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Use of Municipal Sewage Sludge for Improvement of Forest Sites in the Southeast

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ABSTRACT

In eight field experiments dried municipal sewage sludge was applied to forest sites before planting of seedlings. In all cases, tree growth was faster on sludge-amended plots than on plots that received fertilizer and lime or no amendment.

In all studies, concentrations of total nitrogen in the soil were higher on sludge plots than on control or fertilizer plots, even on good forest sites. In seven of the eight studies, concentrations of phosphorus also were higher on sludge plots than on control or fertilizer plots. Nitrogen and phosphorus tended to be higher in foliage from trees growing on sludge plots.

Deep subsoiling was beneficial regardless of soil amendment. Where weeds were plentiful at the outset, they became serious competitors on plots receiving sludge.

Keywords: Reclamation, borrow pit, tree growth, *Pinus taeda*, *Liquidambar styraciflua*, soil nutrients, subsoiling.

Introduction

Municipal sewage sludge contains abundant plant nutrients and is an effective long-lasting amendment for improving normal forest sites and for reclamation of disturbed sites in the Southeast. That conclusion is demonstrated by eight studies of the effects of dried sewage sludge on soils, tree growth, and element concentrations in tree foliage in the Southeastern United States. Of these studies, four were on borrow pits, one on a kaolin spoil, and one in the Tennessee Copper Basin. Two studies were on routine reforestation sites in South Carolina. Although in some cases early results were published previously, this paper contains updated information and draws certain conclusions not possible in the earlier reports.

The use and effects of sewage sludges and effluents for reclamation of surface coal mines and other disturbed sites, as well as effects of sludge disposal on land, have been studied extensively (Bledsoe 1981; Cole and others 1986; National ASU&LGC 1973; Page and others 1983; Sopper and Kardos 1973; Sopper and Kerr 1979; Sopper and others 1982).

The effects of sewage sludge and other organic wastes on soils are discussed by Elliott and Stevenson (1977), and many aspects of reclamation including the use of sewage sludge are discussed by Schaller and Sutton (1978). Two recent guides that deal specifically with revegetation of coal mine spoils are by Vogel (1981) and Sopper and Seaker (1983). Possible health risks associated with sewage sludge have also been reviewed (Bitton and others 1980).

Effects of sewage sludge on tree growth on normal forest sites in the Southeast were reported by Wells and others (1985) and McKee and others (1986). Hinkle (1982) used sludge to reclaim abandoned pyrite mines, and sludge has been used on other disturbed sites (Berry 1977, 1979b, 1982, 1985b; Berry and Marx 1977, 1980; Kormanik and Schultz 1985; and Ruehle 1980). Spot application of sludge, a technique of potential value in rough terrain, has been found to aid initial growth of both loblolly pine (*Pinus taeda* L.) and hardwoods (Berry 1979a, 1983).

A Word About Sewage Sludge

Sewage sludge is obtained from the processing of domestic or industrial wastewater. The initial or primary treatment of wastewater is usually designed to remove settleable solids by some form of physical separation (screening or gravity settling). Next, the wastewater is subjected to chemical or biological processes designed to remove dissolved and colloidal material. Thereafter, wastewater (or effluent) may receive various combinations of physical and chemical treatments. The solids removed during these processes are usually high in organic matter, are biologically unstable, and are characterized by offensive odors. These materials may be stabilized by aerobic or anaerobic digestion. When sludge is removed from digesters, it is in liquid form (containing 3 to 6 percent solids) and can be transported in pipelines, tank cars, or tank trucks. With proper equipment, it can be directly applied to land if State and Federal EPA regulations are met. Usually, however, some form of dewatering process such as sandbed drying, vacuum filtering, or centrifugation is employed before disposal to produce a dry or semidry, semisolid material that can be transported in open trucks and applied to land with standard agricultural equipment. If the dewatering is carried out by vacuum filtration or centrifugation, a chemical flocculant is employed to improve separation of liquid from solid material. The flocculant gives the sludge a semiliquid, gellike character that makes application to land difficult. McCalla and others (1977) discuss the physical, chemical, and biological properties of sludges in detail.

The method of handling sewage sludge depends on solids content. Sludge containing up to 10 percent total solids can be pumped with special equipment. Slurries with up to 5 or 6 percent total solids may be applied with field sprinklers. The sludge must contain at least 25 to 30 percent solids before it can be handled with a shovel or pitchfork.

All sludges used in the experiments reported in this paper were anaerobically digested and sandbed dried and contained at least 35 percent solids. They were also characterized by low heavy metal concentrations; for example, less than 10 p/m Cd and 250 p/m Zn. An analysis of the sewage sludges used in most of the experiments reported here is shown in table 1.

Characteristics of Sites and Studies

All experimental sites were prepared by mechanically removing all woody vegetation present, then by grading, if necessary, to eliminate gullies. Amendments were thoroughly incorporated into surface soil to a depth of 15 to 20 cm by disking. Control plots (no amendment) were similarly disked. In addition, all sites were subsoiled to a depth of from 61 to 92 cm after disking except in Study 3 where a variety of physical soil treatments were tested and in Study 7 where disking was compared with a single subsoiling treatment. Spacing between subsoiled furrows and the pattern of furrows (parallel lines or perpendicular lines) varied with the experiment. In recent experiments, subsoiling was done in early fall to allow furrows to settle before planting. Seedlings were planted the following spring in the closed furrows. Treatment plots containing 16 to 36 trees were replicated three to six times. A randomized complete-block design was used in all except Study 6, in which treatments were completely randomized. Data were subjected to analysis of variance, and means were separated by Duncan's multiple range test.

Soil samples for chemical analysis were collected from the plots in all studies in August 1985. Nine subsamples, taken from the top 15 cm of mineral soil, were composited for each replicate. The samples were air-dried in the laboratory and screened to a particle size of no more than 2 mm. All chemical analyses were done by A&L Laboratories, Inc., 411 N. Third Street, Memphis, TN.

In the fall of 1985, the heights (H) and root-collar diameters (D) of all trees in all studies were measured. Values for D^2H were then computed for each tree and summarized. D^2H has been shown to be a reliable surrogate measure for aboveground biomass of loblolly pine, and it also appears to be a good indicator of stem weight and stem volume (Hatchell and others 1985).

Physical and chemical properties of the upper 16 cm of the soil at the eight study locations are presented in table 2. Additional information on the sites and a description of each study are provided in the next section.

Individual Studies

Study 1

This study was installed on a borrow pit (BP-1a) on the Savannah River Forest Station, at the Savannah River Plant, Aiken, SC, in 1976. The pit originally overlain with Fuqua and Wagram soils, was created in 1950-1952. Soil and substratum to a depth up to 6 m had been removed, leaving a severely compacted ground surface. This borrow pit, like most others at the Savannah River Forest Station had been planted with loblolly pine seedlings in the early 1950's, but little or no fertilizer was used and no subsoiling was done. In 1976 many trees were still surviving, but few were taller than 3 m. The area was prepared for the study by removing all vegetation and subsoiling to a depth of 0.9 m with perpendicular furrows spaced 1.2 m apart in both directions. Loblolly pine seedlings with ectomycorrhizae formed by *Pisolithus tinctorius* (Pers.) Coker & Couch or naturally occurring *Thelephora terrestris* (Ehrh.) ex Fr. were planted 6726/ha (1.2 m x 1.2 m) in plots amended as follows:

- No fertilizer (control)
- Fertilizer[1] & lime[2]
- Fertilizer & lime + tree bark[3]
- Fertilizer & lime + ash[3]
- Fertilizer & lime + bark + ash
- Sewage sludge
- Sewage sludge + bark
- Sewage sludge + ash
- Sewage sludge + bark + ash

The area was thoroughly disked to incorporate amendments, then sown with Ky 31 fescue seed before planting pine seedlings. At age 5, all plots were thinned to 2,691 trees per hectare. Naturally occurring *Pisolithus tinctorius* formed abundant ectomycorrhizae on all seedlings during the first year in the field, precluding any mycorrhizal comparisons.

Sewage sludge alone or with bark and/or ash dramatically improved early seedling growth (fig. 1) and production of grass biomass, compared with other soil treatments (Berry and Marx 1980). After 3 years, grass biomass was five times greater on sludge than on other plots. There was no significant weed growth in this study.

Figure 1.--Three-year-old loblolly pines growing on borrow pit plots. Plot in foreground amended with 560 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of lime. Plots in background amended with 34 Mg/ha of sludge. The approximately 7-m-high wall indicates amount of material removed in creation of borrow pit.

At age 10, plots receiving sludge had more than 2 times as much nitrogen and more than 25 times as much phosphorus as control and fertilized plots. Organic matter content and cation exchange capacity were also considerably higher on sludge plots (table 3). By age 10, crowns had closed on the plots receiving sludge, and D^2H was many times higher on these plots than on fertilized or control plots (table 4).

[1]560 kg/ha of commercial 10-10-10 fertilizer.

[2]2240 kg/ha of dolomitic limestone.

[3]Milled pine bark, bottom furnace ash, and sewage sludge were applied at a rate of 125 m^3/ha, or approximately 1.3 cm deep. With sewage sludge, this rate was equivalent to a dry weight of 34 000 kg/ha.

Study 2

This study was installed on a borrow pit (BP-1b) adjacent to Study 1. Site history and site preparation were the same as for Study 1 and preparation was carried out at the same time. Treatments consisted of 0, 17, 34, or 68 Mg/ha of sewage sludge (2% N, 1% P, and 0.5% K). Plots were planted with sweetgum (Liquidambar styraciflua L.) from two different half-sib families.

After 5 years, there was no difference in growth between the two sweetgum families but the influence of sludge amendment was dramatic. Although competition by fescue, planted as a groundcover, may have retarded early tree growth to some extent, competition from weeds was not significant. Fifth-year growth on unamended plots was poor; tree height averaged less than 1 m. On plots amended with 17 Mg/ha of sludge, mean height was 2.75 m. On plots amended with 34 or 68 Mg/ha, mean height was over 3.6 m (Kormanik and Schultz 1985).

At age 10, the improvements in soil properties associated with 34 Mg/ha of sludge were similar to those observed in Study 1 (table 5). The sweetgum growth response was best after 34 and 68 Mg/ha applications, but did not differ significantly between these two treatments (table 6).

Study 3

This study was installed on a borrow pit (BP-2) originally overlain with Gunter sand. Creation of this borrow pit exposed a substratum on which trees and other vegetation grew poorly.

Eighteen treatments (2 amendments x 9 mechanical site preparation treatments) were installed. Anaerobically digested sewage sludge was obtained from Macon, GA. Sludge was applied to half of the study plots at a rate of 17 Mg/ha, and fertilizer (10-10-10) and pulverized dolomitic limestone were applied at a rate of 1121 kg/ha and 2242 kg/ha, respectively, to the remaining plots. Amendments were applied in September 1978 and incorporated by double-disking to a depth of 15 cm.

Nine mechanical site preparation treatments varied subsoiling depth and spacing of furrows running in either one or two directions. These treatments were applied to both fertilized plots and plots amended with sewage sludge. During the autumn of 1978, the study site was seeded with Ky 31 fescue (Festuca arundinacea Schreb.) at 34 kg/ha.

Loblolly pine seedlings (Livingston Parish source) that had been inoculated and heavily colonized by the ectomycorrhizal fungus Pisolithus tinctorius (Pt index 88) were planted in March 1979. Seedlings were planted at a density of 1,914 trees per hectare and always in a subsoiled furrow except on disked-only plots. No weed control was necessary.

The effect of sewage sludge on growth after 4 years was striking (Berry 1985b). Trees on these plots grew an average of 37 percent more in height and 76 percent more in d.b.h. than trees grown on fertilizer plots. Four-year survival was not influenced by treatment.

Subsoiling interacted with amendments in its influence on tree growth (Berry 1985b). After 4 years on fertilized plots, trees grew 9 percent more in height and 17 percent more in diameter on plots subsoiled 46 cm deep than on plots subsoiled 92 cm deep. When sewage sludge was used, however, there was significantly more growth (4.5% more height and 7.4% more d.b.h.) when plots were subsoiled to a depth of 92 cm rather than 46 cm. After 4 years, no growth differences due to spacing of furrows or whether furrows were parallel or perpendicular were detected.

Seven years after treatment, plots receiving sludge had more than 2 times as much nitrogen, 10 times as much phosphorus, and 2 times as much organic matter as plots that were fertilized (table 7). D^2H values for trees on plots receiving sludge were about four times those on fertilized plots. Subsoiling was beneficial, but growth through age 7 did not differ significantly between the 46- and the 92-cm treatment depths (table 8).

Study 4

This study, also installed on a borrow pit (BP-3), was designed to determine whether several hardwoods besides sweetgum could grow well on substratum material amended with sludge and subsoiled. A split-plot experiment tested 68 Mg/ha of fresh sludge from Athens, GA, or fertilizer (1120 kg/ha of 10-10-10 + 2240 kg/ha of dolomitic lime) or nothing in major plots and compared the relative adaptability of six species to a sludge-reclaimed borrow pit. Species compared in this experiment were sycamore (*Platanus occidentalis* L.), green ash (*Fraxinus pennsylvanica* Marsh.), sawtooth oak (*Quercus acutissima* Carruthers), and yellow-poplar (*Liriodendron tulipifera* L.) as well as loblolly pine and sweetgum. Twenty-five trees were planted at a density of 1,682 trees per hectare in each treatment plot. All species were planted in sludge and fertilizer plots, while only sweetgum, green ash, and loblolly pine were planted in the control (no amendment) plots.

On loblolly pine, sweetgum, and green ash, mycorrhizal inoculation treatments were applied, but in all cases the noninoculated seedlings became contaminated soon after planting in the field, precluding any information on mycorrhizal effect.

A highly significant species x fertility interaction affecting D^2H was observed after the second growing season. Growth of several, if not all, species in this experiment was retarded by weed competition, which has been exceptionally heavy in sludge plots.

By age 4, nitrogen, phosphorus, and organic matter contents were no longer significantly higher on fertilized than on control plots. Sludge plots had more of these elements than the control plots (table 9). In general, trees performed better on sludge plots than on those receiving fertilizer, but the advantage varied considerably by species (table 10). For the three main species in the study, the percentage of improvement in D^2H attributable to sludge was greatest in green ash, next greatest in sweetgum, and least in loblolly pine. Even so, D^2H in loblolly pine was almost five times as high on sludge as on control plots (table 11).

Study 5

This study was installed on a kaolin spoil to determine the feasibility of reclaiming this type of spoil with sludge. About 8498 ha in Georgia had been surface-mined for kaolin clay by 1973, and it was estimated that up to an additional 120 000 ha (297,000 acres) of land will eventually be mined (May 1977). Berry and Marx (1977) found that loblolly pine seedlings grew well in kaolin spoil in microplots when amended with either fertilizer or sewage sludge.

Sweetgum seedlings were planted in plots amended with 34 Mg/ha of old sewage sludge from Athens, GA, 1120 kg/ha of 10-10-10 fertilizer, or nothing. Twenty-five trees at a density of 1,682 trees per hectare were planted in each treatment plot.

Four years after treatment, sludge plots had about 10 times as much nitrogen, 7 times as much phosphorus, and 5 times as much organic matter as fertilized plots (table 12). As a result, D^2H on sludge plots was almost four times as large as on fertilized plots and more than four times as large as on control plots (table 13).

Study 6

This study was installed on a severely eroded and devastated site in the Tennessee Copper Basin originally overlain with Hayesville sandy loam.

The Tennessee Copper Basin is unique in the Eastern United States in that all natural vegetation on 7,000 acres was killed, and the surrounding 17,000 acres were reduced to grassland in the middle to late 1800's by air pollution resulting from primitive processing of copper ore. The subsequent severe erosion of topsoil left deeply gullied subsoil exposed over thousands of acres. As late as the early 1970's, chronic air pollution continued to retard growth and reduce survival of trees in the area. Recent technological innovations, however, have greatly reduced sulfur dioxide emissions. Several other obstacles to reforestation of the area are lack of soil nutrients and organic matter, insufficient moisture during dry periods, and desiccation of trees by wind.

In a completely randomized design of four treatments, noninoculation or inoculation with Pisolithus tinctorius treatments were combined factorially with 34 Mg/ha of fresh sludge from Athens, GA, or fertilizer (896 kg/ha of 10-10-10 with 1417 kg/ha of CaO). Trees were planted at 11 960/ha and thinned after 5 years to 3322/ha.

After 4 years, all three species had grown significantly better on plots amended with sludge than on those with fertilizer. Shortleaf pine grew more in height on sludge plots, but not in root-collar diameter or D^2H. Loblolly and Virginia pines grew more in height, root-collar diameter, and D^2H on sludge-amended plots than on fertilizer-amended plots. Pt ectomycorrhizae produced no significant increase in growth. Loblolly and Virginia pines, which grew at approximately equal rates, were significantly larger than shortleaf (Berry 1982).

As in the studies on borrow pits, the nitrogen, phosphorus, and organic matter contents of the soil 10 years after treatment were considerably higher on sludge plots than on fertilized plots (table 14). At age 10, loblolly pines were tallest, Virginia pines (Pinus virginiana Mill.) next, and shortleaf pines (P. echinata Mill.) markedly shorter. All three species grew best on sludge plots (table 15).

Study 7

This study was installed on a good forest site with Orangeburg soil at the Savannah River Forest Station. A split-split-plot design was replicated in four blocks to test three fertility treatments (34 Mg/ha of old sludge from Athens, 280 kg/ha diammonium phosphate and control) and two mechanical site preparation treatments (subsoiling and disking). Sweetgum seedlings with two mycorrhizal treatments, inoculation with Glomus spp. and no inoculation, were planted the following spring at a density of 1076/ha. In an effort to control weeds, 23 kg/ha of simazine (Princep F-G) were applied in early 1982 and later in the season a 1-percent solution of Round-up was applied at a rate of 3.7 L/ha. Chemical control of weeds was not adequate, however, and additional weed control by disking has been necessary. In July 1983, sludge was applied to one-third of the plots at a rate of 34 Mg/ha. After sludge application, all plots were double-disked and in September one-half of each block was subsoiled to a depth of 76 cm with parallel furrows spaced at 122 cm.

Examinations of root systems revealed that seedlings initially nonmycorrhizal became colonized with resident mycorrhizal fungi within the first months in the field. It therefore was not possible to measure the possible influence of mycorrhizal treatment on growth.

Two years after treatment, soil nutrient levels were significantly higher on sludge plots than on fertilized or control plots (table 16). Subsoiling improved survival and growth. Both sludge and fertilizer application improved growth, and differences between the two treatments were not statistically significant (table 17).

Study 8

This study was installed on a good forest site with Dothan and Norfolk soil at the Savannah River Forest Station. Sweetgum seedlings were planted at a density of 1,682 trees per hectare in plots amended with fresh Athens sludge at 34 Mg/ha, fertilizer (1480 kg/ha diammonium phosphate and 1100 kg/ha ammonium nitrate), or nothing. Early results from this study were interesting in that trees on control plots grew better than trees on plots amended with sludge or fertilizer. Data presented here indicate, however, that after the 4th year, insufficient nutrients were limiting growth on fertilizer and control plots.

At age 7, differences in nitrogen, phosphorus, and organic matter contents among sludge, fertilizer, and control plots are still apparent. The phosphorus level is much lower on control than on fertilizer or sludge plots (table 18). In terms of D^2H, tree growth has been about twice as fast on sludge plots as on fertilized or control plots (table 19).

Combined Results

Effects on Soil Properties

The sites for Studies 1 through 6 were low in nitrogen (< 175 p/m), phosphorus (< 4 p/m), and organic matter ($\leq$ 0.4%) and were regarded as reclamation areas. The two "good" forest sites had considerably higher concentrations of nitrogen ($\geq$ 238 p/m) and organic matter (> 1.6%) but only one of the two (Study 8) had abundant P (31 p/m). Nevertheless, growth of trees on unamended control plots was excellent on both sites 7 and 8.

In all studies, the concentrations of total nitrogen were higher on sludge plots than on control or fertilizer plots, even on the two good forest sites. In all studies but one (Study 7), phosphorus was higher on sludge plots than on fertilizer plots. In Study 8, diammonium phosphate (1480 kg/ha) and ammonium nitrate (1100 kg/ha) were applied to fertilizer plots so that, initially, N, P, and K would be comparable with sludge plots. Organic matter and cation exchange capacity also were usually higher on sludge plots than on fertilizer plots. Potassium levels were usually about equal on sludge and fertilizer plots. Levels of Ca and Mg and pH were always higher on fertilizer plots.

Three studies involving three pine and one hardwood species were 10 years old when data were last taken. The relative nutrient status of sludge, fertilizer, and control treatments that existed in the soil when the studies were installed appears to be just as strong today.

Effects on Tree Growth

In all cases, sewage sludge produced faster growth than fertilizer over the 2- to 10-year period covered by the reported studies. In most studies where a "no treatment" control was installed in addition to a fertilizer treatment, an application of 560 to 1120 kg/ha of 10-10-10 plus 2240 kg/ha of dolomitic lime produced little increase in growth over the "no treatment" control, if any.

In studies where more than one species was examined, there appeared to be a strong interaction between species and type of fertility added. For example, in the Copper Basin study, D^2H of shortleaf pine trees on sludge plots was 164 percent better than on fertilizer plots, while D^2H of Virginia pine was 296 percent more on sludge than on fertilizer plots. Similarly, in the borrow pit study where growth of several hardwood species was compared, diameters of none of the hardwood species differed significantly on sludge plots, while there was considerable difference on fertilizer plots, on which sycamore and sawtooth oak grew faster than green ash which in turn grew faster than yellow-poplar.

The quantity of sludge required to produce the most rapid growth of sweetgum was determined on a borrow pit (Study 2). The optimum growth occurred with 34 Mg/ha of sludge, and there was no increase in growth when the level of sludge was increased to 68 Mg/ha. These data (table 20) agree with results reported previously (Berry 1977) for an eroded forest site (Madison soil series) for loblolly and shortleaf pines.

Duration of Benefits

The long-lasting benefits from sludge application are illustrated by growth of three pine species, 10 years old, in the Copper Basin (figs. 2, 3, and 4), by 10-year-old loblolly pine growing on a borrow pit (fig. 5) and by 7-year-old sweetgum growing on a good forest site (fig. 6). All these examples show rapidly accelerating growth of trees on sludge plots. In none of these cases is there an indication of a slowdown in growth on sludge plots. Growth on the fertilizer and control plots, however, varies with the site and the type and frequency of fertilizer application. Of particular interest is response of sweetgum on Dothan and Norfolk soils, where growth on the sludge plots was no better than on control plots for the first 4 years. Measurements taken after the 5th and 7th years, however, indicate an acceleration of growth of trees on sludge plots, while growth rates on control and fertilizer plots remain about equal and much slower than on sludge plots.

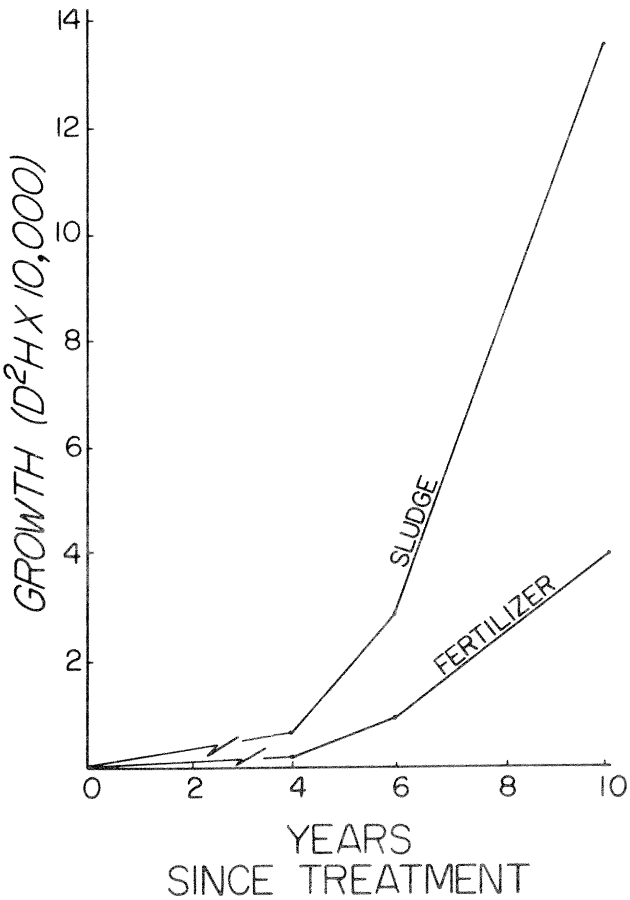

Figure 2.--Growth of loblolly pine on amended plots in the Copper Basin as influenced by sludge (34 Mg/ha) and fertilizer (896 kg/ha of 10-10-10 fertilizer plus 1417 kg/ha CaO).

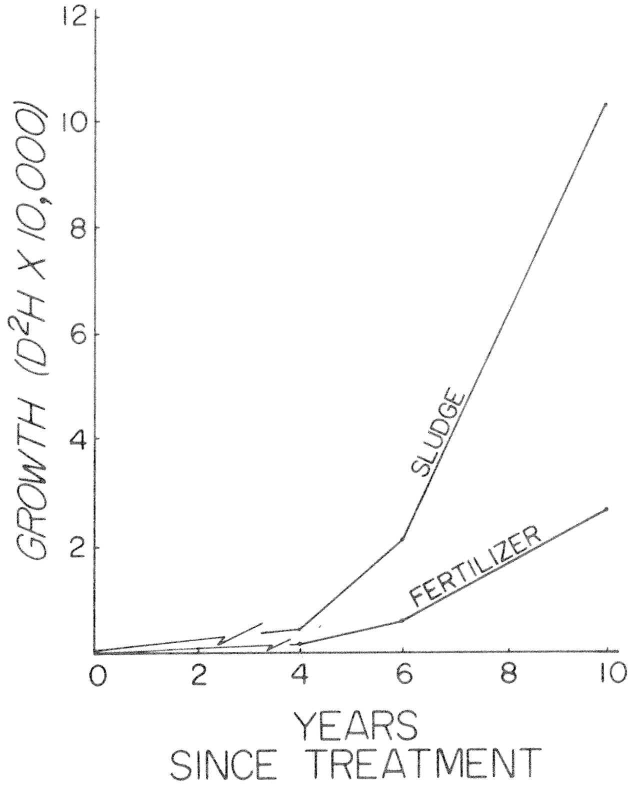

Figure 3.--Growth of Virginia pine on amended plots in the Copper Basin as influenced by sludge (34 Mg/ha) and fertilizer (896 kg/ha of 10-10-10 fertilizer plus 1417 kg/ha CaO).

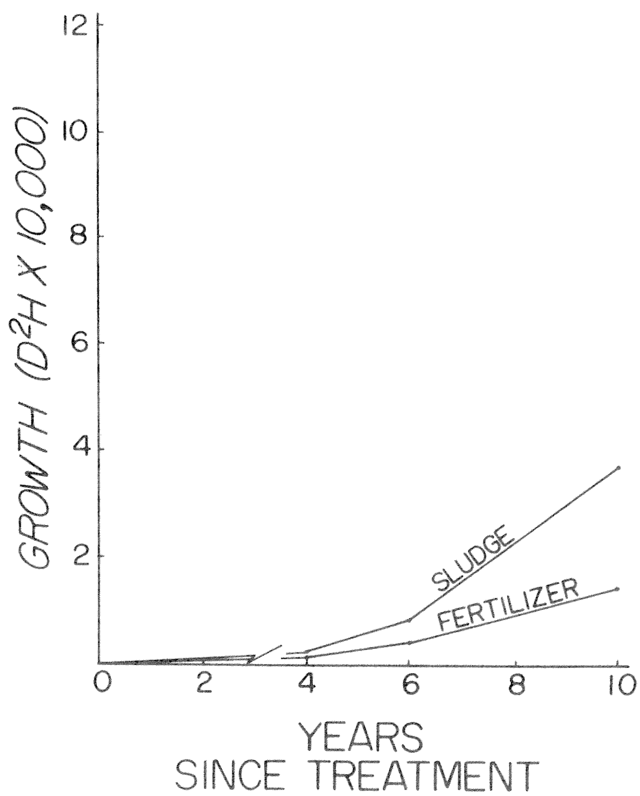

Figure 4.--Growth of shortleaf pine on amended plots in the Copper Basin as influenced by sludge (34 Mg/ha) and fertilizer 896 kg/ha of 10-10-10 fertilizer plus 1417 kg/ha of CaO).

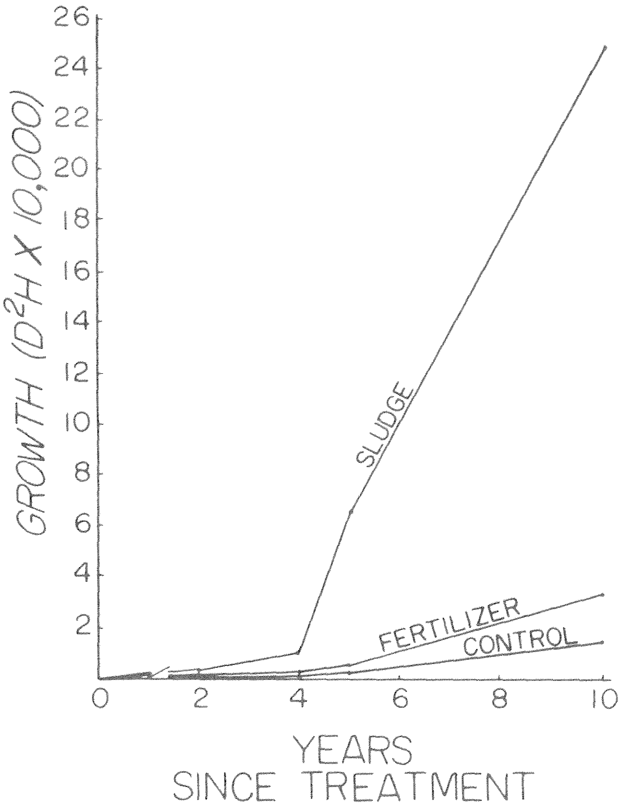

Figure 5.--growth of loblolly pine on a borrow pit as influenced by sludge (34 Mg/ha) and fertilizer (560 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime).

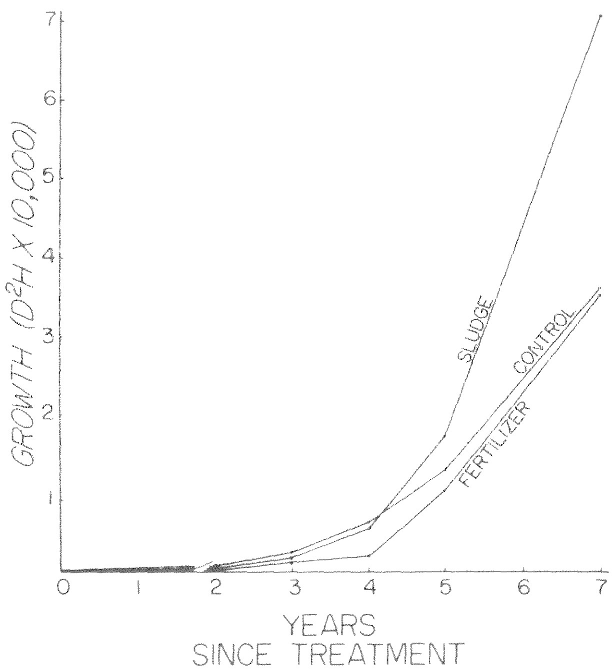

Figure 6.--Growth of sweetgum on a good forest site with Dothan and Norfolk soils as influenced by sludge (34 Mg/ha) and fertilizer (1480 kg/ha of diammonium phosphate plus 1100 kg/ha ammonium nitrate).

Subsoiling

Deep subsoiling--ripping of soil up to 91 cm deep--was used in most studies, and studied as a treatment variable on three sites. In an early study, subsoiling with parallel furrows spaced 80 cm apart and 60 cm deep was compared with disking 15 cm deep (Berry 1979b). Both loblolly and shortleaf pines produced significantly higher D^2H values (19% higher for loblolly and 38% higher for shortleaf) on subsoiled plots than on plots that were disked only. In a study on Orangeburg soil (Study 7), growth of sweetgum after 2 years on disked plots was compared with growth on subsoiled plots (parallel furrows spaced 122 cm apart and 60 cm deep). There were significant increases in height, diameter, and D^2H in trees on subsoiled plots compared with trees on disked plots. There was a 47-percent increase in D^2H on subsoiled plots compared with that on plots that had been disked only. In Study 3, eight intensities of subsoiling plus disking were compared on fertilizer and sludge plots on a borrow pit planted with loblolly pine. When sewage sludge was applied, any degree of subsoiling was significantly better than disking. When fertilizer was used as an amendment, any degree of subsoiling was better than disking for height, but not diameter growth. For D^2H on fertilized plots, subsoiling to 46 cm was significantly better than disking. Neither subsoiling in two directions (perpendicular pattern) rather than one nor spacing furrows at 122 cm instead of 244 cm offered any improvement in growth.

Herbaceous Groundcover

In several studies the sites were seeded to Ky 31 fescue, and in one study grass biomass production was measured. Lush stands of herbaceous material were sometimes produced when sewage sludge was applied. In no case did noxious weeds appear to be introduced by sludge application, but in Study 4 sludge application stimulated weeds already on the site sufficiently to cause severe competition to the planted trees. In a block where weeds were sparse, tree growth was excellent. In other blocks where weed growth was luxuriant, tree growth was moderate. The detrimental effects of weed competition were also illustrated in an early sludge study (Berry 1977) not included in the present paper. The stimulation of ragweed and crabgrass in that study was so great that shortleaf pine did not survive on plots amended with 68 Mg/ha of sludge (table 20). In addition, both survival and growth of shortleaf were less on plots amended with 34 Mg/ha than on plots amended with 17 Mg/ha. Loblolly pine tolerated weeds somewhat better than shortleaf pine.

Effects on Foliar Nutrients

Foliage for tissue analysis was collected in August from branches in the upper one-third of tree crowns. Three or more trees from each treatment plot were sampled. Collections were dried for 48 hours at 75 °C and ground with a UDY Cyclone Sample Mill (UDY Corporation, 201 Rome Court, Fort Collins, CO 80524). Analyses were done by the Soil Testing and Plant Analysis Laboratory, 2400 College Station Road, Athens, GA 30605.

Generally, foliage from trees growing in sludge plots contained more N, P, and Zn than that from trees on fertilizer plots (tables 21 through 28). Ca and Mg were usually higher in foliage from trees in fertilizer plots. Manganese concentrations were several orders of magnitude higher in foliage from trees grown in the Copper Basin than in foliage from trees in the other studies reported here.

DISCUSSION

The heaviest rate of sludge applied in any of the studies was 68 Mg/ha. The primary interest in these data therefore is for use of sewage sludge as fertilizer rather than heavy applications that might be made when disposal on land is the primary goal. While there is no doubt that much heavier amounts of most sludges can be applied in the Southeast with no deleterious effects, one would not expect any increased rate of growth of trees by applying amounts greater than about 34 Mg/ha. Sludge applications of 275 Mg/ha, applied in a nursery experiment (Berry and Marx 1976) had no significant deleterious effect on growth of loblolly or shortleaf pine seedlings or on mycorrhizal formation. It is conceivable, however, that heavy applications of some sludges that are high in salts or heavy metals could inhibit growth and mycorrhizal formation (Berry 1985a). At any rate, care should be taken not to exceed State and Federal guidelines on application of heavy metals to soil or on contamination of ground water with nitrates.

In Study 8, an attempt was made to apply equal amounts of plant nutrients in sludge and fertilizer treatments. As is evident from growth data (table 19), the attempt was unsuccessful. Even though analyses found only nitrogen to be higher on sludge plots and all elements in good supply on fertilizer plots, growth was better on sludge plots. Since most of the nutrients in sludge are in organic form, they become available slowly. All nutrients in most fertilizers used in forestry are water soluble and subject to washing and leaching. Therefore it is impractical to apply much over 1120 kg/ha of 10-10-10 (112 kg/ha of N) in a single application. The effect of leaching of fertilizer was demonstrated in the subsoiling study (Study 3) in which growth of trees during the first 4 years in fertilizer plots was faster on plots subsoiled to only 46 cm than on plots subsoiled to 92 cm, a depth which was more conducive to washing and leaching. Subsoiling to a 92-cm depth produced the fastest growth when sludge was the amendment because moisture relations were better and the nutrients, which were in organic form, were not being leached. Split applications of fertilizer are common in agriculture, but in most cases this approach is impractical with forest trees.

Three of the plantings are now 10 years old or older (Studies 1, 2, and 6). In each case, growth of trees on the sludge plots is excellent and appears to be accelerating. In studies comparing a no-amendment control with fertilizer and sludge treatments, trees on fertilizer plots are not growing much better than those on control plots (Studies 1, 4, 5, 7, and 8).

It has become apparent in recent years that sludge application and incorporation followed by subsoiling will convert the most unproductive site imaginable into a site as productive as the best undisturbed site in the vicinity. Trees on the sludge plots in the Copper Basin and in the borrow pits are growing very well. Previous treatments that did not include sludge (or subsoiling) failed. Metz and others (1970) found 670 to 900 kg/ha of N, 15 to 22 kg/ha of P, and 62 to 108 kg/ha of K in the forest floor and the upper 7.6 cm of mineral soil in 20-year-old southern pine plantations. A sludge application of 34 Mg/ha at 2 percent N, 1 percent P, and 0.5 percent K is equivalent to 680 kg/ha of N, 340 kg/ha of P, and 170 kg/ha of K. Theoretically, the addition of these organically bound, slow-release nutrients should transform the nutrient status of the most barren site to that of an average undisturbed southern pine plantation. Thus, such a treatment appears to be more than adequate for mere reclamation. It promises to enable restoration of a severely devastated site to the status of a fully productive forest.

Trees growing on sludge-amended plots have produced an average of about 8 percent more wood as a percentage of total-tree weight, with proportionately less foliage, than trees on plots amended with inorganic fertilizer (McNab and Berry 1985).

Foliar analyses confirm the value of sludge as a soil amendment. They show elevated nitrogen and phosphorus in foliage from sludge plots compared with that from fertilizer plots. Wells and Allen (1985) discuss the use of foliar analysis for identification of sites where a benefit can be obtained from application of fertilizer. Elevated Mn in foliage from the Copper Basin suggests Mn toxicity as a possible explanation for the somewhat slower growth rate of trees in that area than on sludge-amended borrow pits. Although soil Mn is higher on two other sites, soil pH is lowest in the Copper Basin, creating a situation more conducive for Mn uptake. High velocity drying winds also contribute to reduced growth in the Copper Basin Berry 1982; Hursh 1948).

Figure 7.--Root system of tree from a borrow pit not subsoiled (left) compared with root system from a borrow pit subsoiled to 0.92 m.

The value of subsoiling for growing trees in hard or compacted soil cannot be overstated. In observations made during the subsoiling study (Study 3), roots of loblolly pine were found to penetrate the full depth of 92 cm in a subsoiled trench within 2 years. Roots did not penetrate the soil on this site, if it had not been previously loosened (fig. 7). Even on a good site with deep, rich Orangeburg soil, subsoiling increased early growth. Although increasing the depth from 46 to 92 cm (table 13) or the number of directions from one (parallel lines) to two (creating a grid) did not produce faster growth at 7 years, any degree of subsoiling was significantly better than disking alone. Another advantage observed but not measured in this work was the excellent moisture retention on recently subsoiled plots during rains. One of the most important benefits of subsoiling borrow pits or other extremely hard areas, however, probably will not be seen until the trees are much older and larger. It is believed and observations indicate (fig. 8) that trees growing without the benefit of deep subsoiling will be more prone to windthrow than trees growing on plots that have been subsoiled. All subsoiling in these studies was done with readily available ripping shanks with no special shapes or modifications.

Figure 8.--Trees planted in hard material not subsoiled can be extremely shallow rooted and prone to windthrow.

The use of herbaceous groundcover in conjunction with trees may sometimes have dubious value. Quick stabilization of soil is important, and where fertilizer is being used, groundcover helps capture water-soluble nutrients that might otherwise be lost from the site. Dense herbaceous vegetation, however, competes strongly with tree seedlings for water and nutrients. The best growth of herbaceous plants is usually achieved at a higher pH than what is best for pines. Therefore a quick herbaceous

Figure 9.--Trees planted at close spacing in subsoiled furrows that follow contours control erosion effectively without groundcover.

groundcover must be bought at a price of slower growth of trees. Runoff can be controlled to a large extent by subsoiling on the contour and by planting trees at a close spacing in the furrows (fig. 9). The rows could be spaced normally at 2.44 m or more and trees spaced at 1.22 m within rows.

If sludge is used instead of fertilizer, plant nutrients will be retained on the site because they are released slowly. If weed seeds are present on the site, weed growth will be stimulated by sludge, often to an extent that inhibits growth of tree seedlings. If such a situation can be foreseen, attempts should be made to control weeds, even if tree planting must be delayed a year.

Society is obliged to dispose of sewage sludge by the most environmentally sound means possible. Disposal by application on disturbed sites can result in superior reclamation. Even on high-quality forest sites, judicious disposal of some sludges will promote growth of trees with no deleterious effects.

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TABLES

Table 1.--Chemical analysis of sludges employed in eight field studies

Element	Sludge: Athens Fresh	Sludge: Athens Old	Sludge: Macon
	Percent		
N	2.0	1.0	1.8
P	0.65	0.13	0.71
K	0.05	0.04	0.02
Ca	0.84	0.62	--
Mg	0.11	0.06	0.03
Al	0.90	0.36	--
Fe	0.58	0.33	0.01
	p/m		
Ba	12.0	27.7	--
B	15.5	8.4	--
Cd	5.9	4.5	--
Co	25.0	13.2	--
Cr	40.3	28.6	--
Cu	153.3	115.4	--
Mn	231.0	52.0	93.0
Mo	9.0	2.2	--
Na	121.0	23.0	--
Ni	13.1	9.8	--
Pb	43.7	34.6	--
Sr	41.9	10.4	--
Zn	806.0	505.0	53.0

Table 2.--Characteristics of unamended soil at study locations

Study number	Type of soil	Total N	Available P	K	Mg	Ca	Mn	pH	CEC	Organic matter	Mechanical analysis Sand	Silt	Clay
		- - - - - -	- - - - - -	- - -	p/m	- - -	- - -		meq/100 g	- - - -	- - - %	- - -	- - -
1	Borrow pit (BP-1a)	174	2	29	16	29	2	4.58	1.72	0.1	81	2	17
2	Borrow pit (BP-1b)	102	2	33	21	65	2	4.59	1.29	0.3	81	2	17
3	Borrow pit (BP-2)	99	4	41	56	127	5	4.81	2.14	0.4	79	2	19
4	Borrow pit (BP-3)	84	3	35	38	106	2	4.82	1.73	0.3	73	2	25
5	Kaolin spoil[1]	35	3	21	55	153	--	6.19	1.49	0.1	93	2	5
6	Hayesville, severely eroded	78	3	7	3	3	15	4.40	1.62	0.1	67	15	18
7	Orangeburg	238	31	47	17	111	22	4.96	2.78	1.6	92	5	3
8	Dothan and Norfolk	397	8	51	35	144	6	4.97	3.92	1.8	92	6	2

[1]Samples collected after application of lime; analyses of adjacent unlimed areas have shown a pH of 4.4 to 5.1, Ca of 60 to 100 p/m, Mg of 20 p/m.

Table 3.--Soil chemical properties on a borrow pit (BP-1a, Study 1) 10 years after addition of amendments and being planted with loblolly pine[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	p/m					%		meq/100 g
Sludge[2]	390a	55a	49a	76b	22a	1.3a	4.30b	4.4a
Fertilizer[3]	142b	2b	35b	103a	59a	0.5b	4.90a	1.9b
Control	174b	2b	30b	29c	17b	0.3b	4.54ab	1.5b

[1]Within columns, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]34 Mg/ha.

[3]560 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 4.--Growth of loblolly pine after 10 years on a borrow pit (BP-1a, Study 1) as influenced by sewage sludge and fertilizer[1]

Treatment	Height	Diameter	D^2H
	cm	mm	cm^3 (x 10,000)
Sludge[2]	979a	154a	248a
Fertilizer[3]	454b	68b	31b
Control	265c	41b	18b

[1]Within columns, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]34 Mg/ha.

[3]560 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 5.--Soil chemical properties on a borrow pit (BP-1b, Study 2) 10 years after addition of amendments and planted to sweetgum[1]

Treatment (Mg/ha)	N	P	K	Ca	Mg	O.M.	pH	CEC
	- - - -	- - - -	p/m	- - - -	- - - -	%		meq/100 g
0	102b	2c	33b	65a	21a	0.3c	4.59a	1.3c
17	368a	26b	47a	65a	17a	0.9b	4.35b	5.6b
34	492a	43b	46a	58a	15a	1.3a	4.21b	7.9a
68	596a	72a	52a	76a	21a	1.4a	4.20b	7.9a

[1]Within columns, means followed by the same letter do not differ significantly at $P = 0.05$.

Table 6.--Growth of sweetgum after 10 years on a borrow pit (BP-1b, Study 2) amended with sewage sludge[1]

Sludge treatment (Mg/ha)	Height	Diameter	D^2H
	m	cm	cm^3 (x 10,000)
0	0.63c	3.6b	0.2c
17	4.11b	8.6a	3.6b
34	5.49a	10.6a	7.1a
68	5.57a	10.8a	7.4a

[1]Within columns, means followed by the same letter do not differ significantly at $P = 0.05$.

Table 7.--Soil chemical properties of a borrow pit (BP-2, Study 3) used to test effects of subsoiling treatments on loblolly pine 7 years after amendments were applied[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	- - - - - - - - -	- - -	p/m	- - -	- - - - - - - - -	%		meq/100 g
Sludge[2]	219a	44a	32b	124a	22b	0.8a	4.25b	6.2a
Fertilizer[3]	99b	4b	41a	127a	56a	0.4b	4.81a	2.1b

[1]Within columns, means followed by the same letter do not differ significantly at $P = 0.05$.

[2]17 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 8.--Influence of subsoiling on growth of loblolly pine on a borrow pit (BP-2, Study 3) amended with sewage sludge or fertilizer after 7 years[1]

Subsoiling depth (cm)	Survival	Height	Diameter	D^2H
	%	cm	mm	cm^3 (x 1000)
		SLUDGE[2]		
Control[3]	97.6a	594b	94b	5.8b
46 (4 treatments)	97.4a	662a	108a	8.3a
92 (4 treatments)	97.8a	681a	111a	9.1a
$\overline{X}$ (9 treatments)	97.6A	663A	108A	8.4A
		FERTILIZER[4]		
Control[3]	96.0ab	361b	52a	1.5b
46 (4 treatments)	98.2a	430a	66a	2.3a
92 (4 treatments)	97.2a	413a	61a	2.0ab
$\overline{X}$ (9 treatments)	97.5A	415B	62B	2.0B

[1]Within columns, means followed by the same lowercase or uppercase letter do not differ significantly at $P = 0.05$.

[2]17 Mg/ha.

[3]Disk only, approximately 15 cm in depth.

[4]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 9.--Soil chemical properties on a borrow pit (BP-3, Study 4) planted with hardwoods and loblolly pine 4 years after addition of amendments[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	- - - - - -	- - - - - -	p/m	- - - - - -	- - - - - -	%		meq/100 g
Sludge[2]	302a	69a	37b	199a	41b	1.9a	4.73b	5.6a
Fertilizer[3]	122b	5b	61a	187a	86a	1.2ab	5.25a	5.4a
Control	84b	3b	35b	106b	38b	0.7b	4.82b	3.5b

[1]Within columns, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]68 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 10.--A comparison of growth of six tree species on borrow pit plots (BP-3, Study 4) after 4 years amended with sewage sludge or fertilizer[1]

Species	Survival	Height	Diameter	D^2H
	%	cm	mm	cm^3 (x 10,000)
		SLUDGE[2]		
Loblolly	87.2a	329ab	111a	4.58a
Sycamore	83.6a	375a	57b	2.31b
Sawtooth oak	79.2a	222c	54b	0.78b
Green ash	99.6a	277bc	52b	0.95b
Sweetgum	94.0a	268bc	47b	0.89b
Yellow-poplar	40.8b	198c	37b	0.99b
		FERTILIZER[3]		
Loblolly	92.8a	278a	86a	2.30a
Sycamore	86.8ab	217b	35b	0.34b
Sawtooth oak	85.6ab	144c	37b	0.21b
Green ash	96.8a	132c	24c	0.10b
Sweetgum	95.6a	129c	21cd	0.08b
Yellow-poplar	72.0b	77d	16d	0.03b

[1]Within columns and amendments, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]68 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 11.--Growth of three tree species on a borrow pit (BP-3, Study 4) after 4 years on plots amended with sludge or fertilizer compared with growth on nonamended control plots[1]

Treatment	Survival	Height	Diameter	D^2H
	%	cm	mm	cm^3 (x 10,000)
		GREEN ASH		
Sludge[2]	99.6a	277a	54a	0.95a
Fertilizer[3]	96.8ab	132b	24b	0.10b
Control	93.2b	79c	14c	0.02b
		SWEETGUM		
Sludge[2]	94.0a	268a	47a	0.89a
Fertilizer[3]	95.6a	129b	21b	0.08a
Control	96.8a	80b	14b	0.02a
		LOBLOLLY PINE		
Sludge[2]	87.2a	329a	111a	4.58a
Fertilizer[3]	92.8a	278a	86b	2.30b
Control	90.8a	197b	62c	0.93b

[1]Within columns and species, means followed by the same letter do not differ significantly at $P = 0.05$.

[2]68 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 12.--Soil chemical properties on a kaolin spoil planted with sweetgum (Study 5) 4 years after addition of amendments[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	- - - - - - - - -	- - -	p/m	- - -	- - - - - - - - -	%		meq/100 g
Sludge[2]	795a	79a	31a	379a	52a	2.4a	6.12a	2.7a
Fertilizer[3]	75b	11b	33a	165b	56a	0.5b	6.28a	1.6b
Control[4]	35b	3c	21b	153b	55a	0.3b	6.19a	1.5b

Samples collected after application of lime; analyses of adjacent unlimed areas have shown a pH of 4.4 to 5.1, Ca of 60 to 100 p/m, Mg of 20 p/m, and K of 24 p/m.

[1]Within columns, means followed by the same letter do not differ significantly at $\underline{P} = 0.05$.

[2]34 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

[4]2240 kg/ha of dolomitic lime.

Table 13.--Growth of sweetgum on a kaolin spoil (Study 5) 4 years after addition of amendments[1]

Treatment	Survival	Height	Diameter	D^2H
	%	cm	mm	cm^3 (x10,000)
Sludge[2]	95.0a	145a	26a	0.14a
Fertilizer[3]	99.3a	86b	17b	0.04b
Control[4]	95.3a	76b	17b	0.03b

[1]Within columns, means followed by the same letter do not differ significantly at P = 0.05.

[2]34 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

[4]2240 kg/ha of dolomitic lime.

Table 14.--Soil chemical properties of study plots in the Tennessee Copper Basin planted with three pine species (Study 6) 10 years after addition of amendments[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	- - - - - - - - -	- - - -	p/m	- - - -	- - - - - - - - -	%		meq/100 g
Sludge[2]	374a	18a	64a	61a	14a	1.0a	4.29b	7.1a
Fertilizer[3]	184b	1b	61a	82a	15a	0.3b	4.67a	1.4b

[1]Within columns, means followed by the same letter do not differ significantly at P = 0.05.

[2]34 Mg/ha.

[3]896 kg/ha of 10-10-10 fertilizer plus 1417 kg/ha of CaO.

Table 15.--Growth of loblolly, shortleaf, and Virginia pines in the Tennessee Copper Basin (Study 6) on plots amended with sewage sludge or fertilizer after 10 years[1]

Treatment	Height	Diameter	D^2H
	cm	mm	cm^3 (x 10,000)
		LOBLOLLY	
Sludge[2]	702a	134a	135a
Fertilizer[3]	450b	84b	40b
		SHORTLEAF	
Sludge[2]	475a	77a	37a
Fertilizer[3]	325b	54b	14b
		VIRGINIA	
Sludge[2]	608a	124a	103a
Fertilizer[3]	363b	72b	26b

[1]Within columns and species, means followed by the same letter do not differ significantly at $P = 0.05$.

[2]34 Mg/ha.

[3]896 kg/ha of 10-10-10 fertilizer plus 1417 kg/ha of CaO.

Table 16.--Soil chemical properties of a good forest site planted with sweetgum with Orangeburg soil (Study 7) on the Savannah River Forest Station[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	p/m					%		meq/100 g
Sludge[2]	605a	106a	57a	168a	18a	2.2a	4.79a	2.2a
Fertilizer[3]	248b	36b	42c	94b	15a	1.6b	4.79a	1.3b
Control	238b	31b	47b	111b	17a	1.6b	4.96a	1.4b

[1]Within columns, means followed by the same letter do not differ significantly at $P = 0.05$.

[2]34 Mg/ha.

[3]280 kg/ha of diammonium phosphate.

Table 17.--Growth of sweetgum on a good forest site with Orangeburg soil (Study 7) after 2 years[1]

Treatment	Survival	Height	Diameter	D^2H
	%	cm	mm	cm^3
		MINOR PLOTS		
Sludge[2]	88a	155a	37a	2417a
Fertilizer[3]	83a	144a	36a	2148a
Control	85a	123b	28b	1111b
		MAJOR PLOTS		
Subsoiled	88a	147a	36a	2252a
Not subsoiled	83a	134b	31b	1532b

[1]Within columns for a particular series of plots, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]34 Mg/ha.

[3]280 kg/ha of diammonium phosphate applied 1 year after planting.

Table 18.--Soil chemical properties of a good forest site with Dothan and Norfolk soils (Study 8) planted with sweetgum on the Savannah River Forest Station[1]

Treatment	N	P	K	Ca	Mg	O.M.	pH	CEC
	- - - - -	- - - - -	p/m	- - - - -	- - - - -	%		meq/100 g
Sludge[2]	725a	69a	47a	164a	30a	3.0a	4.83b	2.2a
Fertilizer[3]	492b	63b	51a	143a	36a	2.6ab	4.88a	2.1a
Control	397b	8b	51a	144a	35a	2.2b	4.97a	2.0a

[1]Within columns, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]34 Mg/ha.

[3]1480 kg/ha diammonium phosphate, and 1100 kg/ha of ammonium nitrate.

Table 19.--Growth of sweetgum on Dothan and Norfolk soils (Study 8) at the Savannah River Forest Station, amended with sewage sludge or fertilizer after 7 years[1]

Treatment	Survival	Height	Diameter	D^2H
	%	m	cm	cm^3 (x 10,000)
Sludge[2]	78a	5.29a	10.9a	7.1a
Fertilizer[3]	62a	4.25b	8.6b	3.6b
Control	72a	4.31b	8.6b	3.6b

[1]Within columns, means followed by the same letter do not differ significantly at $P = 0.05$.

[2]34 Mg/ha.

[3]1480 kg/ha diammonium phosphate and 1100 kg/ha ammonium nitrate.

Table 20.--Growth of loblolly and shortleaf pines on eroded forest land (Madison soil series) amended with sewage sludge after 5 years[1]

Sludge treatment (Mg/ha)	Survival	Height	Diameter	D^2H	1st-year weed biomass
	%	cm	cm	cm^3 (x 10,000)	g/m^2
			LOBLOLLY PINE		
0	96a	341a	8.3a	2.46a	121c
17	86a	369a	9.0a	3.39a	341b
34	67a	404a	9.9a	4.13a	321b
69	67a	359a	10.4a	4.13a	475a
			SHORTLEAF PINE		
0	68a	202a	5.9a	0.89a	91d
17	77a	269a	6.8a	2.25a	228c
34	42b	281a	6.5a	1.43a	370b
69	--	--	--	--	563a

[1]Within columns and species, means followed by the same letter do not differ significantly at $P = 0.05$.

Source: Berry 1977.

Table 21.--Chemical analysis of foliage of loblolly pine after growing 10 years on a borrow pit (Study 1) amended with sewage sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	- - -	- - -	%	- - -	- - -	- - -	- - -	- - -	p/m	- - -	- - -	- - -	- - -
Sludge[2]	0.86a	0.12a	0.28b	0.32a	0.14a	280a	36a	597a	17a	1.6a	78a	7a	13a
Fertilizer[3]	0.84a	0.11a	0.45a	0.20b	0.16a	214b	24b	571a	12b	1.8a	33b	4a	3b
Control	0.73b	0.10a	0.45a	0.18b	0.12b	342a	24b	559a	12b	1.8a	33b	5a	7b

[1]Within columns, means followed by the same letter do not differ significantly at *P* = 0.05.

[2]34 Mg/ha.

[3]560 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 22.--Chemical analysis of foliage of sweetgum after growing 10 years on a borrow pit (Study 2) amended with sewage sludge[1]

Sludge treatment (Mg/ha)	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	- - -	- - -	%	- - -	- - -	- - -	- - -	- - -	p/m	- - -	- - -	- - -	- - -
0	0.96a	0.20b	0.61a	0.92a	0.37a	822a	55a	474a	29a	3.7a	65c	25a	44c
17	1.00a	0.33a	0.48b	0.76b	0.29b	335b	22b	261b	27ab	1.9b	89bc	21a	84ab
34	1.01a	0.35a	0.41bc	0.76b	0.27b	312b	22b	288b	24ab	1.7b	110b	21a	95a
68	1.17a	0.30a	0.39c	0.79b	0.30ab	257b	26b	312b	22b	1.9b	140a	19a	68b

[1]Within columns, means followed by the same letter do not differ significantly at *P* = 0.05.

Table 23.--Chemical analysis of foliage of loblolly pine after growing 7 years on a borrow pit (Study 3) amended with sewage sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	- - -	- - -	%	- - -	- - -	- - -	- - -	- - -	p/m	- - -	- - -	- - -	- - -
Sludge[2]	0.94a	0.18a	0.28b	0.30a	0.15b	336a	30a	749a	12a	2.1a	58a	5a	8a
Fertilizer[3]	0.73b	0.12b	0.59a	0.23b	0.18a	120b	29a	712a	10b	1.2b	28b	4b	1b

[1]Within columns, means followed by the same letter do not differ significantly at $P = 0.05$.

[2]17 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 24.--Chemical analysis of foliage of six forest tree species after growing 4 years on a borrow pit (Study 4) amended with sewage sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	%					p/m							
GREEN ASH													
Sludge[2]	1.83a	0.27a	0.47b	0.72a	0.26a	37a	60a	46a	19b	27.4a	36a	17ab	21a
Fertilizer[3]	1.39b	0.12b	0.71a	0.56a	0.22a	22a	47a	56a	25b	16.4a	17b	9b	9b
Control	1.41b	0.12b	0.61ab	0.55a	0.26a	35a	66a	140a	33a	30.6a	16b	21a	12b
SWEETGUM													
Sludge[2]	1.79a	0.24a	0.37b	0.72b	0.34b	703a.	47a	353b	27a	7.8a	129a	13b	23a
Fertilizer[3]	1.06b	0.09b	0.48a	0.93ab	0.47a	356b	36a	402b	29a	4.4b	26b	13b	11a
Control	1.00b	0.11b	0.39b	0.97a	0.43a	659a	64a	568a	28a	4.5b	35b	40a	22a
LOBLOLLY PINE													
Sludge[2]	1.51a	0.17a	0.33a	0.22a	0.10b	368a	34a	557b	12a	3.6a	69a	3a	1a
Fertilizer[3]	1.09b	0.12b	0.41a	0.18a	0.13a	125b	24b	601ab	9b	1.9b	21b	3a	1a
Control	1.08b	0.13b	0.33a	0.17a	0.14a	196ab	23b	686a	11ab	1.8b	23b	5a	2a
SAWTOOTH OAK													
Sludge[2]	2.20a	0.20a	0.42b	0.50b	0.19b	363a	62a	51a	42a	7.8a	42a	21a	29a
Fertilizer[3]	1.70a	0.11b	0.66a	0.55a	0.27a	182b	47b	69a	43a	5.3b	20b	7a	25a
SYCAMORE													
Sludge[2]	2.27a	0.21a	0.44a	0.94a	0.34a	267a	48a	37a	35a	13.7a	52a	26a	28a
Fertilizer[3]	1.39b	0.10b	0.49a	0.99a	0.43a	107a	39a	48a	29a	5.2b	14b	27a	14a
YELLOW-POPLAR													
Sludge[2]	2.05a	0.16a	0.31b	1.25a	0.51a	514a	41a	286a	44a	6.8a	28a	41a	32a
Fertilizer[3]	1.22b	0.08b	0.55a	1.41a	0.54a	207b	37a	447a	37a	3.5b	12a	42a	16b

[1]Within columns and species, means followed by the same letter do not differ significantly at $P = 0.05$.
[2]68 Mg/ha.
[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

Table 25.--Chemical analysis of foliage of sweetgum after growing 4 years on kaolin spoil (Study 5) amended with sewage sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	%					p/m							
Sludge[2]	1.51a	0.52a	0.36c	0.88a	0.43a	853a	58b	359b	20b	5.3a	114a	7a	45a
Fertilizer[3]	0.73b	0.25b	0.73a	0.89a	0.51a	769a	72ab	508a	30a	2.7b	40b	6a	27b
Control[4]	0.83b	0.10c	0.60b	0.82a	0.46a	654b	85a	521a	25ab	3.4b	38b	7a	25b

[1]Within columns, means followed by the same letter do not differ significantly at $\underline{P} = 0.05$.

[2]34 Mg/ha.

[3]1120 kg/ha of 10-10-10 fertilizer plus 2240 kg/ha of dolomitic lime.

[4]2240 kg/ha of dolomitic lime.

Table 26.--Chemical analysis of foliage of loblolly, shortleaf, and Virginia pines after growing 10 years in the Tennessee Copper Basin (Study 6) on plots amended with sewage sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	- - - -	- - - -	%	- - - -	- - - -	- - - -	- - - -	- - - -	p/m	- - - -	- - - -	- - - -	- - - -
Loblolly	1.04b	0.22c	0.44b	0.30b	0.06c	1266b	220a	511b	16b	9.6a	58a	5b	19b
Shortleaf	1.06ab	0.26b	0.65a	0.28c	0.09a	1415b	206a	856a	15b	9.4ab	55a	5b	17b
Virginia	1.11a	0.30a	0.44b	0.47a	0.08b	2165a	206a	824a	28a	8.4b	43b	7a	44a
Mean effects of sludge[2]	1.12A	0.27A	0.51B	0.30B	0.08A	1528A	231A	705A	18A	10.0A	54A	5A	28A
and of fertilizer[3]	1.01B	0.24B	0.54A	0.35A	0.08A	1483A	192B	717A	18A	8.6B	48B	5A	19A

[1]For a particular species and nutrient, means followed by the same lowercase letter do not differ significantly at P = 0.05. For a particular nutrient, means followed by the same uppercase letter do not differ significantly at P = 0.05.

[2]34 Mg/ha.

[3]896 kg/ha of 10-10-10 fertilizer plus 1417 kg/ha of CaO.

Table 27.--Chemical analysis of foliage of sweetgum after growing 2 years on a good forest site with Orangeburg soil (Study 7) amended with sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	- - - -	- - - -	%	- - - -	- - - -	- - - -	- - - -	- - - -	p/m	- - - -	- - - -	- - - -	- - - -
Sludge[2]	2.33a	0.20a	0.66a	0.57b	0.29b	598a	46a	326ab	16b	6.9b	26c	18a	107b
Fertilizer[3]	2.15b	0.20a	0.56b	0.67a	0.27b	452b	39b	278b	23a	8.2	51a	18a	77b
Control	1.74c	0.19a	0.65a	0.66a	0.37a	493b	39b	386a	17b	9.9a	39b	21a	149a

[1]Within columns, means followed by the same letter do not differ significantly at P = 0.05.

[2]34 Mg/ha.

[3]280 kg/ha diammonium phosphate.

Table 28.--Chemical analysis of foliage of sweetgum after growing 7 years on a good forest site with Dothan and Norfolk soils (Study 8) amended with sludge or fertilizer[1]

Treatment	N	P	K	Ca	Mg	Mn	Fe	Al	B	Cu	Zn	Sr	Ba
	- - - -	- - - -	%	- - - -	- - - -	- - - -	- - - -	- - - -	p/m	- - - -	- - - -	- - - -	- - - -
Sludge[2]	1.47b	0.23a	0.45a	0.73a	0.41a	604a	34a	498a	30ab	5.5b	44b	16a	29b
Fertilizer[3]	1.67a	0.26a	0.48a	0.73a	0.39a	560a	33a	498a	27b	6.8a	92a	18a	72a
Control	1.16c	0.14b	0.43a	0.70a	0.37a	552a	28b	473a	32a	4.0c	42b	16a	28b

[1]Within columns, means followed by the same letter do not differ significantly at P = 0.05.

[2]34 Mg/ha.

[3]1480 kg/ha diammonium phosphate plus 1100 kg/ha ammonium nitrate.

Berry, Charles R.

Use of municipal sewage sludge for improvement of forest sites in the Southeast. Res. Pap. SE-266. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 1987. 33 pp.

In eight field experiments dried municipal sewage sludge was applied to forest sites before planting of seedlings. In all cases, tree growth was faster on sludge-amended plots than on plots that received fertilizer and lime or no amendment. Deep subsoiling was beneficial regardless of soil amendment. Where weeds were plentiful at the outset, they became serious competitors on plots receiving sludge.

KEYWORDS: Reclamation, borrow pit, tree growth, *Pinus taeda*, *Liquidambar styraciflua*, soil nutrients, subsoiling.

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