RECLAMATION OF COAL REFUSE WITH A PAPERMILL SLUDGE AMENDMENT[1]

by

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Abstract. Reclamation of coal refuse is difficult due to the harsh growing conditions resulting from the refuse's unfavorable chemical and physical properties. This research program focused on the utilization potential of a papermill sludge produced by the Mead Paper Company in Kingsport, Tenn., which consisted primarily of a mixture of waste wood fiber, lime, kaolin, and traces of fly ash. A field experiment was initiated in 1992. Loading rates were 0, 112, 224 Mg ha^{-1} for the papermill sludge and 0, 112, 224, and 336 kg ha^{-1} for N. Our results suggest that the N-fertilizer additions gave a short-term boost to biomass production, suppressed legume growth, and resulted in a higher yield and thicker vegetation cover in the first year. From the second year on, however, the vegetation on the papermill sludge plots was superior to that on the 0 sludge plots across all N rates, suggesting that papermill sludge did not lead to excessive N-immobilization as expected. By contributing organic matter, acid-neutralization potential, and light color, the papermill sludge significantly improved the refuse pH, increased the available P, increased the water holding capacity, and decreased the refuse temperature during the summer; all of which were beneficial to establishment and maintenance of vegetation. The addition of papermill sludge also improved leachate quality. Thus, a proper combination of N-fertilizer and papermill sludge, for example, 112 kg ha^{-1} N and 112 Mg ha^{-1} sludge, is recommended in addition to balanced P and K fertilization.

Additional Key Words: Revegetation, nitrogen immobilization, acidity, water holding capacity.

Introduction

The safe disposal of papermill sludge and other paper making residuals is a challenging problem. Currently, the majority of wastes are disposed of in landfills. Nevertheless, these alternatives are becoming more expensive and pose substantial threats to water quality if design standards are not strictly met and maintained over the lifetime of the disposal facility. Thus, there is considerable interest in the pulp and paper industry over whether (and which of) their waste residuals can be successfully and safely land-applied. This research program was implemented to determine if a papermill sludge product could be successfully utilized to reclaim coal processing waste materials in southwest Virginia.

Coal refuse disposal areas cover thousands of acres in Virginia alone, and tend to be quite difficult to revegetate or stabilize without topsoil covers or significant surface amendments. The revegetation of coal refuse is limited by low soil water holding capacity, high summer heat loads, and variable levels of soil acidity (Stewart and Daniels, 1992). The refuse from coal preparation is low in organic matter, quite coarse textured, and is generally characterized by poor physical and chemical properties. On many coal refuse piles, revegetation potential is strongly limited by potential acidity and resultant low pH and high salt content of the refuse. A number of Appalachian refuse piles are non-acid forming in overall reaction chemistry, but still suffer from the physical limitations to plant growth discussed above, particularly if they are to be direct-seeded without topsoil covers.

A considerable amount greenhouse and field research has been conducted to date on the utilization of papermill sludge on natural and disturbed lands. These studies have shown that appropriate rates of papermill sludge as a topical amendment have the potential to greatly improve the water holding and aggregation of raw mine spoils and refuse, supply plant nutrients, and decrease acidity. These numerous benefits have led to

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better plant growth and greater vegetative cover, particularly when combined with appropriate fertilization strategies (Owusu-Gyima and Roy, 1991; Del Rosario, 1990: Feagley et al., 1994ab; Bellamy, et al., 1995; Dollar, et al., 1972; Watson and Hoitink, 1985; Cline and Chong, 1991; Pichtel, et al., 1994).

The specific objectives of this study were:

1. To characterize the chemical and physical properties of a papermill by-product material that was available for utilization in the central Appalachian region, and to determine its suitability for land application.

2. To determine the optimal loading rates for the product when used as a surface amendment for direct revegetation of coal refuse.

3. To measure the amendment's influence on coal refuse leachate quality, and to determine the extent of pH buffering over multiple seasons.

Materials and Methods

Papermill Sludge

The papermill sludge generated by Mead Paper Co. in Kingsport (acquired by Willamette Paper in 1995) was particularly attractive for this use since it is a mixture of primarily waste wood fiber (60%) and lime (25%), with minor amounts of kaolin clay (10%) and fly ash (5%). The material is a non-biological water treatment sludge, is finely ground, and can be easily land-applied with manure spreaders or through conventional hydro-seeders. For the balance of this paper, we will refer to this material as lime-fiber mulch since that term best describes its properties and potentially beneficial role in mined land reclamation.

Papermill waste materials can contain dioxins that are a by-product of the bleaching process. There is currently considerable public and agency debate over the environmental and human health risks associated with dioxins (Olson et al., 1988; Owusu-Gyima and Roy, 1991; Baker, 1994). Fortunately, due to process changes at the Kingsport plant in the early 1990's, the dioxin (TCDD) levels in this product were below detection (< 0.3 ppt) when this research experiment was installed. However, a considerably less toxic daughter isomer (TCDF) was detectable at < 5 ppt.

Plot Construction

The experimental area, 45 m by 90 m, was located on the Pine Branch coal refuse pile operated by the Westmoreland Coal Company in Wise County, Virginia. This site was chosen because our earlier regional coal waste research program (Stewart and Daniels, 1992) indicated that Pine Branch was close to the regional median for potential acidity. The area where this particular experiment was installed was near neutral in pH, however, but was very coarse in texture and black on the surface. Noticeable salt accumulations were also apparent at the time of plot installation. Thus, while this location is somewhat atypical of Appalachian coal refuse with regard to acidity, it still posed a severe challenge for revegetation due to water stress coupled with severe N and P limitations. Other studies (Daniels et al., 1989; Stewart, 1990) at this and other refuse piles in the region have established that once potential acidity has been neutralized, N and P are the principal growth limiting nutrients, and that micro-nutrient deficiencies are rare.

This experiment was a randomized complete block design with three replications and two main experimental factors. The first experimental factor was lime-fiber mulch applied at three rates: 0, 112 and 224 Mg ha^{-1}. The second factor evaluated was fertilizer-N at four applied levels, 0, 112, 224 and 336 kg ha^{-1} as ammonium nitrate. All plots also received 336 kg ha^{-1} P and 112 kg ha^{-1} K with the initial fertilization based upon earlier research by Daniels et al. (1989). In March, 1992, the area was graded with a bulldozer and the individual field plots were laid out and sampled for soil analyses.

In May 1992, lime-fiber mulch from Mead's Kingsport plant was trucked to the Pine Branch refuse pile. A front-end loader was used to measure (by loader bucket) and spread the lime-fiber mulch at the appropriate rate on each plot. The weight/density/water content relationships for this material were determined in the lab the week before spreading. The lime-fiber mulch was immediately chisel-plowed to incorporate it into the refuse surface. On June 9, 1992, the entire area was seeded with 17 kg ha^{-1} German millet (*Setaria italica*) as a summer cover crop. The appropriate amounts of fertilizer were applied to each plot just before seeding. The millet was harvested on September 8, 1992, and these plots were then seeded with the reclamation species mix are given in Table 1. On April 13, 1993, N-fertilizer was again applied on each plot at one-half the rate applied in 1992.

Table 1. The seed mixture used in 1992.

Variety	Purity(%)	Ger.(%)
KY-31 Tall fescue *Festuca arundinacea Schreber*	49.00	85
Annual ryegrass *Lolium multiflorum*	9.78	90
Redtop *Agrostis alba*	1.96	90
Alsike clover *Trifolium hybridum*	7.91	90
Alta-swede Red clover *Trifolium pratense*	9.95	90
Birdsfoot trefoil *Lotus corniculatus*	1.92	85
Yellow sweetclover *Melilotus officinalis*	17.72	90

To monitor the effects of the surface treatments on leachate quality, zero-tension lysimeters were installed under four plots In October, 1992. Lysimeters were installed under two treated plots (224 Mg ha^{-1} mulch + 336 kg ha^{-1} N), and two control plots (0 Mg ha^{-1} mulch + 0 kg ha^{-1} N). The lysimeters were made of a 0.4 m length of smooth bore 0.24 m (diam) ABS plastic pipe with a fitted endcap. The lysimeter was plumbed with a plastic tube to evacuate leachate. One end of the tube was fixed to the bottom of lysimeter and was screened with 80 mesh nylon sieve cloth, and other end was brought to the surface. A hole was excavated in the refuse with a shovel (separating the top layer of refuse from deeper refuse) and the lysimeter was put into the hole, with a ten-cm layer of coarse sand in the bottom of the lysimeter. Refuse was then packed around and in the lysimeter with the top layer of refuse returned back over the top of the lysimeter and returned to original grade.

Sampling and Laboratory Analysis

Leachate. Leachates were pumped up monthly from each lysimeter with a vacuum pump. The pH was measured on-site immediately and subsamples were taken into a 250-ml plastic bottle for later laboratory analyses. In the laboratory, the turbid samples were filtered through a #42 filter paper before analysis. Conductance was measured with a conductivity meter and then we acidified these samples with HNO_3 to prepare them for further analysis. The leachate samples were subsequently analyzed for Al, Cu, Fe, Mn, S, Zn, and Ca by ICP and/or AA spectroscopy.

Mine soils and standing biomass. Refuse samples were taken at random from the surface 15 cm of each plot before treatments were applied. The mulch was also sampled before application to develop weight/volume relationships as discussed earlier. Vegetation performance was evaluated for each plot by estimating the percentage ground cover, the species composition and the vigor of growth each spring, summer, and fall. Each fall in September, standing biomass samples were taken from each plot randomly by hand clipping to ground level within two 0.25 m^2 quadrats. The plant tissue was oven-dried at 65°C for 48 hours and weighed. The plant tissue was subsequently ground to determine nutrient and heavy metal levels. Soil samples were excavated beneath the biomass sampling quadrats to a 15-cm depth with a shovel. Soil samples were air-dried and passed through a 2-mm sieve to separate fine soil from coarse fragments. All analyses were performed on the fine-soil fraction. Soil samples were analyzed for pH, water retention, and heavy metals. Soil pH was determined in a 1:1 soil:water slurry with a glass-calomel electrode pH meter (McLean, 1982). Water retention was determined by the method of Klute (1982). Total analysis of the original lime-fiber mulch material and a combined sample of the untreated refuse was determined by ICP and AA spectroscopy after high temperature HF digestion

(Hartstein et al., 1973). The Neutralization potential of the lime-fiber mulch material was estimated by treating the sample with an excess of HCl followed by back titration with NaOH (Sobek et al., 1978). Total N was measured calorimetrically after Kjeldahal digestion (Bremner and Mulvaney, 1982). Plant available P was analyzed with 0.5M $NaHCO_3$ method (Olsen and Sommers, 1982). Total P was determined with the perchloric acid digestion method (Olsen and Sommers, 1982).

Results and Discussion

Effects on Refuse Physical and Chemical Properties

Physical and chemical conditions of the soil are critical for vegetation growth, and the reclamation of coal refuse generally is not successful without topsoiling or heavy use of amendments. For comparative purposes, the total elemental content of the lime-fiber mulch material and the raw refuse from Pine Branch are given in Table 2. The mulch material as applied was 29% C and very high in Ca derived from its waste lime content, which led to a high neutralization potential (197 tons lime/thousand tons material). The Pine Branch refuse averages around 19% C due to its carbonaceous nature (Stewart, 1990).

Previous studies have shown that heavy metal bioaccumulation is generally not a problem for applications of papermill sludge because of the low concentrations applied and the lack of uptake or toxic effects in sensitive crops like tomatoes, cucumbers and peppers (Ritter et al., 1992; Cline and Chong, 1991; and Bellamy et al., 1995). In general, the lime-fiber mulch material applied at Pine Branch was similar to or lower than the host refuse in heavy metals and should pose no long term heavy metal loading concerns, particularly when the pH buffering of the lime component is taken into account. Thus, this waste product appears very attractive as a mine soil amendment, particularly for acid-forming materials. In one application, wood fiber residues are added to work as a surface mulching agent and organic matter amendment, lime is added to neutralize acidity and buffer soil solution pH, and a smaller amount of clay and ash are added to aid with water retention and to slow the rate of water percolation down away from the rooting zone.

Lab analyses indicated that addition of lime-fiber mulch not only increased and stabilized the soil pH, but also increased the available P levels in the soil (Figs. 1 and 2). This portion of the Pine Branch refuse pile was moderate in pH before the plots were established, perhaps due to earlier lime additions by the company. In 1992, the pH of the refuse was around 6.5 with a large amount of point to point variation. Lime fiber mulch additions increased pH to 7.0 to 7.8, but by 1993, the pH of refuse from control plots had decreased somewhat, most likely due to oxidation of trace pyrites due to incorporation disturbance.

It appeared that due to its high neutralization potential, the lime-fiber material neutralized acidity and/or inhibited the pyrite oxidation, and reduced the solubility of Fe (Backes et al., 1986). Pichtel and Dick (1991) report that organic materials can serve as inhibitors to reduce acid production from pyrite by preventing Fe-oxidation and by removing soluble Fe from solution. The effects of Liming and inhibition probably worked together by raising soil pH and reducing Fe and Al levels. This combined effect should also increase the availability of P, since at low pH, P is immobilized mainly by Fe and Al (see discussion of soil leachate properties). The average extractable P increased ($p < 0.05$) from 4.9 to 21.3 mg kg^{-1} with addition of lime-fiber mulch.

Adverse soil water conditions including seasonal waterlogging and drought are common problems during reclamation (Rimmer, 1982). Our monthly field observations indicated that waterlogging and runoff occurred only on the untreated refuse plots in the winter and after heavy storm events in summer. In contrast, there was no waterlogging and/or runoff observed on the lime-fiber mulch plots due to improved infiltration and water holding capacity (WHC). Without lime-fiber mulch, the average WHC was 87 g kg^{-1}; with treatment it increased to 175 and 230 g kg^{-1} with the addition of 112 and 224 Mg ha^{-1} lime-fiber mulch, respectively (Fig. 3). Figure 4 indicates that the increase in WHC occurred mostly in the low tension portion (or readily available) of the curve.

The surface temperature of bare coal waste is very high in the summer, reaching as high as 75^0 C (Deely and Borden, 1973; Lee et al., 1975), a level lethal to plants. Our field measurements indicate that the lime-fiber mulch effectively moderated the surface temperature (Fig.5, $p < 0.05$). This temperature buffering is most likely due to the combined effects of direct mulching, improved vegetative cover, soil albedo effects (lighter), and improved soil WHC.

Table 2. Elemental analysis of coal refuse and lime-fiber mulch materials.

Sample	Neutralization potential	Total N%	Total P%	C%	Si%	Al%	Fe%	Ca%
refuse	------------------	0.27	0.016	19.0	22.2	9.1	3.0	2.3
sludge	197 tons lime $(1000\ tons)^{-1}$	0.14	0.030	29.2	9.5	5.0	2.6	7.9

Sample	Mg%	Zn_{ppm}	Cu_{ppm}	Mn_{ppm}	Pb_{ppm}	Ni_{ppm}	Cr_{ppm}	Cd_{ppm}
refuse	0.8	112.0	26.0	1026	15.8	29.8	83.8	6.4
sludge	0.3	98.7	47.3	1213	24.0	33.7	103.4	2.5

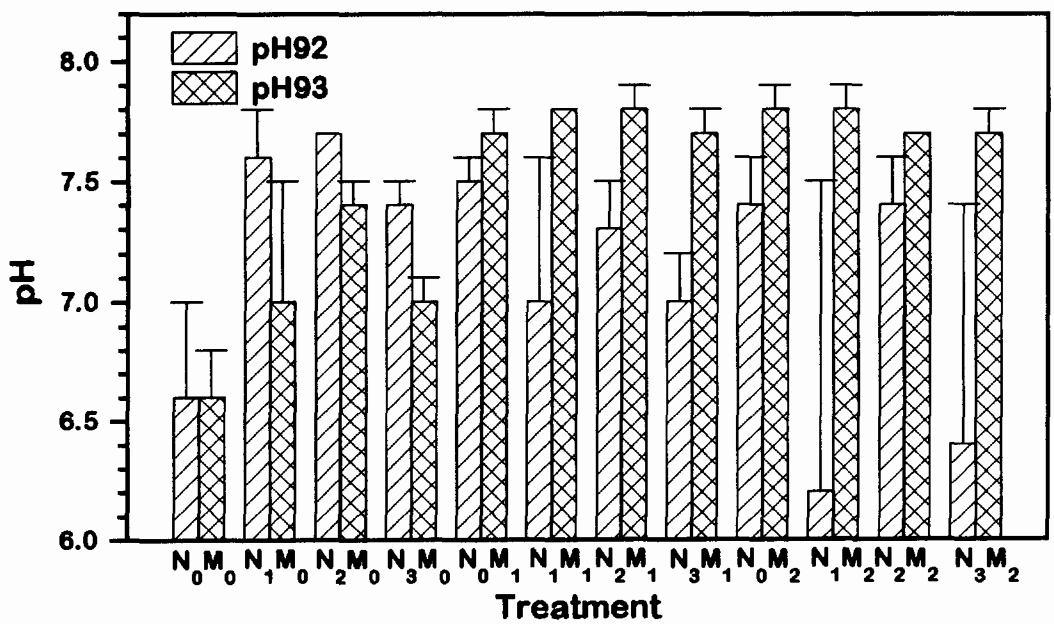

Figure 1. Soil pH in 1992 and 1993. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch; Soil samples taken on March 1992, and on Oct. 1993 before and after application of papermill sludge. Values are means (n = 3) with standard errors.

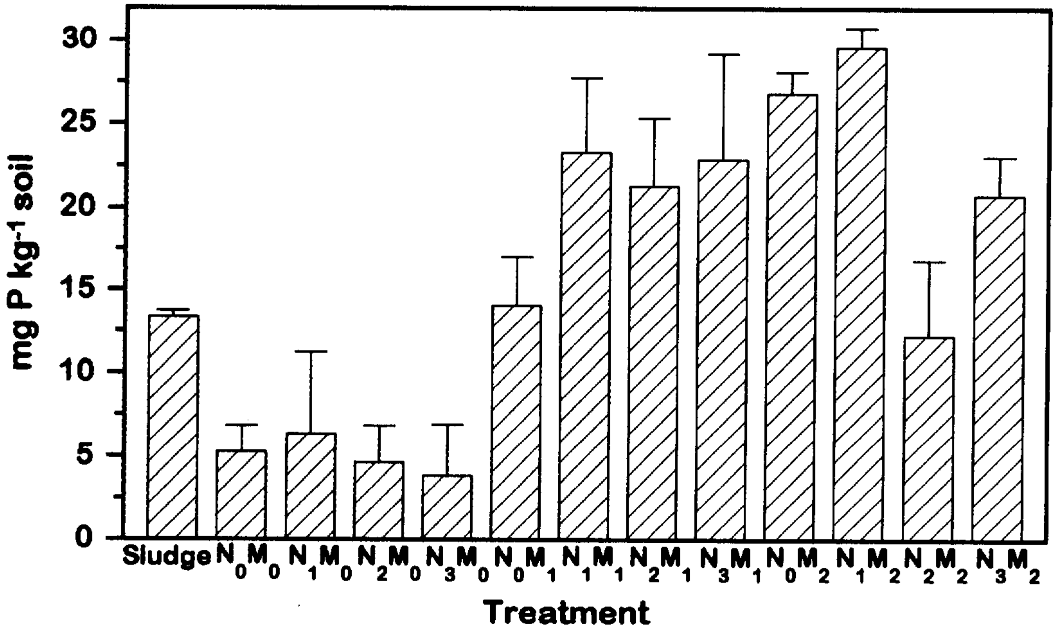

Figure 2. Available P in 1993. Sludge: Lime-fiber sludge; N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch; Soil samples taken on Oct. 1993, and values are means (n = 3) with standard errors.

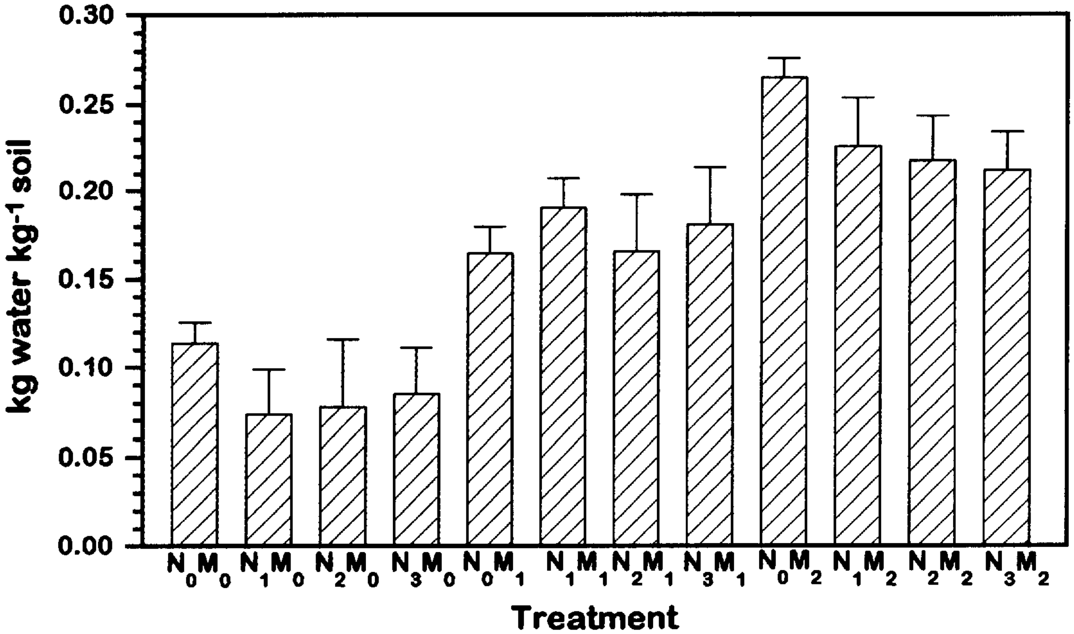

Figure 3. Soil water holding capacities (-0.01Mpa to -1.5Mpa) in 1993. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch. Soil samples taken on Oct.1993, and values are means (n = 3) with standard errors.

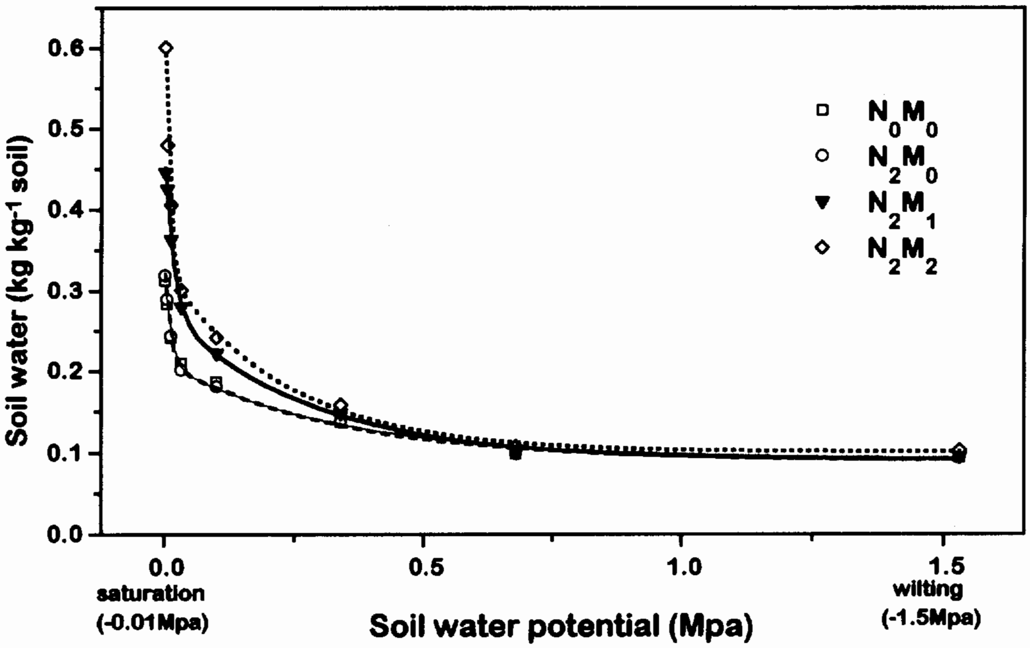

Figure 4. Soil moisture potential curves for samples taken in 1993. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch;

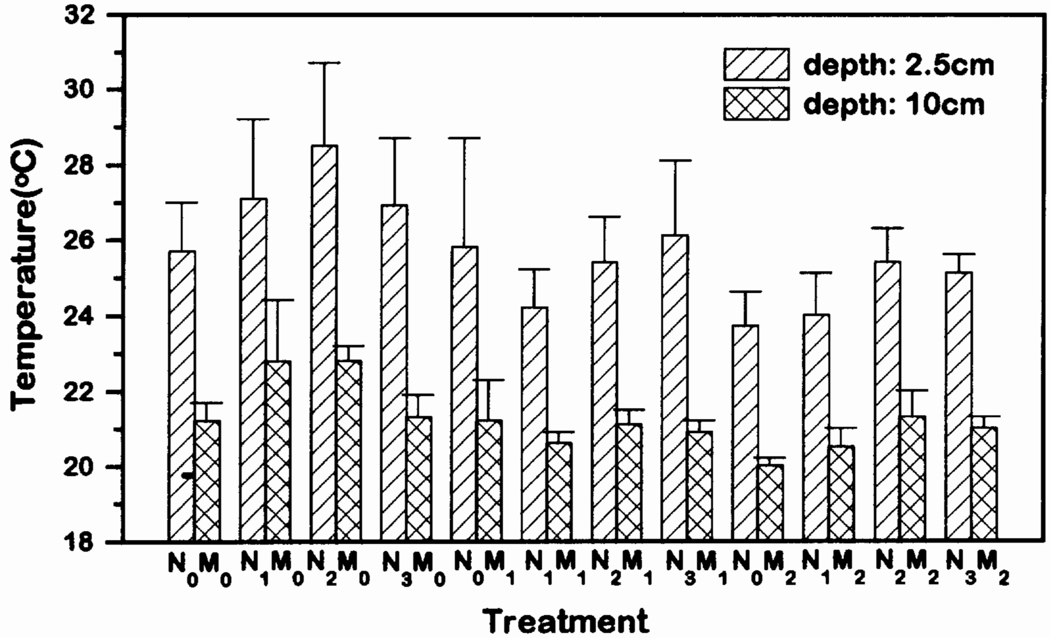

Figure 5. Effects of treatment on soil temperature. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3:336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch; Temperatures measured on Aug. 18, 1994, and values are means (n = 3) with standard errors.

Biomass Yield and Plant Performance

Biomass yield and overall plant performance are the most commonly employed indicators of revegetation success. Total standing biomass yields in the fall of 1992, 1993 and 1994 are shown in Fig. 6. In 1992, standing yields were determined on the German millet cover crop only. In 1992, there were significant effects due to N-fertilizer rate, but no differences among mulch treatments. Millet is known to have a strong N-fertilizer response, and both the raw lime-fiber mulch and the raw refuse are quite N-deficient. Thus, in 1992, the millet biomass accumulation appeared to be driven primarily by fertility with no obvious effect from the mulching treatment. In fact, the mulched treatments appeared to be less vigorous than the unmulched plots. We attribute this to (1) the fact that the millet is adapted to hot summer conditions, (2) our relatively late spring seeding date, and (3) that the wet summer of 1992 may have negated any positive mulching effects.

The mixed grass/legume stand was established in the fall of 1992, and by the fall of 1993 it had established a vigorous and nearly complete cover over the better performing treatments. Both N and mulch application rates influenced ($p=0.01$) yields in 1993 (Fig. 6), and worked well in combination. Variation of biomass production within each treatment was less in 1993 than that in 1992 and the total vegetative production was consistently improved by mulch and moderate N application. The application of lime-fiber mulch increased overall plant cover across all N rates in 1993 (Fig. 7), and provided almost complete vegetative cover when combined with moderate N rates. Increasing the mulch rate from 112 to 224 Mg ha^{-1} did not appear to improve vegetation performance, however. The composition of the vegetation varied ($p < 0.05$) in response to N rate across all mulch treatments. In general, the higher the N application, the less the legume component, and the greater the grass component (Fig. 7). Nitrogen fertilizer applications clearly increased the total vegetative cover but had the tendency to suppress legume growth, which is a commonly observed phenomenon in mixed stands.

Increasing the fertilizer beyond 112 kg ha^{-1} did not appear to improve total biomass production. This indicates that the application of lime-fiber mulch material does not lead to excessive N-fertilizer immobilization by soil microbial decomposers as we had feared. Apparently, the C substrate within the mulch is either extremely resistant to microbial attack or has already been significantly degraded in the water treatment process at the mill. Regardless of the reason, it does not appear that heavy N applications will be necessary for this product to be successfully utilized in mine reclamation.

The overall evaluation of vegetative cover shown in Figure 7 was made in October 1993, integrates both total ground cover and plant vigor, and therefore varies somewhat from the percent cover evaluation for each treatment. Based on the overall evaluation data it is clear that the N_0M_0 (no N, no mulch) plot performance was poor (grade <2.5); while the N_1M_0 (112 kg ha^{-1} N, no mulch) and the N_0M_1 (no N, 112 Mg ha^{-1} mulch) resulted in fair vegetation performance with grades of 3.3 and 2.7, respectively. Treatments that combined lime-fiber mulch and N fertilizer generated thick and vigorous vegetation (Fig. 7), reinforcing our finding that a combination of the lime-fiber mulch and N fertilizer appears to be a very successful treatment for direct seeding of this coarse coal refuse material. The data in Figure 7 also indicate that the ratio of legume/grass can be regulated by the rate of N fertilizer, particularly when the lime-fiber mulch is utilized. This effect was particularly pronounced in the highest mulch rate treatments. Apparently, increasing N-fertilizer in this situation decreases the competitive advantage held by the N-fixing legume and leads to a higher grass/legume ratio in the mixed stand.

The yield data from 1994 indicate that the N treatment effect became some negative, and only the lime-fiber mulch effect continued to be positive and significant (Fig. 8, $p < 0.01$). We also detected a trend of lower 1994 yields with increasing N fertilizer applied. As discussed earlier, N-fertilizer had the tendency to depress legume community establishment; therefore, the legume component clearly decreased with increasing N rate (Figs. 7 and 8). In a short period of time, the N from the original fertilization is lost through leaching, uptake, gaseous loss, etc.. Subsequently, those plots which lack the N-fixation capability of the legumes, become N-deficient for grass production and hence their lower yields over time.

The overall plant performance respond patterns varied between 1993 and 1994. In 1993, there were three performance peaks that corresponded to the high rate of N across the three high lime-fiber mulch rates (Fig. 7). This pattern indicated that both the N fertilizer and lime-fiber mulch were playing an important role in vegetation performance. However, in 1994, the performance appeared as a stair-step

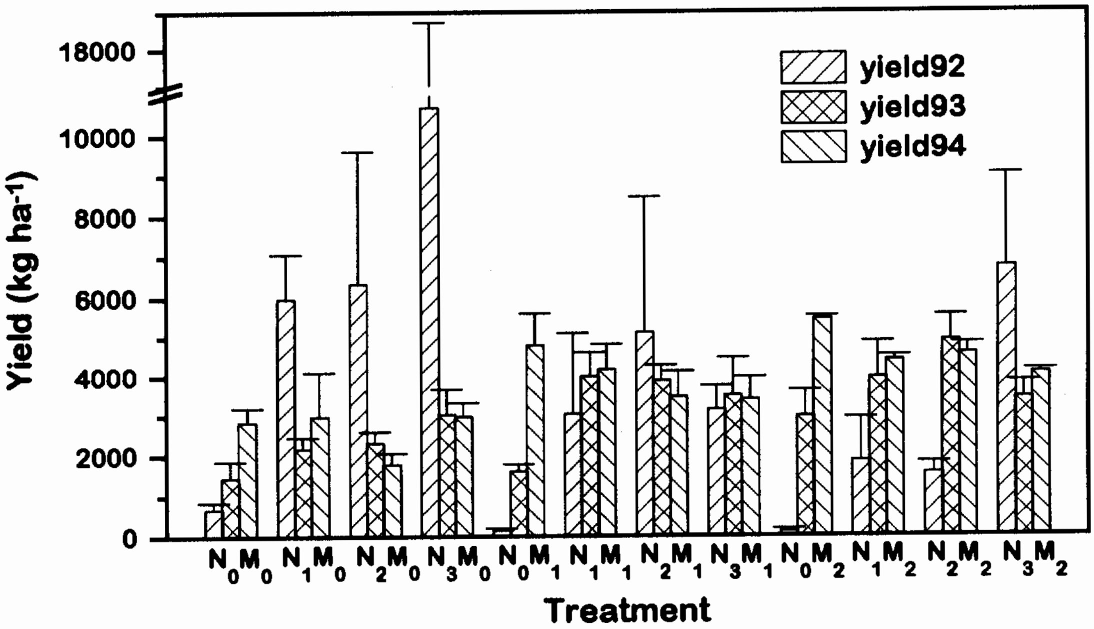

Figure 6. Biomass yield as influenced by lime fiber mulch and N application. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch; values are means (n = 3) with standard errors.

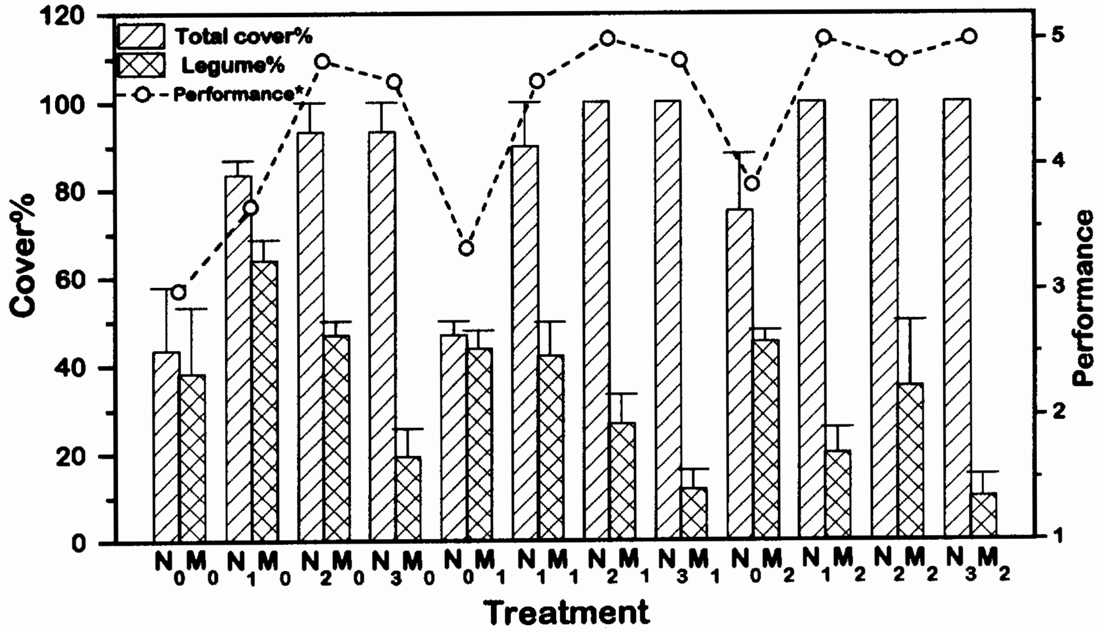

Figure 7. Vegetation cover % and performance evaluation in 1993. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch. *2: poor; 3: fair; 4: good; 5: excellent. Field survey of vegetation on Oct. 5, 1993, and values are means (n=3) with standard errors shown.

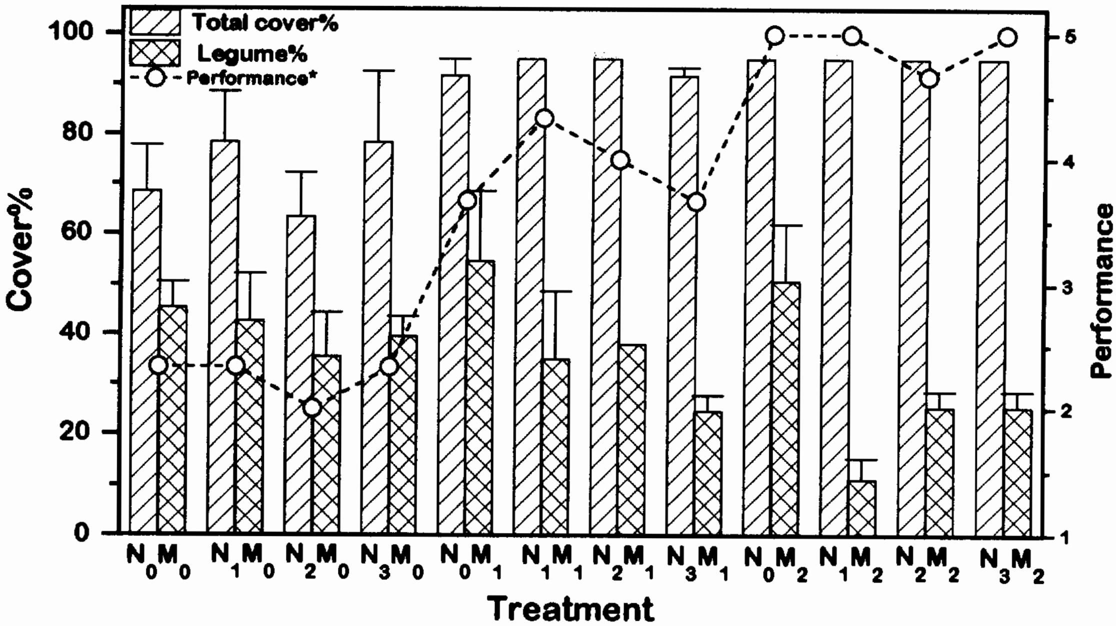

Figure 8. vegetation cover % and performance evaluation in 1994. N_0: no N fertilizer; N_1: 112kg N ha^{-1}; N_2: 224kg N ha^{-1}; N_3: 336kg N ha^{-1}; M_0: no sludge mulch; M_1: 112 Mg ha^{-1} sludge mulch; M_2: 224 Mg ha^{-1} sludge mulch. *2: poor; 3: fair; 4: good; 5: excellent. Field survey of vegetation on Oct. 21, 1994, and values are means (n=3) with standard errors shown.

pattern. The overall performance increased strongly with increasing mulch rate, indicating that the mulch contributed the majority of the positive impact on vegetation performance. It was notable that the higher rate of N appeared to have a negative effect on performance to some extent (Fig. 8). The vegetation performance in the group with no lime-fiber mulch (N_0M_0, N_1M_0, N_2M_0, and N_3M_0) was poor, and had an average grade of 2.2. The vegetation for the N_xM_1 group (112 Mg ha^{-1} lime-fiber mulch) performed well and its average grade was 3.9. The N_xM_2 group as a whole (224 Mg ha^{-1} lime-fiber mulch) exhibited excellent vegetation performance with a grade of 4.9.

During the three years of this study (1992-1994), the yields increased over time on the plots with 0 or low rates of N fertilizer application across all lime-fiber mulch treatments (Fig. 6; see plots of N_0M_0, N_1M_0, N_0M_1, N_1M_1, N_0M_2, N_1M_2). Simultaneously, the yields were decreasing on plots receiving high rates of N fertilizer and no lime-fiber mulch (Groups of N_2M_0, N_3M_0). This result is consistent with other studies that have shown that a single application of N can have a major effect on the initial growth of non-leguminous vegetation, but little effect on establishment of a self-sustaining grass cover on coal waste (Davison and Jefferies, 1966; Bloomfield et al., 1982). There was no doubt that lime-fiber mulch improved both physical and chemical properties of coal refuse, supplied a better condition for plant growth, and led to more vigorous vegetation growth and associated higher yields over multiple seasons.

Soil Leachate Properties

The leachate data from the lysimeters at Pine Branch suggested that with lime-fiber mulch application, the pH of the leachates were relatively stable. The pH varied from 6.5 to 7.2 with an average of 7.2, well within the range suitable for vegetative growth (Table 3) and minimal heavy metal solubility. In contrast, without lime-fiber mulch application, The pH of leachates was lower (5.9) with greater variation (4.5 to 6.9). As mentioned earlier, the levels of soluble Fe, Al were controlled by pH, which in turn determined the level of available P. Lime-fiber mulch treatment reduced the concentration of heavy metal in leachate (Table 3); Mn, Zn, and Cu levels were lower and more stable than untreated controls. The improvement in leachate metal content presumably

Table 3. Average leachate properties under control and lime-fiber mulch plots from December, 1992 to July, 1994 (n=20).

	Treatment	Mean	STD Error	Miximum	Maximum
pH	0 Mg ha^{-1} Mulch	5.88	0.11	4.46	6.90
	224 Mg ha^{-1} Mulch	7.23	0.06	6.53	7.59
EC(S m^{-1})	0 Mg ha^{-1} Mulch	0.09	0.09	0.04	0.16
	224 Mg ha^{-1} Mulch	0.08	0.01	0.04	0.14
Fe(mg l^{-1})	0 Mg ha^{-1} Mulch	1.41	0.50	0.02	8.05
	224 Mg ha^{-1} Mulch	0.08	0.02	0.02	0.48
Al(mg l^{-1})	0 Mg ha^{-1} Mulch	6.64	3.99	0.00	75.94
	224 Mg ha^{-1} Mulch	0.11	0.02	0.00	0.34
Mn(mg l^{-1})	0 Mg ha^{-1} Mulch	1.12	0.51	0.05	9.80
	224 Mg ha^{-1} Mulch	0.09	0.04	0.00	0.55
Zn(mg l^{-1})	0 Mg ha^{-1} Mulch	0.47	0.27	0.00	5.19
	224 Mg ha^{-1} Mulch	0.04	0.02	0.00	0.48
Cu(mg l^{-1})	0 Mg ha^{-1} Mulch	0.07	0.05	0.00	1.00
	224 Mg ha^{-1} Mulch	0.01	0.00	0.00	0.04
Ca(mgl^{-1})	0 Mg ha^{-1} Mulch	190.61	27.03	49.26	471.75
	224 Mg ha^{-1} Mulch	203.24	22.33	89.07	438.50
S(mg l^{-1})	0 Mg ha^{-1} Mulch	210.99	43.58	49.33	861.70
	224 Mg ha^{-1} Mulch	144.54	25.93	20.33	452.70

would benefit deeper water quality in the refuse pile, but the overall effect of this surficial treatment on net pile discharge deserves further study.

The specific conductance of soil leachates is proportional to ionic strength, and is increased dramatically by pyrite oxidation products. Conductance values may also increase due to lime and fertilizer dissolution products. In most cases, the EC of leachates observed under the lime-fiber mulch was lower than that of control over time due to the buffering action of the lime-fiber mulch material (Table 3). The Ca levels in leachates varied from 50 to 370 mg l^{-1} (Fig. 9), while other cations ranged from 0 - 16 mg l^{-1} for control and 0 - 0.5 mg l^{-1} for the lime-fiber mulch treatment (Table 3), respectively. Taken together with Table 3, these data indicate that Ca was the dominant cation in leachates. The solution sulfate (S) levels under lime-fiber mulch decreased with time, and were generally lower than that of controls (Fig. 9). Over time, the S levels for both control and mulch treatments varied between 50 and 400 mg l^{-1}, which was similar to that of Ca. The Ca and S rose and fell along with each other (Fig. 9); correlation coefficients (r) between S and Ca were 0.96 for both control and lime-fiber mulch, indicating that they are controlled by a common solid phase mineral, most likely a complex gypsum salt (Stewart and Daniels, 1992).

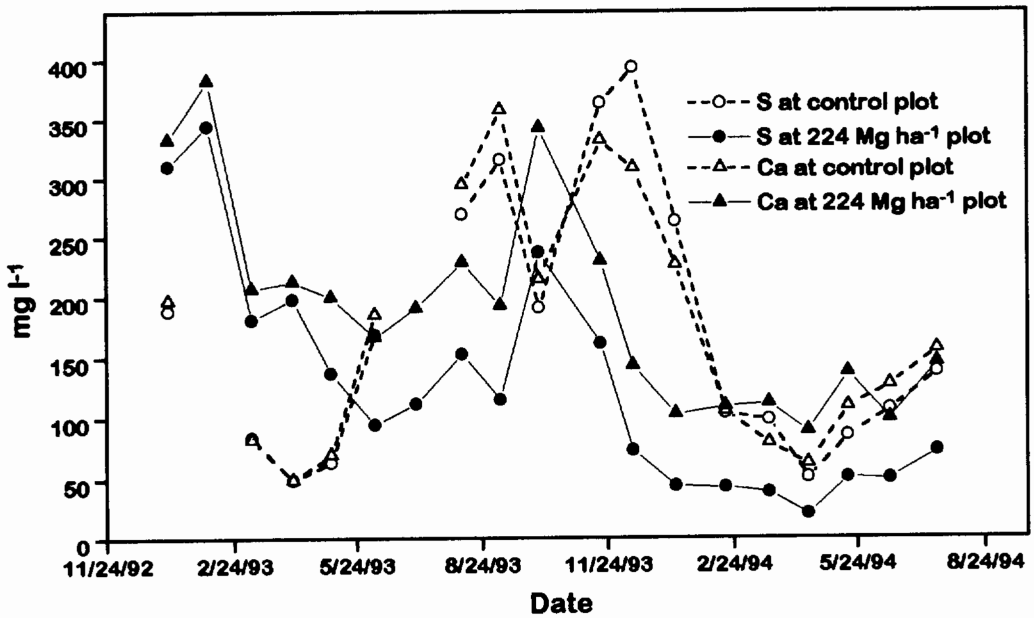

Figure 9. Leachate Ca and S in immediate surface (0.45m in depth) from January 8, 1992 to July 21, 1994.

Overall Conclusions

Application of N-fertilizer in combination with lime-fiber mulch can greatly improve the establishment and growth of vegetation when it is direct-seeded onto coal refuse. Nitrogen fertilizer alone improved millet establishment and gave a short-term boost to biomass production, but lime-fiber applications led to even higher biomass production by buffering the soil pH and improving soil physical conditions over the long term. The combination of N-fertilizer and lime-fiber mulch resulted in the highest mixed stand vegetative cover and production in 1993, and the ratio of grass to legume was regulated by the rate of N fertilizer. The combined mulch and fertilizer treatments produced ground covers greater than 90% at the end of the second growing season. During the third growing season (1994), there was a positive effect from lime-fiber mulch coupled with a significant negative effect of the high N-rate on vegetation due to the suppression of legumes in earlier years.

Application of lime-fiber mulch onto coal refuse is not only beneficial to revegetation objectives, but appears to improve leachate quality as well. With the application of lime-fiber mulch, the leachates were higher in pH and lower in toxic metals, which could reduce the chance of groundwater contamination with heavy metals and moderate the impact of discharged waters on the environment. Surface treatment of an entire pile with a reasonable loading rate of this product could effectively charge all waters percolating through the pile surface with alkalinity. Whether or not this would have any significant impact on whole-pile discharge water quality deserves further study.

In summary, the lime-fiber mulch material appears to have outstanding potential as a soil amendment for coal refuse in the central Appalachians. Due to its lime content, we also presume that this product would have great utility in treating acid-forming materials as well. From both a short and a long-term perspective, a proper combination of N fertilizer (112 kg ha^{-1}) with lime-fiber mulch (112 Mg ha^{-1}) is recommended for the reclamation of coal refuse materials.

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