hardwood competition.

Plot sizes at the Lower Kato Road Site were identical to the 0.2 ha plots established at the other research sites. Gross plots at this site contained 15 rows of trees 46 m long.

Kato Road Site

The response of loblolly pine seedlings at establishment to two sources of sewage sludge at three levels applied with and without disking in combination with tip moth control and herbicides to control weed competition was evaluated at the Kato Road Site. This establishment site is a 14 ha plantation that was treated in February and March 1981 with sewage sludge from both the Augusta Wastewater Treatment Plant and the Horse Creek Pollution Control Facility. Site soils were characteristic of the Orangeburg Series throughout the site.

The establishment site encompassed a complex experimental design. Three replications of twelve combinations of fertilizer sources were designed, along with varying disking and tip moth control treatments (Furadan). Imposed on the twelve treatments were three herbicide treatments consisting of no herbicide application, Velpar® (Du Pont) applied at 0.78 kg/ha and Goal® (Rohm and Haas) applied at 0.56 kg/ha. Sludge and disking treatments were applied prior to planting and herbicides the spring of the first growing season.

The Kato Road Site had two sources of sludge applied at rates equivalent to 0, 402, 632, and 804 kg N/ha compared with 28 and 55 kg N/ha applied as diammonium phosphate. Following amendments and establishment plantings in 1981, soil, soil water, groundwater and growth measurements have been made annually to determine the effectiveness of sewage sludge as a fertilizer and soil conditioner for loblolly pines at establishment.

COLLECTION, ANALYSIS, AND INTERPRETATION OF ENVIRONMENTAL SAMPLES

Prior to and following sludge amendments at the experimental forest research sites, soil, soil water, and groundwater samples were collected and analyzed for all parameters of interest, so that the environmental effects of sludge amendments could be determined. Tree height and/or diameter at breast height measurements were made at the time of the sludge amendment and annually thereafter to gage biomass production and growth response. This section highlights

the environmental and growth response monitoring data obtained prior to and following the sludge application through 1984.

Soil Analyses

Release of nutrients in forest soils is the primary uptake pathway of nutrient sources to trees and understory. Chemical characteristics of forest soils govern the rate of mobility and availability of the nutrients to trees and understory. Low levels of available nitrogen in forest soils have been found to limit loblolly pine production in the southeastern U.S. (Wells, 1970).

Inorganic nitrogen (NH_4^+ and NO_3^-) in sludges added to forest soils becomes immediately available for tree and understory uptake. The organic nitrogen is not immediately available and must be converted to inorganic forms via nitrogen mineralization to render it available for uptake. During the first year after sludge treatments, nitrogen mineralization rates range from about 8 to 20%, with reduced rates occurring in subsequent years (SCS, 1982).

An extensive soil sampling and analysis program was conducted at the experimental forestry sites preceding and following the sludge amendment. Soil analyses included nutrients, cations, and metals.

Soil properties were found to be quite variable following the sludge application, reflecting both the nature of the sludge product and the low cation exchange capacity of the soils (Wells et al., 1982). The most extensive and comprehensive soil analyses were conducted at the 1953 stands. Growth data collected through

1984 indicated that the trees were still responding to the one sludge application in 1981.

Physical and chemical characteristics of the sandy and sandy clay soils at the 1953 stands six months after sludge treatment are presented in Tables 2 and 3. General trends, noted by Wells et al. (1982), were as follows:

- Soil pH decreased as much as 0.5 units with the Augusta sludge but the Horse Creek sludge had no effect on soil pH.
- In the surface 10 cm (4 inches), soil nitrogen content increased with application of the Augusta sludge but not with the Horse Creek sludge.
- Available phosphorus levels increased with application of the Augusta sludge.
- Exchangeable bases (Ca, Mg, K, Na) in soil were reduced from levels prior to sludge application and were attributable to nitrate production near the surface which leached these exchangeable constituents deeper into the soil.
- Organic matter in the soils was reduced at the sandy site and increased at the sandy-clay site. Retention of organic matter was attributed to the lower permeability of clay materials in soils at the Orangeburg Site.

In all, degradation of site soils attributable to sludge amendments was clearly not evidenced.

TABLE 2

Soil Properties 0-10 Centimeters on 1953 Stand Sandy Site — Fuquay Series (Lucy Site)

Soil Properties	No Sludge	Augusta Sludge 402 kg N/ha	Augusta Sludge 804 kg N/ha	Horse Creek Sludge 632 kg N/ha
pH	5.3	5.0	4.8	5.5
	ppm			
Total N	343	335	390	330
Available P	35	21	55	32
	meq/100 g			
Exchangeable Ca	0.88	0.43	0.33	0.67
Exchangeable Mg	0.14	0.07	0.05	0.15
Exchangeable K	0.04	0.02	0.02	0.02
Exchangeable Na	0.01	0.01	0.01	0.02
	ppm			
Total K	35	29	52	22
Total C	128	83	5621	138
Total Mg	74	71	269	60
Total Na	0	0	97	1
Total Pb	1	4	0	1
Total Cu	1	1	1	1
Total Zn	2	3	3	2
Total Fe	1444	1661	1729	1401
Total Ni	3	5	9	2
Total Cd	1	1	1	1
Total Cr	1	2	6	1
Total Mn	124	72	95	75
	percent			
Organic matter	1.78	1.48	1.44	1.48
Clay	8	9	8	8

TABLE 3

Soil Properties 0-10 Centimeters on 1953 Stand Sandy Clay Site — Orangeburg Series (Orangeburg Site)

Soil Properties	No Sludge	Augusta Sludge 402 kg N/ha	Augusta Sludge 804 kg N/ha	Horse Creek Sludge 632 kg N/ha
pH	5.3	4.5	4.9	5.3
	ppm			
Total N	245	255	195	285
Available P	10.0	24	19	13
	meq/100 g			
Exchangeable Ca	0.63	0.49	0.40	0.70
Exchangeable Mg	0.16	0.12	0.07	0.25
Exchangeable K	0.03	0.03	0.02	0.03
Exchangeable Na	0.05	0.04	0.03	0.02
	ppm			
Total K	53	32	49	58
Total C	88	75	63	95
Total Mg	138	91	109	134
Total Na	1.5	1	1	2
Total Pb	9.0	3	5	12
Total Cu	5	2	2	4
Total Zn	6	4	4	6
Total Fe	2023	1575	1705	1995
Total Ni	5	1	1	4
Total Cd	0	1	1	0
Total Cr	1	1	0	1
Total Mn	87	120	125	215
	percent			
Organic matter	0.81	0.91	0.77	1.16
Clay	11	8	9	10

Soil Water Analyses

Soil water samples were collected at the experimental sites following sludge amendments using fritted glass lysimeters so that quantities of nutrients and cations leaching in the soils could be measured. These lysimeters, installed at 0.5 and 1 m depths, were constructed in such a way that solution only contacted glass and polyethylene tubing (Wells et al., 1984). Two pairs of lysimeters at both depths were installed in each of the 0.2 ha experimental plots at the 1953 planted stands. In the 1973, 1978, and 1981 stands, one lysimeter was installed at each depth except for the 1973 stand which had lysimeters in only the heavier clay soil (Wells et al., 1984). Lysimeter samples were collected over a 24-hour period and analyzed offsite for nutrients, cations, and heavy metals.

Results of soil water analyses through 1983 indicated that the age of the pine plantation and the nitrogen concentration in the sludge amendments were the major controlling variables for nitrate-nitrogen in soil water (Wells et al., 1982). One full year after the sludge application, the order of nitrate concentration in soil water at the 0.5 and 1 m depths was one-year-old >27 >8 = three-year-old (Wells et al., 1982). Following the first full year of soil water data, nitrate-nitrogen levels in soil water at all age classes generally declined. Results of soil water analyses showed the following additional trends:

- The 1953 plots at which sludge was applied equivalent to 804 kg N/ha indicated overloading of nitrogen to the system (Figures 1 and 2) at both lysimeter depths; elevated nitrate-nitrogen levels at the 0.5 m depth persisted at the Lucy Site for a full year following the sludge amendment (Figure 2);
- High levels of nitrate-nitrogen at the 1953 stands within a year after treatment indicated extremely rapid nitrification, which was generally unexpected in soils of pH 5.0 (Wells et al., 1982);
- Nitrate-nitrogen levels in soil water at both depths at 1953, 1973, and 1978 stands for control plots, and plots treated with Horse Creek (632 kg N/ha) and Augusta (402 kg N/ha) sludges were all comparable;
- Some nitrate leaching was evidenced from lysimeter samples at the 1973 stands one year after treatment (Figure 3);
- Wells and McKee (1983) documented that no relationship was noted at the 1973 stand between the amount of precipitation and soil water nitrate-nitrogen concentration;
- Nitrate-nitrogen concentrations in soil water peaked at 27 mg/L at the 0.5 m depth in April 1982 at the 1978 stand applied with the high rate of nitrogen in liquid sludge (Figure 4);
- More efficient uptake of nitrates by the stands with little or no nutrient leaching to greater root depths was evidenced at the 1978 stand as compared to the 1973 stand on similar soils and equivalent sludge treatments;

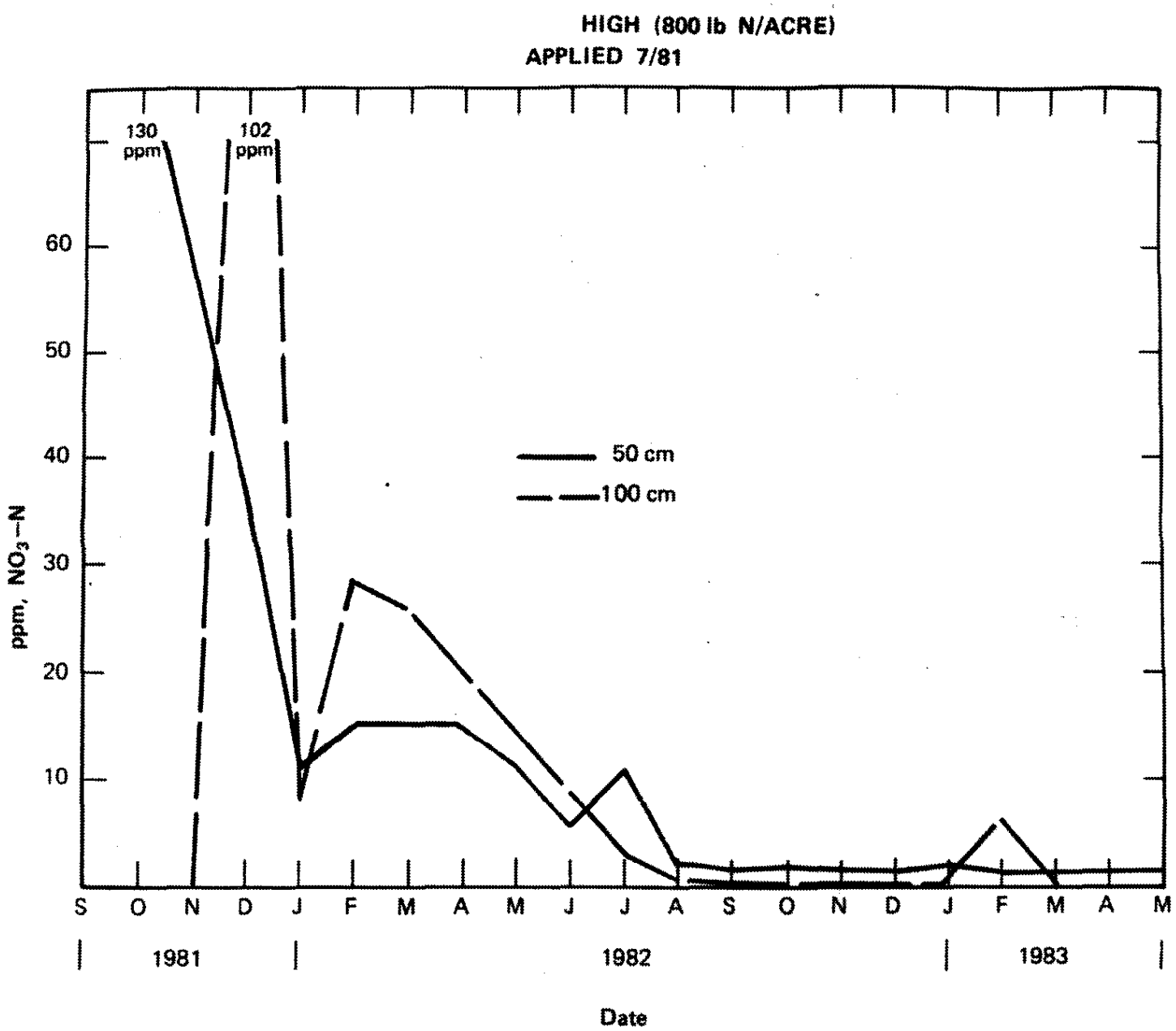

FIGURE 1. Nitrate-Nitrogen Concentrations in Soil Water at 0.5 and 1.0 m Depths on 1953 Stand Clay (Orangeburg) Site Treated with High Rate of Augusta Sludge

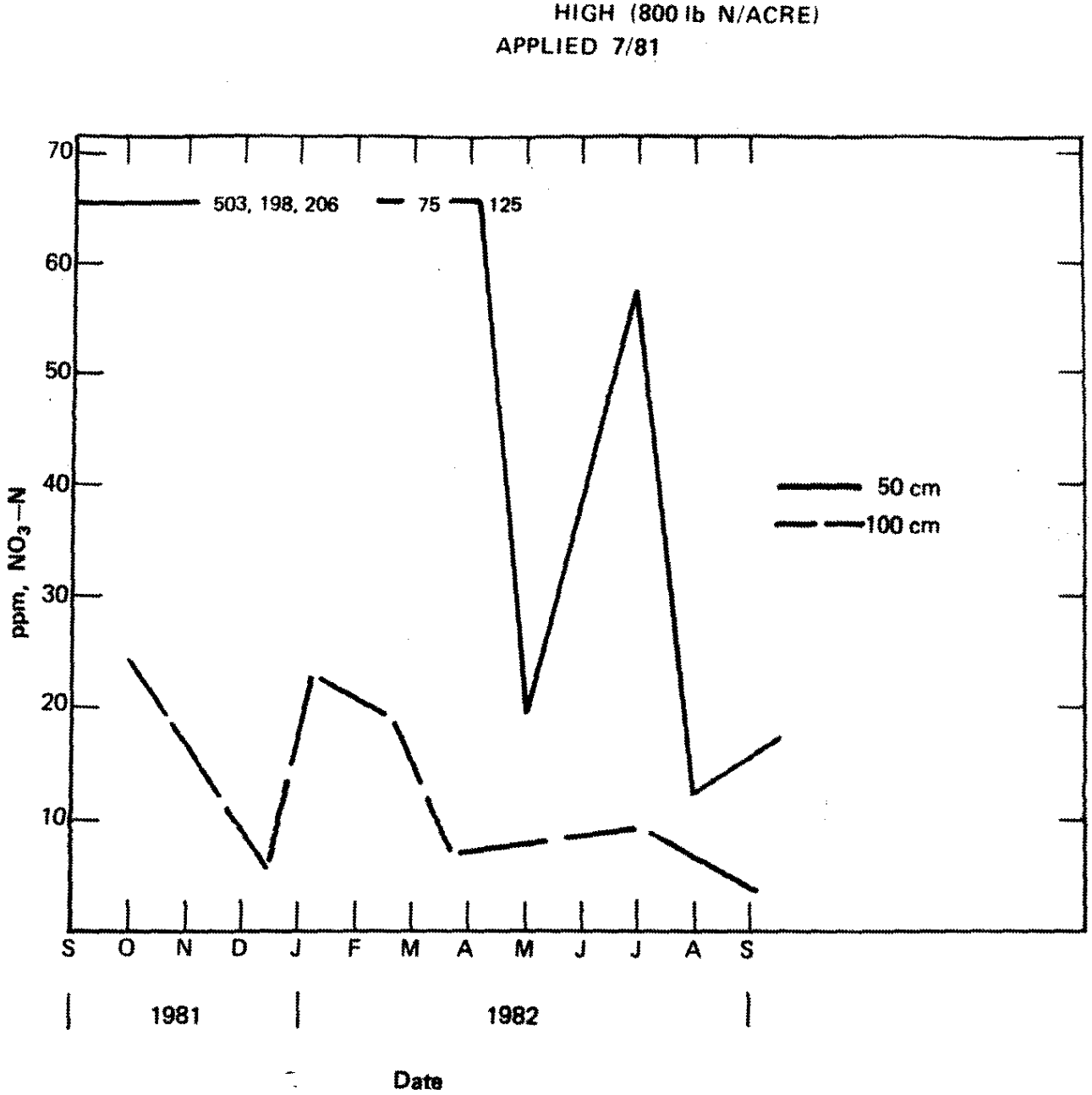

FIGURE 2. Nitrate-Nitrogen Concentrations in Soil Water at 0.5 and 1.0 m Depths on 1953 Stand Sandy Site (Fuquay Series) Treated with High Rate of Augusta Sludge

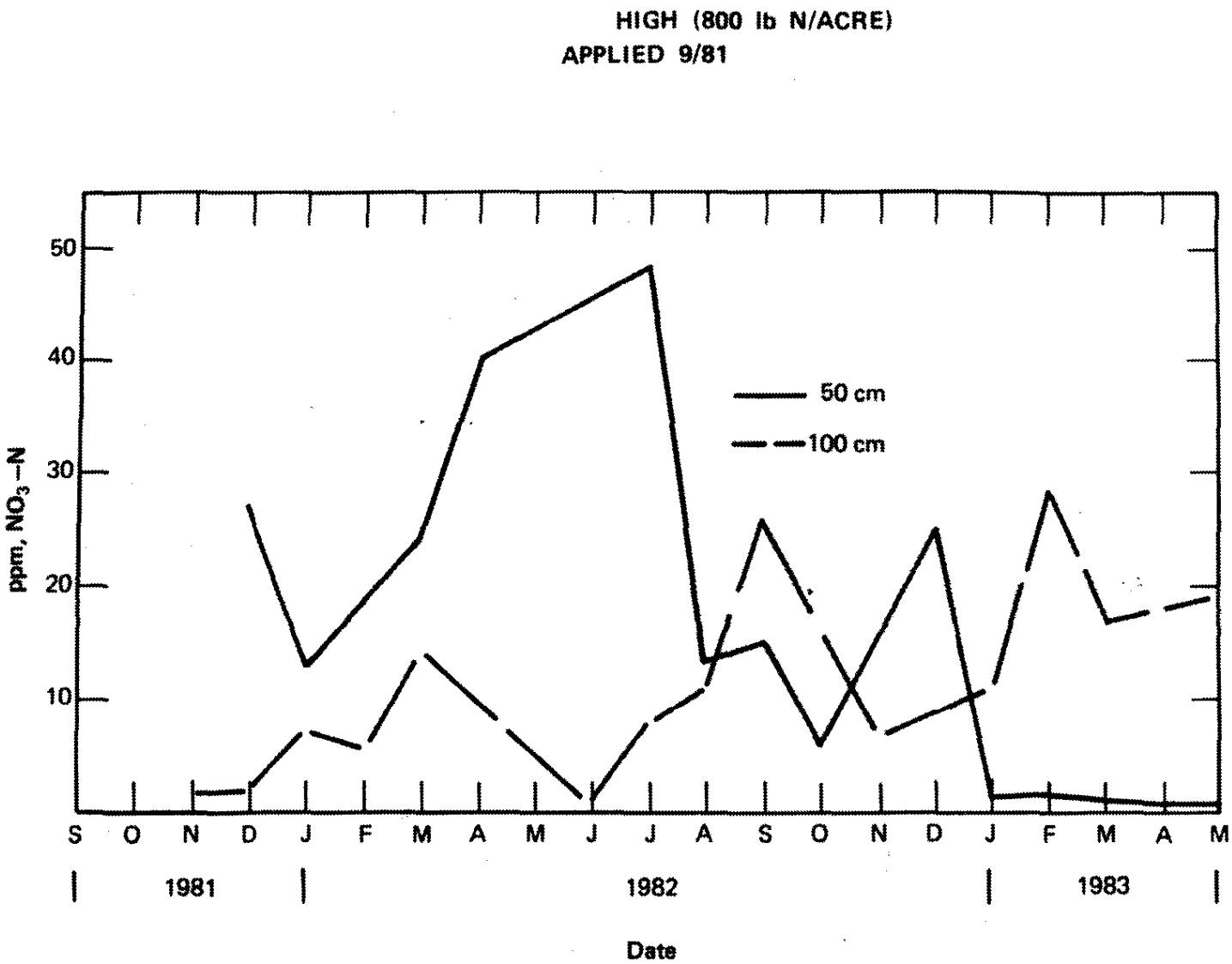

FIGURE 3. Nitrate-Nitrogen Concentrations in Soil Water at 0.5 and 1.0 m Depths on 1973 Stand Clay (Road F) Site with High Rate of Augusta Sludge

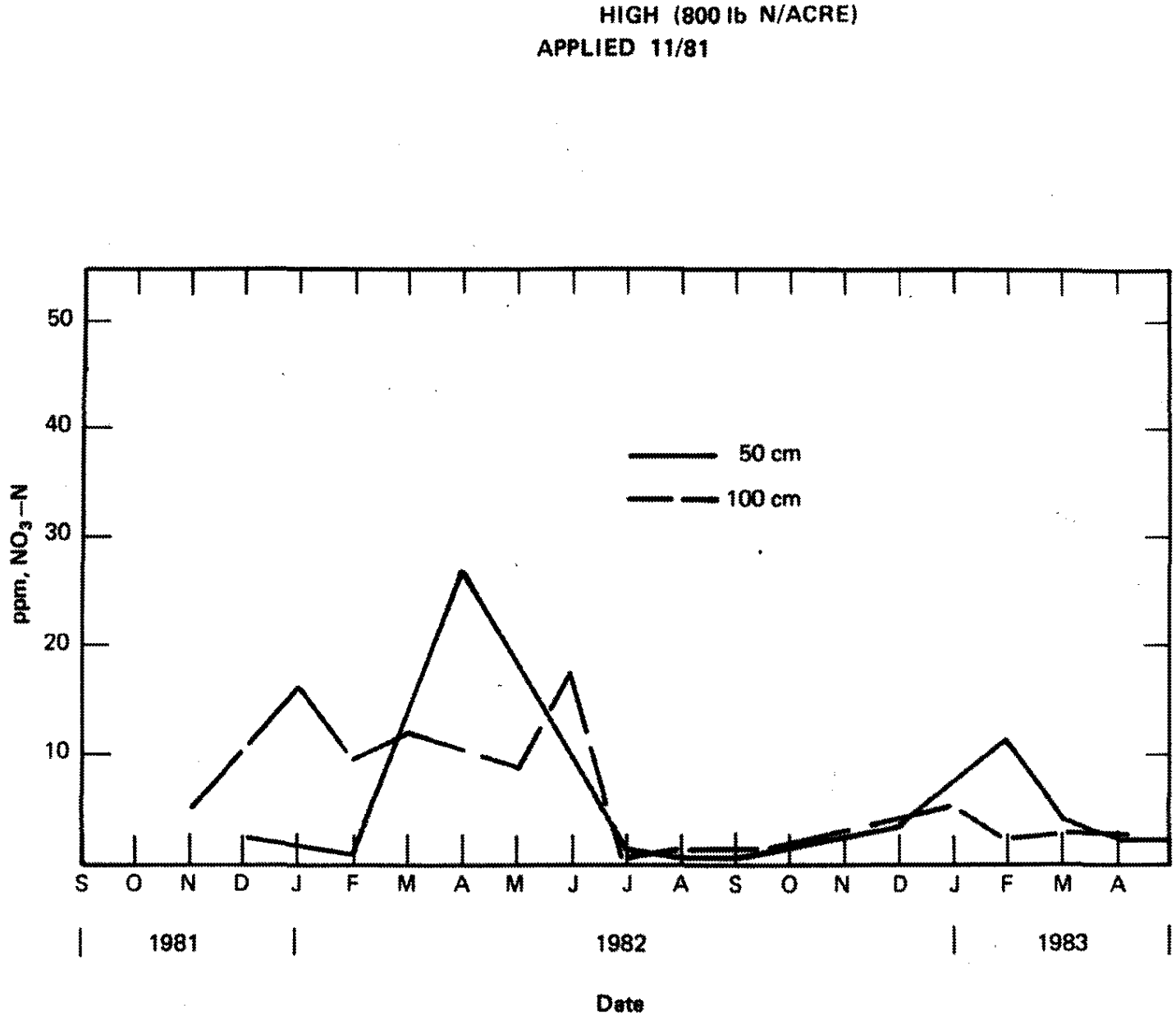

FIGURE 4. Nitrate-Nitrogen Concentrations in Soil Water at 0.5 and 1.0 m Depths on 1978 Stand Clay (Lower Kato Road) Site Treated with High Rate of Augusta Sludge

- At the establishment stand, average values of the replicates for nitrate-nitrogen on each treatment indicated that the high rate of application of Augusta sludge at both the 0.5 and 1 m depths resulted in highest soil water nitrate-nitrogen values (Figures 5 and 6);
- Solid sludge applied at 632 kg N/ha at the establishment stand produced nitrate-nitrogen concentrations only slightly greater than those determined in control plots;
- Typical ammonium-nitrogen concentration at all plots on all age stands ranged from 0.1 to 0.5 mg/L; losses of ammonium-nitrogen from plots on all age stands and sludge treatments were infinitesimal (Wells et al., 1982);
- Treatment effects on phosphorous concentrations at both soil water depths on all age stands were found to be insignificant; losses of phosphorous were found to be less than 1.1 kg P/ha/yr (Wells et al., 1982);
- Calcium was the major cation in soil water solution followed in order by sodium, potassium, and magnesium; all cation concentrations generally appeared to be directly related to nitrate-nitrogen concentrations in soil water;
- Sludge amendments did not increase heavy metal concentrations in soil water at either the 0.5 or 1 m depths (Wells and McKee, 1983).

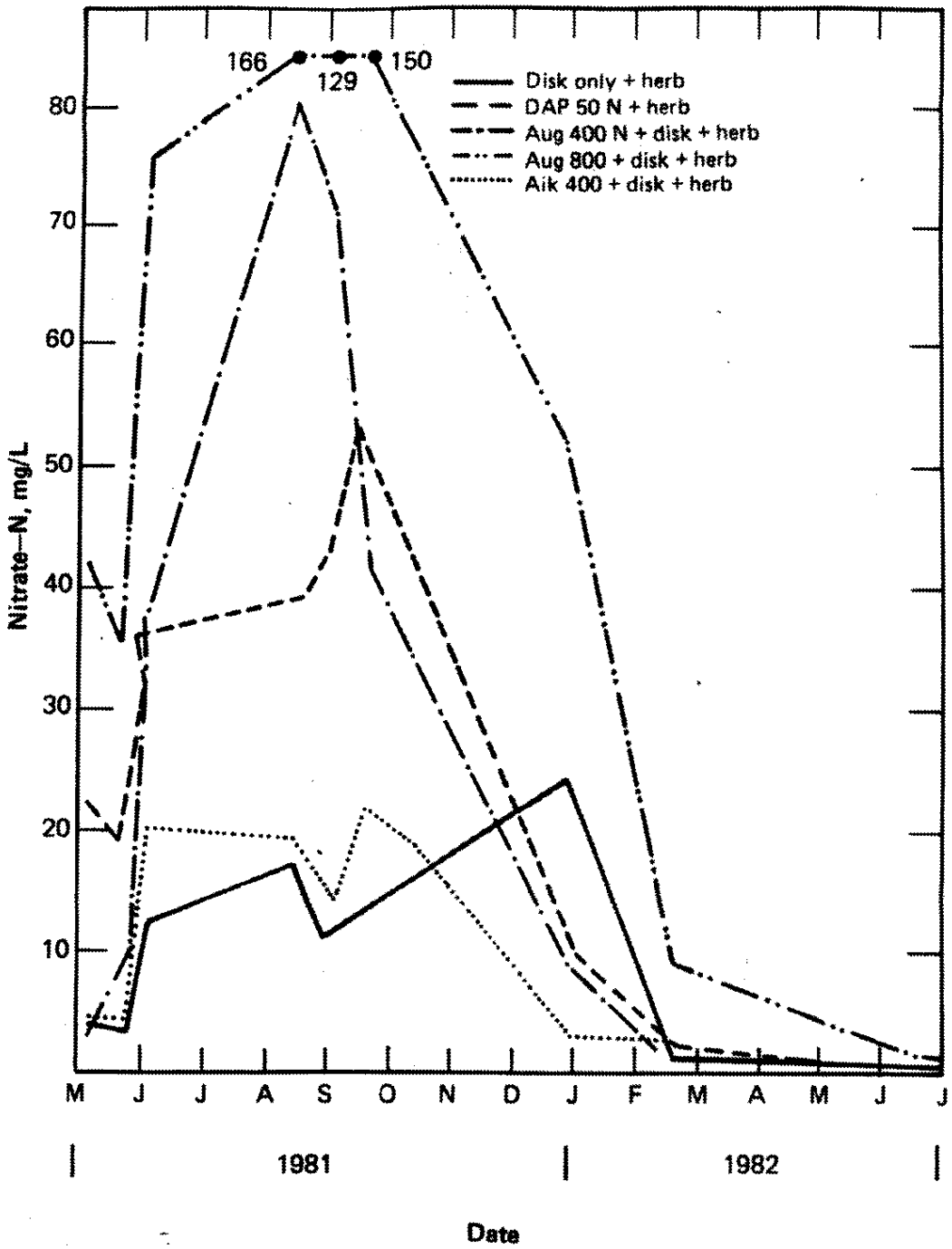

FIGURE 5. Nitrate-Nitrogen Concentrations in Soil Water at 0.5 m Depths at Establishment (Kato Road) Site Amended with Varying Fertilizations

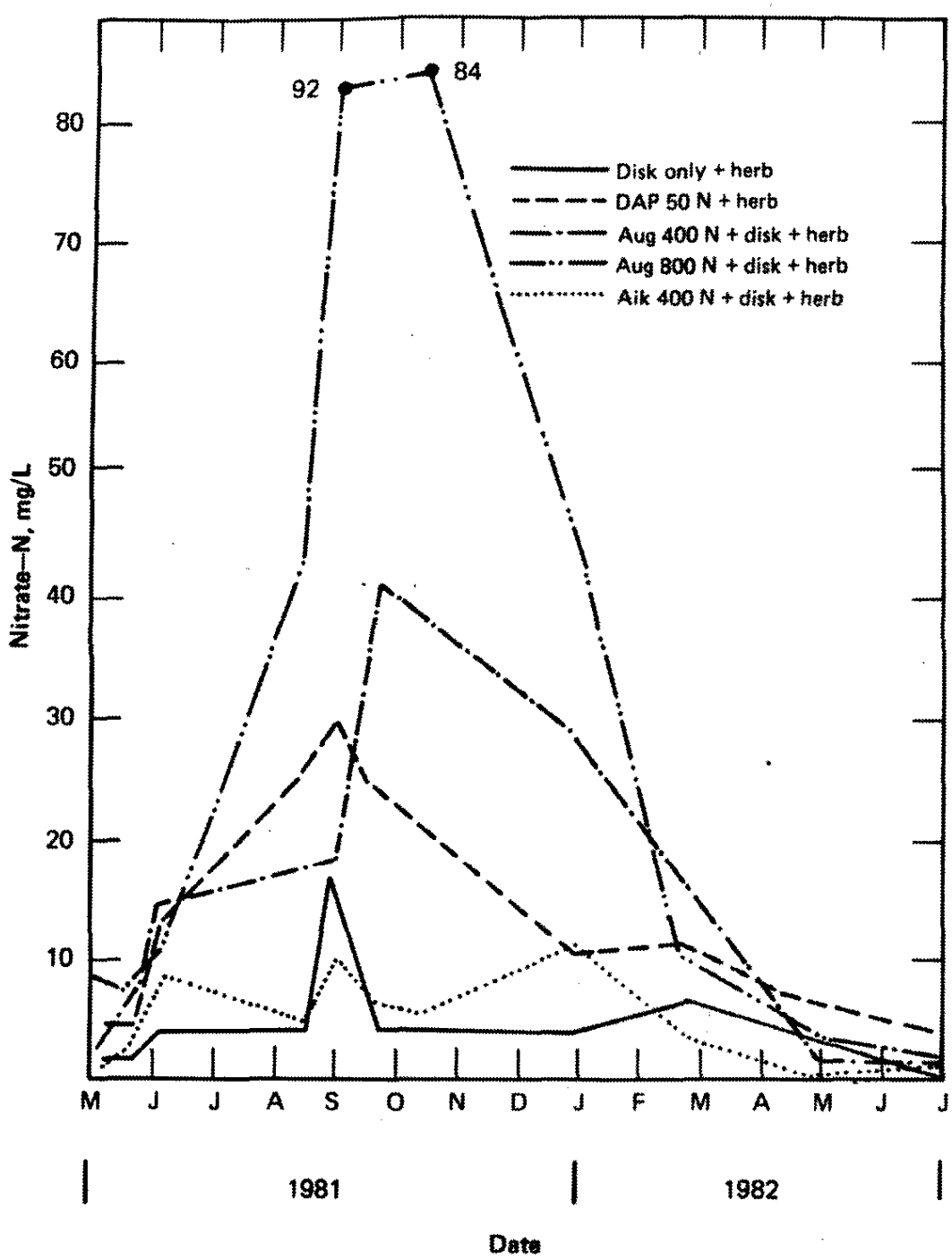

FIGURE 6. Nitrate-Nitrogen Concentrations in Soil Water at 1.0 m Depths at Establishment (Kato Road) Site Amended with Varying Fertilizations

Groundwater Analyses

The terms and conditions of the Industrial Waste Permit issued to SRP for the land application of sewage sludge by the South Carolina Department of Health and Environmental Control (SCDHEC) included extensive groundwater monitoring requirements. SCDHEC mandated that three groundwater wells be installed at each of the experimental forest sites pits receiving sludge amendments. Following well installation, the permit required that groundwater samples be collected quarterly and analyzed for water depth, pH, conductivity, and concentrations of nitrates (as N), total dissolved solids, sodium, and chlorides. Additional well samples were to be collected annually and analyzed for orthophosphates, total Kjeldahl nitrogen, and a variety of cations and heavy metals. A complete listing of required groundwater monitoring parameters is given in Table 4.

In the 4.5 years since the inception of this monitoring effort, groundwater samples from each well have been collected and analyzed seventeen times for quarterly parameters (Table 4) and four times for annual parameters (Table 4). Results of all analyses indicate no groundwater degradation as a consequence of the sludge treatments. A compilation of mean values for quarterly parameters at all well locations is given in Table 5 which clearly indicates that mean nitrate-nitrogen concentrations are well below the 10 mg/L maximum contaminant level. All other quarterly parameters are within ranges typically associated with other ambient,

TABLE 4

Required Groundwater Monitoring Parameters

Quarterly Monitoring	Annual Monitoring
Water depth	Orthophosphates
pH	Total Kjeldahl nitrogen
Nitrate-nitrogen	Cadmium
Total dissolved solids	Copper
Sodium	Iron
Chlorides	Nickel
Conductivity	Lead
	Calcium
	Magnesium
	Manganese
	Potassium

TABLE 5

Results of Groundwater Monitoring at the Sludge Application Sites, 1980-1985

Site	Depth (m)	pH (range)	Mean Value* NO_3^- (N) (mg/L)	TDS (mg/L)	Na (mg/L)	Cl (mg/L)	Conductivity (µmhos/cm)
Lower Kato Road Site	20.00	3.70-5.55	0.51	18	1.58	2.56	17(6)
Lower Kato Road Site	14.36	4.28-5.75	1.10	27	2.14	3.31	23(6)
Lower Kato Road Site	9.39	4.10-5.67	0.65	18	1.37	2.25	16(6)
Orangeburg Site	18.71	4.11-5.22	1.56	32	2.19	3.13	26(6)
Orangeburg Site	14.30	3.90-5.60	0.88	22	1.34	1.76	15(6)
Orangeburg Site	14.27	3.98-5.28	0.82	19	1.09	1.72	15(6)
Lucy Site	22.30	4.20-5.60	3.39	46	8.11	8.54	49(6)
Lucy Site	22.08	4.00-5.71	1.02(14)	23(13)	3.27(14)	3.76(14)	26(6)
Lucy Site	20.76	4.00-5.21	0.81(15)	21(13)	2.47(15)	3.47(15)	23(6)
Kato Road Site	14.54	4.40-6.45	1.10(14)	39(14)	3.00(14)	3.31(15)	25(6)
Kato Road Site	22.74	3.90-6.28	1.68(16)	34(16)	1.98(16)	2.60(15)	26(6)
Kato Road Site	28.40	4.29-6.47	0.29(16)	30(16)	2.56(16)	6.15(15)	26(6)
Road F Site	14.89	4.35-5.72	1.78(13)	29(13)	2.40(13)	1.71(13)	26(6)
Road F Site	14.32	4.45-5.57	0.69(13)	22(13)	1.36(13)	1.83(13)	19(6)
Road F Site	18.23	4.32-5.62	0.80(13)	19(13)	1.58(13)	1.55(13)	15(6)

* 17 analyses, except as noted in parentheses

upgradient shallow groundwaters at SRP. No leaching of heavy metals into local groundwater as a consequence of sludge application has been noted from annual analyses.

Growth Response of Loblolly Pines

Loblolly pine stands planted in 1953 and 1973 responded to the liquid sludge treatment equivalent to 402 kg N/ha but gave no further growth response to the higher nitrogen loading of 804 kg N/ha. Basal area growth was increased more rapidly by sludge treatments on the 1973 stand; however, the total stem volume growth per ha response was larger on the 1953 stands. Weed and hardwood competition was found to prevent growth response on the 1.2 m high, three-year-old (1978) stand (Lower Kato Road Site). On the establishment stand, the supply of nutrients was sufficient for growth without sludge treatments (Wells et al., 1984). Growth response measurements collected to date on the 1953 and 1973 stands indicate that the trees are still responding to the single sludge application in 1985 four years after treatment. Detailed results are found in the paper by McKee et al., in this symposium.

Nutrient Cycling

The nutrient cycle in a forest ecosystem may be described as the flow of nutrients into, within, and from the system. A simplified schematic of the major cycling components - mineral soil, forest floor and vegetation - is given in Figure 7. In this generalized model, boxes represent elemental pools or compartments while arrows represent fluxes of elements between compartments.

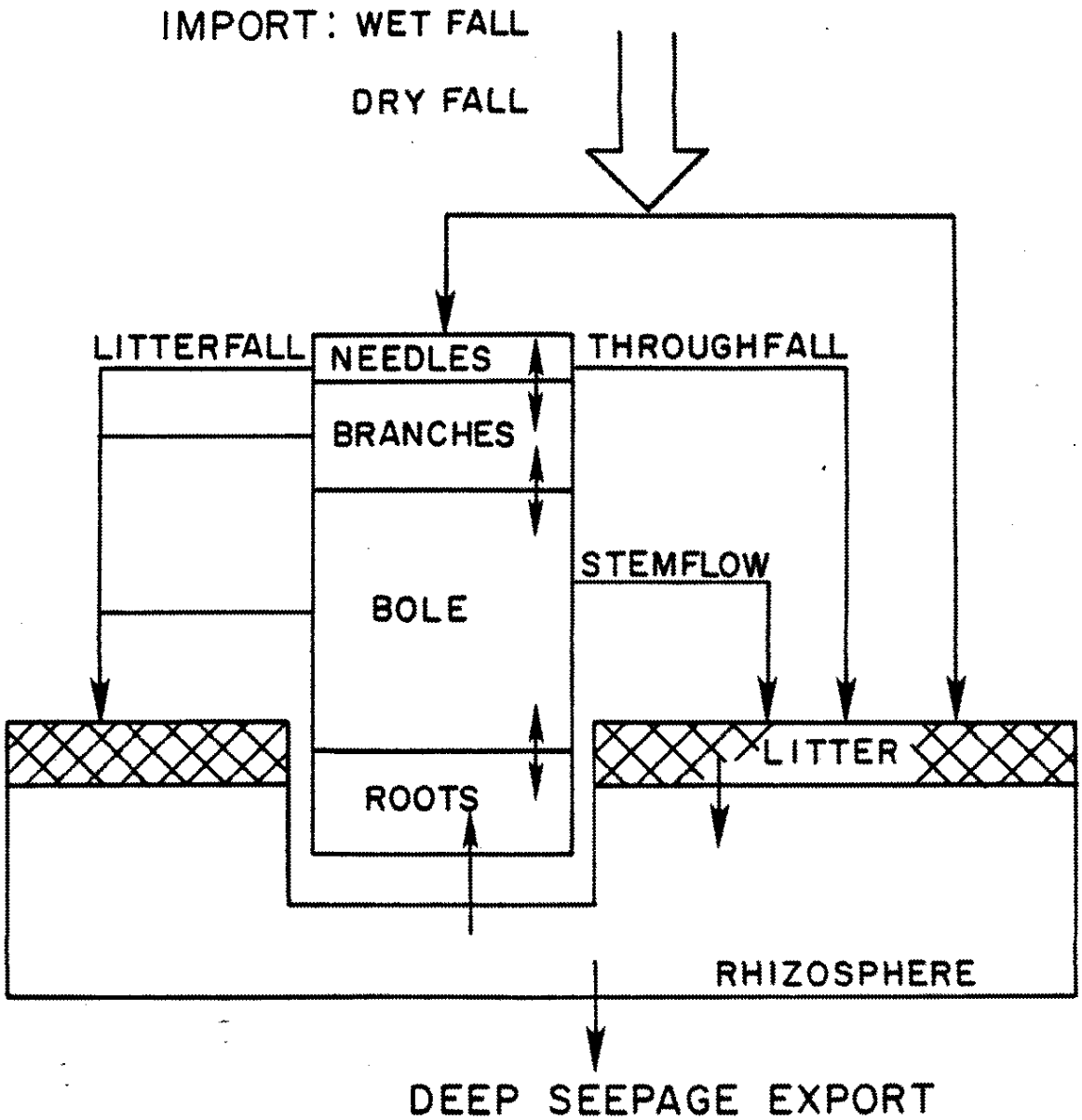

FIGURE 7. Typical Nutrient Cycle in Forest Ecosystem

Nutrient components or pools change rapidly when a stand is first established but tend to reach an equilibrium as the stand matures. After an initial accumulation of nutrients in the trees, a subsequent increase of nutrients in the forest floor occurs at the expense of nutrients in the mineral soil.

Data have shown that the nutrient cycle of undisturbed pine stands in the southeastern U.S. is tight (Waide and Swank, 1975). Nutrient-tight pine systems are generally associated with soils of low nitrification rates, low fertility, and active annual roots. As a result, losses from the system are typically restored via input, although component sizes and rates of transfer change as the stand develops. Extensive discussion of the nitrogen, phosphorous, and potassium cycles is found in the experimental research of Wells (1970), Wells and Jorgensen (1975), and Wells, Nicholas, and Buol (1975), respectively.

Extensive macronutrient and pH analyses in throughfall, stemflow and vegetation were made at the 1953 and 1973 experimental stands from 1982 until late 1983 so that estimates of nutrient flux and system inventory could be made. Wells et al. (1984) documented that liquid sludge applied at rates equivalent to 402 and 804 kg N/ha increased litterfall weight some 20 to 30 percent over that of both the control plot litterfall at both age stands and the solid sludge amended sites (632 kg N/ha) at the 1953 stands. Enhanced summer needlefall above rates associated with control plots were noted at plots amended with liquid sewage sludge. Mean needle

length, as well as increased nitrogen and phosphorous concentrations in needle litterfall, were increased in liquid sludge plots as compared to control plots (Wells et al., 1984). Understory biomass of grass, herb, shrub, and vine were enhanced at the liquid sludge plots on both the 1953 and 1973 stands. Detailed results of the nutrient cycling studies from these plots are discussed by McLeod et al., in the proceedings of this symposium.

CONCLUSION

Biomass production was increased by liquid sludge application on forest stands age eight years and older at an equivalent nitrogen loading rate of 402 kg N/ha. At this loading rate, no adverse environmental impacts occurred in either soil, soil water, or groundwater concentrations of nutrients or metals at the experimental forest sites. Nutrients in the sludge were assimilated by cover vegetation and metals in the sludges were retained in the upper soil layer so as not to have changed soil concentrations from normal background levels.

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