CASE HISTORY OF A COPPER MINE TAILINGS POND RECLAMATION IN DUCKTOWN, TENNESSEE[1]

J L. Branson[2] and J. T. Ammons

Abstract: Cessation of mining operations in Ducktown, TN, left 800-900 acres of barren copper mine tailings. Revegetation activities had met with limited success. In 1998, efforts for revegetation of the tailings materials began anew. The objective of this case history is to provide insight into decision making processes which resulted in conversion of 800-900 acres of barren mine tailings into a vegetated, productive landscape. Phase 1 began with intensive analyses of the tailings materials. Acid-base accounting registered a generally neutral to alkaline pH. Scattered areas were more acid with pH values measuring as low as 1.9. Neutralization potential was adequate in most cases to counteract potential acid formation. Total elemental analysis indicated a maximum of 416 mg kg^{-1} P (total) with essentially none plant available as measured by the bicarbonate P method. Utilizing these data, phase 2 was initiated with the installation of two one-acre plots with variables of 1) P treatments (0, 50, 100, and 200 lb $acre^{-1}$), 2) biosolid/ non-biosolid applications, and 3) fescue/ legumes (birdsfoot trefoil, sericea lespedeza, Korean lespedeza, and Kobe lespedeza). Korean and Kobe lespedeza/fescue on biosolids with 100 lb P $acre^{-1}$ were most productive. Phase 3 was based on data from the test plots. An in situ treatment of 100 lb P $acre^{-1}$ and 2 tons acre $lime^{-1}$ (to counter random generations of acids) with no biosolids and additions of standard fertilizers were applied with incorporation to at least 6 inches. Korean and Kobe lespedeza along with Kentucky 31 tall fescue were planted along with sandy bluestem and switch grass. The warm season grasses (sandy bluestem and switch grass) that were included in the seeding mixture were successful in grass test plots on site.

Additional Key Words: Ducktown, phosphorous, copper mine tailings, lespedeza. Biosolids

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Introduction

Following the discovery of copper in 1843 (Safford, 1869), mining in the Copper Basin was extensive. Countless tons of iron, zinc, and copper were extracted, but massive amounts of surplus wastes remained. At the Isabella Mine near Ducktown, TN, a 900-acre tailings pond endures as the symbol of an industry now departed (Fig 1). Virtually barren, the tailings became a source of concern for environmental quality. Past revegetation efforts had met with limited or no success. Severe wind and water erosion were evident. Rills were wide and numerous. One knob underlain by native soils had a 3-5 cm layer of eolian sand on its surface.

In 1998, the current landowners requested assistance from the University of Tennessee Plant and Soil Science Department to determine the viability of establishing vegetation to reduce erosion on the tailings pond. The objective of this case study is to provide insight into the reasoning behind decisions made relative to reclamation of the copper mine tailings pond at Ducktown, Tennessee.

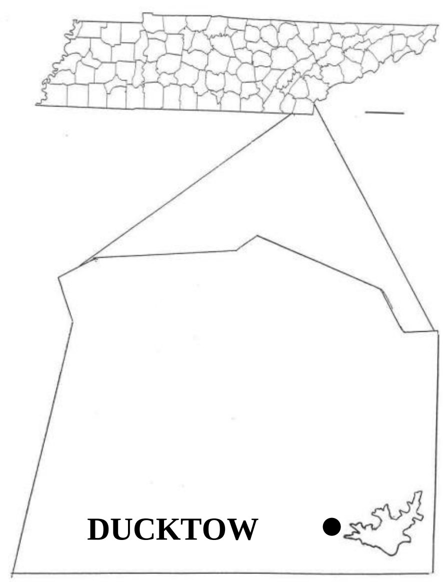

Figure 1. Location of the study site at Ducktown, TN.

Investigative Procedures

This project was set up in three phases. Phase I was the initial investigation to determine the physical and chemical composition of the waste materials. Phase II involved the establishment of trial plots to determine appropriate additions of amendments and plant species suitable for revegetation. Phase III was the final recommendation gleaned from results of this research and implementation by the client over the entire tailings pond section.

Phase I Initial Investigation

Phase I was designed to determine physical and chemical properties of the tailings materials. An initial investigation of the tailings pond area was instigated with the objectives of 1) using acid-base accounting to determine the potential for acid formation in the tailings, 2) establishing the presence or absence of essential nutrients for plant growth, 3) assessing the availability of toxic concentrations of heavy metals, and 4) determining basic soil morphology.

Literature Review

During ore processing, extracted materials were crushed to a size less than 2 mm. Flotation processes subjected these particles to additions of chemicals and mechanical agitation. Compressed air was released producing heavy froth, which rose to the surface, and carried with it the specific minerals of interest. Waste matter did not float but was drawn off at the bottom of the float machines and pumped to a waste disposal lake, i. e. the tailings pond (Maher, 1966).

In most flotation operations, pH values generally ranged from 7 to 13. To control pH, the reagents commonly used are lime (CaO) and soda ash (Na_2CO_3) for alkaline circuits, and sulfuric acid (H_2SO_4) in acid circuits. Lime facilitates the precipitation of toxic salts in water and the depression of pyrite to prevent it from floating (Richards and Locke, 1940).

Heavy metals in tailings waste often occur in concentrations higher than those generally found in naturally occurring soils. Total concentrations of the more common metals in natural or native soils are:

Copper	2-100 mg kg^{-1} (Lindsay, 1979)
Nickel	5-500 mg kg^{-1} (Lindsay, 1979)
Manganese	20-3000 mg kg^{-1} (Lindsay, 1979)
Zinc	10-300 mg kg^{-1} (Lindsay, 1979)

Cadmium	0.06-1.1 mg kg^{-1} (Kabata-Pendias and Pendias, 1992)
Chromium	54 mg kg^{-1} (Kabata-Pendias and Pendias, 1992)

Environmental effects of high levels of such elements include toxicity to vegetation. Heavy metals decrease water and nutrient uptake by plants, decrease root respiration, inhibit cell mitosis in root meristematic regions, and reduce enzymatic activity and microbial communities in soil (Gemmell, 1977) (Clark and Clark, 1981).

Highly reactive with both organic and inorganic soil components, accumulation of copper is a common property of surface soil horizons. Soil microbes effectively "fix" copper and pH dependent surface charges of soil colloids can absorb this element. Copper readily precipitates with carbonates, sulfides, and hydroxides (Kabata-Pendias and Pendias, 1992).

As with copper, clays and organic matter have a strong affinity for zinc (Lindsey, 1972). Zinc becomes immobile in soils containing high levels of calcium and phosphorous, and those well aerated with sulfur compounds. Solubility and availability of Zn is greatest in acid environments (Kabata-Pendias and Pendias, 1992).

Least mobile of the heavy metals, lead precipitates as a hydroxide, phosphate, or carbonate at an alkaline pH (Kabata-Pendias and Pendias, 1992). The greatest accumulations of lead occur in surface horizons, indicating organic matter may act as a sink for Pb (Fleming et al, 1968). Uptake by plant roots has been shown to be enhanced by low pH and low levels of P in soil (Kabata-Pendias and Pendias, 1992)

Nickel co-precipitates mainly with Fe and Mn oxides, and has a great affinity for sulfur. Stable in aqueous conditions, nickel is capable of migration over a long distance (Kabata-Pendias and Pendias, 1992). In surface horizons, Ni appears to occur mainly in organically bound forms (Bloomfield, 1981).

Manganese compounds readily undergo oxidation-reduction in variable soil environments. Reduced Mn not only decreases the availability of oxide exchange sites, but also competes with other cations for available exchange sites. This increases the leaching susceptibility of competing cations and metals. Phytotoxic levels of Mn and other heavy metals may also arise in soil solution (Kabata-Pendias and Pendias, 1992). Soluble manganese has been observed to increase in soils that have been amended with sludge, increasing the possibility of phytotoxic reactions over time (Grove and Ellis, 1980).

Hexavalent chromium (Cr^{6+}) is toxic to plants and animals (Turner and Rust, 1971) and is easily mobilized in both acid and alkaline soils. Controlling the rate of oxidation increases with a decrease in pH. Availability of free Mn^{3+} in solution greatly influences oxidation of chromium under environmental surface conditions (Zasoski and Chung, 1992). (Chung and Zasoski, 1992). Cadmium is strongly associated with Zn in its geochemistry, but Cd is more mobile in acid environments and has a greater affinity for sulfur than Zn. Factors influencing cadmium mobility include pH, organic matter, sesquioxides, and carbonates. Cadmium is most mobile at pH values of 4.5 - 5.5 (Christensen, 1984). Organic matter has a higher affinity for the absorption of Cd than clays (John, 1972). The presence of carbonate is the most effective factor in immobilizing Cd (Christensen, 1984).

Material and Methods

Following a transect across the tailings pond, four sites and one surface grab sample (labeled C') were chosen for examination. Soil morphology was completed and sampled by horizon for each pedon. Particle size analysis was determined by the pipette method (Kilmer and Alexander, 1949).

Soil pH was measured using a 1:1 ratio of water and soil (Olsen and Ellis, 1982a). Acid -base accounting (Sobek et al., 1978), analyzing for total sulfur, acid producing sulfur (pyritic sulfur), sulfate sulfur, and organic sulfur, was determined to assess the potential for these tailings materials to generate an acid environment. Neutralization potential (Jackson, 1982) (Sobek et al., 1978) was utilized to assess the ability of compounds in the tailings to effectively recompense for any acid that might be generated. Iron oxides were extracted by the citrate-dithionite (CD) method (Olsen and Ellis, 1982b) and manganese oxides by a hydroxylamine hydrochloride method (Gambrell and Patrick, 1982).

Double-acid-extractable K, Ca, Mg, Na, Cu, and Fe (Sims and Heckendorn, 1987) were determined by atomic absorption spectrophotometer to measure exchangeable plant nutrients. Sodium bicarbonate extractable P (Olson et al., 1954) and KCl-extractable Al (Barnhisel and Bertch, 1982) were determined to complete the suite of chemical properties to be monitored in the test plots.

Total dissolution analysis (Ammons et al., 1995) was completed to determine if there was potential for release of plant nutrients due to weathering processes for sustaining a vegetative system.

Results

Stratification from multiple depositions was a prominent feature in all four pedons. No A horizon had developed. All layers were designated as C horizons indicating an absence of pedogenic influence (Table 1). Particle sizes ranged from fine sand to loamy fine sand due to the ore crushing process. Silt sized particles comprised 7 (site 2) to 26% (site 4) of the textures. None of the four sites contained more than 7% clay sized particles. No aggregation was evident in any pedon.

Due to procedural differences in ore processing and original rock composition, chemistry was highly variable. Paste pH deviated widely with an 8.2 in site 2 to a 3.6 in site 4 (Table 2). Results of acid-base accounting indicated less than 9% total sulfur present in the tailings materials (Table 3). In site 4, sulfur values were consistently higher in all layers compared with most horizons in the other three sites. Site 4 also had the highest levels of pyritic sulfur (Table 4). The presence of organic sulfur possibly was a result of materials washed into the tailings pond from the surrounding landscapes, which were covered with evergreen trees and shrubs. Calcium carbonate was present in sufficient quantity to neutralize any acid generated in all four sites. The surface grab sample did require additional neutralization materials, as $CaCO_3$ levels were insufficient.

Acceptable quantities of exchangeable calcium and magnesium were present for plants; however, exchangeable potassium was available in minute amounts (Table 2). Phosphorous was definitely limiting at <1 mg kg^{-1} (Table 5). Percent free iron was higher in site 4 (Table 5). Extractable copper was nearly undetectable in sites 1, 2, and 3. Site 4 contained levels of copper ranging from 25 to 132 264 mg kg^{-1}. As expected, total copper was present in large quantity due to the nature of the ore (Table 6).

Table 1.Selected physical characterization data for sites 1, 2, 3, and 4 of the initial transect.

Site 1

Hori-zon	Depth (cm)	Color		Structure	Tex-ture †	% Sand	% Silt	% Clay
C1	0-30	2.5Y 4/2	Dark grayish brown	0SG*	S	88	11	1
C2	30-50	10YR 4/4	Dark yellowish brown	0SG	S	87	12	1
C3	50-70	10YR 4/6	Dark yellowish brown	0SG	S	88	12	0
C4	70-90	5YR 4/6	Yellowish red	0SG	L S	86	13	2

Site 2

C1	0-30	10YR 4/2	Dark grayish brown	0SG	S	91	9	0
C2	30-55	10YR 4/4	Dark yellowish brown	0SG	S	92	8	0
C3	55-100	10YR 4/6	Dark yellowish brown	0SG	S	87	11	2
C4	100-125	2.5YR 3/6	Dark red	0SG	L S	81	12	7
C5a	125-150	2.5YR 2.5/1	Reddish black	0SG	S	92	7	1
C5b	125-150	5Y 3/2	Dark olive gray					

Site 3

C1	0-5	2.5YR4/4	Reddish brown	0SG	L S	83	15	1
C2	5-32	5YR 4/6	Yellowish red	0SG	L S	82	15	3
C3	32-79	2.5Y 5/6	Light olive brown	0SG	L S	86	12	2
C4	79-130	5Y 4/6	Olive	0SG	L S	86	13	1
Cg	130+	5BG 4/1	Dark greenish gray	0SG	S	89	11	0

Site 4

C1	0-15	2.5Y 4/2	Dark grayish brown	0SG	L S	86	14	0
C2	15-40	10YR 3/6	Dark yellowish brown	0SG	L S	80	19	1
C3	40-60	5YR 3/4	Dark reddish brown	0SG	L S	72	26	2
C4	60-85	5YR 4/6	Yellowish brown	0SG	L S	78	19	3
C5	85-110	2.5YR 4/6	Red	0SG	L S	76	21	3
C6	110-130	7.5YR 3/2	Dark brown	0SG	L S	NA‡	NA	NA

Grab Sample

C1’	0-20	5YR 4/6	Yellowish Red	0SG	L S	75	22	3

* 0SG = structureless single grain

† Texture: S = sand; L S = loamy sand

‡ NA= not available

Table 2. Cation exchange capacity, % base saturation, and pH data for the initial transect sites.

Site 1

Horizon	Depth (cm)	CEC	Ca	Mg	Na	K	% Base Saturation	pH
			--------------cmol kg^{-1}	------------------				
C1	0-30	0.92	22.25	1.50	0.04	0.00	>100	7.2
C2	30-50	0.65	59.92	11.60	0.03	0.00	>100	7.4
C3	50-70	0.80	67.52	5.86	0.02	0.00	>100	7.4
C4	70-90	0.65	87.85	15.54	0.04	0.00	>100	7.6

Site 2

C1	0-30	0.77	12.31	1.81	0.03	0.00	>100	8.2
C2	30-55	1.42	15.53	0.14	0.03	0.00	>100	8.0
C3	55-100	0.72	73.32	0.08	0.05	0.01	>100	7.4
C4	100-125	1.48	156.17	1.67	0.04	0.02	>100	6.6
C5	125-150	0.72	48.18	3.07	0.03	0.02	>100	7.0

Site 3

C1	0-5	2.03	16.19	0.73	0.02	0.00	>100	7.8
C2	5-32	1.68	160.21	1.16	0.05	0.00	>100	7.0
C3	32-79	1.09	92.07	0.78	0.04	0.00	>100	7.6
C4	79-130	0.96	84.68	0.80	0.07	0.00	>100	7.4
Cg	130+	0.60	45.64	1.52	0.05	0.02	>100	7.4

Site 4

C1	0-15	0.91	81.26	0.63	0.03	0.00	>100	7.6
C2	15-40	1.55	153.15	1.82	0.03	0.00	>100	6.6
C3	40-60	2.48	121.55	1.90	0.04	0.00	>100	3.0
C4	60-85	2.34	197.74	1.29	0.04	0.00	>100	3.0
C5	85-110	NA	NA	NA	NA	NA	NA	3.8
C6	110-130	NA	NA	NA	NA	NA	NA	3.6

Grab sample

C’	0-30	2.50	167.57	4.02	0.03	0.01	>100	1.9

Table 3. Fractionated forms of sulfur.

Site 1

Horizon	Depth (cm)	Total Sulfur %	Pyritic Sulfur %	Sulfate Sulfur %	Organic Sulfur %
C1	0-30	1.79	<.001	1.54	0.44
C2	30-50	8.22	<.001	6.57	1.72
C3	50-70	1.94	<.001	1.81	0.18
C4	70-90	2.76	.099	2.42	0.24

Site 2

C1	0-30	0.94	028	0.58	0.33
C2	30-55	2.85	<.001	2.66	1.33
C3	55-100	8.26	<.001	5.90	2.36
C4	100-125	5.63	.330	4.18	1.12
C5a	125-150	3.26	<.001	2.86	1.67
C5b	125-150	2.78	<.001	2.51	1.43

Site 3

C1	0-5	2.06	<.001	1.70	1.34
C2	5-32	3.43	<.001	3.11	0.36
C3	32-79	1.31	.064	1.24	0.01
C4	79-130	1.73	.142	1.54	0.05
Cg	130+	1.56	<.001	1.41	0.72

Site 4

C1	0-15	4.16	<.001	3.63	1.06
C2	15-40	7.10	.060	4.84	2.20
C3	40-60	4.84	.160	4.35	0.33
C4	60-85	4.19	.214	3.90	0.08
C5	85-110	6.91	.400	5.43	1.08
C6	110-130	7.14	.757	5.65	0.73

Grab Sample

C’	0-20	7.42	<.001	5.63	2.22

Table 4. Acid-base accounting data calculated from pyritic sulfur values.

Horizon	Depth (cm)	Fizz Test	Color	%S	Max. From %S	N.P. $CaCO_3$ Equiv.	Max Needed (pH 7)	Excess $CaCO_3$
Site 1								
C1	0-30	4	2.5Y 6/2	<.001	.03	219.47		219.44
C2	30-50	4	10 YR 4/4	<.001	.03	211.79		211.76
C3	50-70	4	10 YR 6/3	<.001	.03	166.34		166.31
C4	70-90	3	10 YR 5/4	.099	3.09	109.25		106.16
Site 2								
C1	0-30	4	2.5Y 6/3	.028	.88	174.02		173.14
C2	30-55	5	10 YR 6/3	<.001	.03	245.73		245.70
C3	55-100	5	10 YR5/4	<.001	.03	323.45		323.42
C4	100-125	4	7.5YR 5/4	.330	10.31	143.43		133.12
C5a	125-150	5	2.5Y 5/3	<.001	.03	217.31		217.28
C5b	125-150	4	2.5Y 6/2	<.001	.03	233.02		232.99
Site 3								
C1	0-5	4	10 YR 5/4	<.001	.03	208.08		208.05
C2	5-32	4	7.5YR 5/4	<.001	.03	148.11		148.08
C3	32-79	4	2.5Y 6/4	.064	2.00	109.97		107.97
C4	79-130	4	2.5Y 6/4	.142	4.44	112.73		108.29
Cg	130+	4	2.5Y 6/1	<.001	.03	172.10		172.07
Site 4								
C1	0-15	3	2.5Y 5/3	<.001	.03	144.39		144.36
C2	15-40	3	10YR 4/4	.060	1.88	110.69		118.81
C3	40-60	1	10YR 4/6	.160	5.00	40.46		35.46
C4	60-85	2	10YR 5/6	.214	6.69	59.48		52.79
C5	85-110	1	10YR 5/4	.400	12.5	40.77		28.27
C6	110-30	1	2.5Y 4/4	.757	23.66	30.90		7.24
Surface Grab Sample								
C’	0-20	0	10YR 4/6	<.001	.03	-3.62	3.65	

Table 5. Selected chemical analyses data from the initial transect sites.

Site 1

Horizon	Depth (cm)	% Free Fe	Mn	P	Cu	Total acidity	Al
			---------mg kg^{-1}---------			------cmol kg^{-1} ------	
C1	0-30	1.76	825	<1	1.76	825	<1
C2	30-50	2.26	1040	<1	2.26	1040	<1
C3	50-70	4.42	704	<1	4.42	704	<1
C4	70-90	2.63	715	<1	2.63	715	<1

Site 2

C1	0-30	1.21	979	<1	<.1	0.04	0.00
C2	30-55	1.61	748	<1	<.1	0.08	0.00
C3	55-100	2.85	913	<1	<.1	0.08	0.00
C4	100-125	4.19	660	<1	.15	0.08	0.00
C5	125-150	0.97	809	<1	<.1	0.08	0.00

Site 3

C1	0-5	2.69	1095	<1	.2	0.08	0.00
C2	5-32	3.47	1056	<1	<.1	0.04	0.00
C3	32-79	2.13	627	<1	<.1	0.08	0.00
C4	79-130	1.82	567	<1	<.1	0.08	0.00
Cg	130+	1.10	798	<1	<.1	0.04	0.00

Site 4

C1	0-15	2.76	721	<1	25	0.04	0.00
C2	15-40	7.56	350	<1	10.6	0.08	0.00
C3	40-60	11.11	133	<1	57	1.27	0.48
C4	60-85	17.14	52	<1	49.8	9.77	7.86
C5	85-110	15.20	345	<1	132	3.83	0.99
C6	110-130	18.18	NA	<1	19	NA	NA

Grab Sample

C’	0-30	11.58	36	5.3	11.9	9.95	5.47

Table 6. Specific total elemental content of native soils as compared with the total elemental concentrations in the four pedons from the tailings pond ([1] Lindsay, 1979; [2] Kabata-Pendias and Pendias, 1992)

ELEMENT	% COMMON IN NATIVE SOILS (mg kg^{-1})	SITE 1 (mg kg^{-1})	SITE 2 (mg kg^{-1})	SITE 3 (mg kg^{-1})	SITE 4 (mg kg^{-1})
Cadmium	0.06 - 1.1 [2]	3	3	2	4
Chromium	54 [2]	64	62	57	24
Copper	2 - 100 [1]	839	737	666	2537
Manganese	20 - 3000 [1]	3723	3592	3678	3356
Nickel	5 - 500 [1]	75	63	316	57
Lead	2 - 200 [1]	100	94	96	286
Zinc	10 - 300 [1]	1738	1922	1637	2861

KCl extractable aluminum (Table 5) became more available at a low pH (Table 2). In sites 1, 2, and 3, total acidity concentrations were <1 cmol$^{(+)}$ kg^{-1}. Only in horizons of site 4 having pH values less than 5, was there any measurable total acidity and extractable aluminum on the cation exchange sites.

Cadmium and chromium were present slightly higher concentrations that those common to native soils (Table 6). Cadmium levels averaged 2 to 4 mg kg^{-1} while average chromium ranged up to 64 mg kg^{-1}. Total nickel was present in concentrations comparable to those of native soils. Total zinc was present in high concentrations as expected due to the nature of the ore. Site 4 had a higher than usual level of lead. The source is unknown. This may have been natural or a result of contamination during processing.

Discussion and Conclusions

Results of the analyses indicated that calcium carbonate was sufficiently available to compensate for any acid formed. However, due to the possibility of ‘hot spots’, additional lime would insure neutralization of forming acids. Phosphorous was virtually non-existent in the tailings and there was no sustainable natural source to provide nitrogen to sustain vegetation. Both N and P amendments would be needed. Biological N fixation could be achieved through the establishment of legume species. Since the tailings contain low concentrations of microbial activity, symbiotic microbes associated with those specific legumes would need to be provided. Plant available potassium was present in miniscule amounts, therefore, K fertilizer would assure an adequate supply for young seedlings.

The consistent particle size would facilitate downward movement of moisture through the tailings. Leaching of added nutrients was a major concern. Since there were few colloids in the minesoil, additions of organic matter would provide cation exchange sites to hold plant nutrients as well as moisture for plants.

Most heavy metals and other elements were present in amounts not expected to cause toxicities. In horizons with exchangeable aluminum present, an increase in pH should allow Al to become bound as aluminum hydroxide, thus, decreasing its acidic influence.

Phase II The Establishment of Vegetation on Test Plots

Objectives

Objectives of phase II were to: a) establish vegetation test plots on mine tailings, b) amend the tailings utilizing data determined during phase I, c) monitor for vegetation success and soil chemical changes, and d) develop a plan for amending the tailings materials and establishing a self-sustaining vegetation system of the remaining sections of barren mine tailings.

Literature Review

Soil acidity and a lack of plant nutrients are major limiting factors in establishing adequate vegetation. When soil is slightly acid, pH 6-7, most plants have a good survival rate. Acidity problems can often be overcome with additions of agricultural limestone (Fribourg et al, 1981). Legumes are probably the most important type of plant in establishment of vegetation on spoil or tailings materials. A planting of grasses mixed with legumes has the best probability of success with each plant type providing benefits for the other. Legumes provide much-needed nitrogen for grass vegetation. Grasses provide protective cover for the legumes against erosion (SCS, 1978).

A cool-season grass, tall fescue, *Festuca arundinacea*, can be established over a wide range of site characteristics and provides good cover if fertilized. Fescue does well on slightly acid soils, but success rate decreases with decreasing pH (SCS, 1978).

Birdsfoot trefoil, *Lotus corniculatus*, is a cool-season legume best adapted for regions north of the Ohio River. It can successfully be established in more southern latitudes if there is limited plant competition. Birdsfoot trefoil grows best when mixed with tall fescue. Preferred pH values for growth of birdsfoot trefoil are slightly acidic (SCS, 1978).

Sericea lespedeza, *Lespedeza cuneata*, is a very adaptable warm-season perennial legume. Especially useful in minesoil reclamation, it has a low fertilizer requirement, is acid and drought tolerant, has soil building properties, and is relatively pest resistant. Erosion control is an added benefit, but reseeding may be required to produce full cover (SCS, 1978). Sericea is self-mulching in that it shades itself causing lower leaves to be shed during the growing season. This forms a protective covering on the soil surface and adds organic matter to the soil (USDA, 1950).

Korean lespedeza, *Lespedeza stipulacea*, ceases growth with the first killing frost, but does have excellent reseeding rates. It grows best above pH 5, but can grow in infertile soils. Kobe lespedeza, a cultivar, is more acid tolerant than Korean. Both Korean and Kobe perform well in the same regions as sericea (SCS, 1978).

Materials and Methods

Field Methods. A laser transit was used to establish the location of two one-acre test plots in a representative region of the tailings pond. Variables included 1) phosphorous treatments, 2) grass/legume mixtures, and 3) biosolids/non-biosolid applications. Plot configuration was a randomized split block design. Individual grids were laid out according to treatments (Fig. 2) with each P treatment encompassing 24 ft^2 and each grass/legume treatment on blocks of 12 ft^2. Samples were extracted from each grid block at a depth of 0-6 inches using a Z sampling pattern to establish baseline fertility characterization. Since phase I analyses reflected a deficiency in phosphorous, a control and three P treatments were used. The three rates were 50 lb P $acre^{-1}$, 100 lb P $acre^{-1}$, and 200 lb P $acre^{-1}$ (56 kg P ha^{-1}, 112 kg P ha^{-1}, and 224 kg P ha^{-1}). With a variable pH, plant materials were chosen which had shown success over a wide reaction range.

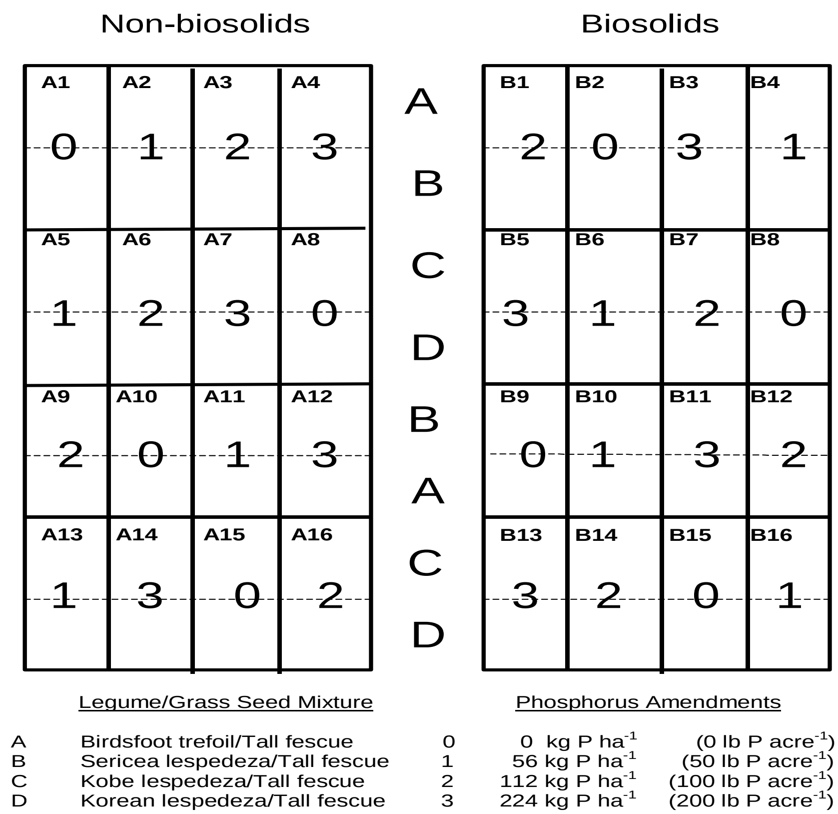

Figure 2. Layout of the two one-acre test plots with P treatments and legume treatments.

Kentucky 31 tall fescue was the grass of choice. Four legumes, birdsfoot trefoil, sericea lespedeza, Kobe lespedeza, and Korean lespedeza, were used. Although the Copper Basin lies below the southern range normally recommended for birdsfoot trefoil, it was thought the higher elevations would compensate for climatic differences. All legumes were pre-inoculated with the appropriate bacterium since microbial populations were presumed to be deficient.

To prepare the plots for seeding, 2 tons acre^{-1} (4.48 Mg ha^{-1}) of lime were applied. Slow release sulfur-coated urea was incorporated at the rate of 50 lb N acre^{-1} (56 kg P ha^{-1}). Potassium was added as potash at 50 lb K acre^{-1} (56 kg P ha^{-1}). These amendments were dispatched with a conventional tractor and fertilizer spreader. To apply the phosphorous, a Gandy fertilizer spreader pulled by a Cub Cadet tractor, was calibrated to deliver at the predetermined rates of P. A tiller was used to incorporate these materials into the upper 6 inches of each plot.

Biosolids, from the Moccasin Bend Waste Treatment Plant at Chattanooga, were distributed by manure spreader on one acre of the research area. The second acre received no biosolids. Of the 27,380 lbs of biosolids applied, 28% (7,666 lbs) was dry weight. Incorporation into the upper 6 inches was by tiller. Seedbed preparation was completed September 24, 1998.

Seeding was completed on October 5, 1998. All seeds were sown with a cyclone hand seeder. Tall fescue was distributed at the rate of 15 lb acre^{-1}. Legumes were sown in specified blocks at the following rates:

Birdsfoot trefoil	10 lb acre^{-1}
Sericea lespedeza	30 lb acre^{-1}
Kobe lespedeza	40 lb acre^{-1}
Korean lespedeza	25 lb acre^{-1}

Immediately following seeding, both plots were mulched with a wheat/rye straw.

Plant counts were determined using a 1ft x 1ft wooden square. This apparatus was tossed randomly within a block. All plants inside the square were catalogued and counted.

Drought conditions in the summer and fall of 1998 resulted in the need to reseed the plot areas. A second seeding was completed March 29, 1999. Legumes and fescue were seeded at the same rate as in October, 1998. Sulfur coated urea was surface applied at the rate of 100 lb N acre^{-1} (112 kg N ha^{-1}) over both plots.

An additional section outside the main plot area was used as a trial area for native grasses. Rows approximately 20 m long were seeded with Indian grass, switchgrass, big blue stem, little blue stem, bromegrass, sand bluestem, and sunflower. P was added at 100 lb P acre^{-1} (112 kg P ha^{-1}). No measurements were taken, but these trials were monitored for survival success.

Laboratory Methods. Double-acid-extractable K, Ca, Mg, Cu, Mn, and Fe (Sims and Heckendorn, 1987) were determined by atomic absorption spectrophotometer. Sodium bicarbonate extractable P (Olson et al., 1954) and KCl-extractable Al (Barnhisel and Bertch, 1982) were measured to complete the suite of chemical properties monitored in the test plots.

Organic C was obtained on all samples by the Walkley-Black method (Jackson, 1958). Total carbon was deduced with a Leco Cr 12 carbon analyzer. Statistical analysis was performed using the GLM procedure on SAS statistical software (SAS, 1990).

Results

Chemical and Physical Characteristics. Following the applications of lime and biosolids, pH increased over time in both plots (Fig. 3). The pH of the biosolid materials was 12.4 explaining higher values attained on the biosolid plots. As expected calcium carbonate was the primary source of carbon. The addition of biosolids logically increased organic carbon content, but the increase observed on the non-biosolids plot indicated additions were coming from the plant materials on those plots (Fig. 4). Since the only source of organic carbon would be from vegetation, this was a significant finding for future retention of nutrients and moisture to sustain the plant community.

Plant available calcium decreased over the sampling period from September 1998 to October 1999 (Table 7). This possibly was a result of plant uptake, losses by leaching, and/or geochemical reactions in the newly tilled tailings materials. Potassium increases occurred and were expected since potash was added during seedbed preparation. Iron and manganese levels did not vary greatly from the first to last sampling. Both manganese and copper increased in availability. There may be several catalysts responsible either singularly or in combination for these changes. Obviously, sampling variation and error could be one source of variability. However, the dynamics within the system had been altered dramatically, not only by the addition of a variety of amendments, but by the vegetative component as well. Microbial populations should have ballooned enormously with the introductions of new and different sources of energy. These alterations quite possibly may have accelerated chemical and physical weathering of the tailings minerals resulting in the release of higher concentrations of certain elements, while others may have become bound to elements previously in short supply.

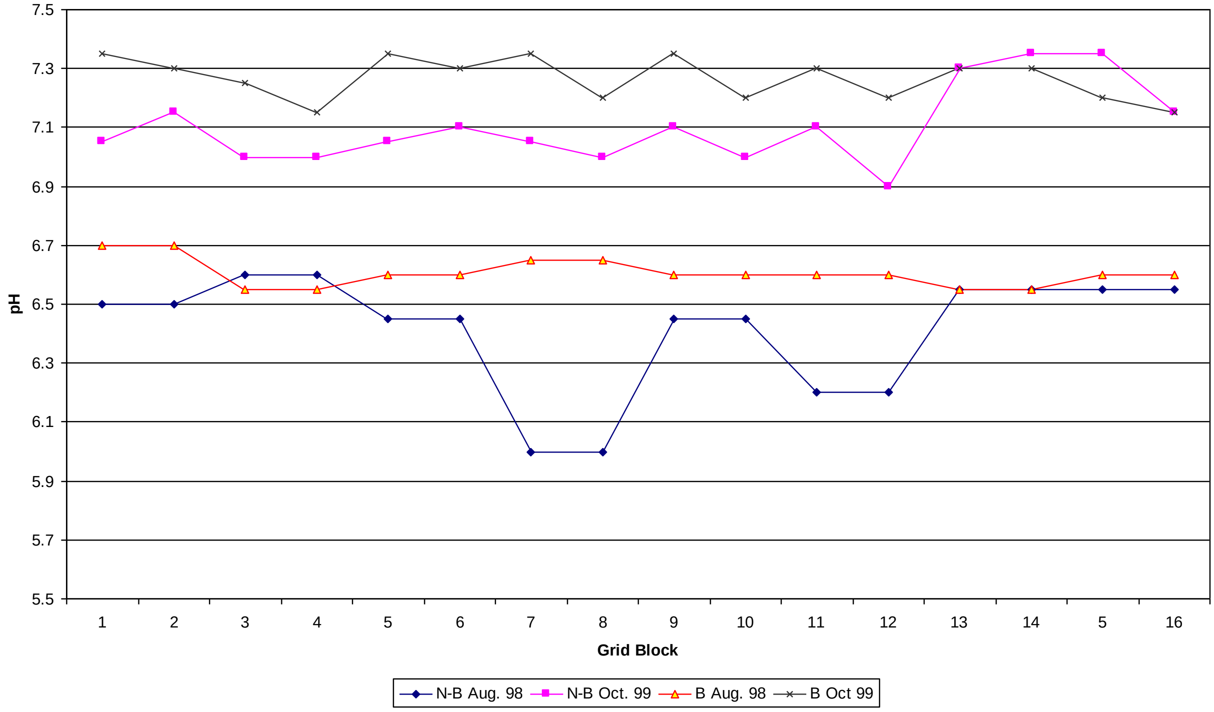

Figure 3. Changes in pH from August, 1998 to October, 1999 on non-biosolid plots (N-B) and biosolid plots (B).

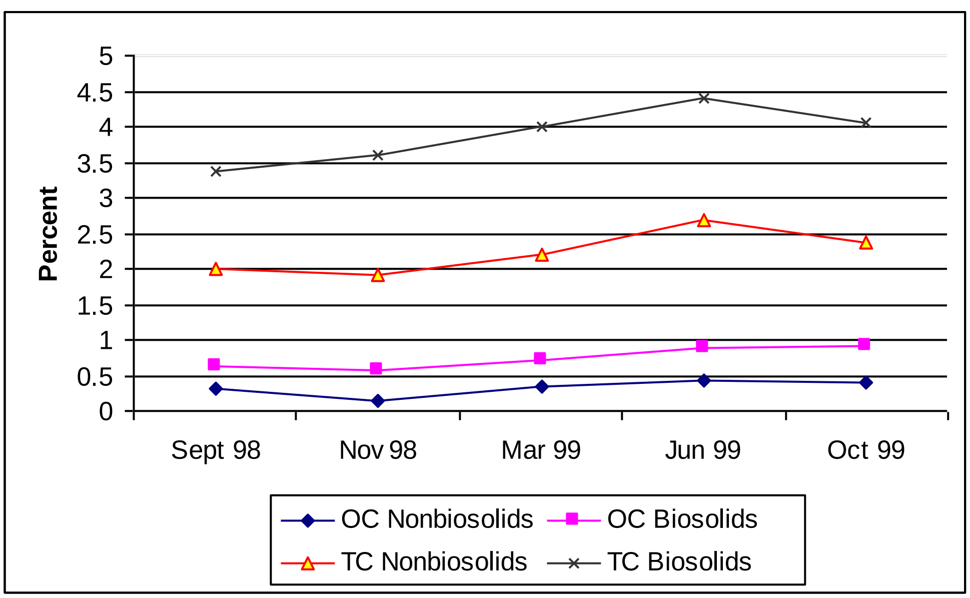

Figure 4. Changes in total and organic carbon over a 14 month period.

Initial concentrations of N were < 500 mg kg^{-1} in both plots (Table 8). In the non-biosolids plots, N values in November, 1998 reflected the addition of ammonium nitrate. By March, legume populations, especially birdsfoot trefoil, had escalated. Since all legume seeds had been pre-inoculated, higher values of N possibly indicated successful N fixation in the plant roots. Observation indicated greater nodule formation (pink interiors) on non-biosolid grids than on those with biosolids.

With reseeding in spring and another fertilizer application, the June nitrogen level had decreased. When available N is sufficient in soil, nodulation and biological N_2 fixation may cease (Foth and Ellis, 1988; Vogel and Berg, 1968). Uptake by new seedlings and the lack of N fixation may explain the lower amount of N. By October, N rates had reach levels similar to those in March. Fertilizer additions appear to have depressed N production on the non-biosolid plot.

Table 7. Comparison of levels of plant available elements over the sampling period from September, 1998 to October, 1999.

Element	September, 1998 Non-Biosolids	(mg kg^{-1}) Biosolids	October, 1999 Non-Biosolids	(mg kg^{-1}) Biosolids
Calcium	16,464	15,946	13,936	14,228
Copper	61	37	123	67
Iron	201	145	18	160
Potassium	183	165	309	293
Magnesium	449	465	475	457
Manganese	609	653	714	752

Table 8. Mean nitrogen concentrations between September, 1998 and October, 1999.

	Sept. 98	Nov 98	Mar 99	June 99	Oct 99
Non-Biosolids	445	1485	1790	1473	1780
Biosolids	445	1399	652	2392	1009

Legume production on biosolids was not as prolific as with the non-biosolids. Nitrogen concentrations increased in November and June, which followed fertilizer applications. Subsequent sampling indicated a decrease. Apparently, the legumes did not as actively produce N when

inorganic N was available, and excess N was being leached easily through the sand sized particles.
Vegetative Responses. Vegetation density was greater on biosolids plots compared to non-biosolids throughout the sampling period. November plant populations consisted primarily of winter wheat from residual seeds in applied mulch. Plant counts were erratic with plots receiving 56 kg P ha^{-1} having the smallest populations (Table 9). More predictable distributions were measured in March and October with control plots being significantly lower statistically.

Table 9. Mean plant counts affected by phosphorus treatments for Nov 98

Phosphorus Treatment	Plant Counts (0.09 m2)		
	Nov 98	Mar 99	Oct 99
0 kg P ha-1	6.9 b*	3.1 b*	2.4 b*
56 kg P ha-1	0.2 a	6.1 a	4.1 a
112 kg P ha-1	9.0 ab	5.8 a	4.4 a
224 kg P ha-1	8.8 ab	5.7 a	4.4 a

* Within columns, means followed by the same letter are no significantly different according to LSD (0.05).

Birdsfoot trefoil was the most productive legume. By March, benefits of added nutrients and moisture retention of biosolids was observable in the greener and denser plant populations. Plants in the non-biosolids plots appeared brittle and less green. All legume populations were extremely low indicating the necessity of a second seeding that spring.

By June of 1999, tall fescue populations had responded well to the reseeding. Birdsfoot trefoil populations noticeably decreased, but Kobe and Korean lespedeza continued to grow well on both plots (Table 10), with slightly higher populations on the non-biosolids plot. Growth of annual lespedezas usually increases during summer months, if soil moisture is adequate (Offutt and Baldridge, 1974). Competition from grasses was noticeably higher on the biosolids plot. By October, 1999, Kobe and Korean lespedeza continued to grow favorably. On the non-biosolids plot, some areas contained very dense populations of these two legumes.

Table .10. Mean legume counts affected by plant mix for June, 1999.

Plant Mix	-----------Legume Counts (0.09 m2)---------	
	March, 99	June, 99
Birdsfoot trefoil/Tall fescue	3.8 a*	5.5 b*
Sericea lespedeza/Tall fescue	0.4 b	3.8 b
Kobe lespedeza/Tall fescue	0.6 b	12.4 ab
Korean lespedeza/Tall fescue	0.2 b	15.9 a

* Within columns, means followed by the same letter are no significantly different according to LSD (0.05).

Vegetative density was variable in June, but by October, populations had become stable. Statistical significance was observed between treatments and only the control plots had a statistically significantly lower density (Table 11). When comparing P treatments with biosolids (Table 12), plant populations were denser on the biosolids at 112 kg P ha^{-1} than at any other level. At the same level on the non- biosolids, plant density was lower than any other treatment except for the control. However, the differences were not extremely large between any P amended treatments.

Native grasses responded very differently to the environmental conditions of the tailings pond. No sunflower seedlings were observed at any time. Big bluestem, little blue stem, Indian grass, and bromegrass survived but were not productive. Switchgrass and sand bluestem thrived and showed evidence of controlling erosion from the tailings.

The erosion control value of vegetation on the plot areas was visible as well. Those grids with controls or low plant populations had definite impact from erosive processes as evidenced by rill formation.

Table 11. Mean percent vegetative cover estimates affected by phosphorus treatments for June and October, 1999.

Phosphorus Treatment	------------------Vegetative Cover (%)--------------------	
	June, 1999	Oct., 1999
0 kg P ha-1	24.5 c*	29.5 b*
56 kg P ha-1	35.3 b	40.7 a
112 kg P ha-1	48.2 a	47.4 a
224 kg P ha-1	44.1 a	45.2 a

* Within columns, means followed by the same letter are no significantly different according to LSD (0.05).Table 12. Mean percent vegetative cover estimates affected by biosolids application and phosphorus treatments for Oct 99.

Biosolids Application	Phosphorus Treatment	Vegetative Cover (%)
Non-biosolids	0 kg P ha-1	3.3 d*
	56 kg P ha-1	35.8 bc
	112 kg P ha-1	31.5 c
	224 kg P ha-1	37.1 bc
Biosolids	0 kg P ha-1	55.8 ab
	56 kg P ha-1	45.6 bc
	112 kg P ha-1	63.3 a
	224 kg P ha-1	53.3 ab

* Within columns, mean followed by the same letter are not significantly different according to LSD (0.05).

Over the duration of the research project, invading species became established on the research plots. Invading vegetation included Carolina geranium (*Geranium carolinianum*), mouseear chickweed (*Cerastium vulgatum*), wild lettuce (*Lactuca scariola*), daisy fleabane (*Erigeron stigosus*), common cockleburr (*Xanthium pensylvanicum*), and ryegrass (*Lolium* sp.). This is an important consideration in establishing biodiversity to sustain a plant system on these mine waste materials.

Discussion and Conclusions

Most of the carbon contained in the tailings material was bound as $CaCO_3$. In the plot amended with biosolids, organic carbon content increased as was expected, however, organic carbon levels in both plots increased as a result of the establishment of vegetation. Plant available Ca was high in both plots resulting from $CaCO_3$ used in the milling process. Both plant available K and Mg were present in the tailings material in sufficient amounts. Variations in other elements were not extreme but may have been a reflection of the changes taking place within the ecosystem. Total N concentrations were low on initial samples on both plots. Increases in N on both research plots were a result of the additions from fertilizers, biosolids, and nodulation by legumes.

Phosphorus applied at a rate of 112 kg P ha^{-1} (100 lb P $acre^{-1}$) produced the highest density of plants on biosolids. While there were differences between P treatments on non-biosolids, they were not significant. Biosolids consistently produced higher plant populations than the non-biosolid plot. Korean and Kobe lespedeza had higher success rates compared to sericea lespedeza and birdsfoot trefoil. Sericea lespedeza will endure after establishment, but the process is slower than for Korean or Kobe lespedeza. Birdsfoot trefoil did well when competition was not intense and with cooler temperatures in fall and winter. The high temperatures of summer were detrimental to this species. Birdsfoot trefoil was not a good choice for this site.

Phase III Final Recommendations for Revegetation of the EntireTailings Pond Region

Objectives

Phase III was the culmination of this study. Objectives were to use the information gleaned during phases II and I and make the best recommendation for application of amendments and plant species to complete revegetation of the remaining tailings section.

Revegetation Recommendation for Establishing Vegetation on the Mine Tailings

The two one acre plots used in this research represented only a small portion of the tailings pond. Chemical and physical characteristics were relatively uniform throughout the two one-acre test plots. These research plots were only a small representation of the entire tailings area and variation in characteristics, such as soil pH and plant nutrients vary greatly across the entire tailings pond.

While initial soil pH on the test plots was relatively neutral to alkaline, some tailings may contain pockets of low pH, as was seen in site 4 in the preliminary investigations on the tailings pond. To neutralize any potential acidity problems, lime should be incorporated at the rate of 4.48 Mg ha^{-1}. Additionally, legumes used in this project have better success rates when grown in soils with pH above 6.5 (Vogel and Burg, 1968). Since mineral N is not naturally available in the tailings, N fertilizer must be added. Biosolids may become an additional source of N as decomposition progresses. Although tailings within the two fertility plots contained sufficient amounts of K, an addition of 56 kg K ha^{-1} should account for any variability in the tailings material as was seen in the adjacent surface horizon (C1') in the initial investigation of the tailings pond.

According to favorable vegetation responses when P was applied, P was the key nutrient limiting the establishment of vegetation. Other studies have shown that with the addition of P to phosphorus deficient mine tailings, revegetation projects have been successful (Hossner and Hons, 1992; Gemmell, 1977). During March, 1999 and October, 1999, plant counts were significantly higher when amended with phosphorus (Table 9). Past studies indicate that legume populations, including Kobe and Korean lespedeza, increase when P was added to the soil (Blair, 1931; Gish and Hutcheson, 1923; Cooper, 1936; Stitt, 1939).

While there were no significant differences in Kobe and Korean lespedeza populations, Korean lespedeza populations were higher than both birdsfoot trefoil and sericea lespedeza populations. Temperatures may have been too warm for the establishment of birdsfoot. The establishment of legumes will add N, and eventually organic matter to the tailings material. However, this will occur more slowly than with organics supplied through the addition of biosolids. The use of the annual lespedezas would be beneficial in that they normally produce enough seed to ensure returns in following years (Offutt *et al*., 1974).

It would be advantageous to seed native grasses such as switch grass and sand bluestem to add diversity to the plant community. These grasses were successful in trials and can sustain themselves in the environmental conditions present on the tailings pond.

Therefore, for successful revegetation of the copper mine tailings pond, P should be applied at a rate of 112 kg P ha^{-1}, biosolids should be applied at a rate of 8.96 Mg ha^{-1}, and Kobe and/or Korean lespedeza should be mixed with tall fescue and native grasses.

After the region is amended and seeded, mulch (hay) should be applied as cover to retain moisture and reduce erosion. Quarterly monitoring should be included in the revegetation plan as nutrients such as N may need to be reapplied or plots may need to be mowed. Over time, as vegetation becomes established, the tailings area should become prime habitat for wildlife.

Summary

Before this project began, there had been several attempts at establishing vegetation on this tailings pond. Generally, these endeavors had met with limited success. There was a prevailing assumption that these tailings were extremely acidic or had concentrations of elements that would be toxic to plant life. Phase 1 results indicated these tailings were not generating great quantities of acids. None of the elements analyzed were determined to be sufficiently available to produce plant toxicities. The major concerns were deficiencies of nitrogen and phosphorous.

Using the data obtained in the initial investigation (Phase I), the second phase was to implement test plots using three phosphorous treatments (56 kg P ha^{-1}, 112 kg P ha^{-1}, and 224 kg P ha^{-1}). Tall fescue was chosen for the grass with birdsfoot trefoil, sericea lespedeza, Kobe lespedeza, and Korean lespedeza as the legumes. One plot received biosolid, while the second plot did not. Plant cover was more dense on biosolid plots receiving 112 kg P ha^{-1}. Of the four legume species, Kobe and Korean lespedeza were the most successful.

From the results of Phases I and II, a final recommendation was formulated. For successful establishment of vegetation on these mine tailings, P should be applied at a rate of 112 kg P ha^{-1}, biosolids should be applied at a rate of 8.96 Mg ha^{-1}, and Kobe and/or Korean lespedeza should be mixed with tall fescue and native grasses.

The project ended in 2000 and no other measurements have been taken. The tailings pond has been seeded using many of the recommendations resulting from the final report. Plant species included some of those used in the test plots as well as other species for diversity. Initial indications are the seeding has been a success.

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