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Reclamation of Acid, Toxic Coal Spoils Using Wet Flue Gas Desulfurization By-Product, Fly Ash and Sewage Sludge

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FOREWORD

This report was prepared by The Ohio State University, Ohio Agricultural Research and Development Center, Wooster, under Department of Energy Contract No. 1432 J0250004. The contract was initiated under the Abandoned Mine Land Research Program. It was administered under the technical direction of the Department of Energy, Pittsburgh Research Center with Mr. David Hyman as technical project officer. Mr. Michael L. Nowicki was the contract administrator for the Department of Energy. This draft final report was submitted by the authors on March 12, 1998.

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Department of Energy or of the United States Government.

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Reclamation of Acid, Toxic Coal Spoils Using Wet Flue Gas Desulfurization By-product, Fly Ash and Sewage Sludge

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I. INTRODUCTION

Establishment of vegetation on acid abandoned minelands requires modification of soil physical and chemical conditions. Covering the acid minesoil with topsoil or borrow soil is a common practice but this method may be restricted by availability of borrow soil and cause damage to the borrow site. An alternative approach is to use waste materials as soil amendments. There is a long history of using sewage sludge (Sopper,1992) and fly ash (Capp,1978; Buck and Houston,1988) as amendments for acid minesoils. Flue gas desulfurization (FGD) by-products are newer materials that are also promising amendments (Stehouwer et al.,1995). Most flue gas sludges are mixtures of calcium sulfate ($CaSO_4$), calcium sulfite ($CaSO_3$), calcium carbonate ($CaCO_3$), calcium hydroxide [$Ca(OH)_2$], and fly ash (Shahandeh and Sumner,1993). Some scrubbing processes produce almost pure gypsum ($CaSO_4 \cdot 2H_2O$).

The primary purpose of our project is to evaluate two wet FGD by-products for effects on vegetation establishment and surface and ground water quality on an acid minesoil. One by-product from the Conesville, OH power plant (American Electric Power Service Corporation) contains primarily calcium sulfite and fly ash. The other by-product (Mg-gypsum FGD) from an experimental scrubber at the Zimmer power plant (Cincinnati Gas and Electric Company) is primarily gypsum with 4% magnesium hydroxide [$Mg(OH)_2$]. These materials were compared with borrow soil and sewage sludge as minesoil amendments. Combinations of each FGD sludge with sewage sludge were also tested. This report summarizes two years of measurements of chemical composition of runoff water, ground water at two depths in the subsoil, soil chemical properties, elemental composition and yield of herbaceous ground cover, and elemental composition, survival and height of trees planted on plots treated with the various amendments. The borrow soil is the control for comparison with the other treatments.

II. METHODS

The study is at Unit II of the Eastern Ohio Resource Development Center in Noble County, Ohio on land mined by contour stripping in 1946. The sites were almost barren despite regrading and planting in 1970. We used a split-plot design with soil amendment treatments as main plots and tree species as subplots, with four replications. One replication faced west on a 24% slope. The other three replications faced southeast on slopes of 6%, 5%, and 19%. One composite soil sample (0-20 cm depth) was collected from each replication before regrading. The soil was extremely acid and had low levels of extractable nutrients (Table 1).

The sites were regraded with a D-6 dozer to remove gullies in summer 1995 and then treated with six soil amendments. Treatments were: 1) aerobically-digested sewage sludge from

Table 1. Characteristics of unamended minesoil, borrow soil, sewage sludge, and flue gas desulfurization (FGD) by-products.

Parameter[1]	Minesoil before regrading	Borrow soil	Sewage sludge	Conesville FGD	Mg-gypsum FGD
pH, (1:1 soil/water)	3.4	7.8	6.6	9.9	9.7
EC, dS/m	0.2	0.2	7.8	na	na
TNP (%$CaCO_3$ equiv)	na[2]	na	na	14	7
Total N, g/kg			9.0	na	na
Organic N, g/kg			8.0		
Ammonia N, g/kg			<1.0		
Major Elements	Extractable[3],		Total Analysis, g/kg		
P	5.5	3	5.0	na	<0.1
K	43	249	4.9	na	0.3
Ca	<125	7150	74	290	240
Mg	36	88	11.9	na	20
S	na	na	na	175	179
Trace Elements			Total Analysis, mg/kg		
As	na	na	10	54	5.4
Cd			1.1	<0.2	<0.2
Cr			84	24	28
Cu			182	19	5.9
Hg			<3.2	<1.0	<1.0
Mo			3.6	3.8	2.4
Ni			39	18	21
Pb			71	9.7	<2.0
Se			0.5	4.2	4.0
Zn			435	44	15

[1]EC = Electrical conductivity; TNP = Total Neutralizing Potential
[2]na = not analyzed
[3]Bray 1 extraction for P. Ammonium acetate extraction for K, Ca, and Mg.

Byesville, Ohio at 100 Mg/ha, 2) gypsiferous FGD by-product (Mg-gypsum FGD) with 4% $Mg(OH)_2$ at 280 Mg/ha, 3) Conesville FGD by-product with fly ash at 600 Mg/ha, 4) sewage sludge plus Mg-gypsum FGD, 5) sewage sludge plus Conesville FGD, and 6) a red, silty clay borrow soil applied to a depth of 25-30 cm. Rates of FGD were based on results of greenhouse studies and aimed at applying equal amounts of neutralizing capacity. The borrow soil was being used in a reclamation project adjacent to the study area. Chemical properties of the borrow soil, sewage sludge, and FGD by-products are listed in Table 1. All amendments were applied by volume using volume rates calculated from bulk densities of amendment materials. Conesville FGD and borrow soil were dumped by front-end loader into the plots and then spread with a small dozer. Sewage sludge and Mg-gypsum FGD were measured by front-end loader into a manure spreader and then distributed on the plots. All amendments except borrow soil were incorporated as deeply as possible by rototilling, but probably to less than 30 cm depth for most treatments. The large volume of Conesville FGD required on each plot was applied in two stages and rototilled after each stage. Treatments were applied in fall 1995 to 9 m by 15 m plots. Plots were separated by berms on all sides to exclude extraneous runoff.

All plots were fertilized with KCl at 900 kg/ha (472 kg/ha K). Plots that did not receive sewage sludge were also fertilized with ammonium nitrate at 280 kg/ha (92 kg/ha N) and triple superphosphate at 493 kg/ha (100 kg/ha P). Sewage sludge contributed 890 kg/ha total N and 500 kg/ha total P to plots receiving sludge. In fall 1995, plots were broadcast seeded with a winter wheat (Triticum aestivum L.) cover crop and a mix (kg/ha) of birdsfoot trefoil-Lotus corniculatus (10), red clover-Trifolium pratense (6.7), perennial ryegrass-Lolium perenne (9), and timothy (Phleum pratense (20.2). Clean wheat straw mulch was applied at 4.5 Mg/ha.

Ten seedlings of white ash (Fraxinus americana L.), black locust (Robinia pseudoacacia L.), sycamore (Platanus occidentalis L.), and sweetgum (Liquidambar styraciflua L.) were planted by dibble bar in each plot in spring 1996. Trees were planted on the contour in two-row subplots at 1.2 m by 1.5 m spacing, with 2.4 m between subplots. The initial planting stock was one-year-old, bare-root seedlings from state nurseries in Ohio and West Virginia. Dead seedlings were replaced in spring 1997 using stock held in a transplant nursery.

A composite soil sample (0-20 cm depth) was collected from each plot in July 1995 after the sites were regraded but before amendments were applied. Composite soil samples were also collected in 10 cm increments to 60 cm depth from two bucket-auger cores in each plot in June 1996 and in 10 cm increments to 90 cm in July 1997. Soil samples were ground to pass a 2 mm screen, extracted with 1 M KCl at 1:10 soil/KCl, and analyzed for Al, B, Ca, Cd, Cr, Cu, Fe, Mg, Mn, Mo, Na, Ni, P, Pb, S, Si, Sr, and Zn using inductively coupled plasma emission spectrometry (Leeman Labs Inc. Model PS2000).. Soil pH was measured by glass electrode on a 1:1 soil/water mix and electrical conductivity was measured on a 1:2 soil/water extract.

Four porous-cup suction lysimeters were installed in each plot, two toward the upper end of the plot and two at the lower end in spring of 1996. One of each pair was at 30 cm, the other at 60 cm. Water at these depths was sampled periodically when precipitation was sufficient to wet the soil profile. We pulled a vacuum of approximately 50 centibars on the lysimeters, waited at least 24 hours, then sampled the water pulled into the lysimeter through the porous cup. These water samples were analyzed for a suite of elements by inductively coupled plasma emission spectrometry of a filtered aliquot. Alkalinity and acidity were determined titrimetrically, and pH was measured with a glass electrode.

A flume for sampling surface runoff was installed in the middle of the lower berm on each plot (Figure 1). Flumes were constructed from treated plywood (copper-chromium-arsenic, ground contact, 0.40 lb/cubic foot) and coated with roofing tar after installation. A slotted PVC pipe was fitted below the mouth of each flume and conveyed a portion of the runoff to a 190 L polyethylene storage barrel. We collected runoff samples after those rainfall events that were heavy enough to produce runoff. The water in each storage barrel was stirred to suspend any sediment and a 250 mL sample was collected. Runoff samples were refrigerated prior to analysis. Conductivity and pH were measured directly on unfiltered samples. An aliquot of runoff sample was digested for 4 hours in a nitric-perchloric mix, then diluted to 50 ml with deionized water and analyzed for elemental composition by inductively coupled emission spectroscopy (ICP). A second aliquot was filtered through Whatman #1 paper. Filterable residue was determined by weighing. Acidity and alkalinity of the filtrate were determined by titration, and elemental composition by ICP. When a complete set of runoff samples was obtained during a major rainstorm, we also determined anion concentrations by ion chromatography using a Dionex Model 14 instrument in 1996 and a Dionex Model DX 120 instrument in 1997.

Ground cover biomass was measured in June 1996 and 1997 by mowing two strips (total area 11.6 m^2 in 1996 and 8.6 m^2 in 1997) in each plot, weighing the moist biomass in the field, and bringing a subsample to the laboratory for moisture determination. Subsamples were dried, weighed, ground in a Wiley mill, ashed in nitric-perchloric acid, and analyzed for Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Si, Sr, V, and Zn using inductively coupled plasma emission spectrometry. Canopy cover percentages (grasses, legumes, other herbs) were visually estimated in square quadrats (0.5 m^2) in June 1997. One sample quadrat was located randomly in the upper, middle, and lower third of each plot (3 quadrats per plot).

Tree survival and height (nearest cm) were measured in June and September 1996 and in September 1997. Data on height growth rather than total height is presented because of variations in initial heights of planted seedlings. Tree foliage samples were collected near the end of the second growing season in August 1997. For each tree species, a composite sample was collected from each plot by combining two or more leaves from each live tree. Samples for black locust and white ash included the leaf rachis as well as the leaflets. Samples were dried, weighed, ground in a Wiley mill, and analyzed for the same suite of elements as for ground cover.

Data were analyzed by analysis of variance, using Statistical Analysis System (SAS) software (SAS Institute Inc.,1987). Data for each year were analyzed separately. Soil chemical data were analyzed separately by sample depth. Data for each lysimeter water quality characteristic were subjected to a separate analysis of variance for each depth, and to an analysis of the main effects of depth and its interactions with soil amendment treatment. When analysis of variance showed that treatment effects or interactions were significant at the 5 % level of probability, the least significant difference (LSD) or Duncan's multiple range test was computed and used in mean separation. In many cases, results within treatments were so variable that treatment effects were not significant, even though there were large differences among means.

III. RESULTS

A. Soil Chemistry

Soil pH. In June 1996 and July 1997, soil pH (0-10 cm depth) was 6.5 or greater for all treatments except sewage sludge alone (pH 4.6) (Table 2). For borrow soil and treatments receiving Conesville FGD, soil pH was elevated to a depth of 20-30 cm in both years, while for the other treatments, there was a sharp drop in pH below 20 cm. This was probably because the high rate of Conesville FGD was applied in two stages and rototilled after each stage, resulting in deeper incorporation of that material. The greater depth of incorporation for Conesville FGD affected depth functions of several other soil properties. In 1997, soil pH at depths below 50 cm was consistently higher under borrow soil than under any of the other treatments (Table 2).

Electrical Conductivity. Electrical conductivity (EC) was generally greater for all FGD treatments than for borrow soil or sewage sludge alone (Table 3). In 1997, EC was appreciably higher at all depths in all treatments receiving FGD than in those with borrow soil or sewage sludge alone, except for some lower depths of the sewage sludge plus Mg-gypsum FGD combination. The increase in EC with depth for borrow soil in 1996 is puzzling because samples from the 40-60 cm depths would be in unamended minesoil, which had a low EC (0.43 dS/m).

Calcium. Ca levels in all treatments with FGD were much higher than those in borrow soil or sewage sludge alone in the upper two soil increments, both in 1996 and 1997 (Table 4). Below 20 cm, extractable Ca in Conesville FGD was generally higher than in the Mg-gypsum FGD treatments. The elevated Ca levels down to 70 cm in soils receiving Conesville FGD suggest improvement in rooting environment down to this depth.

Magnesium. Not surprisingly, treatments using Mg-gypsum FGD had the highest amounts of extractable Mg in the upper 20 com, both in 1996 and 1997 (Table 5). Conseville FGD gave higher concentrations than borrow soil or sewage sludge alone, down to 20 cm. Below 20 cm, both FGD treatments were generally higher in Mg than borrow soil or sewage sludge alone, although below 70 cm, differences among treatments were not statistically significant.

Aluminum. Extractable Al was greatest for sewage sludge alone in both years at all depths. For the other treatments, there was an abrupt increase in Al concentration at some depth, probably marking the transition from borrow soil to spoil or from mixed spoil-FGD to unamended spoil (Table 6).

Sulfur. All plots amended with FGD had extractable S levels greater than those in plots with borrow soil or sewage sludge alone, especially in the upper 30 cm (Table 7).

Boron. Boron is an essential plant nutrient, but with a narrow range between sufficiency and toxicity (Romheld and Marschner, 1991, Vimmerstedt and Glover, 1984) Compared to borrow soil or sewage sludge alone, the Mg-gypsum treatments had greater B in the surface (0-10 cm) layer and the Conesville treatments had greater B throughout the profile (Table 8). The fly ash component of the Conesville FGD contributed the B. The Mg-gypsum FGD apparently contained enough B to produce elevated soil B, although this FGD supposedly contained no fly ash.

Iron and Manganese. These elements are often at high levels in acidic mine spoils. In both years, borrow soil and all the FGD treatments had very low levels of extractable Mn in the upper 10 cm of soil. There were few statistically significant treatment differences at the other depths, although there was a general increase in extractable Mn with depth (Table 9). The only statistically significant treatment effects on extractable Fe were in 1996 in the 50-60 cm depth increment and in 1997 in the 70 -80 cm section. In both cases the sewage sludge treatment was higher in extractable Fe than the other treatments, with the exception of the Mg-gypsum FGD treatment in 1997 (Table 10).

Heavy metals. Cadmium (Table 11), chromium (Table 12), copper (Table 13), molybdenum (Table 14) , lead (Table 15), and nickel (Table 16) were at undetectable or very low levels in both years. Lead was elevated in borrow soil at 70-80 cm in 1997 and relatively higher amounts of Mo were extracted from the 20-30 cm depth in the borrow soil, Mg-gypsum FGD and sewage sludge plus Conesville FGD treatments in 1996. Among the heavy metals, extractable Zn showed the most treatment effects (Table 17). In 1996, sewage sludge alone and sewage sludge plus Mg-gypsum FGD had higher levels of extractable Zn at 10-20 and 20-30 cm than the other treatments. In 1997, Zn was elevated in the sewage sludge treatment at 0-10 and 10-20 cm, as well as in the two lower depths in the sewage sludge and Conesville FGD treatments (Table 17).

Strontium. Sr behavior in soils is somewhat analogous to that of calcium. In both years, the Conesville FGD treatments yielded more extractable Sr in the upper 30 cm of soil than any of the other treatments (Table 18).

Sodium. Sodium is neither an essential plant nutrient nor an element that causes toxicity problems, although it can contribute to excess salinity and soil dispersion. There were no statistically significant treatment effects on the amount of extractable Na in the soil (Table 19).

Silicon. There were no significant treatment effects for extractable Si although below 20 cm depth Conesville FGD tended to have greater Si than the other treatments (Table 20).

Phosphorus. All treatments had low P as extracted by the 1N KCl (Table 21). Extraction with KCl does not provide a good estimate of available P.

Table 2. Soil pH in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	6.97a[2]	6.97A	4.56b	4.22B	7.35a	6.62A	6.53a	6.55A	7.07a	6.66A	7.36a	6.62A
10 - 20	7.09ab	6.93A	3.86d	3.65C	7.36a	6.82A	5.28c	4.70B	7.11ab	6.88A	6.10bc	4.55BC
20 - 30	6.48a	6.31A	3.55b	3.30C	5.88a	5.44B	4.22b	3.78C	6.80a	5.44B	4.15b	3.79C
30 - 40	5.31ab	4.52A	3.62c	3.26C	4.92b	3.97AB	3.65c	3.61BC	5.93a	4.00AB	3.85c	3.72BC
40 - 50	4.42b	4.28A	3.53b	3.46B	4.46ab	3.84AB	3.94b	3.54B	5.41a	3.73B	3.72b	3.59B
50 - 60	3.89	4.53A	3.53	3.48B	4.40	3.74B	3.75	3.48B	4.55	3.70B	3.71	3.62B
60 - 70		4.62A		3.50B		3.71B		3.54B		3.58B		3.61B
70 - 80		4.68A		3.60B		3.55B		3.55B		3.56B		3.62B
80 - 90		4.70A		3.63B		3.62B		3.48B		3.52B		3.62B

[1]Soil samples were collected in June 1996 and July 1997. pH measured on 1:1 soil/water mixture.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 3. Electrical conductivity (dS/m) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.57b[2]	0.38B	0.89b	0.21B	1.96a	1.93A	2.28a	1.98A	1.94a	1.80A	1.96a	1.95A
10 - 20	0.76c	0.44B	0.52c	0.26B	2.09ab	2.03A	2.32ab	1.98A	2.06b	1.94A	2.44a	1.93A
20 - 30	1.05b	0.79B	0.83b	0.51B	2.13a	2.00A	1.82a	2.04A	2.05a	1.96A	2.04a	2.05A
30 - 40	1.01bc	0.51B	0.65c	0.66B	2.08a	1.97A	1.63ab	1.98A	2.10a	1.94A	1.62ab	1.84A
40 - 50	1.28b	0.46C	0.56c	0.42C	2.02a	1.99A	1.64ab	1.52B	2.10a	1.92AB	1.51ab	1.60AB
50 - 60	1.63ab	0.64D	0.66c	0.41D	1.97a	2.00A	1.45abc	1.31C	1.76ab	1.83AB	1.13bc	1.42BC
60 - 70		0.68C		0.45C		1.91A		1.65A		1.92A		1.06B
70 - 80		0.67B		0.55B		1.75A		1.52A		1.64A		0.99B
80 - 90		0.68BC		0.44C		1.64A		1.55A		1.38A		1.08AB

[1]Soil samples were collected in June 1996 and July 1997. Electrical conductivity measured on a 1:2 soil/water extract.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 4. Calcium (Ca) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	3925b[2]	3888B	1699b	1117C	17706a	18697A	14568a	18784A	17837a	18824A	18195a	19224A
10 - 20	4611cd	3870CD	753d	574D	17736a	18817A	8981bc	6842BC	17645a	18689A	13104ab	10226B
20 - 30	3333b	3365B	665b	245B	12905a	12521A	4134b	2925B	15967a	10611A	3529b	2178B
30 - 40	2091c	1515CD	363c	183D	8832b	5036A	1171c	2491BC	13075a	3568AB	1146c	2172BC
40 - 50	1830b	1322BC	276b	143C	5292b	4311A	2459b	2159B	12482a	2978AB	934b	1234BC
50 - 60	1059	1530B	190	121C	5405	3267A	1691	1061BC	5373	2961A	578	903BC
60 - 70		1620BC		107D		2945A		1193CD		2283AB		717CD
70 - 80		1698		204		1744		896		1768		734
80 - 90		1473		83		1316		924		1558		609

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 5. Magnesium (Mg) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	58b[2]	71D	136b	145C	93b	149C	430a	345A	97b	90CD	559a	255B
10 - 20	68b	79C	78b	81C	145b	220B	441a	327A	153b	175BC	584a	355A
20 - 30	80c	70B	64c	54B	172bc	253A	265ab	270A	175bc	230A	362a	278A
30 - 40	65c	55C	68bc	50C	169abc	192AB	209a	254A	190ab	171B	269a	259A
40 - 50	90cd	61CD	67d	52D	139bcd	171AB	230a	224A	170abc	130BC	207ab	231A
50 - 60	88b	95CD	69b	66D	174ab	156BC	223a	213AB	143ab	130BCD	197a	254A
60 - 70		118CD		65D		157BC		202AB		129BCD		243A
70 - 80		126		100		162		164		114		244
80 - 90		137		62		161		153		158		215

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 6. Aluminum (Al) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0[2]	0B	71	176A	1	0B	76	2B	1	0B	0	9B
10 - 20	0b	2B	318a	353A	1b	0B	31b	123B	1b	1B	26b	102B
20 - 30	2c	1C	510a	509A	7c	53C	252b	294B	2c	14C	262b	326B
30 - 40	81c	243B	578a	636A	136bc	267B	330b	360B	0c	208B	346b	346B
40 - 50	212bc	288B	515a	615A	252bc	296B	289abc	432B	86c	339B	374ab	343B
50 - 60	387	237B	526	652A	297	346B	349	442AB	185	344B	359	375B
60 - 70		273B		585A		379B		431AB		402B		425AB
70 - 80		230B		515A		504A		434A		394A		460A
80 - 90		267		544		475		458		448		424

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 7. Sulfur (S) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	247b[2]	91C	469b	106C	13465a	13860B	11640a	14389AB	13622a	13878B	14515a	14504A
10 - 20	575c	139C	249c	160C	13383a	14043A	6863b	4849B	13508a	13587A	10257ab	7481B
20 - 30	518b	258B	410b	256B	9528a	9038A	3145b	2019B	12087a	7233A	2830b	1523B
30 - 40	434c	258C	303c	366C	6495b	3434A	934c	1848B	9778a	2140AB	923c	1514BC
40 - 50	693b	252C	266b	231C	3868b	3012A	1880b	1707AB	9277a	1971AB	840b	922BC
50 - 60	515	347B	329	257B	4199	2342A	1327	917B	3811	2033A	551	666B
60 - 70		334CD		268D		2204A		1043BC		1579AB		582CD
70 - 80		362C		334C		1445A		787BC		1258AB		600C
80 - 90		343		265		1153		853		1222		611

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 8. Boron (B) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	2.5b[2]	0.0B	3.9b	0.0B	14.0a	4.7A	10.5a	3.9A	11.4a	2.9AB	10.0a	5.2A
10 - 20	2.0c	0.0B	2.9c	0.9B	18.9a	8.9A	8.6bc	2.1B	13.4ab	4.1AB	8.4bc	4.2A
20 - 30	2.7cd	0.0C	2.1d	0.3C	9.9ab	4.8A	6.3bc	0.4C	11.6a	3.2AB	4.8cd	1.4BC
30 - 40	2.7b	0.0C	2.7b	0.1BC	8.8a	3.1A	5.3ab	1.1ABC	7.9a	1.0ABC	3.4b	1.5AB
40 - 50	2.4c	0.0C	2.7c	0.0C	6.8ab	2.7A	5.3bc	1.6AB	9.8a	0.5BC	3.7bc	0.1BC
50 - 60	2.0	0.0	3.2	0.0	5.2	1.5	5.3	0.9	5.5	0.0	2.8	0.3
60 - 70		0.0		0.0		1.2		0.2		0.4		0.3
70 - 80		0.0		0.4		1.2		0.7		0.8		0.1
80 - 90		0.0		0.0		0.7		0.1		0.8		0.0

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 9. Manganese (Mn) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.2b[2]	0.3B	8.8a	4.5A	0.0b	0.0B	0.0b	0.6B	0.1b	0.0B	0.1b	0.1B
10 - 20	0.1	0.3	5.4	2.9	0.3	1.4	4.5	6.1	0.3	0.1	4.3	4.0
20 - 30	5.7	2.0	6.6	3.9	3.9	3.1	6.1	10.4	0.9	2.9	7.4	8.9
30 - 40	14.7a	10.0	8.2ab	4.3	5.2b	5.6	7.3b	8.0	2.9b	3.7	7.7a	10.0
40 - 50	25.5	12.6	14.8	5.0	8.1	8.4	8.8	8.1	1.4	4.9	11.1	13.2
50 - 60	28.7	19.3	11.4	9.8	11.6	9.9	11.0	7.7	5.6	6.8	31.0	16.4
60 - 70		23.4		8.5		13.6		16.9		9.1		21.0
70 - 80		37.2		28.0		19.9		14.9		10.2		23.8
80 - 90		58.2		10.4		25.3		19.5		20.5		34.8

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 10. Iron (Fe) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.8[2]	0.0	4.4	4.7	3.6	0.0	5.0	0.0	1.2	0.0	1.8	0.0
10 - 20	0.5	0.0	13.4	23.8	9.7	0.0	4.4	0.3	0.4	0.0	1.0	1.1
20 - 30	0.6	0.0	58.8	100.6	5.1	0.0	10.8	13.2	0.7	0.0	123.7	25.5
30 - 40	3.9	4.0	45.7	171.5	1.8	17.8	18.1	7.1	2.2	0.6	26.7	18.6
40 - 50	66.2	4.4	189.3	69.5	6.6	18.3	16.0	35.6	6.8	19.2	22.3	30.6
50 - 60	10.1b	3.1	75.8a	54.5	9.2b	15.0	15.6b	45.3	5.8b	14.1	34.4b	36.0
60 - 70		1.4		50.2		20.9		62.7		10.8		30.0
70 - 80		2.6C		72.3A		27.0BC		41.4AB		17.8BC		22.3BC
80 - 90		0.9		55.2		36.6		44.2		18.5		34.7

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 11. Cadmium (Cd) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.00[2]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10 - 20	0.00	0.00	0.07	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.26
20 - 30	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.22
30 - 40	0.05	0.03	0.00	0.00	0.00	0.00	0.09	0.04	0.00	0.01	0.05	0.01
40 - 50	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.05	0.01	0.00	0.00
50 - 60	0.00	0.00	0.04	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00
60 - 70		0.01		0.00		0.00		0.00		0.29		0.00
70 - 80		0.00		0.00		0.00		0.00		0.00		0.00
80 - 90		0.00		0.00		0.00		0.00		0.00		0.00

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 12. Chromium (Cr) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.00[2]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
10 - 20	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.23
20 - 30	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.16
30 - 40	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.04
40 - 50	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.06	0.03	0.00	0.00	0.00
50 - 60	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60 - 70		0.00		0.07		0.00		0.00		0.11		0.00
70 - 80		0.00		0.11		0.03		0.01		0.00		0.12
80 - 90		0.00		0.00		0.09		0.00		0.00		0.00

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 13. Copper (Cu) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.00[2]	0.00	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.00
10 - 20	0.10	0.00	0.30	0.46	0.00	0.47	0.18	0.10	0.00	0.00	0.00	0.34
20 - 30	0.00	0.00	0.95	1.30	0.00	0.04	0.40	1.15	0.00	0.05	3.61	0.82
30 - 40	0.01b	0.08	1.12a	1.71	0.00b	0.61	0.09b	0.64	0.00b	0.30	1.47a	1.58
40 - 50	0.25c	0.10	1.92a	2.33	0.06c	0.41	0.21c	2.38	0.32bc	0.96	1.18ab	1.48
50 - 60	0.46	0.38	3.36	2.66	1.44	0.42	0.54	2.40	0.34	0.18	1.71	1.55
60 - 70		0.30		2.26		0.34		2.51		0.98		1.89
70 - 80		0.12		2.48		1.55		1.79		1.26		1.37
80 - 90		0.00		2.56		2.02		1.26		1.44		2.80

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 14. Molybdenum (Mo) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	2.0[2]	0.0	0.3	0.0	0.1	0.0	0.5	0.0	0.8	0.0	0.0	0.0
10 - 20	0.4	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	1.7	0.0
20 - 30	2.5ab	0.0	0.0c	0.0	0.0c	0.0	3.1a	0.0	1.9abc	0.0	0.0c	0.0
30 - 40	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.1	0.5	0.3
40 - 50	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.1	0.0	2.8	0.0
50 - 60	0.0	0.0	0.3	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.1
60 - 70		0.0		0.0		0.0		0.2		0.0		0.0
70 - 80		0.0		0.0		0.0		0.0		0.0		0.0
80 - 90		0.0		0.0		0.0		0.0		0.0		0.0

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 15. Lead (Pb) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.29[2]	0.00	0.00	0.00	0.00	0.00	0.56	0.06	0.63	0.00	0.08	0.00
10 - 20	0.00	0.00	1.20	0.38	0.48	0.00	0.00	0.00	0.97	0.00	0.34	0.00
20 - 30	0.00	0.00	2.27	0.00	0.00	0.00	0.53	0.00	0.74	0.00	0.00	0.00
30 - 40	0.38	0.00	0.01	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40 - 50	0.00	0.00	0.00	0.00	1.08	0.00	0.00	0.12	0.00	0.00	0.00	0.00
50 - 60	0.00	0.00	0.00	0.00	1.86	0.00	0.47	0.02	0.01	0.00	0.00	0.00
60 - 70		0.00		0.56		0.44		0.00		0.79		0.00
70 - 80		1.68A		0.00B		0.00B		0.00B		0.00B		0.00B
80 - 90		0.81		0.00		0.09		0.00		0.00		1.11

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at p = 0.05 using the LSD test.

Table 16. Nickel (Ni) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.16[2]	0.00	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
10 - 20	0.00	0.00	0.00	0.36	0.00	0.22	0.25	0.01	0.00	0.00	0.33	1.03
20 - 30	0.38	0.00	0.00	0.67	0.00	0.31	0.00	0.54	0.00	0.00	0.56	1.66
30 - 40	0.28	0.58	0.52	0.68	0.24	0.80	0.00	0.86	0.00	0.00	0.25	1.36
40 - 50	1.38a	0.64	0.66ab	0.45	0.00b	0.80	0.22b	1.63	0.00b	0.74	0.48b	3.46
50 - 60	0.79	1.30	2.29	1.46	0.43	1.97	0.00	0.76	0.00	1.28	1.06	2.18
60 - 70		1.18		1.94		2.14		2.86		1.83		2.09
70 - 80		1.21B		4.13A		2.54AB		1.49B		2.07B		2.39AB
80 - 90		1.12		3.02		2.92		1.38		2.15		3.91

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 17. Zinc (Zn) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.00b[2]	0.00B	6.59a	3.75A	0.00b	0.00B	0.00b	0.00B	0.00b	0.00B	1.10b	0.00B
10 - 20	0.09b	0.00B	1.90a	2.16A	0.00b	0.25B	0.12b	0.19B	0.08b	0.09B	0.96ab	1.24AB
20 - 30	0.00c	0.00	2.36ab	1.64	0.21c	0.35	0.76bc	0.74	0.00c	0.25	2.79a	2.94
30 - 40	1.27	0.94	2.50	2.05	0.67	1.01	0.84	0.78	0.14	0.54	2.46	2.68
40 - 50	1.51	1.16	1.62	1.73	0.45	1.82	0.96	1.62	0.70	1.10	3.10	1.60
50 - 60	1.98	1.34	3.67	2.30	1.71	3.30	0.43	1.17	0.15	1.29	2.89	1.52
60 - 70		1.60		2.19		2.38		2.26		2.06		1.66
70 - 80		1.71BC		3.88AB		4.84A		1.50C		1.61BC		1.93BC
80 - 90		1.60B		2.65AB		4.51A		1.19B		2.29B		2.80AB

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 18. Strontium (Sr) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	7.9cd[2]	7.7B	6.9d	5.3C	18.0b	17.9A	7.6d	7.7B	20.7a	19.4A	9.9c	9.7B
10 - 20	8.8b	7.5B	3.0c	2.7D	18.2a	20.2A	4.1c	3.0CD	20.5a	21.5A	8.1b	5.9BC
20 - 30	6.3c	5.8B	2.1d	1.2B	12.6b	13.0A	2.1d	1.5B	17.3a	11.7A	2.5d	2.0B
30 - 40	3.9c	2.9BC	1.7c	0.8D	8.9b	5.6A	0.9c	1.4CD	13.8a	4.5AB	1.0c	1.8CD
40 - 50	3.4b	2.7BC	1.3b	0.7D	5.4b	4.6A	1.5b	1.5CD	13.0a	3.8AB	0.8b	1.2CD
50 - 60	2.0b	2.8A	0.8b	0.9B	2.4b	3.5A	1.2b	0.9B	5.9a	3.5A	0.7b	1.0B
60 - 70		3.3A		0.8B		3.1A		0.9B		3.1A		0.8B
70 - 80		3.1A		0.8B		1.9AB		0.8B		2.3AB		0.8B
80 - 90		2.8A		0.4C		1.5ABC		0.7BC		1.9AB		0.9BC

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 19. Sodium (Na) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	3.5[2]	4.6	9.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10 - 20	1.4	0.0	23.1	0.0	0.0	0.0	2.4	2.5	0.0	0.0	0.0	0.0
20 - 30	11.7	4.6	12.8	0.0	0.0	0.0	0.0	0.0	5.8	0.0	1.2	0.0
30 - 40	25.0	0.0	13.7	4.1	8.2	0.0	8.2	0.0	0.0	0.0	5.4	0.3
40 - 50	11.7	0.0	24.1	0.0	0.0	0.0	6.6	3.4	18.4	0.0	6.0	0.0
50 - 60	11.1	0.0	13.7	0.0	11.9	0.0	21.8	0.0	11.6	0.0	2.0	0.0
60 - 70		8.9		0.0		0.0		2.9		0.0		9.8
70 - 80		0.0		6.4		0.0		0.0		0.0		2.9
80 - 90		0.0		0.0		1.4		2.5		4.6		8.7

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 20. Silicon (Si) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	1.82[2]	0.57	0.00	1.90	0.89	3.93	2.00	3.07	1.85	1.88	0.67	2.15
10 - 20	0.99	0.93	0.00	1.37	0.78	4.58	1.24	2.94	0.84	2.05	0.08	1.58
20 - 30	1.62	0.00	0.67	1.37	2.79	5.19	0.77	2.41	1.61	0.00	0.00	1.84
30 - 40	1.52	0.70	0.16	1.74	4.86	8.24	0.46	2.84	1.44	1.10	1.02	1.62
40 - 50	1.56	0.96	0.17	1.59	3.67	7.26	0.30	3.02	1.28	0.43	0.41	0.69
50 - 60	1.21	1.57	0.14	1.53	2.80	6.89	0.71	2.57	1.73	0.00	0.78	1.01
60 - 70		0.59		1.20		5.17		2.91		0.62		1.45
70 - 80		1.04		0.00		4.64		2.38		0.00		1.68
80 - 90		0.70		0.00		4.35		2.56		0.00		1.57

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at p = 0.05 using the LSD test.

Table 21. Phosphorus (P) concentrations (mg/kg) in an acid minesoil amended in fall 1995 with borrow soil, sewage sludge, or flue gas desulfurization by-products.[1]

Depth (cm)	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
0 - 10	0.0[2]	0.2	0.0	0.0	2.2	1.0	2.3	0.0	0.0	1.3	5.3	0.4
10 - 20	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.4	0.0	2.2
20 - 30	0.0	0.5	0.8	0.0	0.0	0.0	1.1	0.1	0.0	0.2	2.0	0.0
30 - 40	3.5	0.8	0.0	1.5	1.7	0.0	2.0	0.0	2.8	0.1	0.0	0.0
40 - 50	0.1	0.0	0.0	1.7	0.0	0.6	0.0	0.0	0.4	1.9	0.6	0.0
50 - 60	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	1.3	1.9	0.0	1.2
60 - 70		0.0		3.7		0.0		0.0		0.0		0.0
70 - 80		0.1		0.7		0.0		0.0		0.6		0.2
80 - 90		1.6		0.0		0.4		0.5		0.0		0.5

[1]Soil samples were collected in June 1996 and July 1997, and extracted with 1N KCl.
[2]Within each sample depth and year, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

B. Water Quality of Vadose Water from Suction Lysimeters

Results reported are for two sampling dates, late fall of 1996 and 1997, when sampling yielded a complete data set for all replications (Tables 22-28).

In 1996 and 1997, there were statistically significant amendment treatment effects at both 30 and 60 cm on electrical conductivity , and on B, Ca, K, Mg and S concentrations. In addition, in 1996 there were significant amendment effects at both depths on pH and acidity, at the 30 cm depth on Al, Ni, and Zn, and at the 60 cm depth on Ba and Si. There were no statistically significant amendment effects in either year on arsenic, beryllium, cadmium, cobalt, chromium, copper, iron, manganese, molybdenum, sodium, phosphorus, lead, or selenium. In no case were there significant amendment effects in 1997 when there had been none in 1996, except for Sr extracted at 60 cm. There were significant effects of lysimeter depth in both years for pH, Mn, and Si; in 1996 for As, B, Ba, Ca, K, and P; and in 1997 for Be, Co, Na, and Sr. Boron and potassium also showed significant interactions of amendment treatment with lysimeter depth in 1996.

Water pH. In 1996, water pH at the 30 cm depth was significantly lower in the sewage sludge, Mg-gypsum FGD, and sewage sludge+Mg-gypsum FGD treatments than in the borrow soil, or sewage sludge +Conesville FGD treatments (Table 22). At 60 cm, pH of water extracted from the borrow soil was significantly higher than that from all other treatments. There were no significant amendment treatment effects in 1997. All treatments had mean water pH below 7.0. In both years, water pH generally decreased as depth of lysimeter sample increased (Table 22).

Electrical Conductivity. In 1996, water from both depths in borrow soil and sewage sludge treatments had lower electrical conductivity than that from treatments with Conesville FGD or sewage sludge + Conseville FGD, which in turn had lower conductivities than water from the sewage sludge +Mg-gypsum or the Mg-gypsum treatment (Table 22). In 1997, all treatments receiving FGD yielded water with higher conductivities than the borrow soil or sewage treatments.

Acidity. In 1996, acidity of water extracted at the 30 cm depth from the sewage sludge + Mg-gypsum FGD treatment was greater than that from all other treatments (Table 22). At the 60 cm depth, the Conesville FGD, Mg-gypsum FGD and the sewage sludge with Conesville or Mg-gypsum FGD had higher acidities than the borrow soil, with the sewage sludge treatment intermediate.

Aluminum. In 1996, water extracted at 30 cm from the sewage sludge + Mg-gypsum treatment had higher Al than all other treatments (Table 23). This result is similar to that for acidity. This was the only statistically significant treatment effect in either year.

Arsenic. There were no statistically significant amendment effects on As concentration of water extracted from the tension lysimeters (Table 23). There was a significant effect of lysimeter sample depth in 1996 due primarily to a decrease in As with increasing depth in the Mg-gypsum treatments. The USEPA recommended maximum contaminant level (RMCL) of 0.05 mg/L (De

Zuane,1990) was equaled or exceeded in 1996 in water from both sample depths in sewage sludge or Mg-gypsum FGD, and from the 30 cm depth in the sewage sludge + Mg-gypsum FGD treatment. In 1997 the RMCL was equaled or exceeded in water from both depths in the sewage sludge + Mg-gypsum FGD treatment and from the 60 cm depth in the Conesville FGD treatment.

Boron. Both treatments that contained Conesville FGD had higher boron concentrations in extracted water than the other treatments (Table 23). Borrow soil and sewage sludge alone produced the lowest B concentrations. There was a significant interaction of amendment treatment with lysimeter depth in 1996 due primarily to the large decrease in B with increasing depth in the Conesville FGD treatment. In 1996, all treatments with FGD had average concentrations of B above 2.0 mg/L, a concentration that produces B toxicity symptoms on lower leaves of sycamore grown in solution culture (Vimmerstedt and Glover, 1984), and in 1997 B concentrations remained above this limit in the two treatments with Conesville FGD . Boron is not an element of concern in drinking water (De Zuane, 1990).

Barium. All barium concentrations were below the USEPA recommended maximum contaminant level of 1.5 mg/L (Table 23). In 1996, barium concentration was higher in water extracted at 60 cm from borrow soil and soil receiving sewage sludge alone than from treatments that included FGD. There was a significant effect of lysimeter sample depth in 1996 owing to the decrease in Ba with increasing depth in both Conesville FGD treatments (Table 23).

Beryllium. Beryllium concentrations were not affected by amendment treatment (Table 24). In 1997, Be increased ($p=0.07$) with lysimeter depth in all treatments except borrow soil and Mg-gypsum FGD.

Calcium. Water samples taken at both depths in both years were lowest in Ca concentration in the treatment with sewage sludge alone (Table 24). Treatments that included FGD were higher than borrow soil, but differences were not always statistically significant. In 1996 there was a significant effect of lysimeter sample depth due to decreased Ca concentrations with increasing depth in all treatments except sewage sludge and Mg-gypsum FGD (Table 24).

Cadmium. In 1996, all water extracted from both depths had Cd concentrations above the RMCL of 0.005 mg/L, but in 1997 only the Conesville FGD and the sewage sludge + Mg-gypsum FGD treatments equaled or exceeded this limit (Table 24).

Cobalt. There were no significant effects of amendment treatment on Co concentrations in either year (Table 24). In both years, Co concentrations generally increased with increasing lysimeter depth, but the main effect of lysimeter depth was significant only in 1997.

Chromium. None of the Cr concentrations equaled the RMCL of 0.12 mg/L (Table 25).

Copper. None of the Cu concentrations equaled the RMCL of 1.3 mg/L (Table 25).

Potassium. In 1996, K concentrations were highest in water extracted from both Conesville FGD treatments at both depths, and lowest in samples taken from the borrow soil plots (Table 25). There was a significant interaction of amendment treatment with lysimeter depth because K concentrations decreased strongly with depth on sewage sludge and both Conesville treatments, but increased slightly with depth on borrow soil and both Mg-gypsum treatments. Results in 1997 were not as clearcut, but highest K concentrations were still from the Conesville plots and lowest concentrations were from the borrow soil plots.

Magnesium. The two treatments with Mg-gypsum yielded water with the highest Mg concentration in both years at both depths, with the sewage sludge treated plots usually giving the lowest concentrations; plots with borrow were similar to sewage sludge (Table 26).

Manganese. Manganese in lysimeter water behaved similarly to cobalt in its responses to amendment treatment and lysimeter depth. In both years, Mn concentrations increased with depth in all treatments, leading to significant effects of lysimeter depth but not amendment treatments (Table 26).

Sodium. There were no significant effects of amendment treatment on Na concentrations in lysimeter water (Table 26). In both years, Na concentrations increased with depth in all treatments except borrow soil and Mg-gypsum with sewage sludge, but the effect of lysimeter depth was only significant in 1997.

Nickel. In 1996, Ni concentration was higher in water extracted from 30 cm in the sewage+ Mg-gypsum treatment than in water from any other treatment at that depth (Table 27).

Phosphorus. The soil amendment treatments did not significantly affect P concentrations in lysimeter water (Table 27). In 1996 there was a significant effect of lysimeter depth due mainly to decreases in P with increasing depth in both Mg-gypsum FGD treatments and on sewage sludge + Conesville FGD.

Lead. The RMCL of 0.02 mg/L was equaled or exceeded only by water from 30 cm in the borrow soil and sewage sludge treatments in 1996 (Table 27).

Sulfur. All water samples from FGD treatments had elevated S concentrations compared with those from either borrow soil or sewage sludge alone (Table 27).

Selenium. All of the water extracts exceeded the RMCL of 0.045 mg/L, but note that the detection limit of our method is 0.093 mg/l (Table 28).

Silicon. In 1996 at the 60 cm depth, Si concentration in water from the borrow soil was lower than from any other treatment (Table 28). There was a significant effect of lysimeter depth in both years due to large increases in Si with increasing depth in both Conesville FGD treatments and in sewage sludge (Table 28).

Strontium. Strontium concentrations are the only case where there were significant amendment treatment effects in 1997 but not in 1996 (Table 28). At the 60 cm depth in the soil, water extracted from the Mg-gypsum FGD treatment had the highest Sr concentration, while sewage sludge + Mg-gypsum and sewage sludge alone were essentially tied for lowest. In 1997, Sr increased with depth in all treatments except sewage sludge and sewage sludge + Mg-gypsum FGD, resulting in a significant main effect of lysimeter depth.

Zinc. In 1996, water extracted at 30 cm from the sewage sludge + Mg-gypsum FGD treatment had greater Zn than water from any other treatment (Table 28). All measured Zn concentrations were below the USEPA suggested maximum contaminant level of 5 mg/L.

Table 22. pH, electrical conductivity (EC), and acidity of water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Parameter	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
pH												
30 cm	5.48a[2]	5.67	3.65b	3.69	4.25ab	4.16	3.54b	3.69	5.11a	4.96	3.60b	4.30
60 cm	4.45a	4.35	3.41b	3.63	3.57b	3.66	3.38b	3.82	3.61b	3.68	3.56b	3.85
EC(μS/cm)												
30 cm	157c	232BC	102c	145C	273b	469A	346b	432A	264b	390AB	439a	452A
60 cm	108c	258B	134c	183B	263b	497A	360a	468A	259b	422A	336a	433A
Acidity (meq/L)												
30 cm	4.94b	3.97	3.43b	2.79	6.51b	8.48	10.36b	6.84	3.70b	3.61	20.33a	11.01
60 cm	2.63b	4.10	7.16ab	5.59	11.84a	12.32	10.28a	5.77	10.53a	7.83	13.59a	11.95

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 23. Concentration (mg/L) of Al, As, B, and Ba in water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Element	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Al												
30 cm	34.0b[2]	27.7	19.4b	16.1	38.1b	51.9	55.3b	38.7	25.4b	21.6	134.5a	60.8
60 cm	16.0	28.2	43.6	36.6	80.4	83.5	68.9	35.6	63.0	52.4	94.9	74.6
As												
30 cm	<0.04	<0.04	0.05	<0.04	0.04	0.04	0.12	<0.04	<0.04	<0.04	0.12	0.05
60 cm	<0.04	<0.04	0.05	<0.04	<0.04	0.07	0.06	<0.04	<0.04	0.04	0.04	0.06
B												
30 cm	0.46c	0.03B	0.51bc	0.09B	11.32a	7.36A	2.53bc	1.36B	9.49a	4.48AB	2.91b	2.04B
60 cm	0.40b	0.03C	0.48b	0.07C	6.85a	5.59A	2.81b	1.66BC	8.19a	4.89AB	2.10b	1.16C
Ba												
30 cm	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.01
60 cm	0.02a	0.02	0.02a	0.01	0.01ab	0.01	0.01b	0.01	0.01ab	0.01	0.01b	0.01

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 24. Concentration (mg/L) of Be, Ca, Cd, and Co in water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Element	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Be												
30 cm	0.01[2]	0.01	<0.01	<0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01	0.02	0.01
60 cm	<0.01	0.01	0.01	0.01	0.02	0.02	0.01	<0.01	0.01	0.01	0.02	0.02
Ca												
30 cm	244b	207BC	94c	81C	418a	366AB	286b	323AB	418a	390AB	314b	437A
60 cm	128c	208B	86c	75C	299ab	318A	288ab	335A	327a	340A	246b	288A
Cd												
30 cm	0.007	0.004	0.007	0.001	0.013	0.003	0.006	0.002	0.009	0.002	0.011	0.003
60 cm	0.006	0.003	0.007	0.003	0.012	0.006	0.008	0.002	0.010	0.003	0.011	0.007
Co												
30 cm	0.18	0.09	0.06	0.03	0.14	0.17	0.12	0.05	0.09	0.06	0.40	0.12
60 cm	0.14	0.19	0.16	0.10	0.32	0.28	0.14	0.09	0.20	0.16	0.56	0.34

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 25. Concentration (mg/L) of Cr, Cu, Fe, and K in water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Element	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Cr												
30 cm	0.005[2]	0.006	<0.005	<0.005	0.005	0.014	0.012	0.017	<0.005	<0.005	0.025	0.017
60 cm	<0.005	<0.005	<0.005	0.006	0.007	0.009	<0.005	0.005	<0.005	0.012	0.005	0.005
Cu												
30 cm	0.08	0.07	0.10	0.05	0.09	0.13	0.13	0.11	0.15	0.05	0.36	0.11
60 cm	0.01	0.05	0.17	0.14	0.15	0.17	0.07	0.06	0.13	0.16	0.11	0.09
Fe												
30 cm	7.68	1.04	5.36	0.27	8.10	10.93	26.01	16.84	5.71	0.36	62.34	30.92
60 cm	5.03	1.56	8.61	2.40	7.78	2.16	7.30	0.92	7.40	2.15	8.25	0.52
K												
30 cm	0.5c	1.2D	17.7b	11.6BC	39.4a	14.3AB	9.0bc	3.9CD	42.0a	21.9A	8.2bc	6.1BCD
60 cm	2.6c	3.8B	7.9bc	7.9B	16.9a	11.3AB	11.8abc	7.3B	18.6a	19.3A	11.3abc	5.7B

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 26. Concentration (mg/L) of Mg, Mn, Mo, and Na in water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Element	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Mg												
30 cm	41c[2]	50BC	28c	22C	96bc	173AB	266ab	177AB	105bc	96BC	475a	262A
60 cm	28b	58CD	42b	33D	129b	190AB	337a	223A	102b	128BC	322a	244A
Mn												
30 cm	4.72	2.66	1.77	1.02	2.55	3.37	3.46	0.94	1.52	1.86	6.51	1.72
60 cm	6.23	6.48	3.88	2.96	7.59	6.53	4.85	4.15	4.72	5.70	25.05	12.12
Mo												
30 cm	0.07	<0.01	0.07	<0.01	0.07	0.014	0.06	<0.01	0.14	0.031	0.10	<0.01
60 cm	0.07	<0.01	0.07	<0.01	0.06	<0.01	0.05	<0.01	0.06	<0.01	0.05	<0.01
Na												
30 cm	9.02	4.22	10.33	2.93	11.19	5.57	5.89	7.52	13.19	4.75	7.96	3.49
60 cm	7.09	5.10	13.56	3.06	17.85	8.53	25.01	15.72	28.47	10.37	7.46	2.65

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 27. Concentration (mg/L) of Ni, P, Pb, and S in water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Element	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Ni												
30 cm	0.32b[2]	0.23	0.11b	0.08	0.19b	0.31	0.19b	0.12	0.13b	0.12	0.79a	0.27
60 cm	0.18	0.36	0.27	0.21	0.56	0.54	0.23	0.16	0.37	0.31	0.67	0.63
P												
30 cm	0.08	0.02	0.07	0.10	0.08	0.10	0.18	0.15	0.09	0.04	0.25	0.19
60 cm	0.05	0.03	0.06	0.02	0.08	0.03	0.03	0.04	0.02	0.04	0.08	0.26
Pb												
30 cm	0.02	<0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
60 cm	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
S												
30 cm	324cd	282C	176d	141C	581bc	646AB	731b	612B	561bc	509B	1198a	844A
60 cm	183c	317B	235c	189B	591b	674A	848a	659A	571b	573A	829a	695A

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at p = 0.05 using the LSD test.

Table 28. Concentration (mg/L) of Se, Si, Sr, and Zn in water from suction lysimeters at two depths (30 cm and 60 cm) in an acid minesoil as affected by soil amendment treatments.[1]

Element	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Se												
30 cm	0.2[2]	<0.1	<0.1	<0.1	0.5	<0.1	0.1	<0.1	0.6	<0.1	1.2	0.1
60 cm	0.5	0.1	0.4	<0.1	0.4	<0.1	0.2	<0.1	0.2	<0.1	0.4	<0.1
Si												
30 cm	16.20	11.58	20.07	16.78	18.02	16.60	19.47	16.66	15.42	13.21	24.41	18.24
60 cm	15.21b	16.48	26.59a	23.53	26.33a	21.69	21.13ab	17.90	23.49a	20.59	25.62a	17.99
Sr												
30 cm	0.56	0.58	1.53	0.82	1.35	1.23	1.69	1.85	1.33	1.21	1.42	1.70
60 cm	1.28	1.65AB	1.36	0.86B	2.47	1.82AB	2.67	3.03A	2.45	2.28AB	1.83	0.89B
Zn												
30 cm	0.91b	0.53	0.58b	0.33	0.61b	0.68	0.59b	0.34	0.52b	0.32	2.17a	0.65
60 cm	0.50	0.74	0.92	0.60	1.50	1.36	0.67	0.38	1.10	0.81	1.70	1.37

[1]Sample dates were Oct. 31, 1996, and Nov. 24, 1997.
[2]Within a row, means for the same year followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

C. Water Quality of Surface Runoff

All element concentrations in runoff that are given below are total concentrations derived from unfiltered samples that were digested with nitric acid-perchloric acid. Depending on the element, there could be substantial differences between total concentration from unfiltered, digested water and dissolved concentration from filtered water. For several elements in 1997, we ran regressions of dissolved concentration on total concentration to fit the linear equation:
Dissolved concentration = a + b (Total concentration).

Element	r^2	a	b
Ca	0.99	1.64	0.975
Mg	0.96	-1.40	0.990
S	0.98	3.58	0.959
Na	0.76	-0.77	1.046
Al	0.06	3.36	0.062
Fe	0.02	0.52	0.021
K	0.36	2.98	0.265
P	0.33	0.07	0.143

For Ca, Mg, S, and Na there was a high correlation (r^2 values near 1) between dissolved and total concentrations, and the dissolved concentration was essentially the same as the total concentration as indicated by b values near 1. Aluminum and iron had a low correlation between dissolved and total concentrations. Dissolved Al was about 6.2% (b=0.062) of total Al, and dissolved Fe was about 2.1 % (b=0.021) of total Fe. There was an intermediate correlation (r^2= 0.36 or 0.33) between total and dissolved concentrations for K and P. Dissolved K was about 26.5% of total K, and dissolved P was about 14.3% of total P. Thus, for Al, Fe, K, P, and probably other elements, the concentrations listed in the tables that follow would be less if dissolved rather than total concentrations were reported.

1. Analysis of Variance of Amendment Treatment Effects on Individual Sample Dates

We ran analysis of variance on general parameters and element concentrations in runoff for two sample dates each in 1996 and 1997 when we had samples for all or most treatment replications. These samples were from some of the heaviest rainstorms experienced, so runoff was more dilute than on other dates involving lesser storms. Water pH, EC, alkalinity, suspended solids, Cr, Ca, Mg, Na, B, Sr, Co, and S showed significant effects of soil amendment treatments on individual sample dates (Tables 29-37).

Water pH, electrical conductivity, alkalinity, and suspended solids (Table 29). On June 10 and August 1, 1996 pH of surface runoff was greatest for borrow soil and least for sewage sludge

(Table 29). There were no significant treatment effects in 1997 but sewage sludge tended to have the lowest runoff pH. Electrical conductivity of surface runoff was generally lower for borrow soil or sewage sludge than for all FGD treatments on both dates in 1996 and on June 3, 1997. The sewage sludge treatment had lowest alkalinity on all sample dates. Suspended solids were greater for the Mg-gypsum treatment than for all other treatments on June 10, 1996.

Arsenic, Barium, Cadmium, and Chromium (Table 30). The concentration of Cr in runoff water was greater for sewage sludge or for Mg-gypsum FGD than for Conesville FGD or sewage sludge + Mg-gypsum FGD in August 1996. Sewage sludge had greater Cr than all other treatments in August 1997. There were no significant treatment effects for As, Ba, and Cd.

Copper, Iron, Mercury, and Manganese (Table 31). Concentrations of Cu, Fe, Hg, and Mn in runoff water did not vary significantly with amendment treatment on any of the sampling dates in 1996 and 1997.

Lead, Selenium, and Zinc (Table 32). Concentrations of Pb, Se, and Zn in runoff water showed no significant effects of amendment treatment on any sampling date in 1996 or 1997.

Aluminum, Calcium, Potassium, and Magnesium (Table 33). Calcium concentrations in runoff were greater for all treatments involving FGD than for either borrow soil or sewage sludge alone on both dates in 1996 and in June of 1997. In 1996, Mg concentrations were much greater in runoff from the two Mg-gypsum FGD treatments than from the other treatments. On June 3, 1997, Mg concentrations for both Mg-gypsum FGD treatments appeared to decrease from 1996 but were still generally greater than for the other treatments. There were no significant treatment effects for Al or K.

Sodium, Boron, Silicon, and Strontium (Table 34). In August 1997, sodium concentrations in runoff were greatest for both Conesville FGD treatments, intermediate for Mg-gypsum FGD or sewage sludge alone, and least for sewage sludge + Mg-gypsum FGD. Boron was generally greater for both Mg-gypsum treatments or for sewage sludge + Conesville FGD than for borrow soil or sewage sludge alone on both dates in 1996. There were no significant treatment effects for B in 1997. Strontium was greater for Conesville FGD with sewage sludge than for borrow soil in August 1966 and June 1997. Silicon concentrations in runoff water did not vary significantly with treatment.

Beryllium, Cobalt, Molybdenum, and Nickel (Table 35) . In June 1997 cobalt in runoff water was greater for Conesville FGD alone than for all other treatments. There were no significant treatment effects for Be, Mo, or Ni.

Phosphate, P, Sulfate, and S (Table 36). On all sample dates except August 1997, sulfate and S were generally greatest for the Mg-gypsum FGD treatments, intermediate for the Conesville FGD treatments, and least for borrow soil or sewage sludge alone. Phosphate or P did not vary significantly with amendment treatment.

Nitrate, Chloride, and Fluoride (Table 37). In June 1997, nitrate concentrations in runoff tended to be greater for all FGD treatments than for borrow soil or sewage sludge alone. The reasons for lower nitrate concentrations for borrow soil or sewage sludge alone are possibly due to sparse ground cover production on borrow soil in 1996, and to inhibition of nitrification by the acid surface soil on sewage sludge plots. Also in June 1997, chloride in runoff was lesser for all FGD treatments than for borrow soil or sewage sludge alone. Fluoride in runoff did not show any significant effects of amendment treatment in 1997.

Table 29. pH, electrical conductivity (EC), alkalinity, and suspended sediment in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	pH				EC ($\mu S/cm$)			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	7.31a[1]	7.37a	6.72	6.68	21c	20c	26bc	41
Sewage Sludge (100)[2]	4.66c	4.08c	4.79	5.44	24c	102bc	19c	53
Conesville FGD (600)	6.62b	6.59ab	5.91	6.45	106b	138ab	116ab	64
Mg-gypsum FGD (280)	6.94ab	6.25b	6.12	5.78	198a	189ab	153a	116
Sewage Sludge (100) + Conesville FGD (600)	6.54b	6.28b	6.62	6.52	101b	153ab	171a	126
Sewage Sludge (100) + Mg-gypsum FGD (280)	7.03ab	6.98ab	6.66	6.50	240a	226a	190a	152

	Alkalinity (mg/L $CaCO_3$)				Suspended Sediment (mg/L)			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	76a	69ab	112a	55a	1212b	466	51	46
Sewage Sludge (100)	2b	0c	3b	4b	1372b	1688	152	57
Conesville FGD[3] (600)	30b	36bc	62ab	38a	1336b	472	327	47
Mg-gypsum FGD (280)	72a	46ab	74a	33a	3245a	1771	123	26
Sewage Sludge (100) + Conesville FGD (600)	31b	54ab	94a	43a	1220b	813	26	37
Sewage Sludge (100) + Mg-gypsum FGD (280)	89a	80a	89a	49a	476b	256	48	48

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

Table 30. Concentrations (mg/L) of As, Ba, Cd, and Cr in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	As				Ba			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.090[1]	<0.035	<0.035	<0.035	0.408	0.025	0.032	0.024
Sewage Sludge (100)[2]	<0.035	<0.035	<0.035	<0.035	0.538	0.140	0.063	0.020
Conesville FGD (600)	0.058	<0.035	0.075	<0.035	0.445	0.085	0.127	0.023
Mg-gypsum FGD (280)	<0.035	0.202	<0.035	<0.035	1.028	0.455	0.038	0.020
Sewage Sludge (100) + Conesville FGD (600)	<0.035	0.095	<0.035	<0.035	0.458	0.172	0.029	0.030
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.035	0.055	<0.035	<0.035	0.172	0.168	0.028	0.036
	Cd				Cr			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	<0.001	<0.001	<0.001	<0.001	0.070	0.042ab	0.008	0.002b
Sewage Sludge (100)	<0.001	0.002	<0.001	<0.001	0.058	0.090a	0.015	0.010a
Conesville FGD (600)	0.005	<0.001	<0.001	<0.001	0.058	0.012b	0.024	0.003b
Mg-gypsum FGD (280)	<0.001	<0.001	<0.001	<0.001	0.080	0.090a	0.010	<0.002b
Sewage Sludge (100) + Conesville FGD (600)	<0.001	<0.001	<0.001	<0.001	0.058	0.045ab	0.005	<0.002b
Sewage Sludge (100) + Mg-gypsum FGD (280)	<0.001	<0.001	<0.001	<0.001	0.025	0.010b	0.004	0.003b

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

Table 31. Concentrations (mg/L) of Cu, Fe, Hg, and Mn in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Cu				Fe			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.030[1]	<0.002	0.023	0.021	53.0	19.9	1.1	1.1
Sewage Sludge (100)[2]	0.060	0.002	0.037	0.080	51.8	51.7	5.1	1.4
Conesville FGD (600)	0.032	<0.002	0.092	0.019	44.3	14.2	10.6	1.0
Mg-gypsum FGD (280)	0.110	<0.002	0.028	0.020	92.0	58.6	2.8	0.9
Sewage Sludge (100) + Conesville FGD (600)	0.035	<0.002	0.032	0.021	43.0	27.2	0.5	0.7
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.020	<0.002	0.027	0.024	12.3	6.9	1.1	1.1

	Hg				Mn			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.092	0.050	NA[3]	NA	0.548	0.255	0.017	0.018
Sewage Sludge (100)	0.090	0.078	NA	NA	0.445	0.718	0.095	0.267
Conesville FGD (600)	0.058	0.080	NA	NA	0.208	0.150	0.055	0.014
Mg-gypsum FGD (280)	0.092	0.068	NA	NA	0.905	0.910	0.092	0.114
Sewage Sludge (100) + Conesville FGD (600)	<0.046	<0.046	NA	NA	0.190	0.322	0.068	0.030
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.110	0.070	NA	NA	0.162	0.145	0.031	0.027

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.
[3]NA = Not analyzed.

Table 32. Concentrations (mg/L) of Pb, Se, and Zn in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Pb				Se			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.055[1]	0.060	<0.019	0.068	0.535	0.265	0.731	0.222
Sewage Sludge (100)[2]	0.072	0.055	<0.019	0.055	<0.093	<0.093	0.665	0.167
Conesville FGD (600)	0.040	0.048	0.189	0.047	0.290	<0.093	0.479	<0.093
Mg-gypsum FGD (280)	0.100	0.062	<0.019	0.046	<0.093	<0.093	0.686	<0.093
Sewage Sludge (100) + Conesville FGD (600)	0.058	0.038	<0.019	0.040	0.650	<0.093	0.612	0.184
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.018	0.032	<0.019	0.050	<0.093	<0.093	0.392	0.093

	Zn			
	1996		1997	
	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.865	0.238	0.146	0.037
Sewage Sludge (100)	0.548	0.452	0.202	0.135
Conesville FGD (600)	0.932	0.185	0.381	0.124
Mg-gypsum FGD (280)	0.672	0.398	0.216	0.061
Sewage Sludge (100) + Conesville FGD (600)	0.410	0.230	0.393	0.046
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.665	0.115	0.238	0.080

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

Table 33. Concentrations (mg/L) of Al, Ca, K and Mg in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Al				Ca			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	108.6[1]	39.3	2.5	2.3	59c	36b	46bc	93
Sewage Sludge (100)[2]	130.2	132.1	11.6	6.8	23c	33b	20c	108
Conesville FGD (600)	106.9	36.0	27.2	2.2	226b	222a	250ab	146
Mg-gypsum FGD (280)	254.3	149.1	6.7	2.1	381a	284a	355a	277
Sewage Sludge (100) + Conesville FGD (600)	109.3	71.6	1.1	1.5	204b	263a	280a	316
Sewage Sludge (100) + Mg-gypsum FGD (280)	36.8	19.6	3.2	2.3	387a	317a	438a	391
	K				**Mg**			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	32.0	13.7	6.6	11.0	12.3b	5.1b	2.4c	4.2
Sewage Sludge (100)	28.2	29.8	8.3	5.8	11.2b	14.4b	4.4c	15.1
Conesville FGD (600)	28.7	15.4	11.1	12.9	15.0b	13.1b	21.8bc	7.9
Mg-gypsum FGD (280)	55.6	33.4	4.4	8.4	107.1a	98.3a	48.9ab	30.9
Sewage Sludge (100) + Conesville FGD (600)	27.4	28.0	9.6	16.2	16.4b	20.8a	14.5c	16.4
Sewage Sludge (100) + Mg-gypsum FGD (280)	19.1	11.7	4.6	13.4	155.3a	115.1a	54.1a	27.9

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

Table 34. Concentrations (mg/L) of Na, B, Si and Sr in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Na				B			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	1.72[1]	0.93	1.51	0.86ab	0.15c	0.55bc	1.13	1.11
Sewage Sludge (100)[2]	1.89	1.73	0.94	0.67b	0.11c	0.29c	0.20	0.39
Conesville FGD (600)	2.20	1.10	1.52	0.97a	1.09bc	1.92abc	1.74	1.11
Mg-gypsum FGD (280)	2.79	2.14	0.95	0.72b	1.25b	2.16ab	1.52	1.16
Sewage Sludge (100) + Conesville FGD (600)	1.84	1.50	0.86	1.06a	0.78bc	2.62a	1.29	1.52
Sewage Sludge (100) + Mg-gypsum FGD (280)	1.38	1.04	0.74	0.43c	2.40a	2.96a	1.71	1.19
	Si				Sr			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.090	0.930	0.387	0.529	0.222	0.105c	0.093d	0.112
Sewage Sludge (100)	0.120	1.378	0.384	0.246	0.258	0.320abc	0.094cd	0.090
Conesville FGD (600)	0.080	0.635	0.678	0.424	0.448	0.352abc	0.410ab	0.195
Mg-gypsum FGD (280)	0.245	1.432	0.257	0.256	0.548	0.378ab	0.212bcd	0.182
Sewage Sludge (100) + Conesville FGD (600)	0.118	0.848	0.263	0.393	0.485	0.565a	0.506a	0.432
Sewage Sludge (100) + Mg-gypsum FGD (280)	<0.014	0.508	0.320	0.275	0.360	0.302bc	0.359abc	0.336

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

Table 35. Concentrations (mg/L) of Be, Co, Mo, and Ni in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Be				Co			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	0.0025[1]	<0.0001	<0.0001	0.0008	0.038	0.008	<0.006b	<0.006
Sewage Sludge (100)[2]	0.0025	0.0050	<0.0001	0.0017	0.050	0.030	<0.006b	0.016
Conesville FGD (600)	<0.0001	<0.0001	0.0010	<0.0001	0.042	0.008	0.020a	0.010
Mg-gypsum FGD (280)	0.0025	0.0050	<0.0001	<0.0001	0.075	0.038	0.010b	<0.006
Sewage Sludge (100) + Conesville FGD (600)	0.0025	0.0025	0.0030	<0.0001	0.042	0.020	0.008b	0.006
Sewage Sludge (100) + Mg-gypsum FGD (280)	<0.0001	<0.0001	<0.0001	<0.0001	0.048	<0.006	0.007b	<0.006
	Mo				Ni			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	<0.011	0.080	<0.011	<0.011	0.042	0.012	0.004	<0.004
Sewage Sludge (100)	0.018	0.152	0.012	<0.011	0.062	0.058	0.014	0.040
Conesville FGD (600)	<0.011	0.108	0.025	<0.011	0.035	0.020	0.009	0.009
Mg-gypsum FGD (280)	0.042	0.095	0.012	<0.011	0.068	0.060	0.010	0.008
Sewage Sludge (100) + Conesville FGD (600)	0.042	0.080	0.017	<0.011	0.040	0.022	0.005	0.010
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.012	0.065	0.012	<0.011	0.012	0.012	0.004	<0.004

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

Table 36. Concentrations (mg/L) of phosphate, P, sulfate, and S in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Phosphate				P			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	ND[1]	ND	0.00[2]	0.11	0.94	0.35	0.10	0.25
Sewage Sludge (100)[3]	ND	ND	0.00	0.00	0.90	0.90	0.16	0.18
Conesville FGD (600)	ND	ND	0.47	0.00	0.78	0.28	0.54	0.26
Mg-gypsum FGD (280)	ND	ND	0.88	0.00	1.90	1.03	0.41	0.18
Sewage Sludge (100) + Conesville FGD (600)	ND	ND	0.00	0.06	0.80	0.46	0.11	0.30
Sewage Sludge (100) + Mg-gypsum FGD (280)	ND	ND	0.00	0.00	0.35	0.21	0.15	0.27
	Sulfate				S			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	34d	30d	27c	197	13d	11d	9c	70
Sewage Sludge (100)	90cd	138cd	57c	344	34cd	53cd	23c	122
Conesville FGD (600)	535b	671bc	680b	345	197b	210bc	216b	126
Mg-gypsum FGD (280)	1196a	1160ab	1060ab	767	421a	367ab	337ab	269
Sewage Sludge (100) + Conesville FGD (600)	471bc	838ab	1116ab	804	184bc	251b	234ab	286
Sewage Sludge (100) + Mg-gypsum FGD (280)	1447a	1328a	1296a	1016	514a	417a	410a	359

[1]ND = Not detectable
[2]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[3]Rate in Mg/ha.

Table 37. Concentrations (mg/L) of nitrate, chloride and fluoride in runoff water on sample dates as affected by soil amendments.

Soil Amendments:	Nitrate				Chloride			
	1996		1997		1996		1997	
	June 10	Aug. 1	June 3	Aug.18	June 10	Aug. 1	June 3	Aug.18
Borrow Soil	1.87[1]	0.89	2.22bc	3.80	1.98	5.13	4.52a	3.91
Sewage Sludge (100)[2]	1.04	0.52	1.60c	2.04	1.51	2.32	4.60a	4.71
Conesville FGD (600)	0.59	0.00	29.39a	4.68	3.00	4.22	1.60b	5.46
Mg-gypsum FGD (280)	0.82	0.00	15.53abc	3.49	1.52	4.76	1.16b	7.35
Sewage Sludge (100) + Conesville FGD (600)	1.58	0.00	15.76abc	5.87	2.16	1.95	0.00b	8.18
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.00	1.06	16.95ab	6.28	0.96	2.24	0.00b	7.68

	Fluoride	
	1997	
	June 3	Aug.18
Borrow Soil	0.40	0.52
Sewage Sludge (100)	0.08	0.42
Conesville FGD (600)	0.78	0.71
Mg-gypsum FGD (280)	0.00	0.08
Sewage Sludge (100) + Conesville FGD (600)	0.00	0.33
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.00	0.42

[1]Within a column, means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.
[2]Rate in Mg/ha.

2. Overall Means, Standard Errors, and Percentages of Samples Above the Recommended Maximum Contaminant Level

We calculated overall means and standard errors for chemical characteristics of runoff samples in 1996 and 1997 (Tables 38-45). The order of characteristics in Tables 38-45 is similar to that in Tables 29-36. For those elements with a recommended maximum contaminant level (RMCL), we also calculated the percentage of runoff samples for each treatment that were above the RMCL (Tables 39-41). Elements with a substantial percentage of concentrations above the RMCL for drinking water included As (Table 39), Hg (Table 40), Pb, and Se (Table 41). Concentrations of Fe and Mn (Table 40) were usually above the level considered desirable for aesthetic reasons.

From 1996 to 1997, overall concentrations of Ba (Table 39), Fe (Table 40), Pb (Table 41), Al, K (Table 42), and Mo (Table 44) appeared to decrease in all treatments except Conesville FGD alone. Boron concentrations (Table 43) appeared to decrease in all FGD treatments. Concentrations of As (Table 39), Cu (Table 40), and Se (Table 41) showed little or no tendency to decrease from 1996 to 1997.

D. Comparison of Water Quality Characteristics in Vadose Water and Runoff

Electrical conductivity and concentrations of Co, Mg, Mn, Na, Ni, S, Si, and Sr were greater in lysimeters than in runoff for both years in all treatments. Other elements having greater concentrations in lysimeter water than in runoff were Zn for all treatments except Mg-gypsum FGD, B for both Conesville FGD treatments, Cd for all treatments in 1996, and Ca for borrow soil only.

Water pH and concentration of Ba were greater in runoff than in lysimeters for both years and all treatments. Other elements having greater concentrations in runoff than in lysimeters were Cr and P for all treatments except sewage sludge + Mg-gypsum FGD, Fe for all treatments not receiving Mg-gypsum FGD, K for borrow soil or Mg-gypsum FGD only, Pb for all treatments in 1996, and Se for all treatments in 1997.

Concentrations of As, Cu, and Mo showed no strong comparative trends in lysimeters versus runoff.

Table 38. Overall mean and standard error of pH, EC, alkalinity, and suspended sediment in runoff samples as affected by soil amendment treatments.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=45	1997 n=23	1996 n=45	1997 n=20	1996 n=49	1997 n=22	1996 n=38	1997 n=8	1996 n=43	1997 n=20
pH												
Mean	7.27	6.43	4.54	4.13	6.63	6.10	6.55	5.18	6.32	6.22	7.01	6.13
Std.Err.	0.03	0.12	0.11	0.24	0.09	0.14	0.13	0.31	0.12	0.22	0.04	0.15
EC ($\mu S/cm$)												
Mean	32	22	49	62	146	85	201	110	129	108	225	106
Std.Err.	5	6	8	14	10	13	12	14	12	26	12	18
Alkalinity (mg/L $CaCO_3$)												
Mean	72	56	1.2	1.7	46	75	51	30	38	47	69	41
Std.Err.	3	8	0.3	0.6	5	20	5	8	5	14	5	8
Sus. Sed. (mg/L)												
Mean	651	317	899	283	1024	2610	1791	543	1745	454	395	199
Std.Err.	94	153	182	100	235	1842	348	238	379	411	62	69

Table 39. Concentrations (overall mean and standard error in mg/L) of As, Ba, Cd, and Cr in runoff samples, and percentages of total samples in which the concentration exceeded the recommended maximum contaminant level.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
As												
Mean	0.056	0.111	0.070	0.044	0.059	0.134	0.055	0.051	0.120	0.045	0.040	0.096
Std.Err.	0.013	0.034	0.020	0.012	0.014	0.052	0.015	0.017	0.034	0.030	0.009	0.026
% > RCML[1]	37	40	32	36	38	30	25	29	40	20	30	45
Ba												
Mean	0.214	0.063	0.252	0.090	0.289	0.296	0.544	0.137	0.488	0.049	0.164	0.050
Std.Err.	0.031	0.017	0.051	0.029	0.072	0.121	0.117	0.056	0.108	0.020	0.024	0.011
% > RCML	0	0	2	0	4	10	10	0	8	0	0	0
Cd												
Mean	<0.001	<0.001	0.001	0.001	0.001	0.001	0.001	0.001	<0.001	0.001	<0.001	0.001
Std.Err.	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
% > RCML	0	0	7	4	2	10	4	5	3	10	0	5
Cr												
Mean	0.046	0.031	0.059	0.056	0.043	0.033	0.061	0.031	0.078	0.015	0.029	0.037
Std.Err.	0.005	0.006	0.008	0.012	0.008	0.009	0.006	0.006	0.013	0.009	0.004	0.009
% > RCML	0	0	7	9	7	5	10	0	10	0	0	5

[1]Percent of total samples in which the concentration exceeded the USEPA recommended maximum contaminant level (RMCL).
RCML (mg/L): As=0.05, Ba=1.5, Cd=0.005, Cr=0.12.

Table 40. Concentrations (overall mean and standard error in mg/L) of Cu, Fe, Hg, and Mn in runoff samples, and percentages of total samples in which the concentration exceeded the recommended maximum contaminant level.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
Cu												
Mean	0.019	0.045	0.036	0.230	0.033	0.102	0.151	0.121	0.059	0.036	0.017	0.059
Std.Err.	0.004	0.007	0.007	0.063	0.012	0.027	0.101	0.029	0.017	0.009	0.004	0.010
% > RCML[1]	0	0	0	0	0	0	2	0	0	0	0	0
Fe												
Mean	27.640	5.050	33.757	11.965	32.218	27.851	54.960	12.136	59.845	2.867	10.582	3.267
Std.Err.	3.549	1.623	6.544	3.200	7.398	11.691	11.780	5.551	13.664	2.030	1.734	0.905
% > RCML	100	95	100	100	98	95	98	90	95	90	98	85
Hg												
Mean	0.059	NA[2]	0.060	NA	0.045	NA	0.047	NA	0.053	NA	0.066	NA
Std.Err.	0.008	NA	0.009	NA	0.007	NA	0.007	NA	0.007	NA	0.010	NA
% > RCML	79	NA	73	NA	71	NA	67	NA	79	NA	81	NA
Mn												
Mean	0.317	0.058	0.613	0.757	0.164	0.180	0.740	0.404	0.291	0.092	0.123	0.045
Std.Err.	0.040	0.021	0.097	0.229	0.031	0.054	0.193	0.106	0.060	0.033	0.023	0.009
% > RCML	84	30	98	91	67	50	76	86	76	60	49	35

[1]Percent of total samples in which the concentration exceeded the USEPA recommended maximum contaminant level (RMCL). RCML (mg/L): Cu = 1.3, Hg = 0.003. Fe (0.3 mg/L) and Mn (0.05 mg/L) do not have official RCML's, but have suggested safe concentrations.
[2]NA = Not analyzed

Table 41. Concentrations (overall mean and standard error in mg/L) of Pb, Se, and Zn in runoff samples, and percentages of total samples in which the concentration exceeded the recommended maximum contaminant level.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
Pb												
Mean	0.060	0.025	0.065	0.028	0.067	0.061	0.075	0.022	0.086	0.025	0.042	0.021
Std.Err.	0.007	0.007	0.008	0.006	0.010	0.028	0.012	0.007	0.014	0.009	0.006	0.005
% > RCML[1]	76	45	73	46	71	55	74	38	74	50	60	40
Se												
Mean	0.278	0.465	0.317	0.396	0.307	0.334	0.248	0.345	0.335	0.264	0.199	0.234
Std.Err.	0.080	0.072	0.080	0.076	0.084	0.065	0.095	0.064	0.111	0.093	0.062	0.049
% > RCML	34	80	43	68	47	75	35	71	37	80	30	70
Zn												
Mean	0.280	0.128	0.392	0.392	0.337	0.444	0.456	0.339	0.359	0.187	0.300	0.175
Std.Err.	0.060	0.021	0.044	0.081	0.074	0.077	0.074	0.080	0.046	0.091	0.067	0.033
% > RCML	0	0	0	0	0	0	0	0	0	0	0	0

[1]Percent of total samples in which the concentration exceeded the USEPA recommended maximum contaminant level (RMCL).
RCML (mg/L): Pb=0.02, Se=0.045, Zn=5.0.

Table 42. Concentrations (overall mean and standard error in mg/L) of Al, Ca, K, and Mg in runoff samples as affected by soil amendment treatments.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
Al												
Mean	57	13	87	36	80	69	150	36	150	7	32	9
Std.Err.	7	4	15	9	18	30	29	15	32	5	5	3
Ca												
Mean	50	39	36	55	268	169	304	207	245	249	337	252
Std.Err.	3	14	4	22	17	30	20	38	23	62	18	45
K												
Mean	18.4	9.4	22.4	7.6	26.0	21.7	33.6	10.1	38.8	12.0	16.4	7.2
Std.Err.	2.0	1.0	2.7	1.4	3.3	6.0	5.2	2.6	5.2	2.0	1.4	1.1
Mg												
Mean	7.1	2.7	12.1	17.0	21.0	21.9	117.9	31.8	25.7	16.1	138.6	24.2
Std.Err.	0.7	0.5	1.3	5.5	2.5	4.3	10.2	5.5	2.6	4.4	12.8	5.3

Table 43. Concentrations (overall mean and standard error in mg/L) of Na, B, Si, and Sr in runoff samples as affected by soil amendment treatments.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
Na												
Mean	1.43	1.82	1.79	1.25	2.67	2.74	2.19	1.37	4.06	1.30	1.46	1.45
Std.Err.	0.12	0.23	0.16	0.11	0.43	0.60	0.29	0.21	1.27	0.26	0.18	0.21
B												
Mean	0.526	0.778	0.251	0.282	2.057	1.332	1.898	0.812	1.730	1.199	2.398	0.905
Std.Err.	0.059	0.090	0.021	0.069	0.212	0.226	0.176	0.166	0.244	0.262	0.208	0.142
Si												
Mean	0.694	0.473	0.809	0.340	0.670	0.828	1.020	0.396	1.191	0.326	0.395	0.298
Std.Err.	0.090	0.050	0.135	0.047	0.096	0.221	0.163	0.070	0.317	0.060	0.066	0.039
Sr												
Mean	0.151	0.077	0.258	0.092	0.510	0.357	0.386	0.174	0.642	0.356	0.339	0.221
Std.Err.	0.012	0.015	0.030	0.013	0.038	0.047	0.041	0.026	0.058	0.099	0.020	0.037

Table 44. Concentrations (overall mean and standard error in mg/L) of Be, Co, Mo, and Ni in runoff samples as affected by soil amendment treatments.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
Be												
Mean	0.001	0.001	0.002	0.004	0.002	0.002	0.004	0.003	0.004	0.001	0.0003	0.0005
Std.Err.	0.0005	0.0003	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.0002	0.0002
Co												
Mean	0.019	0.006	0.034	0.048	0.022	0.017	0.042	0.025	0.034	0.010	0.025	0.007
Std.Err.	0.003	0.001	0.004	0.016	0.004	0.003	0.007	0.006	0.005	0.003	0.003	0.002
Mo												
Mean	0.044	0.005	0.053	0.005	0.054	0.020	0.042	0.007	0.053	0.009	0.033	0.006
Std.Err.	0.007	0.001	0.009	0.001	0.007	0.005	0.006	0.002	0.007	0.003	0.008	0.002
Ni												
Mean	0.025	0.005	0.057	0.100	0.025	0.021	0.051	0.050	0.044	0.006	0.010	0.005
Std.Err.	0.004	0.002	0.009	0.036	0.007	0.007	0.011	0.015	0.010	0.002	0.002	0.002

Table 45. Concentrations (overall mean and standard error in mg/L) of P and S in runoff samples as affected by soil amendment treatments.

	Borrow Soil		Sewage Sludge		Conesville FGD		Mg-gypsum FGD		Sewage Sludge + Conesville FGD		Sewage Sludge + Mg-gypsum FGD	
	1996 n=38	1997 n=20	1996 n=44	1997 n=22	1996 n=45	1997 n=20	1996 n=49	1997 n=21	1996 n=38	1997 n=10	1996 n=43	1997 n=20
P												
Mean	0.51	0.36	0.63	0.25	0.88	1.28	1.05	0.40	1.28	0.28	0.33	0.36
Std.Err.	0.08	0.12	0.12	0.06	0.18	0.55	0.19	0.11	0.28	0.06	0.04	0.08
S												
Mean	16	20	55	110	248	151	396	220	230	223	459	234
Std.Err.	2	13	6	35	17	30	28	35	22	54	29	42

E. Herbaceous Biomass and Canopy Cover

In May 1996 the herbaceous cover on borrow soil was noticeably chlorotic compared to the other soil amendment treatments. First-year (June 1996) biomass of ground cover was greater for the three treatments receiving sewage sludge than for Mg-gypsum FGD alone, Conesville FGD alone, or borrow soil (Table 46). In the first year, weeds were noticeable in plots treated with sewage sludge, but legumes were dominant on borrow soil.

In the second year, biomass increased on borrow soil and on both FGD treatments without sewage sludge, showed little change on both FGD treatments with sewage sludge, and decreased on sewage sludge alone (Table 46). Biomass was greatest on Conesville FGD with sewage sludge, intermediate on Conesville FGD alone, and least on the other treatments (Table 46). Total canopy cover was less ($p=0.08$) for sewage sludge alone (58%) than for the other treatments (77-82%) (Table 46). Legumes dominated the canopy cover in treatments not receiving sewage sludge (Table 46). Canopy cover due to grasses was greater for the three treatments receiving sewage sludge than for treatments not receiving sewage sludge (Table 46). The seeded grass and legume species comprised most of the canopy cover except for a few samples where volunteer yellow sweetclover (Melilotus officinalis) contributed to the legume cover. There was little cover other than grasses and legumes (Table 46).

F. Tree Survival and Growth

Overall tree survival was 86% in 1996 and decreased to 73% in 1997 despite replacement of dead trees in spring 1997. First-year tree survival was not affected significantly by soil amendment treatment but did vary from 75% for Conesville FGD alone to 99% for borrow soil (Table 47). Second-year survival was significantly better on soil amended with sewage sludge alone than on soil amended with all other treatments, and was significantly less on soil amended with Conesville FGD alone than on soil amended with all other treatments (Table 47). First-year height growth was greatest for Conesville FGD with sewage sludge. Second-year height growth did not vary signifcantly with amendment treatment (Table 47).

All tree species except sycamore survived moderately well after two years (Table 47). Black locust grew more than the other species (Table 47).

Table 46. Herbaceous biomass and canopy cover on an acid minesoil as affected by soil amendments.

Soil Amendments:[2]	Aboveground Biomass[1] 1996 (year 1)	Aboveground Biomass[1] 1997 (year 2)	Canopy Cover in 1997 Total	Grasses	Legumes	Other
	------kg/ha-------		---------------%---------------			
Borrow soil	208 c[3]	1878 c	79	6 c	72 a	1
Sewage sludge (100)	2518 ab	1850 c	58	25 b	31 c	1
Conesville FGD[4] (600)	719 c	2632 b	78	11 c	67 ab	0
Mg-gypsum FGD (280)	833 c	1843 c	77	11 c	66 ab	<1
Sewage sludge (100) + Conesville FGD (600)	3194 a	3382 a	82	38 a	44 bc	0
Sewage sludge (100) + Mg-gypsum FGD (280)	1868 b	2171 bc	82	28 ab	54 ab	<1

[1]Based on one harvest in June of each year.
[2]Borrow soil was applied at 25-30 cm depth. Rates (Mg/ha) for other amendments are in parentheses.
[3]Within a column, means followed by the same letter or no letter are not significantly different at $p = 0.05$ using the LSD test.
[4] FGD = Flue gas desulfurization by-product.

Table 47. Tree survival and height growth on an acid minesoil as affected by soil amendments and tree species.

	Survival		Height Growth	
	1996	1997	1996	1997
	(year 1)	(year 2)	(year 1)	(year 2)
Soil Amendments:[1]	--------%--------		--------cm--------	
Borrow soil	99a[2]	80b	7b	18a
Sewage sludge (100)	90a	91a	9b	26a
Conesville FGD[3] (600)	75a	55d	8b	19a
Mg-gypsum FGD (280)	85a	76bc	5b	23a
Sewage sludge (100)+ Conesville FGD (600)	81a	67c	16a	27a
Sewage sludge (100)+ Mg-gypsum FGD (280)	86a	71bc	12ab	24a
Tree Species:				
Black locust	91a	86a	28a	48a
Sweetgum	87a	84a	6b	13c
Sycamore	71b	39b	3bc	21b
White ash	94a	85a	1c	10c

[1]Borrow soil was applied at 25-30 cm depth. Rates (Mg/ha) for other amendments are in parentheses.
[2]Within a column for soil amendments or for tree species, means followed by the same letter are not significantly different at $p = 0.05$ using Duncan's multiple range test.
[3]FGD = Flue gas desulfurization by-product.

G. Element Concentrations in Herbaceous Cover

Element concentrations in herbaceous cover in June 1996 and 1997 are listed in Tables 48-51). Tissue concentrations for N and Ca increased for all treatments from 1996 to 1997 (Table 48). The N concentration for borrow soil moved from least in 1996 to among the greatest in 1997. In both years Ca concentration was least on plots receiving sewage sludge alone. In 1996 tissue concentrations of P and K were greater for all treatments receiving sewage sludge than for treatments not receiving sewage sludge. In 1997 P and K concentrations increased in all treatments not receiving sewage sludge, resulting in less treatment variation for P and K. Tissue Mg concentrations in 1996 were greatest for the Mg-gypsum FGD treatments. Magnesium concentrations generally increased in 1997, and were least for sewage sludge alone and Conesville FGD with sewage sludge (Table 48). Sulfur concentrations in herbaceous cover also generally increased in 1997 (Table 49). Sulfur was least for borrow soil and sewage sludge alone, two treatments that did not involve large additions to soil S.

In both years tissue B concentrations were generally greater for all FGD treatments than for borrow soil or sewage sludge alone (Table 49). All FGD treatments showed substantial decreases in tissue B in 1997. Both Conesville FGD treatments had noticeably elevated Mo in 1997 (Table 49). Zinc concentration in 1997 was greatest for sewage sludge alone (Table 50). Tissue concentrations of Mn, Fe, Al, and Na (Tables 49-50) decreased for all treatments in 1997. High concentrations of Fe and Al in 1996, particularly for borrow soil, were probably due to soil contamination of herbaceous material when raking after mowing. Tissue concentrations for Be, Cd, Co, Cr, and Ni were relatively low for all treatments (Table 51). Although Ni is usually of concern because of its potential toxicity in plants, it is an essential element required at a an approximate concentration of 0.1 mg/kg (Asher,1991). Cobalt is required by N fixing plants. Concentrations were below the detection limits for Hg (2.30 mg/kg), Pb (0.95 mg/kg), and As (1.75 mg/kg) except for borrow soil in 1996 (As=1.87 mg/kg).

Table 48. Concentrations of N, P, K, Ca, and Mg in herbaceous cover during the first two years (June of each year) on an acid minesoil as affected by soil amendments.

Soil Amendments:[1]	N		P		K		Ca		Mg	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
	g/kg									
Borrow Soil	8.1d[2]	27.0a	1.0d	2.3abc	8.0c	26.4a	6.2a	10.4a	1.1c	1.7b
Sewage Sludge (100)	10.6bc	18.3c	2.1b	2.3bc	17.8a	20.7c	2.1d	4.9b	0.8d	1.3c
Conesville FGD[3] (600)	10.6bc	24.7ab	1.5c	2.3bc	11.8b	26.0a	4.8b	9.7a	1.0c	2.0ab
Mg-gypsum FGD (280)	8.8cd	24.5b	1.3cd	2.1c	10.1bc	22.7bc	3.5c	9.3a	1.6b	2.3a
Sewage Sludge (100) + Conesville FGD (600)	13.2a	20.5c	2.5a	2.6ab	18.3a	24.5ab	3.5c	6.0b	1.1c	1.2c
Sewage Sludge (100) + Mg-gypsum FGD (280)	12.3ab	23.8b	2.6a	2.7a	16.9a	22.5bc	3.0cd	8.7a	1.8a	2.1ab

[1]Borrow soil was applied at 25-30 cm depth. Rates (Mg/ha) for other amendments are in parentheses.
[2]Within a column, means followed by no letter or the same letter are not significantly different at $p = 0.05$ using the LSD test.
[3]FGD = Flue gas desulfurization by-product.

Table 49. Concentrations of S, Mn, Fe, B, and Mo in herbaceous cover during the first two years (June of each year) on an acid minesoil as affected by soil amendments.

Soil Amendments:[1]	S		Mn		Fe		B		Mo	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
	g/kg		mg/kg							
Borrow Soil	1.1b[2]	2.4bc	70b	40	1286a	131	10c	19bc	2.8	3.0c
Sewage Sludge (100)	2.0a	2.2c	163a	58	208b	132	13c	13c	2.0	0.8c
Conesville FGD[3] (600)	2.5a	3.1a	58b	45	513b	84	95a	36a	5.0	30.0a
Mg-gypsum FGD (280)	2.0a	3.1a	125ab	51	306b	70	62b	35a	1.7	3.5c
Sewage Sludge (100) + Conesville FGD (600)	2.3a	2.9ab	71b	25	264b	104	122a	26b	3.3	12.7b
Sewage Sludge (100) + Mg-gypsum FGD (280)	2.4a	3.2a	160a	36	195b	78	112a	26b	2.6	3.8c

[1]Borrow soil was applied at 25-30 cm depth. Rates (Mg/ha) for other amendments are in parentheses.
[2]Within a column, means followed by no letter or the same letter are not significantly different at $p = 0.05$ using the LSD test.
[3]FGD = Flue gas desulfurization by-product.

Table 50. Concentrations of Cu, Zn, Al, Na, and Sr in herbaceous cover during the first two years (June of each year) on an acid minesoil as affected by soil amendments.

Soil Amendments:[1]	Cu		Zn		Al		Na		Sr	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
	mg/kg									
Borrow Soil	3.2[2]	7.5ab	19c	23b	2023a	163	48a	9	14	18a
Sewage Sludge (100)	3.5	5.4d	43a	39a	342b	233	21b	12	10	18a
Conesville FGD[3] (600)	3.2	8.1a	27bc	21b	466b	97	34b	14	13	15a
Mg-gypsum FGD (280)	2.7	6.7c	20c	18b	637b	65	26b	14	4	7b
Sewage Sludge (100) + Conesville FGD (600)	4.0	5.7d	37ab	25b	295b	148	24b	13	12	10b
Sewage Sludge (100) + Mg-gypsum FGD (280)	4.2	7.0bc	49a	27b	260b	96	21b	12	5	8b

[1]Borrow soil was applied at 25-30 cm depth. Rates (Mg/ha) for other amendments are in parentheses.
[2]Within a column, means followed by no letter or the same letter are not significantly different at $p = 0.05$ using the LSD test.
[3]FGD = Flue gas desulfurization by-product.

Table 51. Concentrations of Be, Cd, Co, Cr, and Ni in herbaceous cover during the first two years (June of each year) on an acid minesoil as affected by soil amendments.

Soil Amendments:[1]	Be		Cd		Co		Cr		Ni	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
	mg/kg									
Borrow Soil	0.05	<0.005	0.25	0.05b	0.46	<0.30	1.66	0.28	1.81	1.83ab
Sewage Sludge (100)	0.03	<0.005	0.29	0.14a	<0.30	<0.30	0.54	0.32	1.26	2.76a
Conesville FGD[3] (600)	0.02	<0.005	0.27	0.05b	<0.30	<0.30	0.53	0.18	0.52	1.95ab
Mg-gypsum FGD (280)	0.00	<0.005	0.34	0.06b	<0.30	<0.30	0.54	0.17	0.69	1.11bc
Sewage Sludge (100) + Conesville FGD (600)	0.02	<0.005	0.25	0.07b	<0.30	<0.30	0.55	0.22	0.56	0.48c
Sewage Sludge (100) + Mg-gypsum FGD (280)	0.02	<0.005	0.35	0.07b	<0.30	<0.30	0.60	0.13	1.02	1.04bc

[1]Borrow soil was applied at 25-30 cm depth. Rates (Mg/ha) for other amendments are in parentheses.
[2]Within a column, means followed by no letter or the same letter are not significantly different at $p = 0.05$ using the LSD test.
[3]FGD = Flue gas desulfurization by-product.

H. Tree Foliar Element Concentrations

Element concentrations in tree foliage during the second growing season are listed in Tables 52-59. Calcium, boron, and molybdenum showed similar concentration relations with treatment in both tree foliage and herbaceous cover. As in herbaceous cover, tree foliage had least Ca on plots amended with sewage sludge alone (Table 53). All tree species had greater B for all FGD treatments compared to borrow soil or sewage sludge alone (Table 54). White ash, sycamore, and black locust had greater Mo on both Conesville FGD treatments than on other treatments (Table 55). On Conesville FGD, Mo concentrations were strikingly elevated in black locust (Table 55) and in herbaceous cover (Table 49). The N fixing abilities of black locust and the legumes that dominate the herbaceous cover (Table 46) may explain the similarities in Mo concentrations for locust and the herbaceous cover. Molybdenum is a component of the nitrogenase enzyme that functions in N fixation. High Mo concentrations in black locust and herbaceous cover may represent luxury consumption by these N fixing plants. The Mo levels in black locust and herbaceous cover are probably not toxic to those plants. A Mo concentration greater than 135 mg/kg was necessary to produce toxicity in barley, and some plant species tolerate 500 mg/kg Mo (Jones,1991).

Foliar N did not vary significantly with soil amendment treatment except in white ash (Table 52). White ash had greater foliar N for both treatments involving Conesville FGD than for other treatments. Foliar P was generally least for trees grown on borrow soil or on Mg-gypsum FGD alone (Table 52). All species except sycamore generally had least foliar K (Table 52) but greatest foliar Mg (Table 53) on Mg-gypsum FGD alone. All species had low foliar Mg on borrow soil. Foliar S was greatest for black locust on sewage sludge + Mg-gypsum FGD and for white ash on Mg-gypsum FGD alone (Table 53).

Of the micronutrient elements, only B and Mo, which are described above, and Ni showed strong effects of soil amendment treatment. All species except sycamore had greatest Ni concentrations on borrow soil or sewage sludge alone (Table 59). In white ash, foliar Mn for both Conesville FGD treatments (Table 54, 15-17 mg/kg) was near deficiency levels (Stone,1968). Manganese concentrations of 20 to 500 mg/kg are considered normal for a variety of plant species (Jones,1991). Foliar Fe, Cu, and Zn (Tables 54-55) were at sufficient levels for all tree species.

Concentrations of Al, Si, Ba, and Sr (Tables 56-57) showed significant treatment variations in one or more tree species, but the biological significance of these variations is uncertain. Concentrations of Be (Table 57), Co, Cd, Cr (Table 58), and Pb (Table 59) were relatively low for all tree species. Sycamore did have greater Cd on sewage sludge alone than on several other treatments. All tree species had concentrations below the detection limits for As (1.75 mg/kg) and Se (4.65 mg/kg).

Table 52. Foliar concentrations (g/kg) of nitrogen (N), phosphorus (P), and potassium (K) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
N	Black locust	34.3	35.0	36.4	35.4	37.5	35.7
	Sweet gum	19.4	17.3	21.2	19.0	20.3	20.9
	White ash	20.5bc	18.4d	23.1a	18.9cd	22.4ab	19.6cd
	Sycamore	22.4	20.9	24.1	24.7	24.0	24.4
P	Black locust	2.3c	2.4bc	2.9a	2.3c	2.7ab	2.7ab
	Sweet gum	2.0b	2.5ab	2.5ab	1.9b	3.2a	3.1a
	White ash	2.8d	4.2bc	3.3cd	3.1cd	6.0a	5.5ab
	Sycamore	2.0d	2.7bcd	2.4cd	2.9bc	3.3ab	3.7a
K	Black locust	17.5ab	19.1ab	19.4a	13.6c	19.5a	16.8b
	Sweet gum	8.2c	11.1a	10.6a	8.7bc	11.3a	10.2ab
	White ash	14.2b	15.8a	14.3ab	12.3c	15.8a	13.7bc
	Sycamore	8.2	11.3	10.0	11.3	12.5	10.1

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 53. Foliar concentrations (g/kg) of calcium (Ca), magnesium (Mg), and sulfur (S) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Ca	Black locust	9.9	5.8	9.3	12.5	10.8	11.3
	Sweet gum	8.3a	5.6b	7.9a	7.7a	8.2a	6.8ab
	White ash	9.1	7.0	10.6	10.5	9.6	8.7
	Sycamore	14.0ab	9.2c	15.6a	10.7bc	15.2ab	13.2abc
Mg	Black locust	1.1b	1.2b	1.3b	2.3a	1.2b	2.0a
	Sweet gum	2.1c	2.4c	3.1b	4.0a	3.1b	3.4b
	White ash	1.6e	1.9de	2.5cd	4.1a	2.7bc	3.1b
	Sycamore	1.8c	2.5abc	3.3ab	3.5ab	2.4bc	3.7a
S	Black locust	3.3c	3.2c	3.9abc	4.1ab	3.6bc	4.7a
	Sweet gum	2.0	1.7	3.3	2.6	2.2	2.3
	White ash	3.0b	3.5b	3.4b	4.6a	3.0b	3.2b
	Sycamore	6.2	6.6	9.2	7.9	7.6	7.3

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 54. Foliar concentrations (mg/kg) of manganese (Mn), iron (Fe), and boron (B) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Mn	Black locust	91a	80a	27b	83a	26b	50ab
	Sweet gum	377ab	443ab	323abc	489a	225bc	101c
	White ash	49	42	17	29	15	21
	Sycamore	69	124	281	196	37	101
Fe	Black locust	62b	65b	73ab	73ab	82a	69b
	Sweet gum	63ab	43b	70a	79a	74a	60ab
	White ash	76	63	81	81	78	69
	Sycamore	61	46	80	66	55	57
B	Black locust	23c	26c	155ab	131ab	165a	102b
	Sweet gum	15c	16c	151ab	131b	185a	129b
	White ash	16b	20b	52a	48a	45a	34ab
	Sycamore	18c	27c	136b	147b	229a	143b

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 55. Foliar concentrations (mg/kg) of copper (Cu), zinc (Zn), and molybdenum (Mo) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Cu	Black locust	7.0	6.9	6.9	5.9	6.8	6.7
	Sweet gum	7.1	6.9	8.1	6.9	7.1	7.5
	White ash	18.8	16.0	19.3	16.2	19.0	21.9
	Sycamore	13.7	10.8	11.2	14.7	13.9	16.0
Zn	Black locust	28.6	34.2	32.1	28.8	31.9	38.7
	Sweet gum	31.8b	40.6a	28.3b	31.6b	28.9b	33.6ab
	White ash	14.0	15.6	15.4	13.9	17.4	15.5
	Sycamore	21.5	19.9	23.1	20.5	23.1	27.0
Mo	Black locust	<0.55c	<0.55c	31.89a	<0.55c	18.35b	1.94c
	Sweet gum	<0.55	<0.55	<0.55	<0.55	<0.55	<0.55
	White ash	<0.55b	<0.55b	0.89a	<0.55b	0.95a	<0.55b
	Sycamore	<0.55c	<0.55c	1.10a	<0.55c	0.71ab	0.56bc

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 56. Foliar concentrations (mg/kg) of aluminum (Al), sodium (Na), and silicon (Si) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Al	Black locust	84	29	20	37	31	40
	Sweet gum	238	257	286	303	152	152
	White ash	67a	48bc	49bc	54ab	39c	47bc
	Sycamore	31	38	103	30	31	45
Na	Black locust	<2.7	<2.7	<2.7	<2.7	<2.7	<2.7
	Sweet gum	8.2	5.7	26.4	13.1	27.0	20.3
	White ash	<2.7	<2.7	3.4	<2.7	<2.7	<2.7
	Sycamore	<2.7	<2.7	<2.7	<2.7	<2.7	<2.7
Si	Black locust	<0.7	<0.7	<0.7	<0.7	<0.7	0.7
	Sweet gum	41.3b	41.9b	41.8b	56.6a	32.6b	31.6b
	White ash	16.3b	22.5a	8.6d	13.2bc	7.9d	9.1cd
	Sycamore	9.0	6.3	12.3	2.7	8.0	4.6

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 57. Foliar concentrations (mg/kg) of barium (Ba), strontium (Sr), and beryllium (Be) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Ba	Black locust	7.3a	3.5b	0.7c	0.7c	0.9c	0.9c
	Sweet gum	6.2a	1.9c	4.2b	4.0b	4.4ab	1.6c
	White ash	12.8a	8.5abc	11.5a	11.1ab	6.6bc	5.7c
	Sycamore	7.1a	5.2b	3.9b	3.7b	1.8c	3.9b
Sr	Black locust	12.7	15.1	11.3	6.4	15.3	10.1
	Sweet gum	8.1bcd	8.7abc	10.1ab	5.3cd	12.1a	5.2d
	White ash	10.4b	14.7a	11.6ab	6.6c	12.3ab	6.6c
	Sycamore	18.4ab	27.4a	25.6a	8.0b	25.0a	12.2b
Be	Black locust	0.024	<0.005	<0.005	<0.005	<0.005	<0.005
	Sweet gum	<0.005	<0.005	0.071	<0.005	<0.005	<0.005
	White ash	0.015	0.025	0.006	0.007	<0.005	0.010
	Sycamore	<0.005	0.008	0.030	<0.005	<0.005	0.036

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 58. Foliar concentrations (mg/kg) of cobalt (Co), cadmium (Cd), and chromium (Cr) in trees during the second year (Aug. 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Co	Black locust	0.44	0.53	<0.30	0.33	<0.30	0.40
	Sweet gum	<0.30	0.34	0.54	0.58	0.37	<0.30
	White ash	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30
	Sycamore	<0.30	<0.30	0.64	0.50	<0.30	<0.30
Cd	Black locust	0.05	<0.05	<0.05	<0.05	<0.05	<0.05
	Sweet gum	0.11	0.11	0.09	0.08	0.08	0.11
	White ash	<0.05	<0.05	0.06	<0.05	0.05	0.08
	Sycamore	<0.05c	0.19a	0.07bc	0.09abc	<0.05c	0.14ab
Cr	Black locust	<0.10	<0.10	<0.10	<0.10	0.13	<0.10
	Sweet gum	0.15	<0.10	0.12	0.17	0.21	0.15
	White ash	0.28	0.24	0.28	0.32	0.31	0.34
	Sycamore	0.18	0.19	0.13	0.15	0.21	0.29

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

Table 59. Foliar concentrations (mg/kg) of nickel (Ni) and lead (Pb) in trees during the second year (August 1997) on an acid minesoil as affected by soil amendment treatments.[1]

Element	Tree Species	Borrow Soil	Sewage Sludge	Conesville FGD	Mg-gypsum FGD	Sewage Sludge + Conesville FGD	Sewage Sludge + Mg-gypsum FGD
Ni	Black locust	5.1a	6.4a	1.2c	2.1bc	1.2c	2.7b
	Sweet gum	6.5ab	8.3a	4.6bc	3.9cd	2.4cd	1.7d
	White ash	2.5a	3.0a	0.8b	1.2b	0.5b	0.8b
	Sycamore	2.6	6.5	3.7	5.3	1.3	3.9
Pb	Black locust	<0.95	<0.95	<0.95	<0.95	<0.95	<0.95
	Sweet gum	2.75	<0.95	<0.95	<0.95	<0.95	<0.95
	White ash	<0.95	<0.95	1.24	<0.95	<0.95	<0.95
	Sycamore	0.99	<0.95	1.05	<0.95	<0.95	<0.95

[1]Within each element and tree species, amendment treatment means followed by no letters or similar letters are not significantly different at $p = 0.05$ using the LSD test.

IV. DISCUSSION

A. Element Concentrations in Runoff

We report elemental analyses of unfiltered runoff samples that were digested four hours with a nitric acid-perchloric acid mix. This digestion undoubtedly dissolved some suspended mineral and organic particles, thus increasing the total (digest) concentrations for elements such as Al, Fe, K, and P. These analyses give an idea of total amounts of elements coming from the various treatments, but are an upper bound for estimating elements exported in solution.

We built the runoff collection flumes from exterior plywood, pressure-treated with chromated copper arsenate, and we coated them with roofing tar following installation. We can not rule out the possibility that some of the Cr, Cu, and As found in runoff samples came from the treated wood. The manufacturer states that chromated copper arsenic forms a complex with wood that makes it relatively resistant to leaching. If additional funding becomes available, we will coat the flumes with waterproof fiberglass resin or some other waterproofing agent.

B. Plant Growth

All treatments resulted in a complete cover by herbaceous plants, up to February 26, 1998. How long this cover will remain intact is an open question that can be answered by continued monitoring. In the long run, some of the planted trees, especially black locust and sweetgum, will dominate the plots but they are not contributing to erosion prevention at present. Browsing by a large deer population, and competition from the ground cover is reducing tree survival and preventing rapid tree growth. There is thus a tradeoff between the desirable effect of ground cover on erosion prevention, and its less desirable effect on tree establishment. Of course, some land managers may not be interested in tree establishment, so from their viewpoint herbaceous cover effects would be wholly positive.

Did the sewage sludge and FGD treatments result in plant cover equal to or better than borrow soil, in terms of ground cover yield and erosion protection? The short answer is "Yes." In 1996, herbaceous biomass was least on the borrow soil plots, and up to 15 times greater on plots treated with a combination of FGD and sewage sludge (Table 46). In 1997, yield differences were less dramatic, but all other treatments were at least as productive as borrow soil, and sewage sludge + Conesville FGD gave significantly higher aboveground biomass. In 1997, total canopy cover did not differ among treatments, although there were significant treatment differences in percent cover by grasses and legumes (Table 46). Borrow soil had the lowest proportion of grasses and the highest proportion of legumes of any treatment.

Tree survival was most promising on sewage sludge alone, intermediate on borrow soil, and least promising on all treatments with FGD. Both treatments with Conesville FGD had notably poor tree survival compared to borrow soil or sewage sludge alone. Decreased tree survival for FGD treatments may have resulted from elevated soluble salts (electrical conductivity) and boron in the soil. In the second year, trees on Conesville FGD treatments may have suffered from greater herbaceous competition in the presence of greater herbaceous biomass. Increased herbaceous competition on Conesville FGD treatments is of questionable overall importance for tree survival because first-year survival tended to be least on Conesville FGD alone even though this treatment had sparse first-year herbaceous biomass.

C. Boron and Molybdenum in Plants

In a boron toxicity study with American sycamore, nutrient solutions containing 2 or 4 mg of B per liter caused B toxicity symptoms of chlorotic or necrotic zones along margins of lower leaves. Water extracted from suction lysimeters in all FGD treatments in 1996 at both 30 and 60 cm exceeded 2.0 mg/L B, as did extracts from the Conesville treatments in 1997. Boron concentration in runoff from FGD-treated plots was elevated above sewage sludge or borrow soil treatments on two sample dates in both 1996 and 1997, but exceeded 2.0 mg/L only in the August 1, 1996 samples. Foliage of sycamore, collected in 1997, had significantly higher concentrations of B in samples from FGD-treated plots (Table 54), but with concentrations that were below those giving toxicity symptoms in nutrient solution culture studies of Vimmerstedt and Glover (1984). Boron in herbaceous tissue from FGD-treated plots was also greater than that from borrow soil or sewage sludge treated plots, with larger differences in 1996 than in 1997 (Table 49). Boron in the FGD did not reduce plant yields below those from the non-FGD treatments (Table 46). In a study with black locust seedlings (Kost and Vimmerstedt, 1992), fly ash from the Conesville power plant contained high levels of B, and we consider fly ash to have been the source of B in the Conesville FGD treatments in this research. We are puzzled by finding high B in the Mg-gypsum FGD treatments, because this supposedly contained no fly ash.

The relatively high Mo concentrations in ground cover on Conesville FGD plots could induce Cu deficiency in grazing animals. To prevent Cu deficiency, it is suggested that the Cu/Mo ratio in animal diets should be 2:1 for cattle and as high as 4:1 for sheep (Miller et al.,1991). In 1997, the Cu/Mo ratio in ground cover was 1:3.7 for Conesville FGD alone and 1:2.2 for sewage sludge + Conesville FGD.

V. CONCLUSIONS

All FGD treatments resulted in initially successful reclamation of acid, toxic coal spoils, with herbaceous plant cover equal to or better than that on borrow soil, in terms of providing protection from soil erosion. In both 1996 and 1997, sewage sludge + Conesville FGD gave the highest aboveground biomass. Determination of long term effects requires continued monitoring.

Trees survived best on the sewage sludge plots, but height growth did not differ among treatments in 1997. Several more years of observation are needed to assess treatment effects on trees.

Elevated boron concentrations in soil, vadose water, runoff, and plant tissue from FGD treatments indicates that boron toxicity may be a problem for plants grown in soils amended with FGD, although there was no evidence of plant growth reduction due to high B.

The rather high frequency with which runoff samples exceeded the recommended maximum contaminant level (RCML) for arsenic, mercury, lead and selenium is of concern. Preservative-treated plywood is a possible source of the As. Concentrations of Ba, Cd, Cr, Cu and Zn in runoff water are not a problem.

Concentrations of Fe and Mn in runoff, while not a health hazard, were often higher than suggested limits for aesthetic reasons.

VI. REFERENCES

Asher, C.J. 1991. Beneficial elements, functional nutrients, and possible new essential elements. p. 703-723 *In* J.J. Mortvedt et al. (ed.) *Micronutrients in agriculture*. Second ed. Number 4 in the Soil Science Society of America Book Series, Soil Science Society of America, Madison, WI.

Buck, J.K., and R.J. Houston. 1988. Direct revegetation of anthracite refuse using coal fly ash as a major soil amendment. p.236-245 *In Information Circular 9184,* USDI Bureau of Mines, Washington, DC.

Capp, J.P. 1978. Power plant fly ash utilization for land reclamation in the eastern United States. p. 339-353 *In* F.W. Schaller and P. Sutton (ed.) *Reclamation of Drastically Disturbed Lands.* American Society of Agronomy, Madison, WI.

De Zuane, J. 1990. Drinking water quality: standards and controls. Van Nostrand Reinhold, NY. 523 p.

Jones, J.B. Jr. 1991. Plant tissue analysis in micronutrients. p. 477-521 *In* J.J. Mortvedt et al. (ed.) *Micronutrients in agriculture*. Second ed. Number 4 in the Soil Science Society of America Book Series, Soil Science Society of America, Madison, WI.

Kost, D.A., and J.P. Vimmerstedt. 1992. Fly ash-amended resoiling materials: Establishment, growth, and nutrition of tree seedlings in greenhouse. *Int. J. of Surface Mining and Reclamation* 6:39-46.

Miller, E.R., X. Lei, and D.E. Ullrey. 1991. Trace elements in animal nutrition. p. 593-662 *In* J.J. Mortvedt et al. (ed.) *Micronutrients in agriculture*. Second ed. Number 4 in the Soil Science Society of America Book Series, Soil Science Society of America, Madison, WI.

Romheld, V., and H. Marschner. 1991. Function of micronutrients in plants. p. 297-328 *In* J.J. Mortvedt et al. (ed.) *Micronutrients in agriculture*. Second ed. Number 4 in the Soil Science Society of America Book Series, Soil Science Society of America, Madison, WI.

SAS Institute Inc. 1987. *SAS/STAT guide for personal computers, version 6 edition.* SAS Institute Inc. Cary, NC. 1028 p.

Shahandeh, H., and M.E. Sumner. 1993. Establishment of vegetation on by-product gypsum materials. *J. Environ. Qual.* 22: 57-61.

Sopper, W.E. 1992. Reclamation of mine land using municipal sludge. *Advances in Soil Science* 17: 351-431.

Stehouwer, R.C., P. Sutton, and W.A. Dick. 1995. Minespoil amendment with dry flue gas desulfurization by-products: Plant growth. *J. Environ. Qual.* 24: 861-869.

Stone, E.L. 1968. Microelement nutrition of forest trees: A review. p.132-175 *In* G.W. Bengston et al. (ed.) *Forest fertilization theory and practice*. Symp. on Forest Fertilization, Gainesville, FL. April 1967. Tennessee Valley Authority, Muscle Shoals, AL.

Vimmerstedt, J.P., and T.N. Glover. 1984. Boron toxicity to sycamore of minesoil mixed with sewage sludge containing glass fibers. *Soil Science Society of America Journal* 48:389-393.