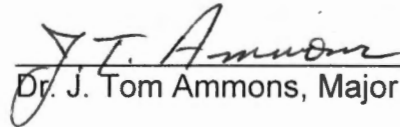


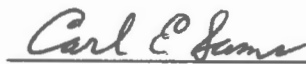
To the Graduate Council,

I am submitting herewith a thesis written by Thomas E. Cook entitled "Revegetation of Copper Mine Tailings in the Copper Basin, Tennessee." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant and Soil Sciences.

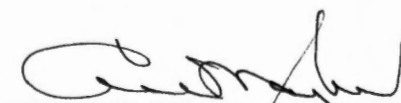

Dr. J. Tom Ammons, Major Professor

We have read this thesis and
recommend its acceptance:


Dr. Mike D. Mullen


Dr. Carl E. Sams

Accepted for the Council:


Associate Vice Chancellor and Dean of
The Graduate School

Revegetation of Copper Mine Tailings in the Copper Basin, Tennessee

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Thomas E. Cook

August 2000

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DEDICATION

This thesis is dedicated to my fiancée, Nancy E. Scarborough, in memory of my father, Frederick W. Cook.

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ABSTRACT

A century of copper and pyrite mining activities near Ducktown, Tennessee has resulted in several reclamation challenges. One such challenge is the revegetation of mine tailings, a by-product of the milling process for extraction of metals. Revegetation of mine tailings requires extensive chemical analysis to establish a reclamation protocol for future land use. The objectives of this study were to: 1) conduct initial investigation of the tailings pond to determine current of potential problems which may limit vegetation and 2) establish test plots on mine tailings using soil treatments and grass/legume mixtures and monitor chemical properties of fertility samples quarterly over a one-year period.

A total of four cores were extracted and sampled to standard soil survey manual methods. Laboratory procedures included particle size analysis, pH, KCl exchangeable acidity, acid-base accounting, free iron, exchangeable bases, cation exchange capacity, Mehlich (dilute double acid) III, and total elemental analysis.

Due to high amounts of CaCO_3 used in the milling process, neutralization potential was very high as pyritic sulfur values were low in all 4 sites. Only an extra surface horizon required additional neutralizing. Available phosphorus concentrations were very low in all 4 sites. For successful revegetation, P will need to be amended into the tailings. Since nitrogen concentrations were low, the addition of nitrogen fertilizer and/or the establishment of nitrogen fixing

legumes will be needed to further supply available N. Toxic concentrations of heavy metals were not found in the tailings.

Two one-acre test plots were established and monitored over a one-year period. Treatment variables included 1) a biosolids application, 2) 4 P treatments (0, 56, 112, and 224 kg ha⁻¹), and 4 grass/legume mixtures (tall fescue, birdsfoot trefoil, kobe, Korean, and sericea lespedeza). Plots were monitored with plants and fertility sampling quarterly throughout the year.

Vegetation was significantly increased with phosphorus applications. Phosphorus control plots had little or no vegetation growing on them. Overall, more vegetative cover (ryegrass, winter wheat, and fescue) was found on the biosolids treated plot. The application of biosolids significantly increased vegetative cover and biomass weights while total plant counts and legume counts were unaffected. Kobe and Korean lespedeza were significantly higher on both plots compared to sericea lespedeza and birdsfoot trefoil. For successful revegetation of the tailings, phosphorus should be applied at a rate of 112 kg P ha⁻¹, biosolids should be applied, and kobe and/or Korean lespedeza should be used in the grass/legume mixture.

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CHAPTER I

Copper Basin – The History of Events

Introduction

The Copper Basin is located in the southwestern section of the Appalachian Mountains, about 72 km (45 mi) east of Chattanooga, Tennessee (Figure 1.1). This 24 300 ha (60 000 acre) area is part of the Blue Ridge physiographic province and lies primarily in Polk County, Tennessee, Fannin County, Georgia, and Cherokee County, North Carolina. Although not an actual geological basin, the area is an intermontane depression caused by bedrock erosion and is surrounded by mountains giving the area a bowl like feature. The mountains surrounding the basin include the Pack Mountains to the east, the Stansbury Mountains to the north, and the Little Frog Mountain to the west. Along the southern border of the Copper Basin flows the Ocoee River. The mine tailings associated with this project lie just to the east of Ducktown and are about .5 km (.3 mi) north of the London Flotation Plant (Figure 1.2). The elevation of the Copper Basin is approximately 520 meters (1700 ft) above sea level and is in the mesic (8 – 15° C) temperature regime.

The Copper Basin receives an average of 152 cm (60 in) of precipitation which is equally distributed throughout the year with mean monthly temperatures ranging from 7°C (44°F) in the winter to 21°C (70°F) in the summer (NCDC, 2000).

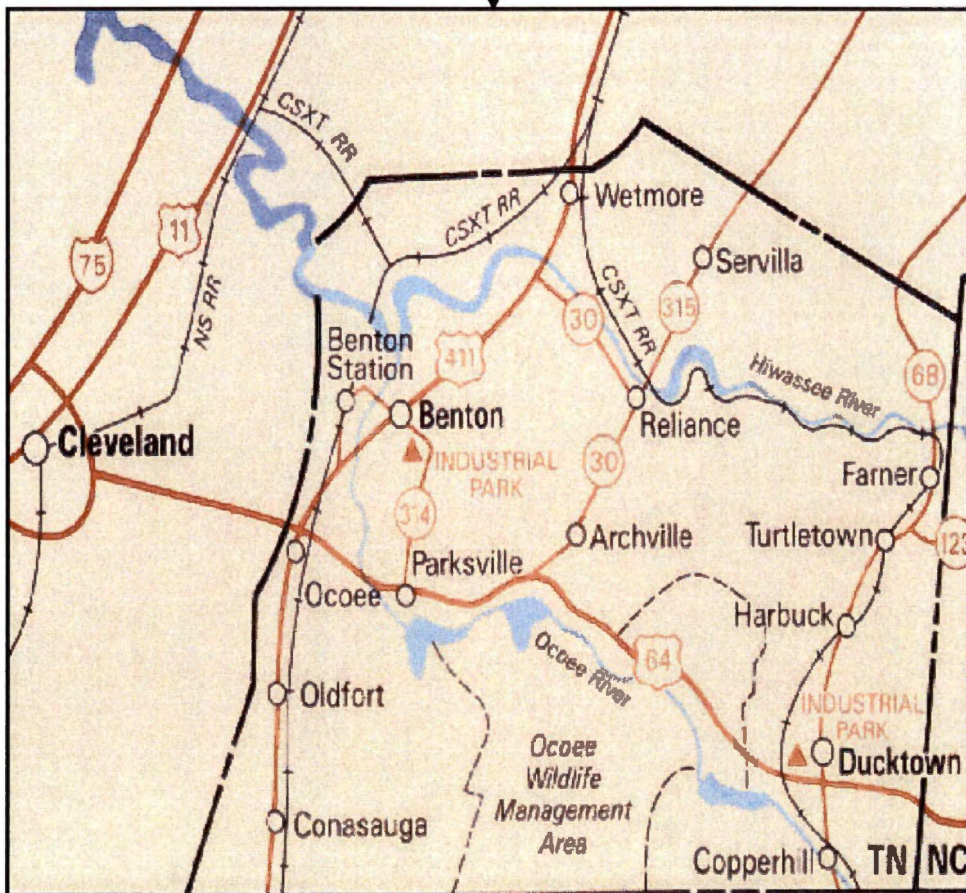
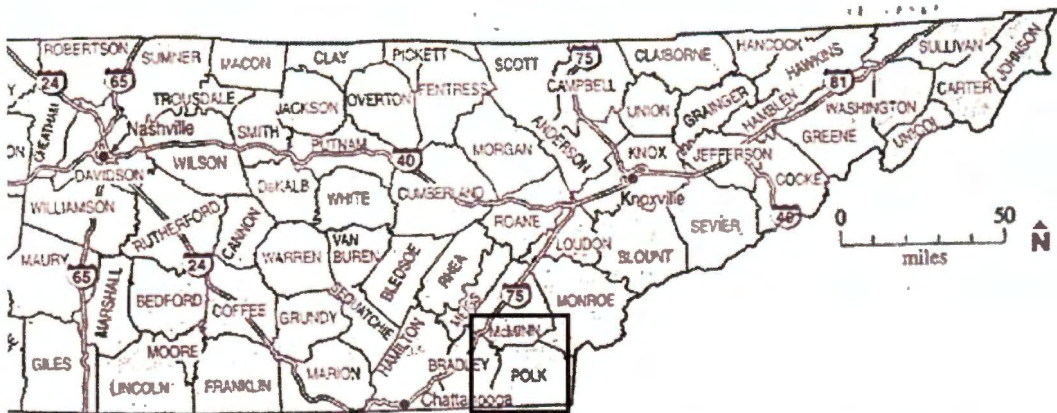


Figure 1.1. Polk County location map

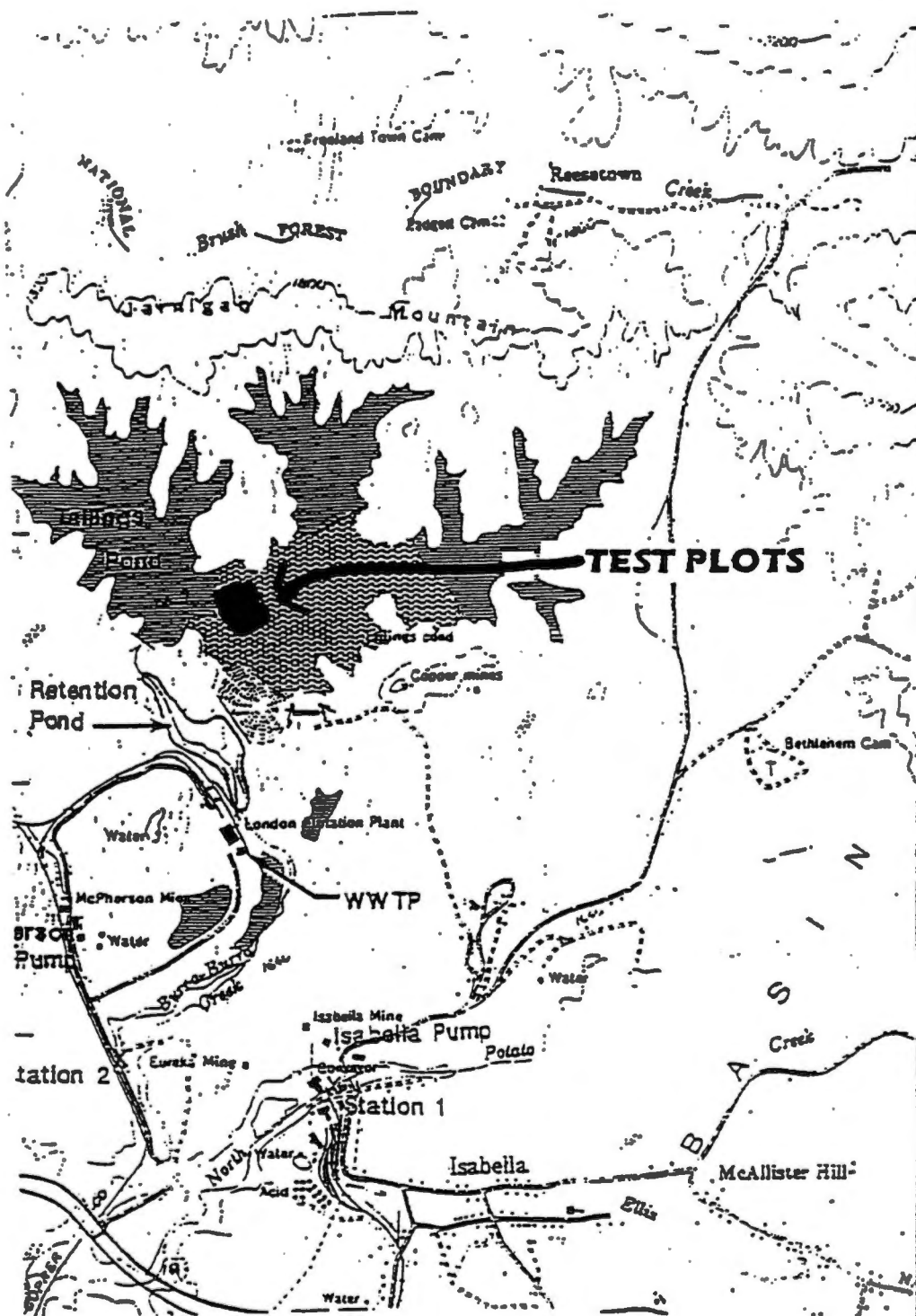


Figure 1.2. Location of tailings pond.

Geology

The geology of Polk County is complex in that it contains a wide array of geologic formations. Rock formations in this area range from the Late Proterozoic Era to the Upper Ordovician Period (800 to 435 million years before present) (USGS, 1993). Although the true origins of these Precambrian rocks are either granitic or sedimentary, they have been deformed and affected by metamorphism (Moore, 1994).

During the Late Proterozoic Era, rocks in east Tennessee underwent massive folding and intense deformation known as the Allegheny Orogeny. This was a result of the east coast of North America colliding with the west coast of Africa forming the basic structures of the Blue Ridge and the Valley and Ridge Provinces. Other results from the Allegheny Orogeny are 6 major thrust faults that run northeast to southwest in the Polk County area (USGS, 1993).

These rock formations are a part of the Ocoee Supergroup (Figure 1.3). The Ocoee Supergroup overlies the Greenville basement by unconformable or fault contact (USGS, 1993). The Greenville basement includes granite, gneiss, schist, and gabbro rock types and is believed to be mostly igneous or sedimentary in origin that have been metamorphosed (Moore, 1994). The Ocoee Supergroup is exposed throughout eastern Tennessee within the Great Smoky Mountain National Park and into the southeastern part of the state including Polk County. These rocks have undergone significant metamorphism to produce high concentrations of minerals (Moore, 1994). The Ocoee Supergroup is mostly

Ocoee Supergroup	Walden Creek Group	
	Great Smoky Group	Dean Formation
		Hothouse Formation
		Hughes Gap Formation
		Copperhill Formation
	Snowbird Group	
Greenville basement		

Figure 1.3. Geology of the Copper Basin.

composed of quartzite, slate, phyllite, and schist. The sedimentary deposits of this group include sandstone, siltstone, and shale. These rocks have undergone massive folding and faulting forcing them into complex arrangements.

Within the Ocoee Supergroup there are three distinct groups which occur in thrust slices (King *et al.*, 1958). These include (ascending order) the Snowbird Group, Great Smoky Group, and the Walden Creek Group. Within the Great Smoky Group lies most of the rocks that comprise the Copper Basin. These rocks are estimated to be about 7600 m (25 000 ft) thick (USGS, 1993) and include metasedimentary rocks which form the core of the southern Appalachian Mountains (Byerly, 1994). Rocks of the Great Smoky Group include metagraywacke or feldspathic metasandstone, slate, phyllite, and schists and are composed of poorly sorted, coarse- to fine-grained quartz, feldspar, micas, and chlorite (USGS, 1993). The Great Smoky Group is subdivided into four different formations including the Copperhill, Hughes Gap, Hothouse, and Dean Formations.

The Copper Basin lies within the rocks of the Copperhill Formation (Moore, 1994). The Copperhill Formation is primarily composed of metagraywackes, metagraywacke conglomerates, and metapelites (USGS, 1993).

The ores within these rocks were formed below the depth of weathering by ore-bearing solutions of unknown origins. The uplift of the mineral-containing rock mass followed by exposure to atmospheric oxygen and percolating water

resulted in the formation of secondary iron and copper minerals. Through this process, iron ores were formed at or near the surface with an underlying copper deposit that extended beneath the water table. These enriched zones that underwent weathering and oxidation were termed “gossan” ores and were mined, but have long been exhausted (Maher, 1966).

History of Copper Basin Mining

During the period of North American colonization, the Cherokee populated the area known today as the Copper Basin. As Europeans moved westward, the white settlers increasingly pressured the government to remove the Cherokee from their lands. These pressures increased in 1828 when gold was discovered near the present day site of Dahlonega, Georgia, a town 65 km (40 mi) southeast of the Copper Basin (Mathews, 1995). The Copper Basin itself had limited farming land, therefore few farmers were attracted to the area when it was open to European settlers. It did attract those in search of precious minerals, especially gold.

Copper ore was first discovered in the Basin in 1843 by a man named Lemmons while he was searching for gold (Mathews, 1995). In 1847, a charcoal-powered open pit iron-smelting furnace was constructed for extracting “black copper” (chalcocite) ore from the gossan. Shipments from this mine were hauled by mules to Dalton, GA. A difficult obstacle faced by the miners at this time was the lack of roads and railroads leading into the Copper Basin (Maher, 1966). In 1851, John Caldwell, a miner pioneer, began construction of a wagon

road along the Ocoee River gorge to Cleveland, Tennessee, the site of a closer railroad station. This resulted in increased copper production and the construction of additional mines which totaled fourteen by 1855 (Maher, 1966; Safford, 1869).

The early methods of removing the sulfur from the ore called “open pit” roasting caused substantial damage to the vegetation in the Copper Basin. This process was done in open pit smelting (heap-roasting) releasing sulfur dioxide (SO₂) into the atmosphere (Muncy, 1986). As the SO₂ was released, it was oxidized to sulfate particles as follows:



Sunlight and dust particles act as catalysts speeding up the reactions. The introduction of H₂SO₄ into already acidic soils increased soil acidity within the Basin (Nwadialo, 1982). In addition, the lumbering of wood to keep the furnaces burning contributed to the already decreasing vegetative cover. With an average of about 152 cm (60 in) of rainfall per year, the bare hills of the Copper Basin began to suffer severe soil loss due to erosion, furthering destruction caused by the mining process (Muncy, 1986). Eventually an estimated 130 km² (50 mi²) of land had suffered the effects of SO₂ emissions and harvesting of timber for fuel (Muncy, 1991). In 1907, the environmental devastation reached its peak with an estimated 800 to 2600 km² (310 to 1000 mi²) devoid of vegetation (Quinn, 1988).

In 1858, the consolidation of five local mines led to the establishment of the Union Consolidated Company where copper production was so successful, a refinery was constructed in Cleveland, Tennessee (Maher, 1966). The refinery was destroyed during the Civil War in 1863 by Union troops occupying the territory. Mining activities ceased not only from the destruction of the refinery but also from the depletion of forest from timber harvesting and acid rain (Maher, 1966). However, by 1890, advanced smelting methods allowed mining activities to resume as Union Consolidated was acquired by Ducktown Sulphur, Copper, and Iron Company of London, England (Mathews, 1995).

In 1891, railroad services reached the Copper Basin area, greatly increasing mining operations. In 1899, another mining company by the name of Tennessee Copper Company (TCC) was established (Maher, 1966). Increasing fuel demands prompted TCC to expand production forcing the construction of several roasting yards, thus resulting in further vegetation destruction.

Numerous law suites were filed against the copper companies by the state of Georgia due to vast amounts of damage to vegetation extending across the state line. As new techniques in the smelting process emerged, the first court award was made in 1903 (Mathews, 1994).

The mining industry saw the end of “open pit” roasting in 1904 as the more advanced “closed chamber” smelting process evolved. This new pyritic smelting process consisted of a closed pit roasting process. As opposed to the open pit roasting process, the closed pit was able to trap SO₂ keeping it from being

emitted into the atmosphere. The reduced amounts of SO₂ in the air reduced acid rain and allowed some vegetation to return. However, the bare soil was still susceptible to erosion, which continued to be a problem (Quinn, 1988). In 1906, TCC completed a facility to process the trapped SO₂, and began production in late 1907. Other mining companies including Ducktown Sulphur, Copper, and Iron Company followed suit, constructing similar acid processing plants in 1908 (Maher, 1966).

At about the same time TCC began to trap and recover SO₂, the agriculture industry had an increasing need for sulfuric acid (H₂SO₄) in the production of fertilizers. Tennessee Copper Company was able to sell the recovered sulfur to fertilizer producers (Muncy, 1991). Demands for H₂SO₄ escalated with the onset of the two world wars as this was a key ingredient for munitions production (Mathews, 1995). The construction of a large contact sulfuric acid plant in Copperhill during the early 1940's increased H₂SO₄ production (Maher, 1966). What was once a harmful byproduct of mining was now a useful commodity, increasing profits for TCC. Other mining improvements such as the construction of the London Flotation plant in 1922 helped make other minerals more available including iron and zinc, formally lost during the separation process (Mahar, 1966).

Ducktown Sulphur, Iron, and Copper Company was bought out by TCC in 1936 leaving them in sole control of all operations in the basin. From the 1960's to the present day, the operations and assets of this mining company changed

hands several times. In 1963, Cities Service Company (CSC) merged with TCC, giving CSC sole proprietorship of assets and operations (Maher, 1966). Mining operations continued for the next twenty years until Tennessee Chemical Company purchased CSC in 1982. Mining operations in the Copper Basin ceased in 1987. In April of 1989, Tennessee Chemical Company filed for bankruptcy under Chapter 11 and in September of the following year BIT Manufacturing Inc. acquired a portion of Tennessee Chemical Company's assets (Muncy, 1991). Today, the area is owned by Occidental Petroleum Company and although no mining activities are currently ongoing, a H_2SO_4 refinery is still active in Copperhill, Tennessee.

Reclamation in the Copper Basin

After years of mining activities, the damage levied upon the vegetation was apparent. By 1900, essentially all timber within hauling distance to the processing plants had been harvested and vegetation within the vicinity of the smelters was destroyed from the SO_2 emissions (Tyre and Barton, 1986). Reclamation efforts in the basin were initiated in the 1930s with the combined efforts the Tennessee Valley Authority (TVA), other Federal and State agencies, and the mining companies (Muncy, 1986).

Along the Ocoee River, TVA operates three dams for hydroelectric production. Eroded soil from the denuded hills washed down into the Ocoee River causing substantial damage to downstream dams, increasing hydroelectric costs. The sediment caused extensive damage to the turbine runners and

penstocks in the reservoirs located along the Ocoee River. Estimates by TVA showed that up to 3.3 cm (1.3 in) of soil was being lost annually (Muncy, 1986). After 30 years of operation, TVA's Ocoee #3 dam lost 80% of useful storage capacity (Muncy, 1991). TVA assisted in developing revegetation plans which provided some success to the area (Rush, 1998).

In 1939 the Tennessee Copper Company, with the help of TVA, established the Civilian Conservation Corps Camp. The Corps provided labor for planting various tree species including loblolly pine (*Pinus taeda* L.), shortleaf pine (*P. echinata* Mill.), and Virginia pine (*P. virginiana* Mill.). In addition, Pitch pine (*P. rigida* Mill.), and black locust (*Robinia pseudoacacia* L.) were planted to help impede erosion in and around the Basin (Muncy, 1991; Allen, 1950). Even with the harsh environmental conditions present in the Basin, the trees fared well (Allen, 1950). Cummings (1947) reported successful results with Weeping lovegrass (*Eragrostis curvula*) surpassing 21 other grasses and legumes in field tests on various plots between 1941 to 1945 by TVA.

In 1954, the Tennessee Copper Company with the help of a Fannin County, Georgia agriculture agent initiated revegetation work with financial aid from the U.S. Soil Conservation Service. Many of these attempts succeeded while others failed due to escaping SO₂ gas (Anonymous, 1971). Experiments with kudzu (*Pueraria lobata*) to slow erosion were attempted, but were terminated because of its invasive nature (Mathews, 1995).

During the late 1960s and well into the 1970s, the United States experienced an increase in environmental awareness marked with elevated concerns for air and water quality. Federal laws resulting in more stringent standards were passed bringing change to the Copper Basin (Quinn, 1988).

When Cities Service Company (CSC) purchased the Tennessee Copper Company in 1963, revegetation programs were accelerated. To comply with new air quality standards, CSC spent about \$30 million on acid operations alone (Quinn, 1988). Cities Service Company contributed to reclamation efforts by continuing tree plantings and experimenting with other forms of ground cover such as Japanese Knotweed (*Polygonum cuspidatum* Sieb and Zucc) to retard soil erosion. Sericea Lespedeza (*Lespedeza cuneata*) and Loblolly pines were planted along accessible mountaintops with the aid of aerial fertilizer distribution (Muncy, 1986). Independent investigations in the early 1970s by an area Soil Scientist revealed a 50% reduction in devastated land from 13 000 to 6 800 ha (32 000 to 16 800 acres) with combined efforts of the U.S. Forest Service and the U.S. Soil Conservation Service (Cities Services Company, 1975).

Today, Occidental Petroleum, in conjunction with the Tennessee Department of Environment and Conservation (TDEC) and the University of Tennessee at Knoxville (UTK), is active in revegetating areas of the Copper Basin. Simultaneously on areas near the London Water Plant, TDEC is involved with constructive wetland pilot programs (Rush, 1998) and UTK is active in

establishing vegetative cover, wetland delineation, and monitoring wind erosion on the tailings pond.

Research Objectives

The objectives of this research project were to:

1. Conduct an initial investigation of the tailings pond to determine current or potential problems which may limit vegetation.
2. Establish test plots on mine tailings using soil treatments and grass/legume mixtures and monitor chemical properties of fertility samples quarterly over a one-year period.

CHAPTER II

Preliminary Investigations on the Tailings Pond

Introduction

Many environmental problems such as air, soil, and water pollution can be attributed to mining activities. The mining operations at the Copper Basin were no exception. The mining process involved many procedures to convert the recovered ore to a useful commodity. Final products were sold and shipped to refineries all across the United States. As with many manufacturing processes, a waste by-product was produced. This unwanted material, or tailings, was deposited into a waste disposal lake known as the tailings pond (Rush, 1998).

Tailings are waste materials generated by the grinding and processing of ores and other materials containing economically retrievable minerals (Hossner and Hons, 1992). This process includes separating the desired element(s) from the unwanted portion of the ore. This unwanted portion was then deposited, as slurry, into a retention pond where the water was then evaporated or drained. According to a former Cities Services Employee, 55% of the mined material in the Copper Basin ended up as tailings and deposited in the pond (Russell, 1999). The typical size of a retention pond can range from 50 to over 1000 ha (100 to over 2400 acres), and is created using available valleys or depressions and constructing dams or embankments to completely enclose the area (Hutchison and Ellison, 1992).

Once the slurry is dumped into the pond, it settles out according to the size of particles. These particles usually settle out in three different regions. Larger, sand-sized particles settle first near the slurry inlet. Finer clay-sized particles (slime) settle out at a much slower rate where the water is ponded. In between the two ends of the basin, the tailings become stratified due to meandering of the slurry stream and decreasing water velocities. These different regions can differ in water retention, structure, and infiltration rates (Shetron, 1983).

Origin of Tailings

In the early 1930s before flotation processes were used, only copper and sulfur were mined as these elements were the only ones that could be economically separated. As separation (flotation) processes were perfected, other elements besides copper became of commercial importance (Maher, 1966). From the mined ore, useful materials such as copper, copper sulfate, iron sinter, sulfuric acids, fungicides, zinc concentrate, ferric sulfate, slag, liquid sulfur dioxide, sodium hydrosulfite, and organic chemicals were produced.

The actual mining operation included several stages to bring the ore bodies to the surface. The first process involved reaching the ore bodies in the earth's crust. Next, the ore had to be drilled and/or blasted to loosen and pulverize it to smaller particles. This was done using an ammonium nitrate fuel oil (Anonymous, 1974). The ore was then loaded and hauled to underground crushers where it was ground to a maximum size of 7 ½ inches before being

elevated to the surface. Once the ore was at the surface, it was loaded onto cars and transported to the London Flotation Plant via railroad (Maher, 1966).

The ore was processed by flotation, which involved separating valuable minerals from unwanted rock (gangue) and sequestering individual elements of copper, iron, and zinc sulfides. The ore was first crushed in primary and secondary crushing apparatuses to 3 inches and $\frac{3}{4}$ inch respectively. Next it was reduced to 50% minus 200 mesh in rod and ball mills. This process was carried out with the addition of water to produce a pulp or slurry constancy to allow flotation to take place (Anonymous, 1974).

The pulp first entered the primary (bulk) flotation process (Figure 2.1). The flotation process involved aerating crushed ore with reagents to allow mineral particles to adhere to air bubbles and float to the surface and overflow as froth. These mineral particles included the bulk concentrates of copper, iron, and some zinc and were sent to the copper recovery process. Gangue and other unwanted particles (tailings) settled to the bottom and were removed and sent to the zinc recovery process (Anonymous, 1974).

The minerals sent to the copper recovery process were reground to 80% minus 200 mesh and treated with lime to maintain a pH of about 10.6. The pulp was then conditioned with sodium silicate and cyanide prior to another flotation. Froth was removed for further processing while the tailings was sent to the tailings pond (Anonymous, 1974).

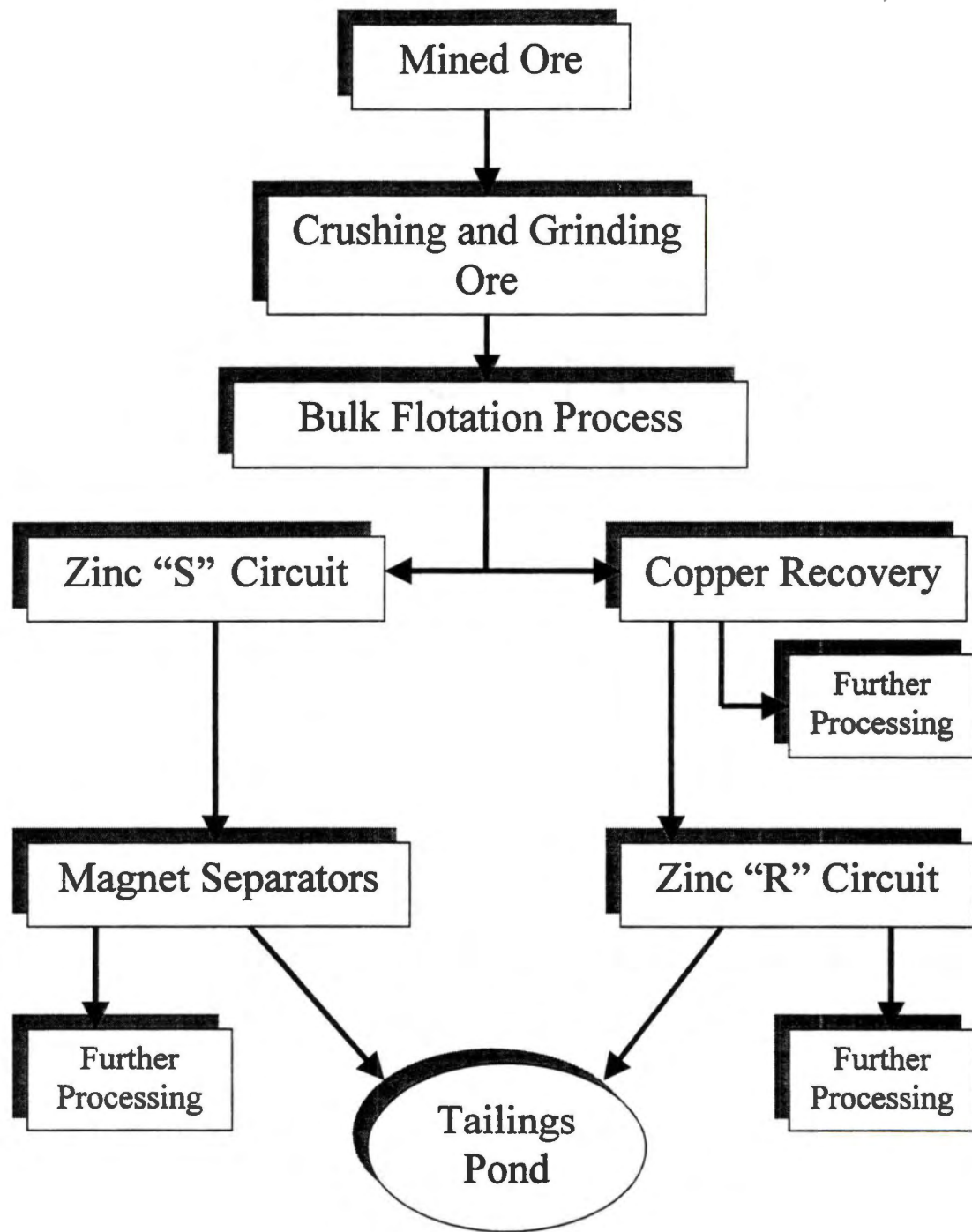


Figure 2.1. Copper Basin mining process

The zinc recovery process consisted of two separate circuits (S & R) each producing zinc concentrates that were processed for sale. The "S" circuit received tailings from the bulk floatation and was treated with copper sulfates. This caused the zinc sulfides to float where they were then removed from the top. The tailings from this stage were sent to a magnetic separator for recovery of magnetite. The recovered magnetite was mixed with iron concentrates and sent to iron roasters. The remaining material was deposited into the tailings pond. The "R" circuit received tailings from the copper recovery process. The tailings feed was then conditioned with copper sulfate to a pH of 11 where zinc was floated from the top and removed for further processing. The remaining tailings consisted mostly of iron sulfide and was sent to an iron roaster (Anonymous, 1974).

The site of the present day tailings pond was previously submerged under water. An earthen dammed channel was constructed in the early 1970s to help drain the water away from the area so that it could be used for the disposal of tailings waste (Russell, 1999). This channel helped the fluvial deposited tailings to pond, settle, and dry out. The flow of the tailings was about 7500 L min^{-1} ($2000 \text{ gal min}^{-1}$) with a constancy of about 15% solids. This area encompassed 16 ha (40 ac) of land for the waste to be distributed. As tailings continued to be poured in to the holding pond, available room for disposal began to run low. In 1977 the channel was lengthened about 90 m (100 yds) towards the east so the tailings pond could be increased. The distribution pipe was moved in 1977 and

again in 1980 to equally disburse the tailings. By the end of the mining activities, 80 ha (200 acres) had being used for disposal. In 1987, the mining company went out of business and since then, mining operations have ceased (Rush, 1999).

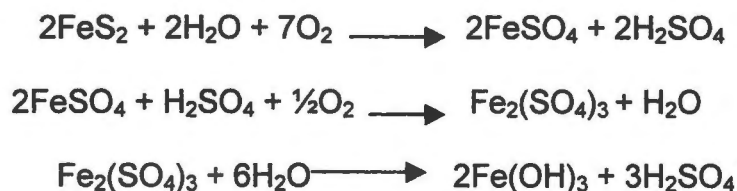
Tailings Pond Characteristics

The physical and chemical characteristics of tailings are very diverse. Chemical compositions of tailings are dependent on what mineral(s) are being mined. For example, cyanide compounds have been found in tailings from gold mining operations. In aluminum mining operations, concentrated sodium hydroxide is used to extract aluminum from bauxite. Once these tailings are deposited in some type of pond or retention basin, these chemicals can undergo even further reactions, changing their character ore (Hossner and Hons, 1992).

Some tailings may contain toxic ions in sufficient concentrations to prevent vegetative growth. Tailings are known to contain concentrations of heavy metals originating from the original ore and/or as a by-product of the processing operation that are higher than commonly found in undisturbed soils (Whitby and Hutchinson, 1974; Lan *et al.*, 1997). Toxic ions may contaminate soils and waters that are adjacent to smelters (Rutherford and Bray, 1979) or tailings through seepage, runoff, and eroded sediments (Johnson and Eaton, 1980). Zinc and Lead mine tailings in China had significant concentrations of Pb, Zn, Cu, and Cd (Lan *et al.*, 1997). Heavy metals can decrease root respiration, water

and nutrient uptake, and inhibit cell mitosis in root meristematic regions (Gemmell, 1977).

Acid drainage due to sulfide oxidation can also be associated with mine tailings (Hossner and Hons, 1992). Exposure of sulfide-bearing minerals (pyrite, pyrrhotite, chalcopyrite, arsenopyrite, cobaltite) to the atmosphere is a common result of mining. During the mining process, not all pyritic materials are removed from the tailings product, thus they may have high concentrations of sulfide materials. When these minerals are exposed, they react with water and oxygen forming sulfuric acid as illustrated using iron (Fe) sulfides by the following equations:



These reactions result largely from the metabolic activity of *Thiobacillus* ferrooxidans. The formation of sulfuric acid (H_2SO_4) reduces pH, increasing solubility of heavy metals and limits the availability of essential plant nutrients in the tailings. Aluminum toxicity presents problems in many acidic tailings (Foy, 1974). Not all tailings are problematic with low pH. The mining process may include reagents that may act as a buffer and raise the pH of the tailings. Lan *et al.* (1997) recorded slightly alkaline tailings with a pH of 7.8 in China. Miles and Tainton (1979) reported alkaline conditions in mining waste in South Africa.

Tailings usually are devoid of vegetation and lack organic matter (OM) which can result in higher surface temperatures (Lan *et al.* 1997; Shetron, 1983; Hossner and Hons, 1992). Temperatures on tailings without vegetative cover can have temperatures of 55° to 65° C (Shetron, 1983). In sand tailings, the absence of OM and a predominance of coarse-sized particles often result in low water-holding capacity (Tanpibal and Sahunalu, 1989; Miles and Tainton, 1979). These high temperatures and reduced water-holding capacity can cause high evapotranspiration rates limiting available water in growing season (Shetron, 1983). Finer textured tailings usually have a greater water-holding capacity but may have poor structural characteristics from the consolidation and compaction of particles thus limiting water percolation (Hossner and Hons, 1992). Erosion of tailings can also cause sedimentation pollution in stream and river channels (Tanpibal and Sahunalu, 1989).

Another major problem associated with bare tailings is wind erosion (Johnson and Eaton, 1980). These wind blown particles can pollute air, streams, and lakes, chafe vegetation, decrease esthetics and create health problems for communities adjacent to the waste site (Hossner and Hons, 1992). On copper mine tailings, wind erosion caused severe contamination to bordering areas in Ireland (O'neil *et al.*, 1998) and severed plants fifteen days after planting in Arizona (Day and Ludeke, 1973).

The objective of this study was to conduct an initial investigation of the tailings pond to determine current or potential problems which may limit vegetation.

Methods and Materials

In order to facilitate a successful reclamation plan, an initial investigation was performed to identify the chemical and physical characteristics of the mine tailings. The tailings are located just north of the London Flotation Plant with approximate coordinates of 35°02' N and 84°21' W (Figure 1.2), found on the Isabella Quadrangle (USGS, 1978).

Field Methods

To determine soil physical and chemical properties of the tailings material that would influence plant growth, four pedons were extracted in an "L" formation (Figure 2.2). The exact latitude and longitude of each site was recorded using a GPS unit (Table 2.1). Using *Soil Taxonomy*, Cook *et al.* (1999) classified the soils of the tailings material as mixed, mesic Typic Udipsamments. For each pedon, morphological and physical properties were recorded. Samples were taken by horizon and depth for laboratory analysis (Soil Survey Staff, 1996).

Laboratory Methods

Each sample was air dried and sieved through a 2 mm diameter screen to separate coarse fragments greater than 2 mm. A fraction of the 2 mm sample was ground to less than 60 mesh using ceramic plates to minimize metallic contamination (Soil Survey Staff, 1996).

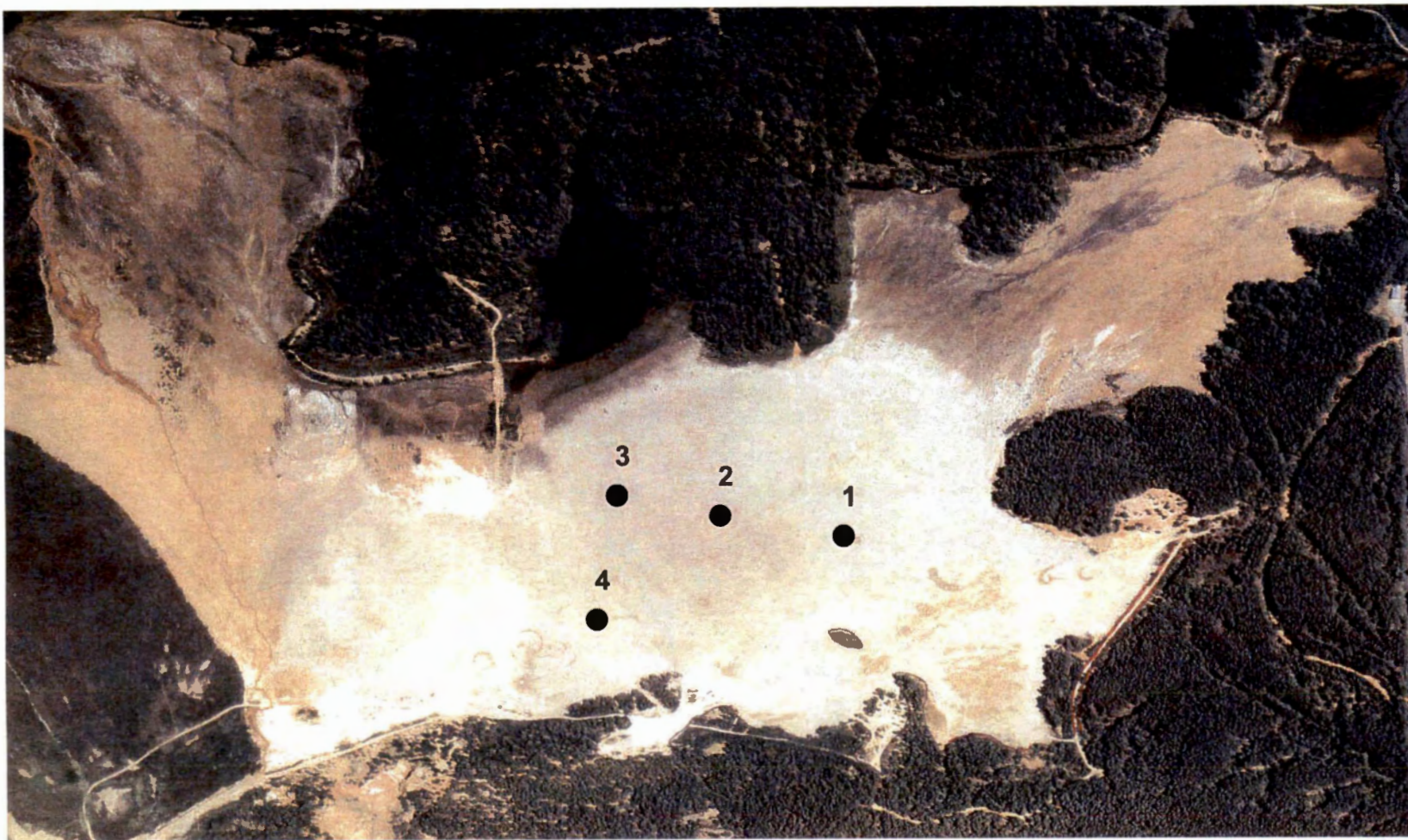


Figure 2.2. Aerial view of tailings pond showing site locations

Table 2.1. Latitude, longitude, and elevation for all four sites.

Site	North Latitude	West Longitude	Elevation m (ft)
1	35° 02' 49.9" N	84° 21' 16.7" W	530.4 (1740)
2	35° 02' 49.8" N	84° 21' 14.5" W	530.4 (1740)
3	35° 02' 55" N	84° 21' 28.4" W	530.4 (1740)
4	35° 02' 49.1" N	84° 21' 35.9" W	536.4 (1760)

Particle size analysis was measured by the pipette method (Kimler and Alexander, 1949). Sands from the particle size analysis were then fractionated by sieving them into very coarse, coarse, medium, fine, and very fine sand sizes (Gee and Bauder, 1986).

Soil pH was measured for each sample using an Orion Research analog pH meter model 301 with 1:1 soil to water and 2:1 soil solution in 0.02 M CaCl_2 (Olsen and Ellis, 1982a). Acid-base accounting (Sobek *et al.*, 1978) was performed to estimate potential acidity or alkalinity of the spoil material. Iron oxides were extracted by the citrate-dithionite (CD) method (Olsen and Ellis, 1982b) and analyzed using a Perkin-Elmer 5000 Atomic Absorption Spectrophotometer. Total acidity was determined using the KCl-extractable Al method (Barnhisel and Bertch, 1982).

Cation exchange capacity (CEC) was determined using acidified NaCl to displace NH_4^+ from the soil samples. The NH_4^+ extract was then steam distilled using a LabConco Rapid Distillation Unit to determine $\text{cmol}^+ \text{kg}^{-1}$ for CEC (Chapman, 1965). Base saturation was obtained using the ammonium acetate at pH 7 method (Hammer and Lewis, 1987). The exchangeable base cations included Na^+ , K^+ , Ca^{2+} , and Mg^{2+} . A Perkin-Elmer 5000 Atomic Absorption Spectrophotometer was used to obtain concentrations of each base cation.

Oxidizable organic C was obtained on all samples by the Walkley-Black method (Jackson, 1958). Total elemental analysis was performed on the first and second fertility samples and the biosolids using microwave oven digestion

with hydrofluoric acid and Aqua Regia (Ammons *et al.*, 1995). Following digestion, the extract was analyzed on a Thermo Jarrell Ash Inductively Coupled Plasma (ICAP) Spectrometer System for 23 elements including Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Si, Sr, Ti, Zn, and Zr. Total C, N, and S were determined using a LECO CNS 2000. Total S was fractionated to pyritic S, sulfate S, and organic S (Sobek *et al.*, 1978).

Mehlich I (dilute-double acid) extraction was used to assess soil fertility (Mehlich, 1953). Elements analyzed were P, K, Ca, Mg, Fe, Na, and Cu.

Results and Discussion

Site 1

This site was located near one of the intlets for tailings disposal (Figure 2.2). The elevation of site 1 was approximately 530.4 m (1740 ft) above mean sea level and was located on mine tailings. Soil morphology was described to a depth of 90 cm. The parent material for this site was alluvial deposited mine tailings.

The deposition of tailings into the pond ceased in the early 1980s resulting in relatively young soils. All layers were designated as C horizons indicating an absence of pedogenesis (Table 2.2). Soil textures ranged from sand in the upper 70 cm to loamy sand in the lower horizon. As tailings are deposited into a holding pond, larger sand-sized particles settle out near the inlet (Shetron, 1983). Fine sands made up about 40 to 50% of the total sand content (Table 2.3). Total silt and clay percentages were very low (< 14 and 3%, respectively) throughout

Table 2.2. Morphology of Site 1.*

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Boundary	Consistence	Mottles
C1	0 – 30	2.5Y 4/2	S	SLS SG	C	L	2.5Y 3/6; 5YR 5,8
C2	30 – 50	10YR 4/4	S	SLS SG	C	L	
C3	50 – 70	10YR 4/6	S	SLS SG	C	L	
C4	70 – 90	5YR 4/6	LS	SLS SG	C	L	

*Abbreviations for morphology designations are given in Appendix A.

Table 2.3. Sand fractionation for Site 1*.

Horizon	Depth (cm)	Size Class and Particle Diameter (microns)				
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50
				%		
C1	0 - 30	0	10	19	43	16
C2	30 - 50	0	15	15	43	14
C3	50 - 70	3	24	14	38	10
C4	70 - 90	0	17	17	40	13

*Abbreviations for size class abbreviations are given in Appendix A.

the entire profile (Figure 2.3). As a result of the high total sand percentages and lack of aggregation of the sand-sized particles, all horizons had structures of structureless-single grain (Table 2.2). Over a long period of time, multiple depositions of waste material were emptied into the tailings pond. Colors varied throughout the profile due to stratification of the tailings material (Table 2.2; Figure 2.4).

Chemical composition of the tailings material is dependent on what type of mineral(s) is being mined (Hossner and Hons, 1992). Various pre-treatments used for mineral separation and original parent material (ore) composition caused differences in chemical characteristics over the tailings pond. Large amounts of lime (CaCO_3) were used in the milling process to help maintain a high pH during mineral separation (Anonymous, 1974). Soil pH of site 1 increased from 7.2 to 7.6 with increasing depth (Table 2.4). The high amounts of calcium carbonates present in the soil act as a buffering mechanism, restricting change in pH.

Acid-base accounting (ABA) was performed to predict the total amount of acidity and alkalinity the site could potentially produce. The maximum potential acidity (expressed as a negative) and total potential alkalinity (termed neutralization potential) are summed together to determine the net effect. Sobek *et al.* (1978) estimated that 3.125 g CaCO_3 is theoretically capable of neutralizing the acid produced from 1 g pyritic (sulfide) sulfur. Site 1 contained trivial amounts of pyritic sulfur with values less than .1%. Table 2.4 shows that the

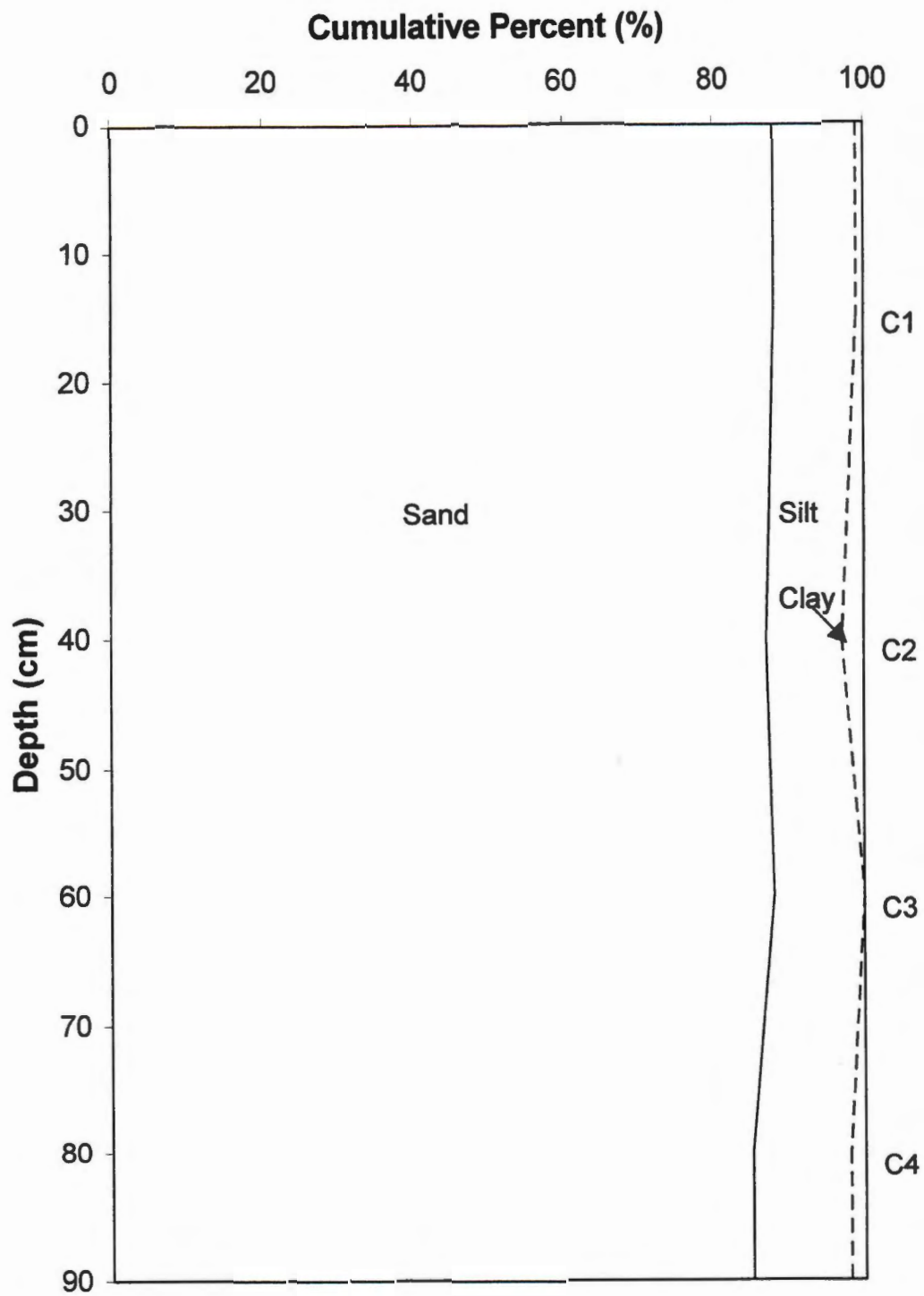


Figure 2.3. Particle size plot for Site 1.

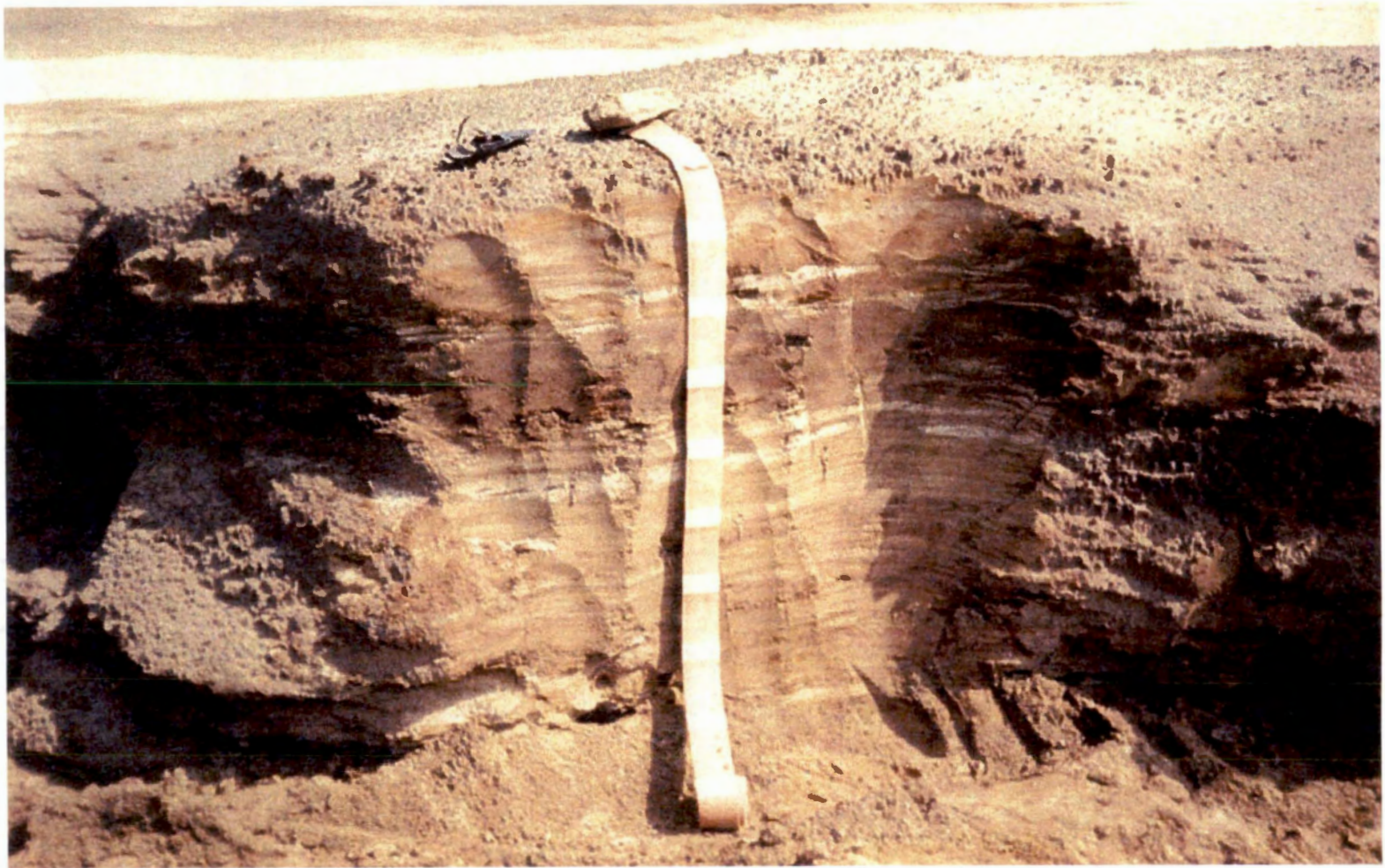


Figure 2.4. Typical mine tailings profile showing stratification.

Table 2.4. Soil pH, percent pyritic sulfur, acid base accounting, KCl extractable aluminum, and total acidity (KCl) for Site 1.

Horizon	pH 1:1 H2O	Pyritic	NP	Pyritic Sulfur Acidity	Fizz	Al	Total
		Sulfur		CaCO ₃ Equivalent	Test	(KCl)	Acidity
		%	-----Tons 1000 Tons ⁻¹ Material-----	(2 M HCl)	-----cmol kg ⁻¹ -----	(KCl)	
C1	7.2	< .001	219.47	0.03	Very Strong	0.01	0.20
C2	7.4	< .001	211.79	0.03	Very Strong	0.00	0.08
C3	7.4	< .001	166.34	0.03	Very Strong	0.00	0.04
C4	7.6	.099	109.25	3.09	Very Strong	0.00	0.04

neutralizing potential (NP) in all horizons for site 1 was in excess of the maximum acidity that could be produced from pyritic sulfur. Included in ABA was a fizz test rating with 2M HCl to check NP determination, as there should be a correlation between the two. All horizons had violent reactions with the acid indicating high amounts of CaCO_3 .

Site 1 had minimal amounts of extractable aluminum with the highest aluminum concentrations in the surface horizon at $0.01 \text{ cmol kg}^{-1}$ (Table 2.4). As soil pH increases, aluminum precipitates out as aluminum hydroxides and is virtually nonexchangeable (Rich, 1964). Exchangeable aluminum and hydrogen increased with decreasing pH. Total acidity was low throughout the profile indicating that very little aluminum and hydrogen were bound to the exchange sites. Therefore, pH remained nearly neutral. High acidity should not be a problem when initiating vegetation near site 1.

Due to the low clay and organic matter content and high sand percentages, cation exchange capacity (CEC) was very low in all horizons (Table 2.5). Sands are not negatively charged therefore they lack the capability of retaining cations. Organic carbon was higher on the surface and in C3 indicating most of the exchange sites resulted from organic matter (Figure 2.5). The large difference between percent organic carbon and percent total carbon suggest that most of the carbon was in the form of inorganic carbon, or calcium carbonate. The high concentrations of calcium carbonates coupled with relatively low exchange sites resulted in a base saturation greater than 100% in all horizons.

Table 2.5. Cation exchange capacity, exchangeable Ca, Mg, Na, K, and percent base saturation for Site 1.

Horizon	CEC (NH ₄ OAc)	Ca	Mg cmol kg ⁻¹	Na	K	Base Saturation %
C1	0.92	22.25	1.50	0.04	0.00	> 100
C2	0.65	59.92	11.60	0.03	0.00	> 100
C3	0.80	67.52	5.86	0.02	0.00	> 100
C4	0.65	87.85	15.54	0.04	0.00	> 100

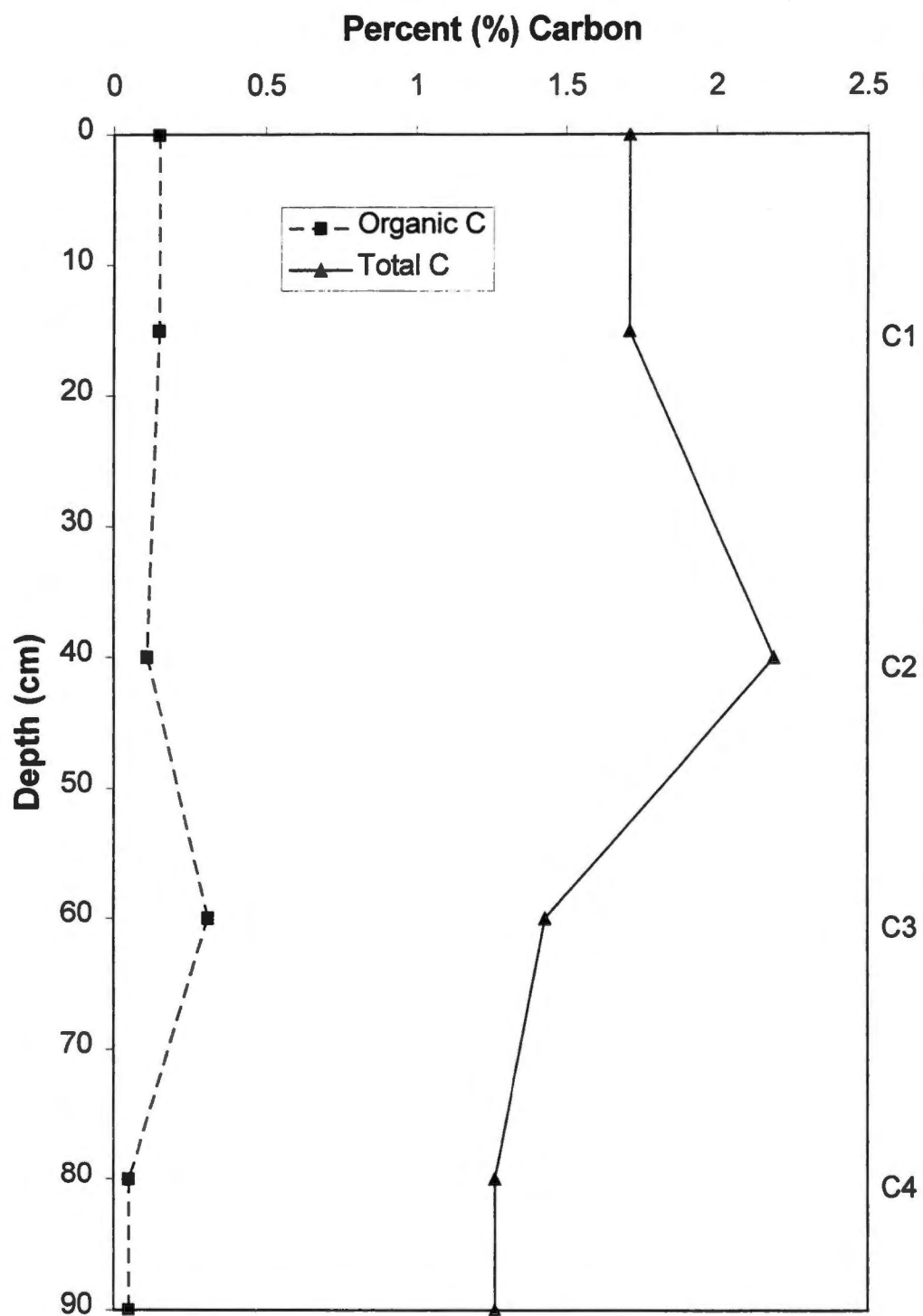


Figure 2.5. Percent total and organic carbon for Site 1.

Problems that may stem from low organic matter may include the inability to retain moisture during dry periods.

Concentrations of the plant available potassium, calcium, and magnesium were present in amounts that should not cause deficiencies (Table 2.6). Total nitrogen was highest in the surface horizon but decreased with depth. Nitrogen can be quickly lost due to volatilization, leaching, and denitrification (Foth and Ellis, 1988) therefore, initiating a revegetation plan may require the addition of nitrogen fertilizer and/or the establishment of nitrogen fixing legumes to further supply available nitrogen. Plant available phosphorus was found to be the limiting nutrient in the tailings material at site 1. In early stages of soil evolution, available phosphorus is low and may limit plant growth (Foth and Ellis, 1988). Phosphorus deficiency is also a common problem in minesoil reclamation (Coyne *et al.*, 1998). Total phosphorus was low with concentrations below 250 mg kg⁻¹ in all horizons. Amendments of phosphorus will be needed to establish vegetation on the tailings pond.

Plant available iron was lowest in the surface horizon, but increased with increasing depth (Table 2.6). Soil pHs above 7.0, low moisture content, and low organic matter content can lead to iron deficiencies (Foth and Ellis, 1988). Soils with low pH and/or increased reducing conditions may contain more soluble forms of iron that can be present in sufficient concentrations to be toxic to plants (Loeppert and Inskeep, 1996). Both plant available sodium and copper were very low in all horizons (Table 2.6).

Table 2.6. Selected total and plant available nutrients analyzed by an independent laboratory for Site 1.

Horizon	Total		Plant Available						
	N	P	P	K	Ca mg kg ⁻¹	Mg	Fe	Na	Cu
C1	971.4	166.0	< 0.5	111.0	6900.0	272.0	479.0	7.8	< 0.1
C2	875.7	93.0	< 0.5	89.0	6750.0	264.0	900.0	4.5	< 0.1
C3	842.9	231.0	< 0.5	138.0	6550.0	331.0	960.0	7.3	< 0.1
C4	921.5	242.0	< 0.5	281.0	4780.0	615.0	2020.0	10.9	0.5

Heavy metals in significant concentrations can be frequently found in tailings material limiting revegetation (Hossner and Hons, 1992). Levels of specific elements in the tailings material were compared to concentrations found in native soils (Lindsay, 1979; Kabata-Pendias and Pendias, 1992). Total nickel and lead were not present in high concentrations, unlikely to cause toxicity (Table 2.7). Total cadmium, chromium, and manganese were slightly higher as compared to native soil concentrations. Total copper and zinc values were present in much higher quantities. This was to be expected, as ore from the Copperhill Formation is rich in Cu and Zn (USGS, 1993). Since extractable copper was almost undetectable, toxicity should not be a problem (Table 2.6). Plant available data were not determined for the other elements.

Site 2

Site 2 was located northeast of site 1 on the talings pond (Figure 2.2). This site was also on mine tailings and had an elevation of approximately 530.4 m (1740 ft). Soil morphology was described to a depth of 150 cm. The parent material for this site was alluvially deposited mine tailings. In horizon C5, two different colors were sampled within the same depth and have been designated as C5a and C5b. These markings are not to be confused with subordinate distinctions within master horizons and layers.

All horizons in this site were designated as C horizons indicating little influence from pedogenic activity (Table 2.8). While horizon C4 had a texture of loamy sand, all other horizons had sand textures. As with site 1, fine sands

Table 2.7. Total elemental analysis of selected elements for Site 1 compared to normal soil concentrations (*Kabata-Pendias and Pendias, 1992; #Lindsay, 1979).

Horizon	Cd	Cr	Cu	Mn	Ni	Pb	Zn
	mg kg ⁻¹						
C1	3.0	21.4	898.0	3973.2	73.0	105.5	1734.2
C2	2.1	81.3	904.2	4257.0	91.2	103.5	1075.0
C3	3.1	113.3	967.6	3643.4	82.0	105.1	2235.1
C4	3.0	41.2	587.1	3020.3	52.4	88.0	1909.4
Normal Range	0.06 – 1.10*	54*	2 – 100#	20 – 3000#	5 – 500#	2 – 200#	10 – 300#

Table 2.8. Morphology of Site 2.*

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Boundary	Consistence	Mottles
C1	0 – 30	10YR 4/2	S	SLS SG	C	L	
C2	30 – 55	10YR 4/4	S	SLS SG	C	L	
C3	55 – 100	10YR 4/6	S	SLS SG	C	L	
C4	100 – 125	2.5YR 3/6	LS	SLS SG	C	L	
C5a	125 - 150	2.5YR 2.5/0	S	SLS SG	C	L	
C5b	125 - 150	5Y 3/2	S	SLS SG	C	L	

*Abbreviations for morphology designations are given in Appendix A.

comprised the majority of the total sand content (Table 2.9). Total silt and clay percentages were again very throughout the entire profile (Figure 2.6). There was a slight increase in total silt and clay (12 and 7%, respectively) in the C4 horizon. Soil structure was structureless single grain in all horizons. Colors varied due to the stratification of the tailings material.

Soil pH of site 2 varied from 6.6 in horizon C4 to 8.2 on the surface (Table 2.10). Pyritic sulfur was highest (.33%) in horizon C4, correlating to the lower pH (6.6). Neutralizing potential was still in excess of the maximum acidity that could be produced by the pyritic sulfur in all horizons (Table 2.10). Fizz tests for all horizons were violent, indicating high amounts calcium carbonates. Extractable aluminum was undetectable due to the higher pHs. Total acidity was lowest on the surface and only reached a high of $.08 \text{ cmol kg}^{-1}$ in the lower horizons (Table 2.10). Low pH should not be a problem in establishing vegetation near site 2.

Cation exchange capacity was again very low resulting from low clay percentages and low organic matter content (Table 2.11). Exchangeable calcium was still very high resulting from the high amounts of calcium carbonates present in the soil. A low CEC and high base content resulted again in a base saturation of greater than 100%.

Percent carbon (Total and organic) changed very little throughout the profile (Figure 2.7). There was still a large difference between total carbon and organic carbon. As was with site 1, most of the carbon was bound as inorganic carbon in the form of calcium carbonate.

Table 2.9. Sand fractionation for Site 2*.

Horizon	Depth (cm)	Size Class and Particle Diameter (microns)				
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50
				%		
C1	0 – 30	0	5	11	53	22
C2	30 – 55	0	13	21	43	14
C3	55 – 100	1	16	14	41	14
C4	100 – 125	0	7	13	42	18
C5	125 - 150	1	20	15	46	11

*Abbreviations for size class abbreviations are given in Appendix A.

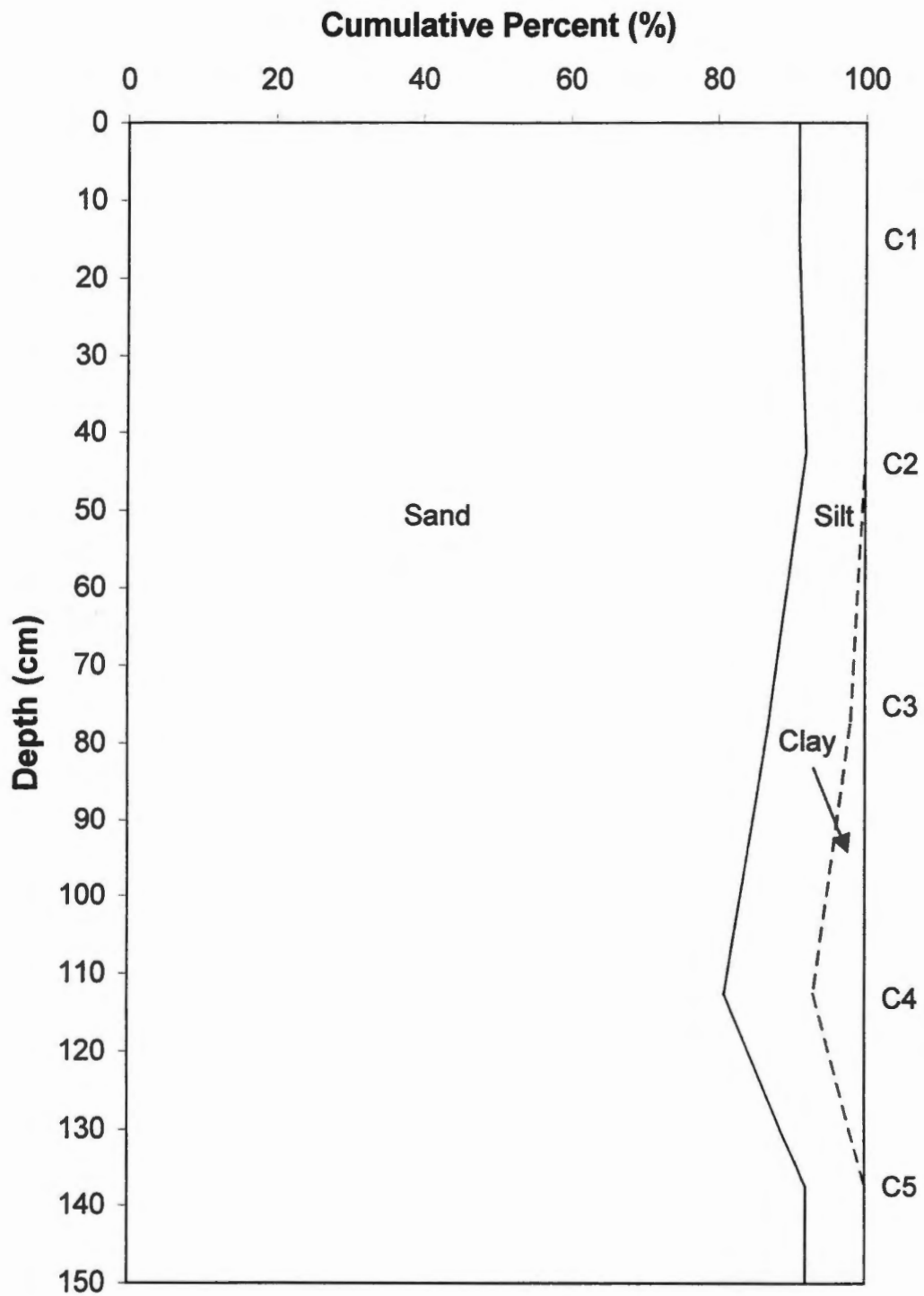


Figure 2.6. Particle size plot for Site 2.

Table 2.10. Soil pH, percent pyritic sulfur, acid base accounting, KCl extractable aluminum, and total acidity (KCl) for Site 2.

Horizon	pH 1:1 H2O	Pyritic	NP	Pyritic Sulfur Acidity	Fizz	Al	Total Acidity
		Sulfur %	CaCO ₃ Equivalent -----Tons 1000 Tons ⁻¹ Material-----	Test (2 M HCl)	(KCl) -----cmol kg ⁻¹ -----	(KCl)	
C1	8.2	.028	174.02	0.88	Very Strong	0.00	0.04
C2	8.0	< .001	245.73	0.03	Very Strong	0.00	0.08
C3	7.4	< .001	323.45	0.03	Very Strong	0.00	0.08
C4	6.6	.330	143.43	10.31	Very Strong	0.00	0.08
C5	7.0	< .001	217.31	0.03	Very Strong	0.00	0.08

Table 2.11. Cation exchange capacity, exchangeable Ca, Mg, Na, K, and percent base saturation for Site 2.

Horizon	CEC	Ca	Mg	Na	K	Base Saturation %
	(NH ₄ OAc)					
			cmol kg ⁻¹			
C1	0.77	12.31	1.81	0.03	0.00	> 100
C2	1.42	15.53	0.14	0.03	0.00	> 100
C3	0.72	73.32	0.08	0.05	0.01	> 100
C4	1.48	156.17	1.67	0.04	0.02	> 100
C5	0.72	48.18	3.07	0.03	0.02	> 100

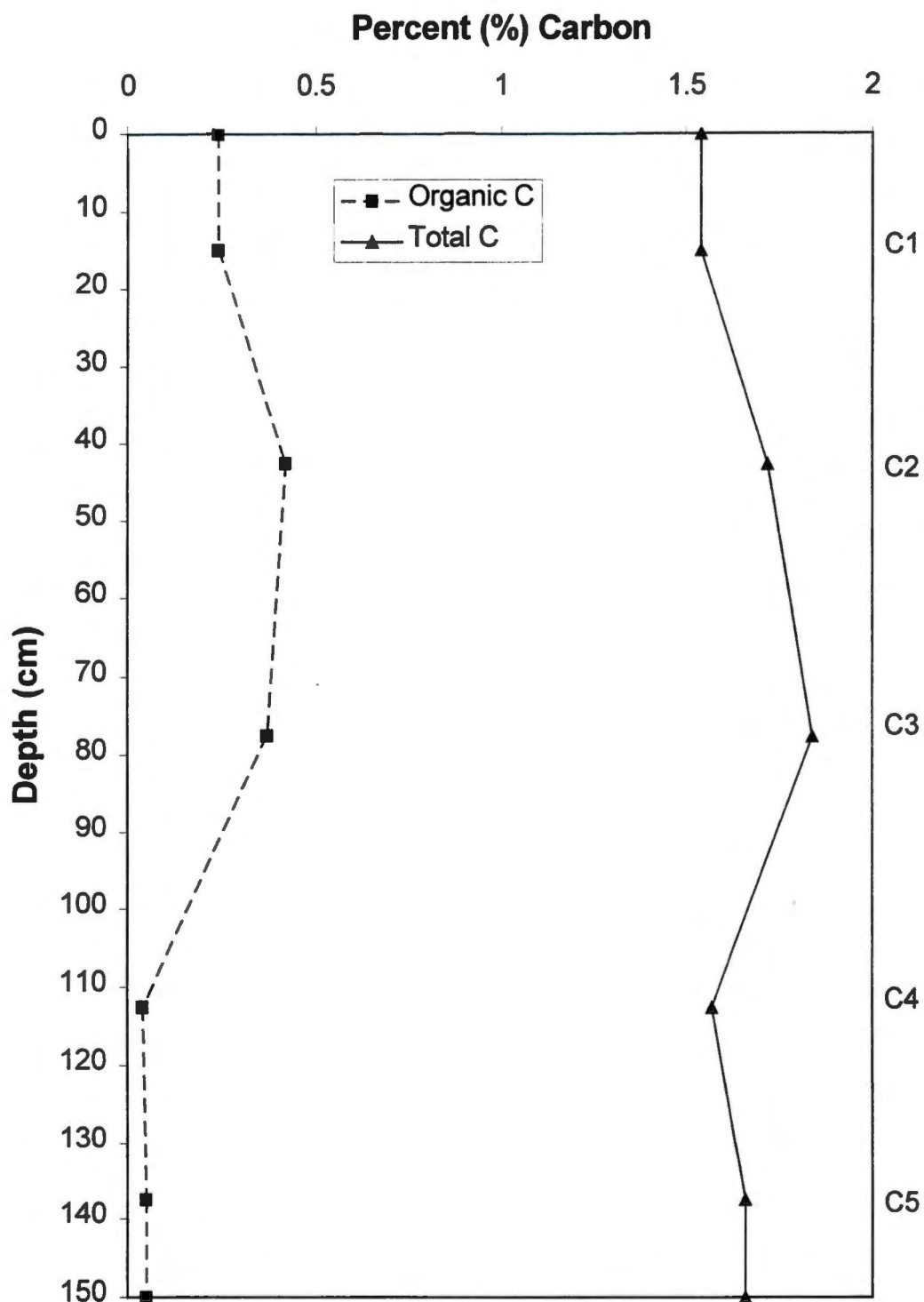


Figure 2.7. Percent total and organic carbon for Site 2.

Concentrations of the plant available potassium, calcium, and magnesium were present in amounts that should not cause deficiencies (Table 2.12). Total nitrogen was highest in the surface horizons and decreased with depth. Plant available phosphorus was again the primary limiting nutrient in site 2. Total phosphorus was also low with concentrations only reaching 355 mg kg⁻¹ in horizon C4. Plant available iron was higher in lower horizons as concentrations increased with decreasing pH (Table 2.12). Both plant available sodium and copper were very low in all horizons.

Heavy metal concentrations were similar to those found in site 1 (Table 2.13). Total nickel and lead were within native soil concentrations while total cadmium, chromium, and manganese were slightly higher. Total copper and zinc were present in much higher concentrations, again most likely due to the nature of the ore. Although total copper was high, plant available copper was very low and should not cause toxicity problems (Table 2.12). Plant available data on the other elements were not determined.

Site 3

Site 3 was located on the northern end of the tailings pond farthest away from the tailings inlet and near the wetlands that have formed (Figure 2.2). Similarly to sites 1 and 2, this site was also on mine tailings with an approximate elevation of 530.4 m (1740 ft). Parent material for this site was alluvial deposited mine tailings. Soil morphology was described to a depth of 130+ cm.

Table 2.12. Selected total and plant available nutrients analyzed by an independent laboratory for Site 2.

Horizon	Total		Plant Available						
	N	P	P	K	Ca mg kg ⁻¹	Mg	Fe	Na	Cu
C1	819.3	312.0	< 0.5	191.0	6600.0	2200.0	132.0	7.3	< 0.1
C2	853.9	289.0	< 0.5	122.0	7000.0	273.0	705.0	6.6	< 0.1
C3	949.5	237.0	< 0.5	092.0	6750.0	303.0	770.0	4.6	< 0.1
C4	614.7	355.0	< 0.5	073.0	4745.0	376.0	1260.0	9.8	0.2
C5a	373.5	199.0	< 0.5	106.0	6700.0	363.0	1580.0	6.4	< 0.1
C5b	373.5	199.0	< 0.5	119.0	6550.0	320.0	1450.0	7.5	< 0.1

Table 2.13. Total elemental analysis of selected elements for Site 2 compared to normal soil concentrations (*Kabata-Pendias and Pendial, 1992; #Lindsay, 1979).

Horizon	Cd	Cr	Cu	Mn	Ni	Pb	Zn
	-----mg kg ⁻¹ -----						
C1	3.0	51.2	405.2	3584.1	48.1	80.3	1407.6
C2	3.1	122.1	678.0	3450.5	78.2	85.4	1458.4
C3	3.1	55.0	1033.6	3732.0	79.0	104.6	2979.2
C4	3.0	31.6	700.1	3678.0	35.6	96.1	939.4
C5	3.1	51.4	871.4	3516.4	73.3	106.5	2829.6
Normal Range	0.06 – 1.10*	54*	2 – 100*	20 – 3000*	5 – 500*	2 – 200*	10 – 300*

All horizons were designated as C due to the lack of pedogenic activity (Table 2.14). The lower horizon was designated as Cg indicating a low chroma color, or gleying (Buol *et al.*, 1997). This horizon was within the water table causing reducing conditions, creating the gleyed colors. Horizons C1 through C4 were loamy sand in texture (Figure 2.8). Finer sized particles settle out further away from the point of deposition as water becomes ponded and particles settle out at a slower rate (Shetron, 1983). The lower horizon (Cg) had a texture of sand most likely from previous tailings depositions. Fine sands comprised the majority of sand content (Table 2.15). Total silt and clay percentages were very low throughout the entire profile (< 16 and 4%, respectively) and decreased with increasing depth. Total silt percent was a little higher compared to sites 1 and 2, most likely due to the distance from the tailings deposition outlets. Structure in all horizons were structureless single grain. Soil colors varied due to the stratification of the tailings material.

Soil pH ranged from 7.8 on the surface horizon to 7.0 in the C2 horizon (Table 2.16). Pyritic sulfur was highest in the C4 horizon only reaching .142% (Table 2.16). The NP for all horizons were in excess of the potential pyritic acidity. Fizz tests were violent in all horizons indicating high amounts of calcium carbonates in the soil. Extractable aluminum was undetectable in all horizons and total acidity was very low which corresponded to the high pHs.

Cation exchange capacity was again very low due to the low clay percentages and low organic matter content (Table 2.17). CEC was highest on

Table 2.14. Morphology of Site 3.*

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Boundary	Consistence	Mottles
C1	0 – 5	2.5YR 4/4	LS	SLS SG	C	L	
C2	5 – 32	5YR 4/6	LS	SLS SG	C	L	
C3	32 – 79	2.5Y 5/6	LS	SLS SG	C	L	
C4	79 – 130	5Y 4/6	LS	SLS SG	C	L	
Cg	130+	5BG 4/1	S	SLS SG	-	L	

*Abbreviations for morphology designations are given in Appendix A.

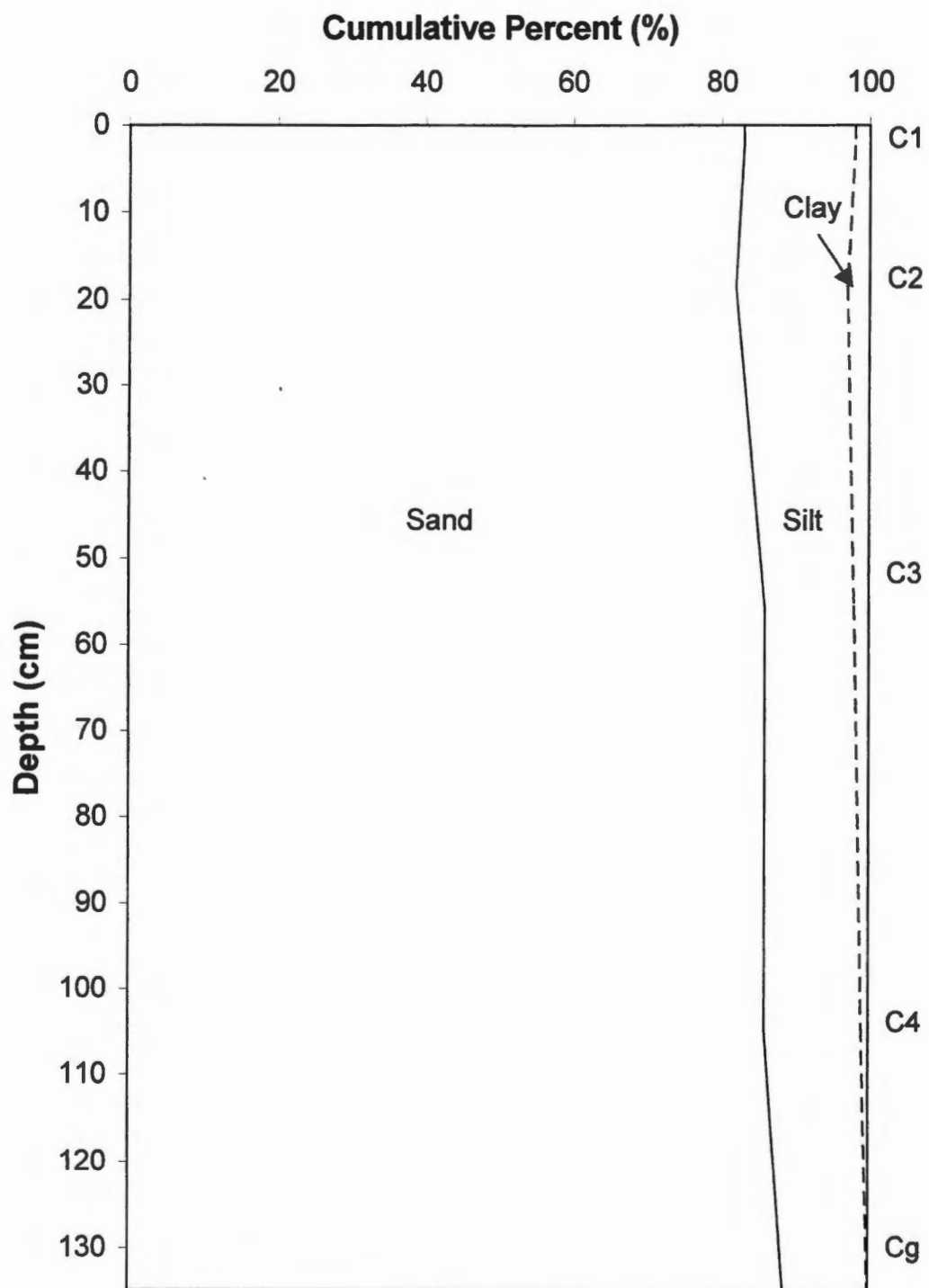


Figure 2.8. Particle size plot for Site 3.

Table 2.15. Sand fractionation for Site 3*.

Horizon	Depth (cm)	Size Class and Particle Diameter (microns)				
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50
				%		
C1	0 - 5	0	2	5	44	31
C2	5 - 32	0	6	7	49	20
C3	32 - 79	0	4	10	52	20
C4	79 - 130	0	3	6	56	21
Cg	130+	0	5	10	50	24

*Abbreviations for size class abbreviations are given in Appendix A.

Table 2.16. Soil pH, percent pyritic sulfur, acid base accounting, KCl extractable aluminum, and total acidity (KCl) for Site 3.

Horizon	pH 1:1 H2O	Pyritic	NP	Pyritic Sulfur Acidity	Fizz	Al	Total Acidity
		Sulfur %	CaCO ₃ Equivalent -----Tons 1000 Tons ⁻¹ Material-----	Test (2 M HCl)	(KCl) -----cmol kg ⁻¹ -----	(KCl)	
C1	7.8	< .001	208.08	0.03	Very Strong	0.00	0.08
C2	7.0	< .001	148.11	0.03	Very Strong	0.00	0.04
C3	7.6	.064	109.97	2.00	Very Strong	0.00	0.08
C4	7.4	.142	112.73	4.44	Very Strong	0.00	0.08
Cg	7.4	< .001	172.10	0.03	Very Strong	0.00	0.04

Table 2.17. Cation exchange capacity, exchangeable Ca, Mg, Na, K, and percent base saturation for Site 3.

Horizon	CEC (NH ₄ OAc)	Ca	Mg cmol kg ⁻¹	Na	K	Base Saturation %
C1	2.03	16.19	0.73	0.02	0.00	> 100
C2	1.68	160.21	1.16	0.06	0.00	> 100
C3	1.09	92.07	0.78	0.04	0.00	> 100
C4	0.96	84.68	0.80	0.07	0.00	> 100
Cg	0.60	45.64	1.52	0.05	0.02	> 100

the surface horizon and decreased with depth. The low CEC and high amounts of exchangeable calcium resulted in a base saturation greater than 100%.

Percent total and organic carbon was higher on the surface horizon and decreased with depth (Figure 2.9). This correlated to the higher surface CEC values. Total carbon increased very little from C4 to Cg while organic carbon decreased.

Concentrations of the plant available potassium, calcium, and magnesium were present in amounts that should not cause deficiencies (Table 2.18). Phosphorus was again the primary limiting nutrient. Total phosphorus was low with concentrations reaching only 416 mg kg^{-1} on the surface horizon. Plant available iron increased with increasing depth (Table 2.18). Plant available sodium and copper were very low in all horizons.

Heavy metal concentrations were similar to those found in sites 1 and 2 (Table 2.19). Total nickel and lead were within native soil concentrations while total cadmium, chromium, and manganese were slightly higher. Total copper and zinc were present in much higher concentrations, as compared to native soil. Although total copper was high, plant available copper was very low and should not cause toxicity problems (Table 2.18). Plant available data for the other elements were not determined.

Site 4

Site 4 was located southwest of site 3 and was closer to one of the original outlets for tailings material (Figure 2.2). Site 4 was also on mine tailings but with

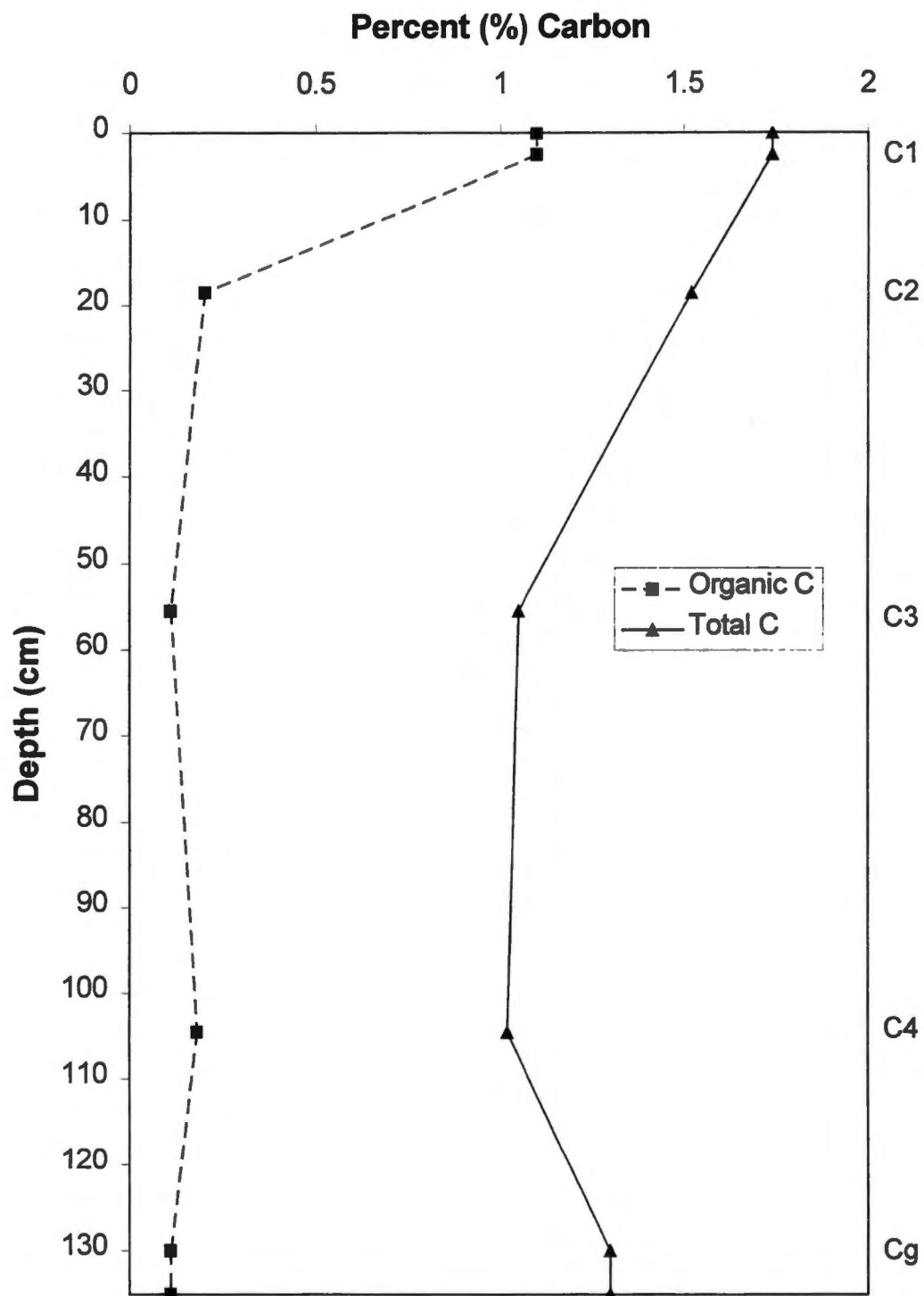


Figure 2.9. Percent total and organic carbon for Site 3.

Table 2.18. Selected total and plant available nutrients analyzed by an independent laboratory for Site 3.

Horizon	Total		Plant Available						
	N	P	P	K	Ca mg kg ⁻¹	Mg	Fe	Na	Cu
C1	381.0	416.0	< 0.5	127.5	6450.0	224.5	276.0	6.4	0.2
C2	352.5	254.0	< 0.5	136.0	6500.0	321.5	590.0	5.8	< 0.1
C3	457.6	260.0	< 0.5	168.5	6500.0	352.0	650.0	7.0	< 0.1
C4	369.3	278.0	< 0.5	177.5	6600.0	380.5	920.0	7.5	< 0.1
Cg	240.6	160.0	< 0.5	156.0	6400.0	297.5	1210.0	6.9	< 0.1

Table 2.19. Total elemental analysis of selected elements for Site 3 compared to normal soil concentrations (*Kabata-Pendias and Pendial, 1992; #Lindsay, 1979).

Horizon	Cd	Cr	Cu	Mn mg kg ⁻¹	Ni	Pb	Zn
C1	2.1	54.4	750.5	4330.8	68.2	99.5	1911.5
C2	2.0	88.0	767.1	4204.0	66.5	96.9	1980.4
C3	2.2	66.3	423.2	3099.1	65.8	85.4	1375.4
C4	3.0	32.4	417.0	3084.6	47.0	94.2	1545.6
Cg	2.1	43.5	973.6	3673.4	50.4	108.1	1376.0
Normal Range	0.06 – 1.10*	54*	2 – 100 [#]	20 – 3000 [#]	5 – 500 [#]	2 – 200 [#]	10 – 300 [#]

a higher elevation of approximately 536.4 m (1760 ft). Parent material for this site was alluvial deposited mine tailings. Soil morphology was described to a depth of 130+ cm. Included in site 4 was an additional surface horizon labeled C1' that was suspected to contain some acidity. Results of C1' are included below the lower horizon of site 4 and are not to be confused as a lower horizon. Due to limited sample quantity, some data was unavailable for horizons C5 and C6.

As with the prior 3 sites, all horizons were designated as C horizons showing little influence of pedogenic activity (Table 2.20). All horizons were loamy sand in texture with fine sands comprising most of the sand content (Table 2.21). Total silt and clay percentages were low but increased with depth (Figure 2.10). Silt percentages in site 4 were higher compared to the other 3 sites. Particle size data was unavailable for horizon C6. All horizons had structureless single grain structure. Soil color varied again due to the stratification of the tailings material.

Soil pH ranged from 3.0 in the C3 and C4 horizons to 7.6 on the surface (Table 2.22). The extra surface sample (C1') had a low pH of 1.9. Percent pyritic sulfur was lowest on the surface horizon and increased with depth correlating to the lower pHs. Although the C1' sample had minimal amounts of pyritic sulfur, there was practically no NP, thus causing a low pH. The low pH was most likely a result of the oxidizing pyritic sulfur that was present before this investigation. Neutralizing potential was higher in the C1 and C2 horizons, but

Table 2.20. Morphology of Site 4.*

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Boundary	Consistence	Mottles
C1	0 – 15	2.5Y 4/2	LS	SLS SG	C	L	
C2	15 – 40	10YR 3/6	LS	SLS SG	C	L	
C3	40 – 60	5YR 3/4	LS	SLS SG	C	L	
C4	60 – 85	5YR 4/6	LS	SLS SG	C	L	
C5	85 – 110	2.5YR 4/6	LS	SLS SG	C	L	
C6	110 – 130+	7.5YR 3/2	LS	SLS SG	-	L	
C1'	0 - 20	5YR 4/6	LS	SLS SG	C	L	

*Abbreviations for morphology designations are given in Appendix A.

Table 2.21. Sand fractionation for Site 4*.

Horizon	Depth (cm)	Size Class and Particle Diameter (microns)				
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50
				%		
C1	0 - 15	1	10	11	39	25
C2	15 - 40	6	23	15	26	10
C3	40 - 60	6	21	12	23	10
C4	60 - 85	13	20	10	26	9
C5	85 - 110	2	18	14	31	11
C6	110 - 130	NA	NA	NA	NA	NA
C1'	0 - 20	7	31	10	20	7

*Abbreviations for size class abbreviations are given in Appendix A.

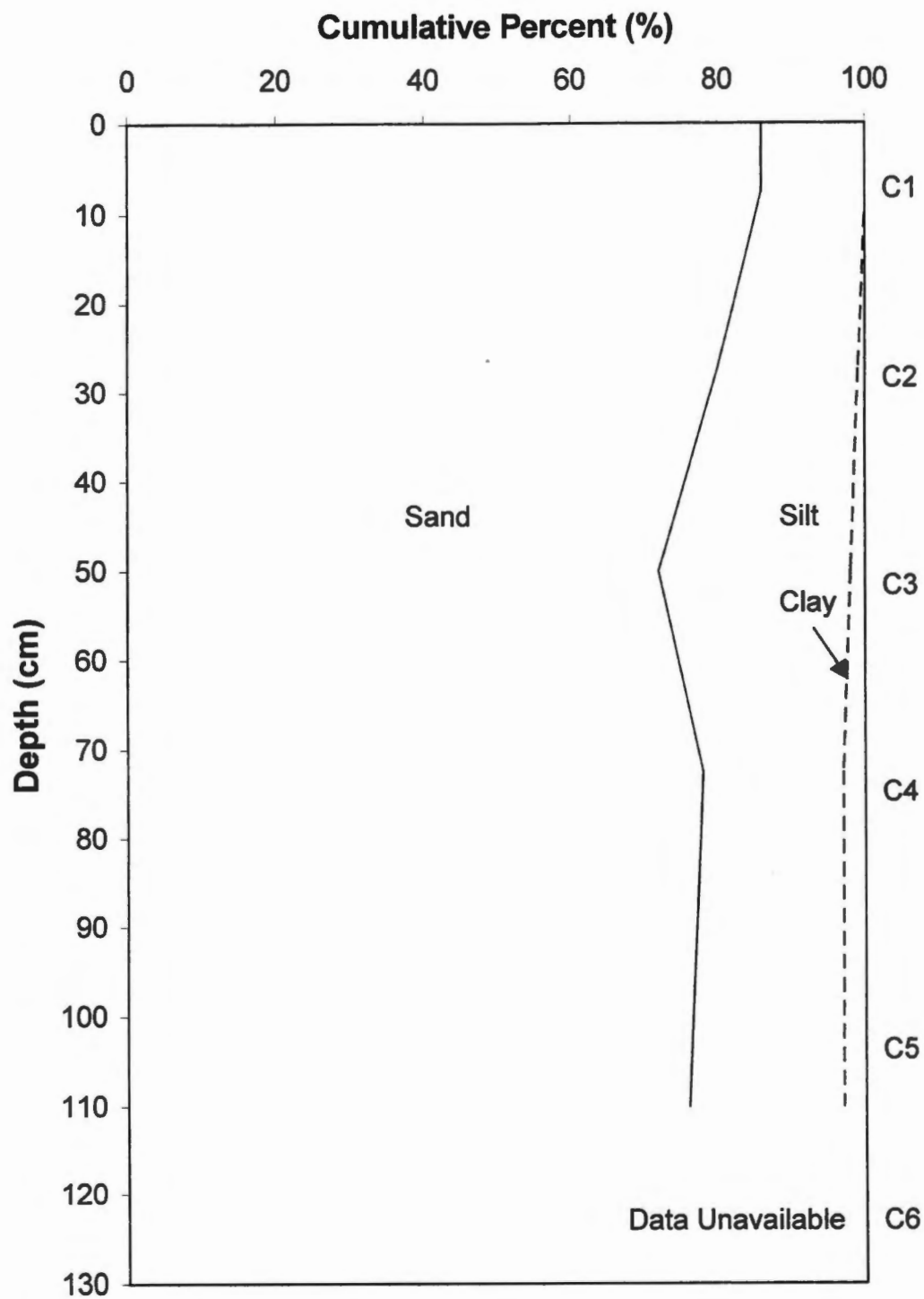


Figure 2.10. Particle size plot for Site 4.

Table 2.22. Soil pH, percent pyritic sulfur, acid base accounting, KCl extractable aluminum, and total acidity (KCl) for Site 4.

Horizon	pH 1:1 H ₂ O	Pyritic	NP	Pyritic Sulfur Acidity	Fizz	Al	Total
		Sulfur %	CaCO ₃ Equivalent -----Tons 1000 Tons ⁻¹ Material-----	Material-----	Test (2 M HCl)	(KCl) -----cmol kg ⁻¹ -----	Acidity (KCl)
C1	7.6	< .001	144.39	0.03	Very Strong	0.00	0.04
C2	6.6	.060	110.69	1.88	Very Strong	0.00	0.08
C3	3.0	.160	40.46	5.00	None	0.48	1.27
C4	3.0	.214	58.48	6.69	None	7.86	9.77
C5	3.8	.400	40.77	12.50	None	0.99	3.83
C6	3.6	.757	30.90	26.66	None	NA	NA
C1'	1.9	< .001	-3.62	0.03	None	5.47	9.95

dropped in the C3 and C4 horizon correlating to the low pH. Out of all 4 sites investigated, only the C1' horizon in site 4 required additional neutralization treatment. Before vegetation is established, amendments of lime should be amended to neutralize localized acidity problems. Fizz tests confirmed the low pHs by having no reaction to the acid (Table 2.22). An acid test without a reaction indicates the absence of calcium carbonates. The upper 2 horizons still had a violent reaction to the acid. As pH dropped, aluminum was more exchangeable as seen by the increased amounts in the lower horizons (Table 2.22). Total acidity increased with the decreasing pH.

Cation exchange capacity increased with depth correlating to the increase in clay percent (Table 2.23). Data was unavailable for horizons C5 and C6. Again, high amounts of calcium coupled with the low CEC resulted in a base saturation greater than 100%.

Total carbon was highest on the surface and decreased with depth (Figure 2.11). Organic carbon was almost equal to total carbon in C2, but dropped to 0%. This confirms that the increase in CEC was most likely attributed to the increase in clay percent (Figure 2.10). Data was unavailable for horizons C5 and C6.

Concentrations of the plant available potassium, calcium, and magnesium were present in amounts that should not cause deficiencies (Table 2.24). Plant available potassium was higher in the upper horizons, but decreased in the lower horizons (C5 and C6) and was very low in the extra surface horizon (C1'). To

Table 2.23. Cation exchange capacity, exchangeable Ca, Mg, Na, K, and percent base saturation for Site 4.

Horizon	CEC (NH ₄ OAc)	Ca	Mg cmol kg ⁻¹	Na	K	Base Saturation %
C1	0.91	81.26	0.63	0.03	0.00	> 100
C2	1.55	153.15	1.82	0.03	0.00	> 100
C3	2.48	121.55	1.90	0.04	0.00	> 100
C4	2.34	197.74	1.29	0.04	0.00	> 100
C5	NA	NA	NA	NA	NA	NA
C6	NA	NA	NA	NA	NA	NA
C1'	2.50	167.57	4.02	0.03	0.01	> 100

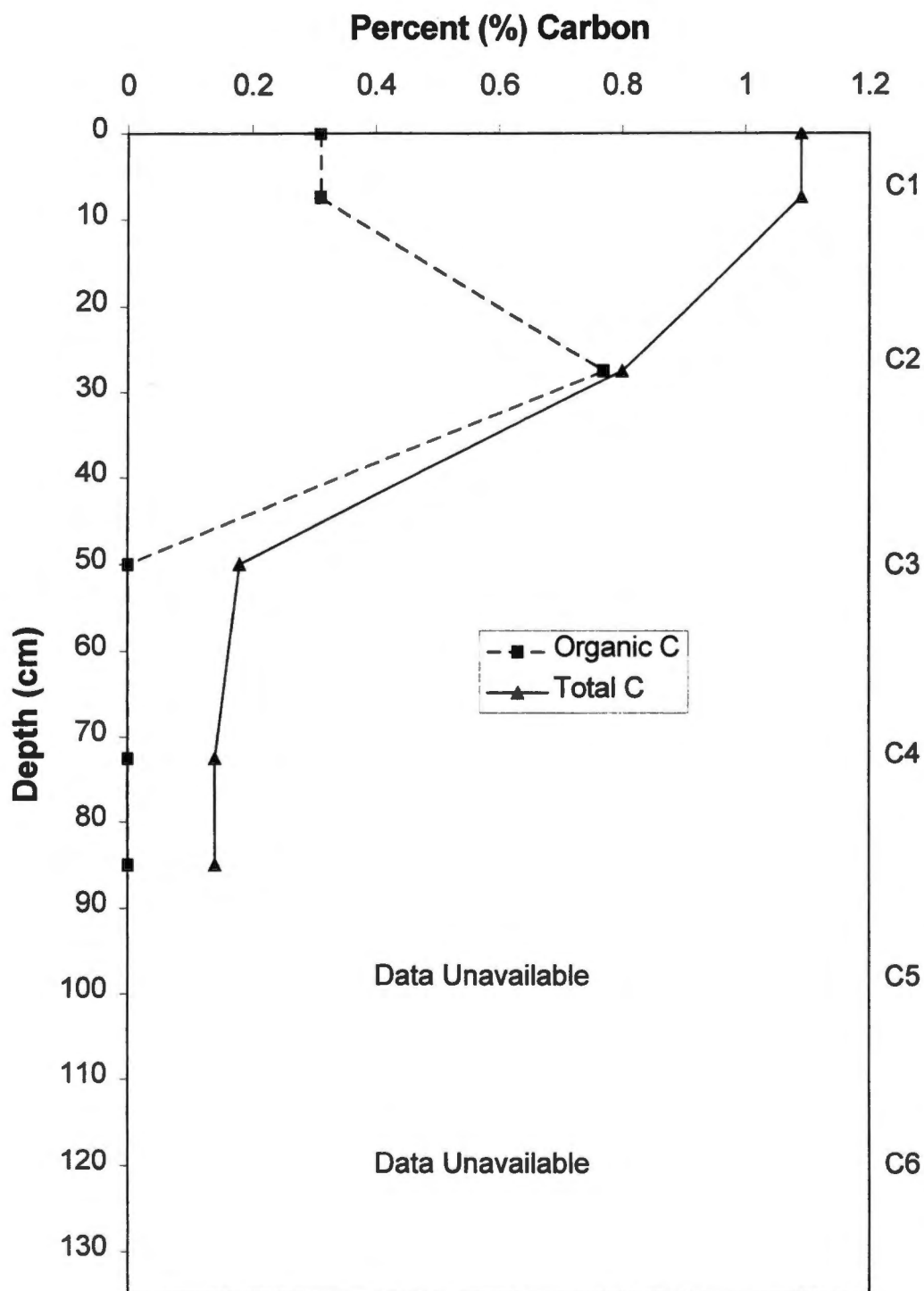


Figure 2.11. Percent total and organic carbon for Site 4.

Table 2.24. Selected total and plant available nutrients analyzed by an independent laboratory for Site 4.

Horizon	-----Total-----		-----Plant Available-----						
	N	P	P	K	Ca mg kg ⁻¹	Mg	Fe	Na	Cu
C1	293.2	279.0	< 0.5	141.0	5900.0	471.0	1255.0	6.25	0.3
C2	332.0	201.0	< 0.5	162.5	4920.0	840.0	2380.0	5.85	10.6
C3	440.5	74.0	< 0.5	207.0	4570.0	600.0	2770.0	7.15	57.0
C4	434.0	31.0	< 0.5	111.5	4795.0	920.0	2280.0	7.55	49.3
C5	NA	90.0	< 0.5	148.0	4180.0	990.0	4035.0	7.40	132.0
C6	NA	51.0	< 0.5	85.0	3965.0	790.0	3415.0	5.95	19.0
C1'	357.8	88.0	2.7	25.1	4520.0	805.0	3210.0	4.25	11.9

combat potential deficiencies, amendments of potassium should be incorporated into the revegetation plant. Plant available phosphorus was the main limiting nutrient in all horizons. In the extra surface sample (C1'), available phosphorus was present, but in a small amount (2.65 mg kg^{-1}). Total phosphorus was low in all horizons with the highest concentration reaching only 279 mg kg^{-1} on the surface horizon. Plant available iron was high as concentrations increased with decreasing pH. Plant available copper was highest in site 4 with concentrations reaching 132 mg kg^{-1} in C5 horizon.

Total elemental analysis revealed that concentrations of chromium and nickel were within normal limits as compared to normal soils while cadmium, manganese, and lead were slightly higher (Table 2.25). Concentrations of copper and zinc were again very high. Plant available copper was still low and should not cause toxicity problems (Table 2.23). Plant available data were not determined for the other elements.

Conclusions

1. All 4 sites were located on recently (< 20 years) deposited alluvial mine tailings. All layers in all 4 sites were designated as C horizons indicating little influence from pedogenic activity.
2. Due to the relatively young age of the soils, all four sites had textures ranging from sand to loamy sand. Fine sands comprised the most of the sand content.

Table 2.25. Total elemental analysis of selected elements for Site 4 compared to normal soil concentrations (*Kabata-Pendias and Pendias, 1992; #Lindsay, 1979).

Horizon	Cd	Cr	Cu	Mn	Ni	Pb	Zn
	-----mg kg ⁻¹ -----						
C1	4.0	25.4	1845.5	4839.8	47.1	206.5	3614.4
C2	4.1	30.5	3077.6	3960.1	53.4	261.4	4599.6
C3	2.2	14.4	1336.0	2539.5	42.5	467.6	1126.5
C4	3.1	19.7	3209.4	2330.4	52.7	309.3	1058.4
C5	4.0	29.4	3067.5	3167.3	70.2	254.0	2545.5
C6	8.1	29.5	2687.1	3302.2	79.6	216.4	4224.8
C1'	2.2	40.4	1072.4	2338.6	64.4	244.6	921.0
Normal Range	0.06 – 1.10*	54*	2 – 100 [#]	20 – 3000 [#]	5 – 500 [#]	2 – 200 [#]	10 – 300 [#]

3. Colors varied throughout all horizons due to the stratification of the tailings material.
4. Soil pH ranged from 6.6 to 8.2 in sites 1, 2, and 3. Site 4 had low pH values as low as 3.0 in lower horizons. The extra surface sample near site 4 (C1') had the lowest pH of 1.9. To neutralize localized acidity problems, amendments of neutralizing material should be incorporated into the revegetation plan.
5. Pyritic sulfur was very low in all sites with a high of only .8% in site 4, correlating to the low pHs.
6. The high amounts of calcium carbonate were sufficient to neutralize the acid production potential of the pyritic sulfur. Only the extra surface horizon (C1') in site 4 required additional neutralizing.
7. Cation exchange capacity was very low due to the low clay and organic matter content and high sand percentages. Due to the high amounts of calcium and low CEC, base saturation was greater than 100% in all 4 sites.
8. Total carbon ranged from 0.09 in the extra surface sample (C1') to 2.19 in site 1. Most of the carbon was bound as inorganic calcium carbonate as organic carbon percentages were very low at all sites.
9. Total nitrogen was available in low, but adequate amounts in all sites. However, as nitrogen is easily lost via volatilization, leaching, and denitrification, the addition of nitrogen fertilizer and/or the establishment of

nitrogen fixing legumes will be needed to further supply available nitrogen for a successful reclamation plant.

10. Plant available phosphorus concentrations were deficient in all 4 sites. Deficiencies in plant nutrients prevent vegetative growth. For successful revegetation of the mine tailings, an amendment of phosphorus will be required. Total phosphorus was low with the highest concentration reaching 416 mg kg^{-1} in site 3.
11. While plant available potassium was found in adequate amounts in all 4 sites, the extra surface horizon (C1') had low amounts (25 mg kg^{-1}). To insure successful establishment of vegetation, potassium fertilizer should be incorporated into the reclamation project.
12. Total elemental concentrations of nickel were comparable with those of native soils, while cadmium, chromium, and lead were slightly higher. Total copper and zinc concentrations were much higher than in native soils.
13. Although total copper concentrations were high, extractable copper was very low and should not pose any toxicity problems.

Chapter III

Reclamation of Mine Tailings

Introduction

While many efforts to reestablish vegetation in the Copper Basin have yielded satisfactory results, few have involved the reclamation of the tailings pond. Mine tailings reclamation is often difficult because it usually comprises only a fraction of a revegetation project and the tailings often have adverse physical and chemical characteristics (Hossner and Hons, 1992). However, establishment of vegetation on barren tailings can increase the aesthetics of the land and decrease pollution sources. To achieve this, essential plant nutrients and various types of vegetation suitable for the harsh environmental conditions may be needed to facilitate the project. Additionally, biosolids may be added to provide necessary nutrients and increase soil moisture retention.

Minesoil Fertility

Mine tailings are often deficient in many essential plant nutrients. The application of needed elements in sufficient amounts is necessary before any revegetation project can be initiated. The deficiencies of plant nutrients are primary problems associated with the revegetation of mineral waste (Day and Ludeke, 1973). Mine reclamation sites often have deficient amounts of N and P, thus limiting restoration efforts. When reclaiming a disturbed site, restoring the N cycle in the soil is essential in initiating vegetative growth (Coyne *et al.*, 1998).

Copper mine tailings are generally deficient in plant available N and may lack other essential nutrients including P and K (Hossner and Hons, 1992; Day and Ludeke, 1973). Shetron (1983) reported deficiencies in plant available N, P, K, Ca, and Mg in copper mine tailings in Michigan. Tailings from the mining of lead and zinc in China had moderate concentrations of P and K but deficiencies in N (Lan *et al.*, 1997). Analysis of kimberlite tailings in South Africa by Miles and Tainton (1979) showed that while total P was high, extractable P by the Olsen method was nonexistent. They theorized that P was bound by Ca in well-crystallized calcium phosphates, which are highly insoluble in alkaline environments. Further analysis of the tailings revealed high amounts of K, Ca, and Mg.

Day and Ludeke (1980) showed revegetation difficulties in copper mine waste in the southwestern United States were associated with deficiencies of essential plant nutrients. Reclamation tests on copper mine tailings in Great Britain showed an increase in plant growth when N, P, and K were added (Gemmell, 1977). Studies have shown that with the amendments of N, P, and K on Cu mine waste, revegetation attempts have been successful (Ludeke *et al.*, 1974; Hossner and Hons, 1992). Warman (1988) reported successful revegetation attempts in pot and field studies when high amounts of N, P, and K were added to mine waste. Initial investigations showed that the essential limiting nutrient on the tailings pond in Polk County was P.

Legumes and Grass for Reclamation

Legumes are advantageous in reclamation in that these plants are able to increase soil fertility through nitrogen fixation. The use of nitrogen fixing legumes along with grass vegetation has been widely used for disturbed soil reclamation. Due to the fact that mine waste is generally associated with low concentrations of nitrogen and legumes are able to fix nitrogen from the air, these types of plants are of utmost interest in mine-spoil reclamation (Vogel and Berg, 1968). Many strip-mine spoils in the eastern USA have been successfully established using grass and legume mixtures (Grandt and Lang, 1958; Mills, 1964).

Members of the *Rhizobium* and *Bradyrhizobium* genus of bacteria form nodules and fix N on the legume roots (Troeh and Thompson, 1993). The host plant supplies the N-fixing organisms with fixed C, a photosynthate, and the host plants benefit from the N fixed. The presence of bacteria adjacent to a root hair causes branching and curling, followed by the invasion of the bacteria. An infection thread is formed and penetrates the root as the bacteria continue to divide and multiply. Plants respond with the formation of tumorous nodules containing bacteroids. These bacteroids are supplied with a photosynthate from the host plant, which is used for respiration and N-fixing activities. The N fixed as ammonia is excreted from the bacteroids to the legume cells and is then transported as C-N compounds in the vascular system (Foth and Ellis, 1988).

Over time, plant residue accumulates in the soil. As these residues decompose, the mineralization of organic N will supply the soil with available N.

The Lespedezas

The Lespedezas have been used extensively for soil restoration as well as for pasture and hay crops. Only two lespedezas are annuals while the others are herbaceous or shrubby perennials. The two annual lespedezas, Kobe (*Lespedeza striata*) and Korean (*L. stipulacea*), along with Sericea lespedeza (*L. cuneata*), a perennial, are common forms of legumes used in disturbed soil reclamation.

Annual Lespedezas

Annual lespedezas are tolerant to many types of soil and fertility levels. They are known to grow well in acid soils that have been eroded and are low in phosphorus even without prior soil treatment although they grow best on productive, well-drained soils (Offutt *et al.*, 1974). Annual lespedezas are capable of improving pasture quality, provide symbiotically fixed nitrogen, and reseed when properly managed (Davis *et al.*, 1994). Lespedezas normally produce enough seed to ensure returns the following year and should maintain itself indefinitely in open or closely grazed sods (Offutt *et al.*, 1974).

Growth of annual lespedezas is relatively slow during late spring into early summer, but increases rapidly until late summer if soil moisture is adequate. By late fall, seed is abundant for wildlife and the crop residue is useful for erosion control (Offutt *et al.*, 1974). Growing usually ceases for both annual lespedezas

after the first frost. Studies by Tysdal and Pieters (1934) showed Kobe lespedeza to be more cold resistant than Korean.

While Korean is more tolerant to alkaline soils and Kobe is more adapted to acid soils, they both have positive responses to acid soils that have been limed and fertilized (Offutt *et al.*, 1974). In an experiment to see how well Korean lespedeza responded to lime applications, Vanderford (1940) discerned that when additional applications of calcium carbonate were added, Korean was able to absorb more nutrients when grown in Grenada silt loam.

In a study conducted by Vogel and Berg (1968), Kobe lespedeza grew better in soils below pH 5.0 compared to Korean and sericea lespedeza and birdsfoot trefoil (*Lotus corniculatus*). However, when pH was above 5.0, Kobe and Korean grew equally well.

It is essential for soils with a low pH that nodules form on roots to facilitate nitrogen fixing. Tests by Duggar (1934 and 1935) revealed more nodulation on Kobe than Korean lespedeza when grown on Norfolk sandy loam. Field test by Pieper *et al.* (1935), showed that some soils often need applications of phosphorus for lespedezas. Korean, Kobe, and sericea all have shown increases in yield when P was added to the soil (Blair, 1931; Gish and Hutcheson, 1923; Cooper, 1936; Stitt, 1939). With soils that had a pH as low as 5.0, Korean showed positive results when P fertilizer was added (Vogel and Berg, 1968).

Sericea Lespedeza

Sericea is an effective legume that aids in soil building and is vigorous on soils where other legumes are hard to establish. It can adapt to poor fertility and responds well to lime and fertilizer on depleted acid soils (Offutt *et al.*, 1974).

Sericea has a higher tolerance to acidic soils than other forage legumes when supplied with N, P, and K (Cline and Silvernail, 1997). It is also tolerant to aluminum-toxicity conditions, which makes it valuable in soils with pH below 5.0 (Ball and Mosjidis, 1995). Aluminum tolerance in acidic soils can be attributed to roots excluding aluminum from uptake in sericea (Joost *et al.*, 1986). Many acidic soils pose problems for root systems of plants grown on soils with low pH. Joost and Hoveland (1986) noted that sub-surface soil acidity did not affect root growth of sericea.

Sericea is able to fix N and grow well in acidic, infertile soils under drought conditions. This makes this species valuable for reclamation of disturbed soil (Ball *et al.*, 1991). Cline and Silvernail (1997) found that Mn may inhibit growth of sericea in acidic soils when the activity of water-extractable Mn^{2+} exceeds 0.4 mM and it may not sufficiently fix N_2 unless available soil N is quite low. Sericea can grow and nodulate in soils with a pH as low as 4.5, but does better where pHs are higher (Vogel and Berg, 1968).

With a deep root system, sericea is also drought tolerant (Ball and Mosjidis, 1995). Root systems of sericea have shown to penetrate deeper than 120 cm (Hyland, 1938). During a fertility experiment by Stitt (1939) on sericea, a

few consecutive months were very dry thus testing drought tolerance. Sericea, with its perennial root, was not affected by the lack of rain.

Sericea can be very valuable in controlling erosion as well. The thick growth of the plant and the coating of fallen leaves can help prevent soil loss (Mooers and Ogden, 1935). In addition, the root system penetrates deep into the soil subsurface, thus improving soil structure (Ball and Mosjidis, 1995). It is estimated that a field with a four year stand of sericea lespedeza grown for soil conservation or biomass production may have over 8960 kg ha⁻¹ (8000 lb acre⁻¹) of residue on the soil surface (Ball and Mosjidis, 1995).

Because sericea lies dormant during the winter months, seeding cool-season grasses should be accompanied to maintain growth of vegetation where cover is of concern (Hoveland *et al.*, 1990). Sericea can be grown with other grasses to help obtain a healthy stand of a grass/legume mixture. Kalburtji and Mosjidis (1993a, 1993b) recognized that root exudates, substances released into the surrounding soil medium, from sericea lespedeza had no effect on the establishment of tall fescue when grown in a mixture nor does it affect the germination of tall fescue.

Although sericea is widely used to revegetate disturbed soils, cover is often established slowly. When grown in spoils with pH above 5.0, sericea did not show response to phosphorus fertilizer after 60 days, but did respond when nitrogen was also added (Vogel and Berg, 1968).

Birdsfoot Trefoil

Birdsfoot trefoil (*Lotus corniculatus*) is a perennial legume that is utilized for pasture, hay, silage, and soil conservation (Seaney, 1974). Birdsfoot trefoil can grow on several types of soils from clayey to sandy loams and in a number of soil moisture conditions from poorly drained to droughty soils. Although they grow best on fertile, moderately well drained soils having a pH between 6.2 to 6.5, they can adapt to many chemical conditions including nutrient deficient, acidic, or mildly alkaline soils (Seaney, 1974). With the application of correct amounts of fertilizer and lime, yields can be greatly increased (MacDonald, 1946). Birdsfoot has been successful when grown on Verndale sandy loam with pH of 6.5 with adequate amounts of P and K (Rehm *et al.*, 1998).

Rhizobium loti bacteria are required for successful inoculation of birdsfoot trefoil. Specific strains of these bacteria are needed, as strains commonly used for other legumes are not effective. Seeds should be thoroughly mixed with the inoculate before planting. When successful inoculation occurs, small pink nodules are found on the plant roots and symbiotic bacteria can fix nitrogen from the air (Seaney, 1974). If birdsfoot is planted in soils that have a pH lower than 6.2, seedling growth and establishment may be retarded, and nodulation and nitrogen fixation may be delayed or inhibited (McKee, 1961). Field studies by Vogel and Berg (1968) revealed growth and nodulation of birdsfoot in soils with a pH as low as 4.5. Compared to lespedezas, birdsfoot grew better in field tests involving mine spoils (Vogel and Berg, 1968).

It is essential that abundant amounts of phosphorus be applied to promote healthy seedling growth in early stages. Applications of potassium in early summer can aid in maintaining productive stands. Nitrogen applications can cause grasses and weeds to compete with birdsfoot but can be useful in low productive soils (Seaney, 1974).

Tall Fescue

Tall fescue (*Festuca arundinacea* Schreb) is a grass widely used in disturbed soil reclamation. Because of its tolerance to a wide range of environmental conditions, tall fescue is the most commonly used reclamation grass in the Appalachians (Roberts *et al.*, 1988). This is because grasses help establish quick cover and protect legumes against erosion (SCS, 1978). On copper mine tailings, grasses have produced the most efficient initial ground cover (Day and Ludeke, 1973). Many grasses have been incorporated with legumes on reclamation sites so that a steady supply of N is available for uptake (Sopper, 1992).

On slightly acidic soils, tall fescue does well (SCS, 1978), but Vogel and Berg (1968) reported a decrease in success in soils with pH below 5.4. In tests comparing weeping lovegrass (*Eragrostis curvula*) and tall fescue in acid mine spoils, Fleming *et al.* (1974) noted favorable results from fescue in soils with pH of 4, but saw inhibited growth when pH dropped below 4. Tall fescue (K-31) has been utilized for spoil-bank reclamation in Kentucky and adjoining states. Most of the stands included a mixture of lespedeza on spoils of about pH 4.5 and

above. Fescue planted alone required nitrogen fertilizer for satisfactory stands (Vogel and Berg, 1968).

Municipal Waste

Much research has been dedicated to exploring the feasibility of using municipal waste on reclaiming vegetation on mined land. Although most studies involve coal mined areas, the application of biosolids may be applied to other disturbed sites as well (Sopper, 1992). The application of biosolids from municipal wastewater treatment plants to disturbed soils can be advantageous in supplying needed nutrients, organic matter (OM) necessary for plant growth and moisture retention. Biosolids may even contribute to the stabilization of soil structure and improve infiltration and water holding capacity (Younos *et al.*, 1982; Henry and Brown, 1997).

Not only can reclamation efforts expand from the application of biosolids, but municipalities may benefit as well. An increasing environmental problem facing many cities is the disposal of treated sewage sludge. Land application of biosolids provides an economically and environmentally sound way of handling municipal waste (Joost *et al.*, 1987).

Biosolids may add essential plant nutrients to the soil including N, P, K, Ca, and Mg although not every element may increase in concentration. The effects of a slow release of nutrients common in biosolids provide "residual" fertilization to vegetation (Sopper, 1992). Studies on coal refuse material in Illinois by Pietz *et al.* (1989) showed increases in exchangeable N and available

P while K concentrations remained constant on sludge amended test plots compared to untreated plots. Walker *et al.* (1996) saw increases in P availability on mined soils with biosolids applied on the Cumberland Plateau, Tennessee. Concentrations of K remained the same on both treated and untreated plots. When sewage sludge was applied to copper tailings in Arizona, plant yield was increased compared to plots receiving well water plus N, P, and K fertilizer treatments (Verma *et al.*, 1977). Sabey *et al.* (1990) reported increased levels of N, P, and K availability on copper mine spoils when municipal sewage sludge was added. The application of biosolids has also increased soil pH reducing heavy metal runoff. On surface mining areas in Beckley, West Virginia, Younds *et al.* (1982) observed an increase in pH from 4.6 to 7.2 on areas with biosolids application.

When establishing vegetation with grasses and legumes on disturbed soils, biosolids can contribute to the increase of plant growth and cover (Joost *et al.*, 1987). In iron tailings revegetation reclamation studies, sludge application produced far superior results in establishing vegetative cover as opposed to inorganic fertilizers (Sopper, 1992). On the Cumberland Plateau experiment, kobe, Korean, and sericea lespedeza growth and cover increased when sludge or sludge plus P was applied (Walker *et al.*, 1996). In the Illinois studies by Peitz *et al.* (1989), tall fescue cover was increased on coal refuse material receiving sludge.

The application of biosolids has yielded unfavorable results. The decomposition of sewage sludge can release inorganic N. Some N may be leached into the groundwater in the form of NO_3 , causing potential health hazards (Joost *et al.*, 1987).

Heavy metals that may pose problems include Zn, Cu, Ni, Cd, and Pb (EPA, 1977). On average, vegetation grown on soil receiving biosolids treatment generally has higher concentrations of these metals (Sopper, 1992). Although this may be a problem with sewage sludge applications, uptake of heavy metals can vary greatly among types of plants (EPA, 1977). Sabey *et al.* (1990) found increased levels of Cd and Pb in leaves of shrubs grown on amended copper mine spoils, while Joost *et al.* (1987) reported tolerable concentrations of Cd, Cr, Pb, and Ni on treated coal refuse spoils. Pietz *et al.* (1989) noted that levels of Al, Fe, Pb, and Zn exceeded phytotoxic limits in the Illinois study.

Copper Basin Tailings Revegetation

There have been few revegetation attempts focused primarily on the tailings pond associated with this research project. According to Russell (1999), initial efforts of reclamation by Cities Service Company in 1977 involved spreading 15 cm (6 in) of topsoil over the eastern side of the tailings pond to aid in vegetation establishment in the late 1970s. In addition, lime was applied at 11.2 Mg ha^{-1} (5 tons acre^{-1}) and fertilizer at 784 kg ha^{-1} (700 lbs acre^{-1}) of 12-24-24 and 112 kg ha^{-1} (100 lbs acre^{-1}) of 6-12-12. Grasses and legumes planted on the tailings pond included sericea lespedeza, weeping lovegrass, ryegrass

(*Lolium* sp.), clover (*Trifolium* sp.), and fescue. In the late 1980s, a local Boy Scout chapter assisted in planting Locust trees along the northern edge of the tailings pond (Russell, 1999). About 50% of these trees remain today with some appearing to be doing better than others. These reclamation efforts succeeded in establishing vegetation on about 40 ha (100 acre) of the tailings, but as time passed environmental problems took their toll on the vegetation. Russell (1999) pointed out problems with sandblasting (damage to plants from wind blown sand) and extreme soil temperatures harmed the established stands and retarded further growth. Loblolly pines, planted by TVA in the early 1940s, cover the hills and gullies that border the tailings pond. Other remaining vegetation on the sight included sparse stands of sericea mixed in with thicker establishments of weeping lovegrass.

Materials and Methods

Site Selection

The study site was placed on the northern end of the tailings pond (Figure 1.3). Two 0.405 ha (1 acre) plots were measured and laid out using laser transit surveying equipment. Plots measured 91.5 m (300 ft) long by 45.7 m (150 ft) wide. A 9.1 m (30 ft) wide aisle separated the two plots. Both plots were divided into 16 sections for fertility monitoring purposes (Figure 3.1). A fence was erected along the perimeter of the two plots to help keep human and animal disturbances to a minimum. A silt fence was put up along the west, north, and eastern sides to decrease wind erosion (sand blasting).

Non-biosolids

A1	A2	A3	A4
0	1	2	3
A5	A6	A7	A8
1	2	3	0
A9	A10	A11	A12
2	0	1	3
A13	A14	A15	A16
1	3	0	2

A

B

C

D

B

A

C

D

Biosolids

B1	B2	B3	B4
2	0	3	1
B5	B6	B7	B8
3	1	2	0
B9	B10	B11	B12
0	1	3	2
B13	B14	B15	B16
3	2	0	1

Legume/Grass Seed Mixture

A	Birdsfoot trefoil/Tall fescue
B	Sericea lespedeza/Tall fescue
C	Kobe lespedeza/Tall fescue
D	Korean lespedeza/Tall fescue

Phosphorus Amendments

0	0 kg P ha ⁻¹	(0 lb P acre ⁻¹)
1	56 kg P ha ⁻¹	(50 lb P acre ⁻¹)
2	112 kg P ha ⁻¹	(100 lb P acre ⁻¹)
3	224 kg P ha ⁻¹	(200 lb P acre ⁻¹)

Figure 3.1. Test Plot Layout

Field Methods

Fertility samples were obtained using a punch probe to a depth of 15 cm (6 in). Fifteen to eighteen samples were taken in a random "X" pattern over each section (Figure 3.2). Samples were pulled prior to any treatments to establish initial fertility characterization.

Both plots were amended with lime at a rate of 4.48 Mg ha^{-1} (2 tons acre^{-1}) to neutralize any acidity problems that may be present in the tailings material over the two test plots. Nitrogen was applied to both plots at two different times. In September 1998, N was added at 56 kg ha^{-1} (50 lb N acre^{-1}) in the form of ammonia nitrate. In March 1999, N was added again at 112 kg ha^{-1} (100 lb N acre^{-1}) in the form of sulfur-coated urea. Potassium was added in the form of KCl at 56 kg ha^{-1} (50 lb K acre^{-1}). These amendments were applied by a Ford 4100 tractor with a conventional fertilizer spreader.

Plots were configured to a randomized split-split block design (Figure 3.1). Variables on the research plots included 2 levels of biosolids application (main plot), 4 levels of phosphorus treatments (split 1), and 4 grass/legume mixtures (split 2).

Biosolids were added to one of the 0.405 ha (1 acre) plots from the Moccasin Bend Treatment Plant, Chattanooga. The biosolids were applied at a rate of 8.96 Mg ha^{-1} (4 tons acre^{-1}) (dry weight) using a manure spreader and incorporated into the upper 15 cm (6 in) of the soil using a tiller. Of the 12 419 kg



Figure 3.2. Picture showing fertility sampling (top) and plant counts (bottom).

(27 380 lb) biosolids applied, 28%, or 3477 kg (7666 lb) were dry weight. The other plot did not receive any biosolids.

Table 3.1 shows biosolids data, which was obtained by total elemental analysis using the microwave oven digestion with hydrofluoric acid and Aqua Regia (Ammons *et al.*, 1995). The pH of the biosolids was 12.4 according to a sample analysis report from the treatment plant.

Various rates of P were amended into the soil so that the effects of these rates could be monitored over time. Rates were 0 kg P ha⁻¹ (0 lb P acre⁻¹), 56 kg P ha⁻¹ (50 lb P acre⁻¹), 112 kg P ha⁻¹ (100 lb P acre⁻¹), and 224 kg P ha⁻¹ (200 lb P acre⁻¹) designated as 0, 1, 2, and 3 respectively. Phosphorus was applied in the form of triple super phosphate. Phosphorus was added using a Gandy fertilizer spreader pulled by a Cub Cadet tractor. The fertilizer spreader was calibrated to distribute the predetermined rates of P. Once all soil amendments were applied, a tiller was used to incorporate these materials into the top 15 cm (6 in) of the soil.

Grass and legumes with high success rates over wide ranges of soil pH were chosen for this experiment. Kentucky 31 tall fescue was the chosen grass to use. Two annual and two perennial legumes were chosen. The annual legumes were kobe and Korean lespedeza and the two perennial legumes were sericea lespedeza and birdsfoot trefoil. Although the Copper Basin borders the southern limit for birdsfoot trefoil, the higher elevation may offset the higher temperatures.

Table 3.1. Total elemental analysis of biosolids.

Element	mg kg ⁻¹
Al	20273.0
As	50.0
Ba	289.3
Ca	229120.4
Cd	2.0
Co	30.9
Cr	123.0
Cu	197.8
Fe	29753.6
K	1141.5
Mn	326.2
Mo	5.0
Ni	159.5
P	12840.2
Pb	72.4
S	6412.1
Si	22930.3
Sr	120.3
Ti	13186.6
Zn	963.3
Zr	95.1

The seeding of the grass/legume mixtures took place on two different occasions. The first seeding took place on October 5, 1998. Due to summer and fall drought conditions, a second seeding was necessary and completed on March 29, 1999. Seeds were distributed in September and March by the following rates:

Tall Fescue	16.8 kg ha ⁻¹	(15 lb acre ⁻¹)
Birdsfoot trefoil	11.2 kg ha ⁻¹	(10 lb acre ⁻¹)
Sericea lespedeza	33.6 kg ha ⁻¹	(30 lb acre ⁻¹)
Kobe lespedeza	44.8 kg ha ⁻¹	(40 lb acre ⁻¹)
Korean lespedeza	28.0 kg ha ⁻¹	(25 lb acre ⁻¹)

Following the September seeding, both plots were mulched with a wheat/rye straw at a rate of 80 bales 0.405 ha⁻¹ (1 acre⁻¹).

Initial fertility sampling, application of amendments, and seeding were completed by September 24, 1998. Plots were monitored quarterly throughout the year by simultaneous plant counts and fertility sampling. A 0.09 m² (1 ft²) wooden square was randomly thrown within each subplot to conduct plant counts (Figure 3.2). Plants inside the square were counted and recorded. Percent vegetative cover was estimated within the square on the final two monitoring visits. This sequence was repeated three times. During the final plant count, biomass samples on a 1.625 m² (17.5 ft²) area from each subplot were taken. These clippings were dried and weighed to compare biomass weights.

Laboratory Methods

Fertility samples were air dried and sieved through a 2 mm diameter screen to separate coarse fragments greater than 2 mm. A fraction of the 2 mm sample was ground to less than 60 mesh using ceramic plates to minimize metallic contamination (Soil Survey Staff, 1996).

Acid-base accounting (Sobek *et al.*, 1978) was performed on the initial fertility sample to estimate potential acidity or alkalinity of the tailings material. Total C, N, and S on the first two fertility samples were determined using a LECO CNS 2000. Total S was fractionated to pyritic S, sulfate S, and organic S (Sobek *et al.*, 1978).

Total acidity on the first two fertility samples was determined using the KCl-extractable Al method (Barnhisel and Bertch, 1982). Base saturation was obtained on the first two fertility samples using the ammonium acetate at pH 7 method (Hammer and Lewis, 1987). The exchangeable base cations included Na^+ , K^+ , Ca^{2+} , and Mg^{2+} . A Perkin-Elmer 5000 Atomic Absorption Spectrophotometer was used to obtain concentrations of each base cation. Cation exchange capacity (CEC) on the first two samples were determined using acidified NaCl to displace NH_4^+ from the soil samples. The NH_4^+ extract was then steam distilled using a LabConco Rapid Distillation Unit to determine $\text{cmol}^+ \text{kg}^{-1}$ for CEC (Chapman, 1965).

Organic C was obtained on all samples by the Walkley-Black method (Jackson, 1958). Total elemental analysis was performed on the first and second fertility samples and the biosolids using microwave oven digestion with

hydrofluoric acid and Aqua Regia (Ammons *et al.*, 1995). Following digestion, the extract was analyzed on a Thermo Jarrell Ash Inductively Coupled Plasma (ICAP) Spectrometer System for 23 elements including Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Si, Sr, Ti, Zn, and Zr.

Mehlich I (dilute-double acid) extraction was used to assess soil fertility on all samples (Mehlich, 1953). The elements Ca, Mg, K, Na, Fe, Mn, Cu, and Zn were analyzed using a Perkin-Elmer 700 Atomic Absorption Spectrophotometer. Extractable P was obtained on all fertility samples using the sodium bicarbonate extractable P method (Olson *et al.*, 1954).

Moisture retention was determined on both the non-biosolids and biosolids plot from the Nov 98 (2nd) and Oct 99 (5th) samples at 0.03, 0.05, and 0.1 MPa (0.3, 0.5, 1.0 bar) using a SOILMOISTURE® extractor (Klute, 1986). Surface (7 cm) and subsurface (15 cm) temperatures were recorded using a HOBO® H8 Pro Series temperature logger.

Statistical Analysis

Statistical analyses were performed using the GLM procedure of the SAS statistical software package (SAS, 1990). Comparisons of laboratory data, total plant counts, legume counts, percent vegetative cover, and biomass weights were completed using analysis of variance (ANOVA) and LSD mean separation at 0.05 level of probability.

Results and Discussion

Chemical and Physical Characteristics

Acid-base accounting was performed to determine the total amount of acidity or alkalinity the research plots could potentially produce. Acid-producing potential is determined by pyritic sulfur content while base-producing potential is determined by the sum of neutralizing bases present in the soil and are expressed as a CaCO_3 equivalent (CCE) (Sobek *et al.*, 1978). Both plots contained minute amounts of pyritic sulfur with values less than 0.1% (Table 3.2). Pyritic sulfur values were low possibly due to previous oxidation pyrite prior to this project. Maximum acidity due to pyritic sulfur reached only 2.75 tons 1000 tons⁻¹ material. The milling process required high amounts of CaCO_3 to maintain a high pH during the separation of elements from the ore (Anonymous, 1974). The tailings had high amounts of NP due to the high concentrations of CaCO_3 present in the tailings material. Neutralizing potential values were greater than the maximum acidity produced by pyritic sulfur (Table 3.2). Revegetation efforts were not hindered due to acidity problems on the research plots. Future acidity problems on the research plots should not be problematic due to the high buffering capacity contained in the tailings.

Low soil pH increases solubility of heavy metals and limits the availability of essential plant nutrients in the mine tailings (Foy, 1974). Soil pH on the tailings was obtained on <60 mesh samples, termed paste pH. Paste pH ranged from 6.0 to 6.7 on both plots before soil amendments were applied (Table 3.3). Lime and biosolids application have both been shown to increase minesoil pH (Mathias *et al.*, 1979). Paste pH increased over time on both the non-biosolids

Table 3.2. Acid-base accounting for fertility samples

Block	Pyritic Sulfur %	Maximum Acidity From Pyritic Sulfur	Neutralization Potential	
			1 st Sample CaCO ₃ Equivalent Tons 1000 Tons ⁻¹ Material	2 nd Sample
A1	0.00	0.00	160.08	105.02
A2	0.00	0.00	160.08	168.48
A3	0.00	0.00	103.59	133.01
A4	0.00	0.00	103.59	131.46
A5	0.00	0.00	126.61	129.36
A6	0.00	0.00	126.61	127.84
A7	.088	2.75	129.34	132.40
A8	.088	2.75	129.34	113.58
A9	0.00	0.00	110.85	124.79
A10	0.00	0.00	110.85	95.72
A11	.076	2.38	108.73	133.83
A12	.076	2.38	108.73	116.58
A13	0.00	0.00	100.01	122.96
A14	0.00	0.00	100.01	126.01
A15	.085	2.66	120.84	120.85
A16	.085	2.66	120.84	122.35
B1	0.00	0.00	167.27	149.53
B2	0.00	0.00	167.27	157.17
B3	0.00	0.00	150.88	165.56
B4	0.00	0.00	150.88	122.66
B5	0.00	0.00	109.34	112.04
B6	0.00	0.00	109.34	134.73
B7	0.00	0.00	161.00	163.63
B8	0.00	0.00	161.00	183.35
B9	0.00	0.00	122.66	140.31
B10	0.00	0.00	122.66	138.48
B11	0.00	0.00	139.70	146.63
B12	0.00	0.00	139.70	164.42
B13	0.00	0.00	121.75	108.06
B14	0.00	0.00	121.75	163.43
B15	0.00	0.00	141.53	155.96
B16	0.00	0.00	141.53	130.21

Table 3.3. Paste pH for fertility samples

Block	1 st Sample	2 nd Sample	3 rd Sample Paste pH	4 th Sample	5 th Sample
A1	6.5	6.6	6.8	7.1	7.1
A2	6.5	6.2	7.0	7.1	7.2
A3	6.6	6.3	7.1	7.2	7.0
A4	6.6	6.3	7.1	7.1	7.0
A5	6.5	6.5	7.2	7.1	7.1
A6	6.5	6.2	7.2	7.0	7.1
A7	6.0	6.3	7.3	7.0	7.1
A8	6.0	6.1	7.2	7.0	7.0
A9	6.5	6.3	7.3	7.2	7.1
A10	6.5	6.5	7.5	7.1	7.0
A11	6.2	6.0	7.5	7.0	7.1
A12	6.2	6.0	7.5	7.0	6.9
A13	6.6	6.0	7.5	7.0	7.3
A14	6.6	6.4	7.5	7.2	7.4
A15	6.6	6.5	7.5	7.1	7.4
A16	6.6	6.6	7.6	7.4	7.2
B1	6.7	6.5	7.4	7.4	7.4
B2	6.7	6.6	7.5	7.2	7.3
B3	6.6	6.4	7.5	7.4	7.3
B4	6.6	6.3	7.4	7.2	7.2
B5	6.6	6.4	7.4	7.2	7.4
B6	6.6	6.5	7.5	7.3	7.3
B7	6.7	6.6	7.4	7.3	7.4
B8	6.7	6.9	7.4	7.3	7.2
B9	6.6	6.6	7.5	7.2	7.4
B10	6.6	6.4	7.3	7.0	7.2
B11	6.6	6.7	7.4	7.0	7.3
B12	6.6	6.6	7.3	7.2	7.2
B13	6.6	6.6	7.4	7.0	7.3
B14	6.6	6.7	7.2	7.2	7.3
B15	6.6	6.7	7.3	7.2	7.2
B16	6.6	6.6	7.2	7.0	7.2

and biosolids plots with slightly higher values on the biosolids plot. As stated earlier, the pH of the biosolids was 12.4. This most likely caused the slightly higher pH values in the biosolids plot. Fertility samples from Mar 99 (3rd) revealed an increase in paste pH in all blocks due to the lime that was added to the plots following the Sep 98 (1st) samples (Table 3.3). Because of the droughty conditions between the Sep 98 and Nov 98 (1st and 2nd) sampling dates, results of this application were not evident until the Mar 99 (3rd) samples. Calcium carbonate is quite insoluble, dissolves slowly, and has very limited downward mobility (Foth and Ellis, 1988). Paste pH in the Jun and Oct 99 (4th and 5th) samples remained unchanged or slightly increased or decreased.

Exchangeable Al from the Sep 98 and Nov 98 (1st and 2nd) samples were low in all blocks correlating to the high pH with very little differences between the non-biosolids and biosolids plots (Table 3.4). As soil pH increases, aluminum precipitates out as aluminum hydroxides and is virtually non-exchangeable (Rich, 1964). As pH decreases, Al becomes more soluble and can attach to exchange sites. Total acidity was low on both non-biosolids and biosolids plots showing very little Al and H was bound to the exchange sites (Table 3.5).

Exchangeable Ca was very high in all blocks on both the non-biosolids and biosolids plots correlating to the high NP (Table 3.6). Calcium carbonate used during the separation process resulted in high concentrations in the tailings material. Cation exchange capacity (CEC) was low on both initial and second fertility samples in both the non-biosolids and biosolids plot reaching a high of

Table 3.4. Extractable aluminum (KCl) for fertility samples.

Block	1 st Sample	2 nd Sample
	cmol kg ⁻¹	
A1	0.04	0.08
A2	0.04	0.00
A3	0.05	0.05
A4	0.05	0.00
A5	0.04	0.00
A6	0.04	0.03
A7	0.07	0.00
A8	0.07	0.00
A9	0.05	0.00
A10	0.05	0.00
A11	0.05	0.00
A12	0.05	0.00
A13	0.05	0.00
A14	0.05	0.00
A15	0.06	0.00
A16	0.06	0.10
B1	0.03	0.08
B2	0.03	0.07
B3	0.01	0.09
B4	0.01	0.00
B5	0.04	0.00
B6	0.04	0.00
B7	0.01	0.00
B8	0.01	0.00
B9	0.02	0.00
B10	0.02	0.00
B11	0.01	0.00
B12	0.01	0.00
B13	0.03	0.04
B14	0.03	0.04
B15	0.03	0.04
B16	0.03	0.01

Table 3.5. Total acidity (KCl) for fertility samples.

Block	1 st Sample	2 nd Sample
	cmol kg ⁻¹	
A1	0.02	0.00
A2	0.02	0.00
A3	0.02	0.00
A4	0.02	0.02
A5	0.00	0.03
A6	0.00	0.02
A7	0.02	0.02
A8	0.02	0.00
A9	0.00	0.02
A10	0.00	0.00
A11	0.02	0.00
A12	0.02	0.00
A13	0.02	0.00
A14	0.02	0.02
A15	0.00	0.02
A16	0.00	0.02
B1	0.00	0.02
B2	0.00	0.02
B3	0.02	0.02
B4	0.02	0.02
B5	0.02	0.02
B6	0.02	0.02
B7	0.00	0.02
B8	0.00	0.02
B9	0.00	0.02
B10	0.00	0.02
B11	0.02	0.02
B12	0.02	0.02
B13	0.02	0.02
B14	0.02	0.02
B15	0.02	0.02
B16	0.02	0.02

Table 3.6. Exchangeable calcium (NH₄OAc), cation exchange capacity (CEC), and base saturation for fertility samples.

Block	Exchangeable Ca (NH ₄ OAc)		CEC		Base Saturation %
	1 st Sample	2 nd Sample	1 st Sample	2 nd Sample	
	cmol kg ⁻¹				
A1	74.08	38.38	1.10	1.05	> 100
A2	74.08	66.22	1.10	0.92	> 100
A3	102.19	93.99	1.67	1.78	> 100
A4	102.19	84.47	1.67	1.21	> 100
A5	99.30	89.22	1.43	1.41	> 100
A6	99.30	119.08	1.43	1.29	> 100
A7	106.15	110.07	1.66	1.42	> 100
A8	106.15	145.49	1.66	1.26	> 100
A9	89.31	59.28	1.44	1.51	> 100
A10	89.31	119.63	1.44	1.18	> 100
A11	107.90	89.46	1.42	1.19	> 100
A12	107.90	90.07	1.42	1.30	> 100
A13	65.64	62.90	1.31	1.43	> 100
A14	65.64	52.40	1.31	0.87	> 100
A15	87.12	45.68	1.19	0.98	> 100
A16	87.12	55.84	1.19	1.07	> 100
B1	89.05	89.02	2.45	1.06	> 100
B2	89.05	69.38	2.45	1.18	> 100
B3	139.27	101.49	2.11	1.11	> 100
B4	139.27	104.67	2.11	1.25	> 100
B5	103.41	100.90	2.45	1.50	> 100
B6	103.41	81.12	2.45	1.20	> 100
B7	84.63	58.77	1.79	1.07	> 100
B8	84.63	45.06	1.79	0.97	> 100
B9	125.00	54.32	2.00	0.88	> 100
B10	125.00	69.84	2.00	1.43	> 100
B11	118.41	88.52	1.47	1.31	> 100
B12	118.41	89.74	1.47	0.85	> 100
B13	91.77	60.63	1.81	1.49	> 100
B14	91.77	32.32	1.81	1.28	> 100
B15	107.77	98.45	2.61	0.00	> 100
B16	107.77	92.36	2.61	0.00	> 100

2.61 cmol kg⁻¹ (Table 3.6). Values were low due to the sandy textures and low clay percentages in the tailings material. The high amounts of exchangeable calcium present in the soil coupled with low CEC values resulted in high base saturation with values greater than 100% (Table 3.6).

Most of the C in the tailings material was bound as inorganic CaCO₃. Means of percent total carbon in both research plots were significantly affected by interactions between biosolids by sample date (Table 3.7). Over time, there were no increases or decreases in total carbon in the non-biosolids plot (Figure 3.3). Total carbon in the biosolids plot did increase in sequential sampling dates compared to the initial fertility sampling, correlating to the application of biosolids. Overall, after initial sampling, total carbon percentages were higher in the biosolids plot compared to the non-biosolids plot (Figure 3.3).

Organic carbon was also significantly affected by interactions between biosolids by sample date (Table 3.7). Percent organic carbon in the non-biosolids plot fluctuated between sampling dates (Figure 3.4). Comparing the initial and final sampling dates, there were no significant differences in organic carbon within the non-biosolids plot. In the biosolids plot, the Nov 98 (2nd) samples revealed an increase in organic carbon from initial fertility samples correlating to the amendment of biosolids (Figure 3.4). Final fertility samples revealed no differences in percent organic carbon between the non-biosolids plot and the biosolids plot (Figure 3.4). Increases in organic carbon on the non-biosolids plot were most likely from accumulations of plant residues.

Table 3.7. AVONA table for percent total carbon, organic carbon, and moisture retention.

Source of Variation	Total Carbon	Organic Carbon	Moisture Retention
Biosolids (B)	***	***	NS
Sample Date (S)	***	NS	NS
B*S	***	***	NS

*, **, *** Significant at $P=0.05$, 0.01, 0.001 levels, respectively.
NS, Nonsignificant

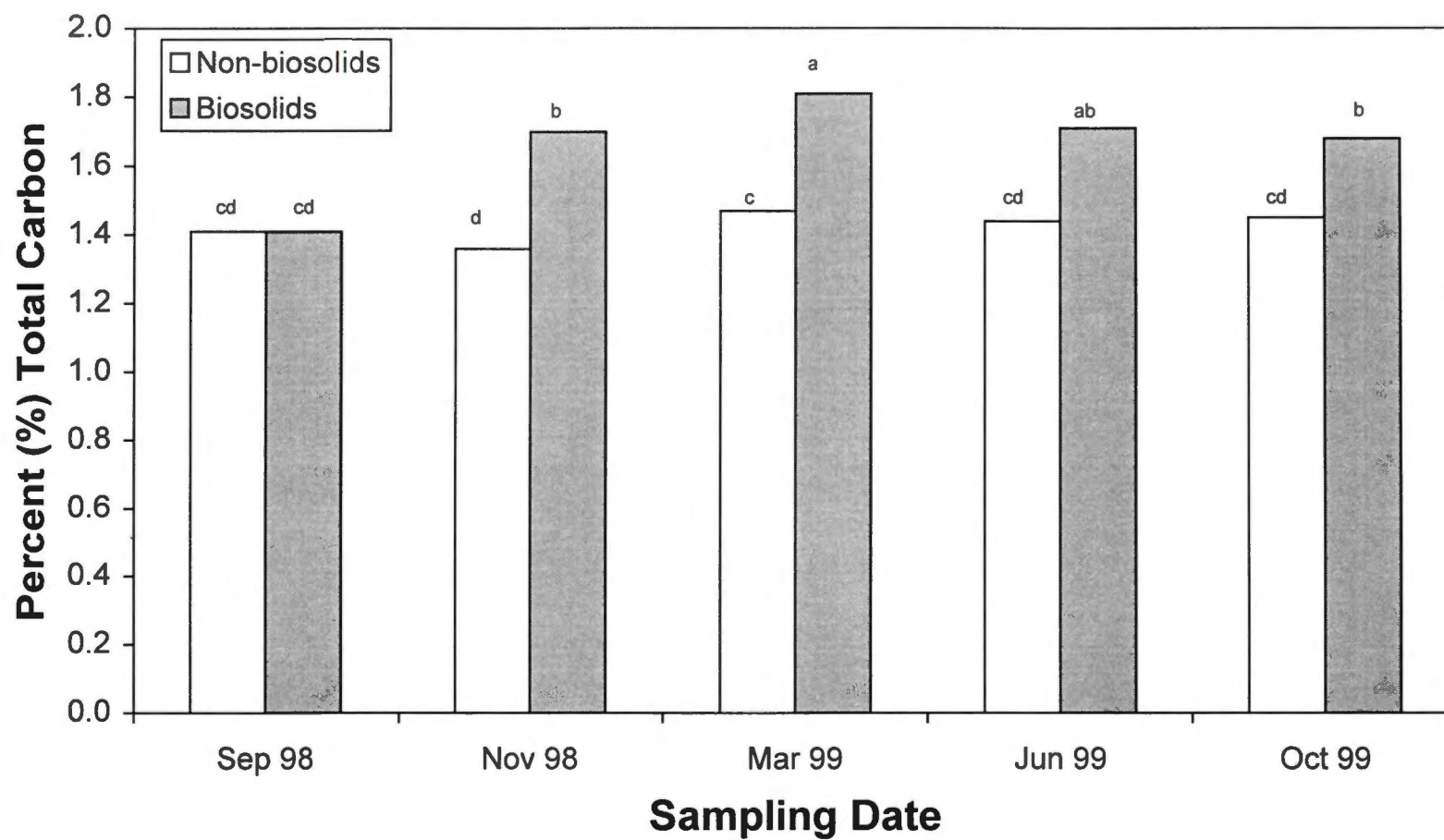


Figure 3.3. Mean percent total carbon in the non-biosolids and the biosolids plot over time. Means followed by the same letter are not significantly different according to LSD (0.05).

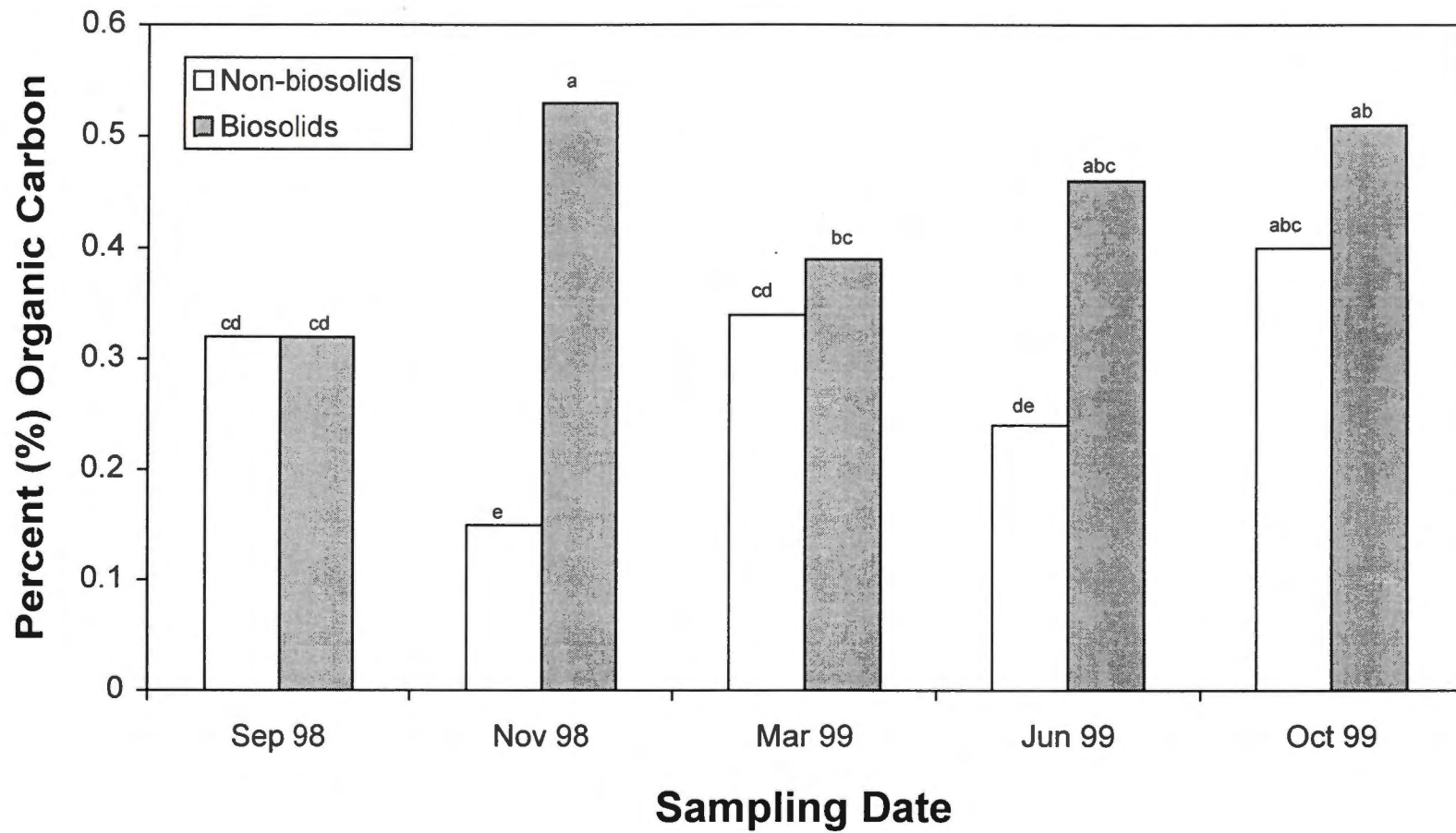


Figure 3.4. Mean percent organic carbon in the non-biosolids and the biosolids plot over time. Means followed by the same letter are not significantly different according to LSD (0.05).

The addition of biosolids to mine tailings may increase soil organic matter (Sopper, 1992). Organic matter increases soil water-holding capacity, which in turn improves the ability of mass flow of nutrients for plant uptake (Barber, 1984). Organic matter may retard evapotranspiration rates in sandy soils by increasing cover and aiding in the retention of water. Although moisture retention differences on both the non-biosolids plot and the biosolids plot were not significantly affected over time by the application of biosolids (Table 3.7), samples from the final (Oct 99) monitoring visit appeared to have higher moisture retention on the plot receiving biosolids (Figure 3.5).

Soil Fertility

Nitrogen, P, K, Ca, and Mg are nutrients required in relatively large amounts to sustain plant growth and development. Micronutrients, including Cu, Fe, Mn, and Zn, are also essential for plant growth and development but in lesser amounts than macronutrients. Plant available (double-acid extractable) Cu, K, Mg, and Na were significantly affected by interactions between biosolids by sample date (Table 3.8). Calcium, Fe, Mn, and Zn were not affected by biosolids, but did have differences affected by sampling date alone.

Plant available Ca was high compared to undisturbed soils due to the high amounts of CaCO_3 contained in the tailings. Copper mine tailings are commonly rich in Ca reflecting the mineralogical composition of the ore body and reagents used during the milling process (Shetron, 1983). While biosolids did not significantly affect plant available Ca, the combined means from both the non-

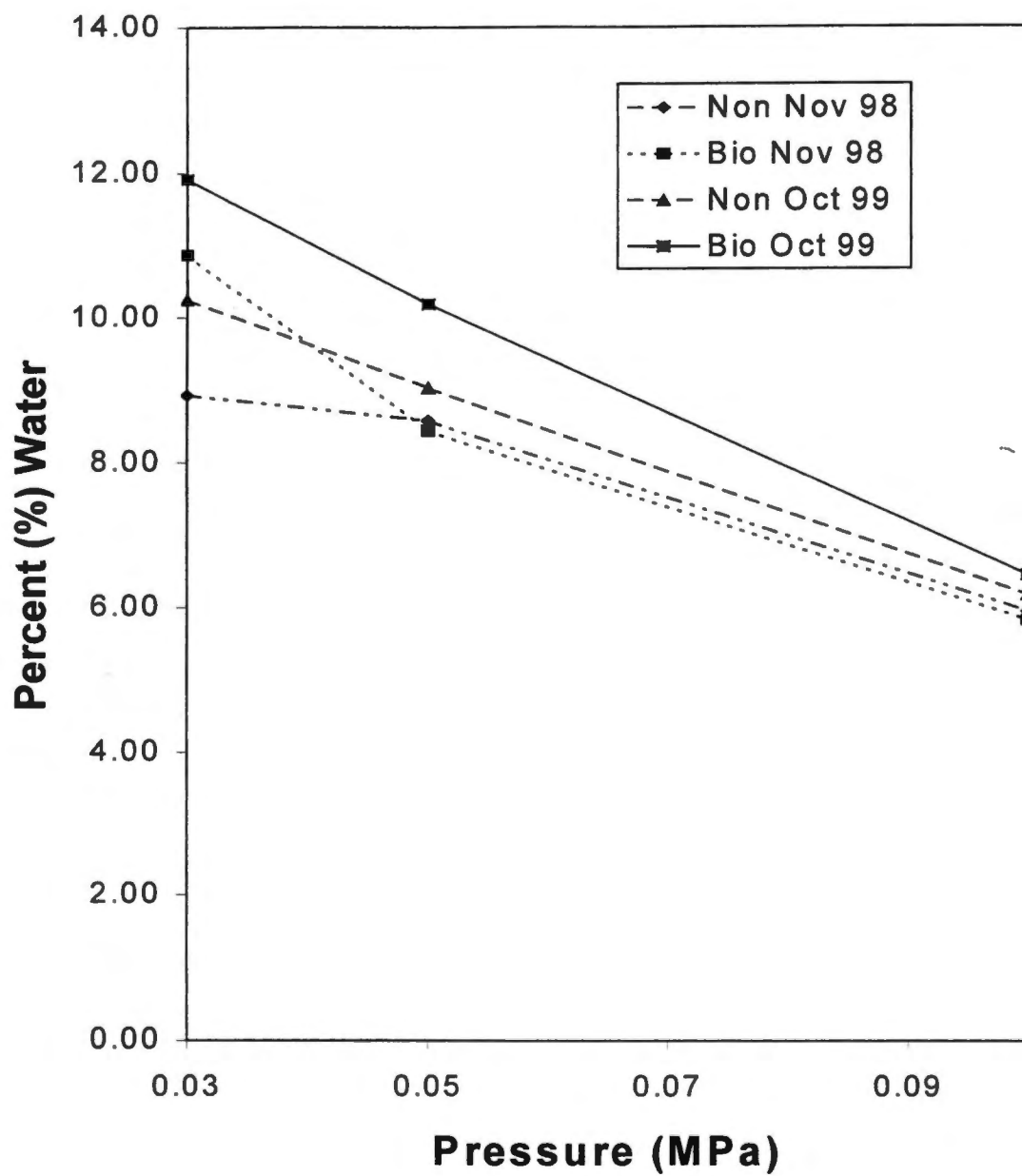


Figure 3.5. Moisture retention for nonbiosolids and biosolids samples for the 2nd and 5th sampling dates (Nov 98 & Oct 99).

Table 3.8. ANOVA table for mean plant available (double-acid extractable) nutrients in tailings.

Source of Variation	Ca	Cu	Fe	K	Mg	Mn	Na	Zn
Biosolids (B)	NS	***	*	***	*	NS	***	NS
Sample Date (S)	***	***	**	***	***	***	***	***
B*S	NS	**	NS	**	**	NS	***	NS

*, **, *** Significant at $P=0.05$, 0.01 , 0.001 levels, respectively.
NS, Nonsignificant

biosolids plot and the biosolids plot decreased in comparing initial samples to final samples (Table 3.9). The increase in Ca during the Mar 99 (3rd) sampling date may have resulted from the amendment of lime (CaCO_3) after initial sampling. Calcium deficiencies do not generally occur in limed soils (Rowell, 1994).

Available K in undisturbed soils range from 150 to 200 mg kg^{-1} (Barber, 1962). Table 3.9 shows plant available K was present in adequate amounts as deficiencies are uncommon in copper mine tailings (Shetron, 1983). Plant available K increased over time with final samples in both the non-biosolids plot and the biosolids plot having significantly higher concentrations in final fertility samples compared to the initial sampling (Table 3.9). There were no differences in K concentrations between the non-biosolids plot and the biosolids plot in final fertility samples. Increases in K were most likely caused by the amendments of KCl to both plots after initial sampling (Table 3.9).

Plant available Mg concentrations were adequate for plant growth. The lowest mean concentration of available Mg was $> 350 \text{ mg kg}^{-1}$, well above undisturbed soil concentrations (Barber, 1962). In comparing final fertility samples to initial samples in the non-biosolids plot and the biosolids plot, concentrations of plant available Mg were not different (Table 3.9). Differences in Mg concentrations in the non-biosolids plot over time may have resulted from variation from sampling. Concentrations of Mg did not differ between the non-biosolids plot and the biosolids in final fertility samples (Table 3.9).

Table 3.9. Mean plant available (double-acid extractable) nutrients in tailings over time.

Sampling Date	Ca		Cu		Fe	
	Overall		Non-biosolids	Biosolids	Overall	
			mg kg ⁻¹			
Sep 98	16 205	a*	61.4	cd	191.0	d Non-biosolids [#]
Nov 98	14 201	c	67.4	bc	198.1	d 255.6 a
Mar 99	15 367	ab	76.6	b	221.8	c
Jun 99	14 856	bc	77.0	b	292.3	b Biosolids
Oct 99	14 082	c	122.8	a	366.4	a 252.3 a

Sampling Date	K		Mg		Mn	
	Non-biosolids	Biosolids	Non-biosolids	Biosolids	Overall	
			mg kg ⁻¹			
Sep 98	182.9	d	165.1	d	449.0	bc 631.0 c
Nov 98	177.6	d	109.0	e	370.7	e 520.4 e
Mar 99	187.2	d	172.6	d	425.9	cd 575.8 d
Jun 99	328.9	a	276.8	c	541.7	a 677.0 b
Oct 99	308.5	ab	293.2	bc	475.1	b 732.9 a

Sampling Date	Na		Zn	
	Non-biosolids	Biosolids	Overall	
			mg kg ⁻¹	
Sep 98	15.2	bc	14.5	bcd 191.0 d
Nov 98	16.2	ab	14.9	bcd 198.1 d
Mar 99	13.3	cd	15.5	b 221.8 c
Jun 99	17.9	a	13.1	d 292.3 b
Oct 99	13.3	cd	10.1	e 366.4 a

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

[#]Not affected by sampling date.

Excess concentrations of soluble salts are commonly present in many tailings material. The salt may consist largely of Na which may pose problems in reclamation of the tailings (Hossner and Hons, 1992). However, plant available Na remained low on both plots throughout the entire sampling period. In comparing initial fertility samples to final samples in the non-biosolids plot, plant available Na did not differ (Table 3.9). In the biosolids plot, Na was lower in final fertility samples compared to the previous four sampling dates. Final fertility samples revealed that Na was lower in the biosolids plot compared to the biosolids plot (Table 3.9).

Metal toxicities or imbalances are commonly found in mine waste or tailings due to the nature of the ore and/or milling processes (Hossner and Hons, 1992). The ore in which these tailings originated are from the Copperhill Formation, rich in sulfide deposits of Cu, Fe, and Zn (USGS, 1993). Studies by Oneil *et al.* (1998) revealed Cu concentrations in tailings material can reach as high as 470 mg kg⁻¹ although concentrations of Cu in the tailings associated with this project were below 130 mg kg⁻¹ (Table 3.9). Initial fertility samples showed significant differences in plant available Cu between the non-biosolids plot and the biosolids plot most likely due to variation in sampling. Comparing final fertility samples to initial samples, concentrations of Cu increased in both the non-biosolids plot and the biosolids plot with higher concentrations found in the non-biosolids plot (Table 3.9).

Plant available Zn was high in both the non-biosolids and the biosolids plot over time, most likely due to the nature of the ore (Table 3.9). While these values are higher than have been found in other tailings material (Shetron, 1983; Miles and Tainton, 1979), concentrations of Zn have been known to be as high as 755 mg kg⁻¹ (Oneill *et al.*, 1998). Plant available Zn was unaffected by the addition of biosolids, but mean concentrations over both the non-biosolids plot and the biosolids plot changed over time (Table 3.9). Concentrations of Zn increased over time, as final fertility samples were significantly higher in Zn than initial samples.

Although tailings generally contain high amounts of Fe and Mn (Hossner and Hons, 1993), plant available forms of Fe and Mn in these tailings were not present in concentrations that may limit vegetation (Table 3.9). Plant available Fe was significantly affected by sampling date and biosolids alone (Table 3.8). Combined mean Fe concentrations over both the non-biosolids plot and the biosolids increased over time (Table 3.9). There were no significant differences in plant available Fe caused by the application of biosolids. Similar results were found in plant available Mn as well. Combined mean plant available Mn concentrations fluctuated over time, most likely due to variation in sampling (Table 3.9).

Total N in the tailings material differed according to sample date and biosolids application (Table 3.10). Concentrations of N prior to soil amendments were low on both the non-biosolids and biosolids plots (Figure 3.6). Low N

Table 3.10. ANOVA table for mean total nitrogen in tailings.

Source of Variation	N
Biosolids (B)	NS
Sample Date (S)	***
B*S	**

*, **, *** Significant at $P=0.05$, 0.01, 0.001 levels, respectively.

NS, Nonsignificant

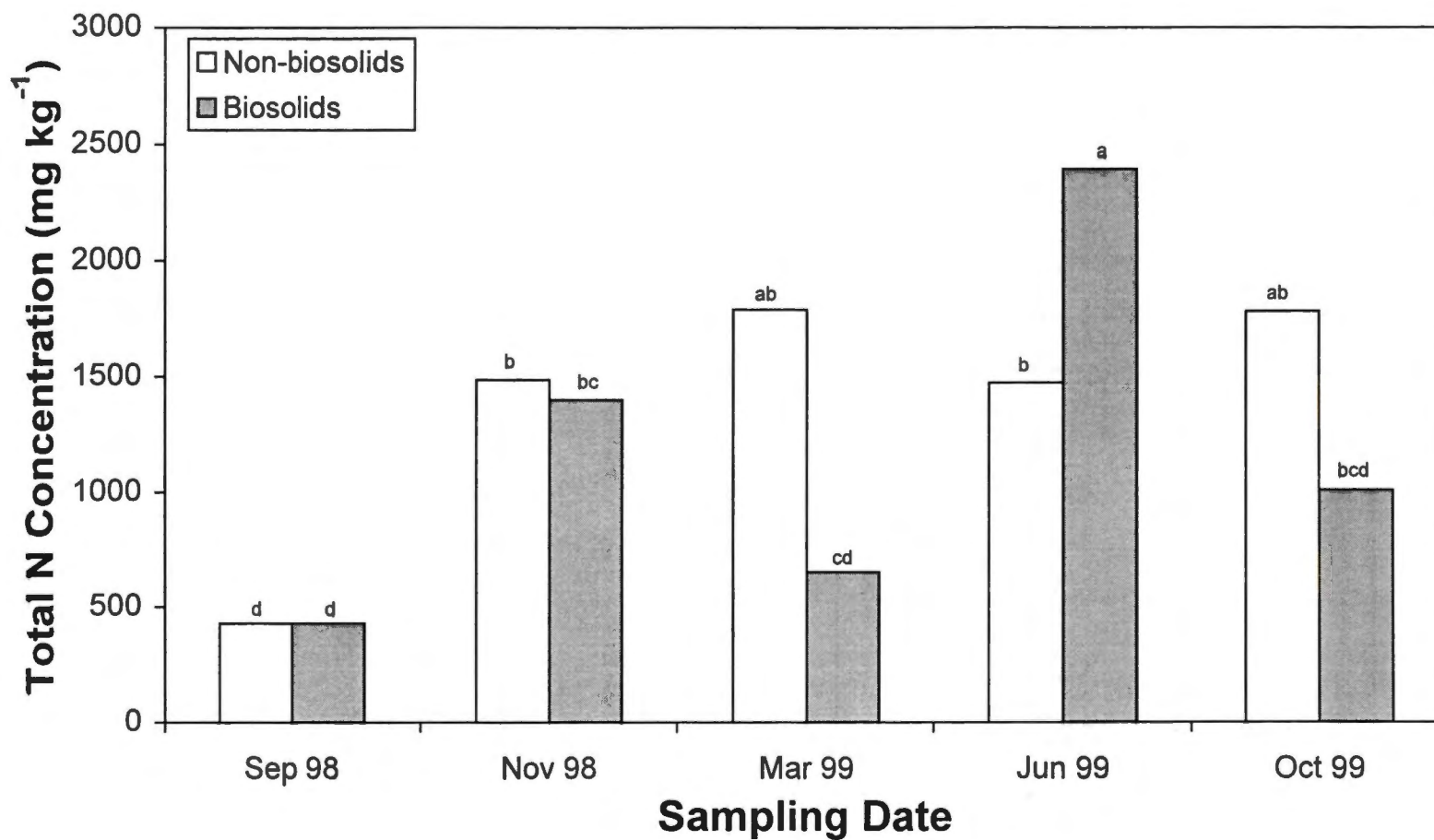


Figure 3.6. Mean total nitrogen concentrations in the non-biosolids and the biosolids plot over time. Means followed by the same letter are not significantly different according LSD (0.05).

concentrations are common in tailings material (Hossner and Hons, 1992; Shetron, 1983; Day and Ludeke, 1973). Samples from the Nov 98 (2nd) sampling period revealed an increase in total N concentrations in both non-biosolids and biosolids plots. This increase in N reflected results from the addition of N fertilizer (ammonium nitrate) after initial sampling. The Mar 99 (3rd) samples revealed differences in N between the non-biosolids plot and the biosolids plot as the non-biosolids plot had higher N concentrations. Legume populations were noticeably higher on the non-biosolids plot as compared to the biosolids plot, namely birdsfoot trefoil. Higher legume populations were able to fix more N₂, thus contributing to the addition of soil N. Although no data were taken, nodulation on legume roots on the non-biosolids plot were noticeably higher compared to legumes on the biosolids plot. When available N is sufficient in soil, nodulation and biological N₂ fixation may cease (Foth and Ellis, 1988; Vogel and Berg, 1968). This may explain the higher N rates on the non-biosolids during the Mar 99 fertility sampling.

Between the Mar 99 and Jun 99 (3rd and 4th) sampling periods, a second amendment of N was applied in the form of sulfur-coated urea. Results of this application were evident on Jun 99 (4th) fertility samples as non-biosolids plot N concentrations remained high and biosolids N concentrations increased (Figure 3.6). There were no differences in total N from the Jun 99 (4th) samples to the Oct 99 (5th) sampling period in the non-biosolids plot, but total N did decrease in the biosolids plot. This decrease may have been attributed to high uptake of N

from the grasses. There was noticeably a better establishment of grasses on the biosolids plot compared to the non-biosolids plot. When available N is plentiful, grasses tend to be highly competitive with legumes (Seaney, 1974). Total N did not significantly differ between the non-biosolids and the biosolids plot in final fertility samples. As vegetation continues to grow, plant residues will continuously supply organic matter, furthering N cycling (Foth and Ellis, 1988). Restoring and maintaining the N cycle will be beneficial in long-term management of vegetation on the tailings material.

As stated earlier, P was suspect of being the limiting nutrient preventing the establishment of vegetation on the mine tailings. In younger soils, limited amounts of available P can severely limit vegetative growth (Foth and Ellis, 1988). Phosphorus deficiencies have been found to be common in copper mine tailings (Coyne *et al.*, 1998; Hossner and Hons, 1992; Shetron, 1983; Day and Ludeke, 1973). The use of superphosphates is an excellent source of P when coupled with a management program that utilizes liming to maintain a soil pH above 6.0, including calcareous soils. When applied to calcareous soils, P may precipitate as calcium-phosphates secondary minerals and/or is adsorbed to Ca and clay minerals (Havlin *et al.*, 1999).

Concentrations of extractable P in the tailings material were significantly affected by interactions between phosphorus treatment by sample date and between biosolids application by sample date (Table 3.11). Initial extractable P were low on both plots with mean concentrations less than 1.0 mg kg⁻¹ (Figures

Table 3.11. ANOVA table for extractable (sodium-bicarbonate) phosphorus in tailings.

Source of Variation	P
Biosolids (B)	NS
Phosphorus Treatment (P)	***
B*P	NS
Sample Date (S)	***
B*S	*
P*S	***
B*P*S	NS

*, **, *** Significant at $P=0.05$, 0.01 , 0.001 levels, respectively.

NS, Nonsignificant

3.7 and 3.8). Concentrations of extractable P increased on both plots correlating to the levels of P treatments (Figure 3.7). Over time, extractable P did not differ between plots receiving 0 or 56 kg P ha⁻¹. By the final sampling date, P concentrations on these plots were similar to concentrations found in the initial samples. Concentrations of P were significantly higher on plots receiving 224 kg P ha⁻¹ compared to the other plots from the Mar 99 to Oct 99 (3rd to 5th) sampling dates (Figure 3.7). Figure 3.8 shows increases over all levels of P amendments in both the non-biosolids plot and the biosolids plot. Although vegetation on P control plots were noticeably higher on the biosolids plot compared to the non-biosolids plot, significant differences in extractable P were not evident until the Jun 99 (4th) sampling date (Figure 3.8). As biosolids decompose, P is mineralized thus supplying the soil with available P. Declines in extractable P in the non-biosolids plot and the biosolids plot were most likely due to plant uptake.

As P concentrations in soil solution are diminished by P removal, it is buffered by the release of adsorbed P (Kuo, 1996). Phosphorus that can quickly replenish depleted supplies by entering the soil solution in a matter of several days to a few weeks is known as labile P. Very sandy soils are able to hold only small quantities of P in the adsorbed form with weak bonds (Foth and Ellis, 1988). Over time as plant residues accumulate and supply organic matter to the soil, organic P will also be supplied. As the organic matter decomposes, organic P will mineralize thus restoring available P.

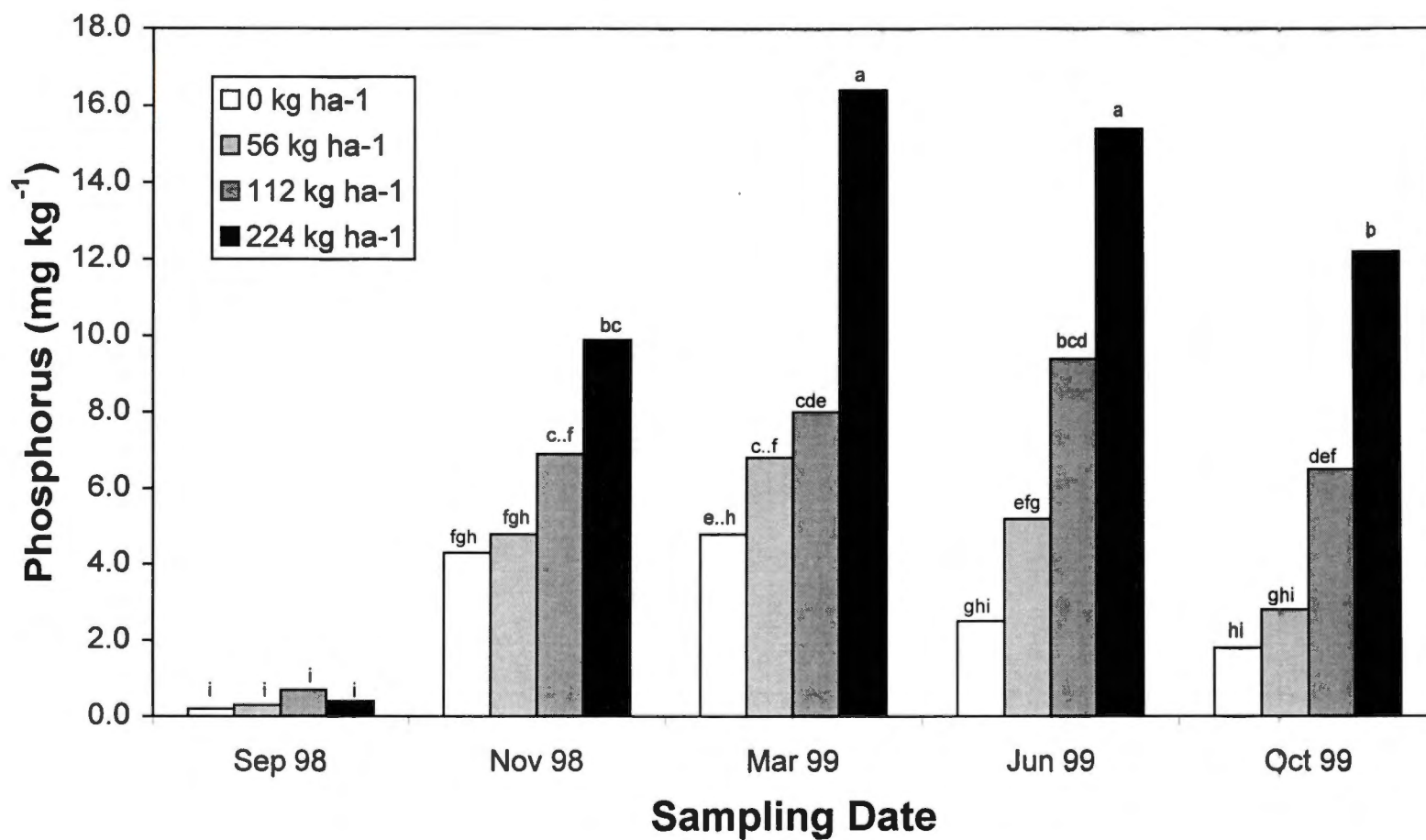


Figure 3.7. Mean extractable (sodium-bicarbonate) phosphorus affected by phosphorus applications over time. Means followed by the same letter are not significantly different according to LSD (0.05).

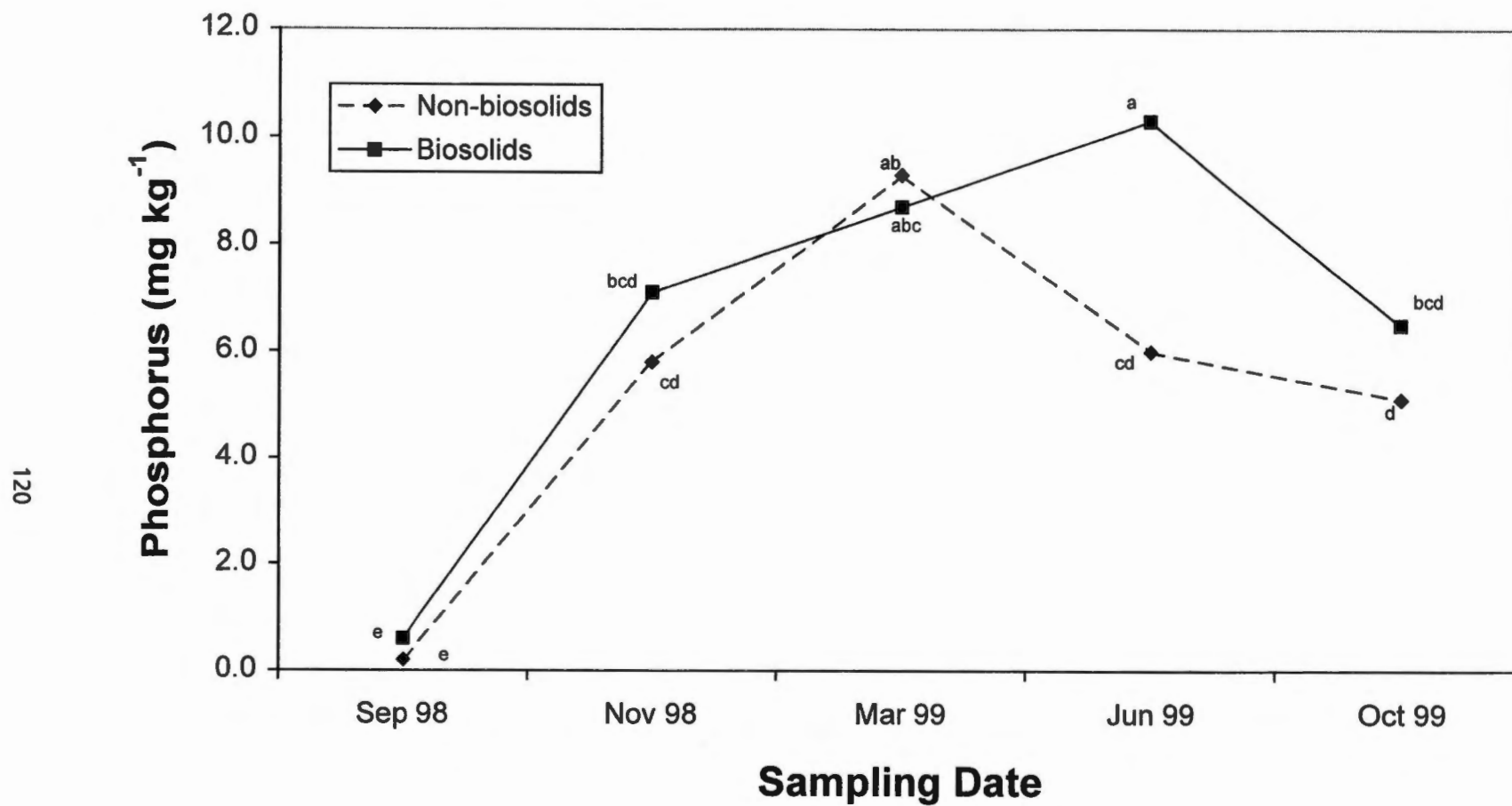


Figure 3.8. Mean extractable (sodium-bicarbonate) phosphorus affected by the application of biosolids over time. Means followed by the same letter are not significantly different according to LSD (0.05).

Additional problems preventing the establishment of vegetation include high surface temperatures. Although no statistical analyses on temperate data were performed, daily summer (Jun through Aug) high temperatures at a depth of 7 cm (2.8 in) were noticeably cooler (nearly 10°C) on plots that had established cover (sod) compared to bare tailings (Figure 3.9). Similar results were found by Shetron (1983), as surface temperatures on bare copper mine tailings in Michigan were as high as 20°C warmer during the summer months. In the winter months, plots with established vegetation were able to retain more heat, as winter lows on vegetated tailings were slightly warmer compared to bare tailings (Figure 3.9). At a depth of 15 cm (5.9 in), results were similar with less pronounced extremes (Figure 3.10).

Vegetative Responses

Scattered vegetation, mainly grasses, began appearing on both plots one month after initial seeding. Grasses offer effective initial ground cover to copper mine tailings material (LeRoy and Keller, 1972) and help protect legumes against erosion (Roberts *et al.*, 1988). Vegetation on the non-biosolids plot was sparser compared to the biosolids plot. Field observations in Nov 98 began to show definite boundaries outlining P control plots with very little or no vegetation on both non-biosolids and biosolids plots. Winter wheat began to appear on both plots resulting from seed contamination from the straw. Tall fescue populations were low on both the non-biosolids plot and the biosolids plot. Birdsfoot trefoil appeared to be doing better than the other legumes.

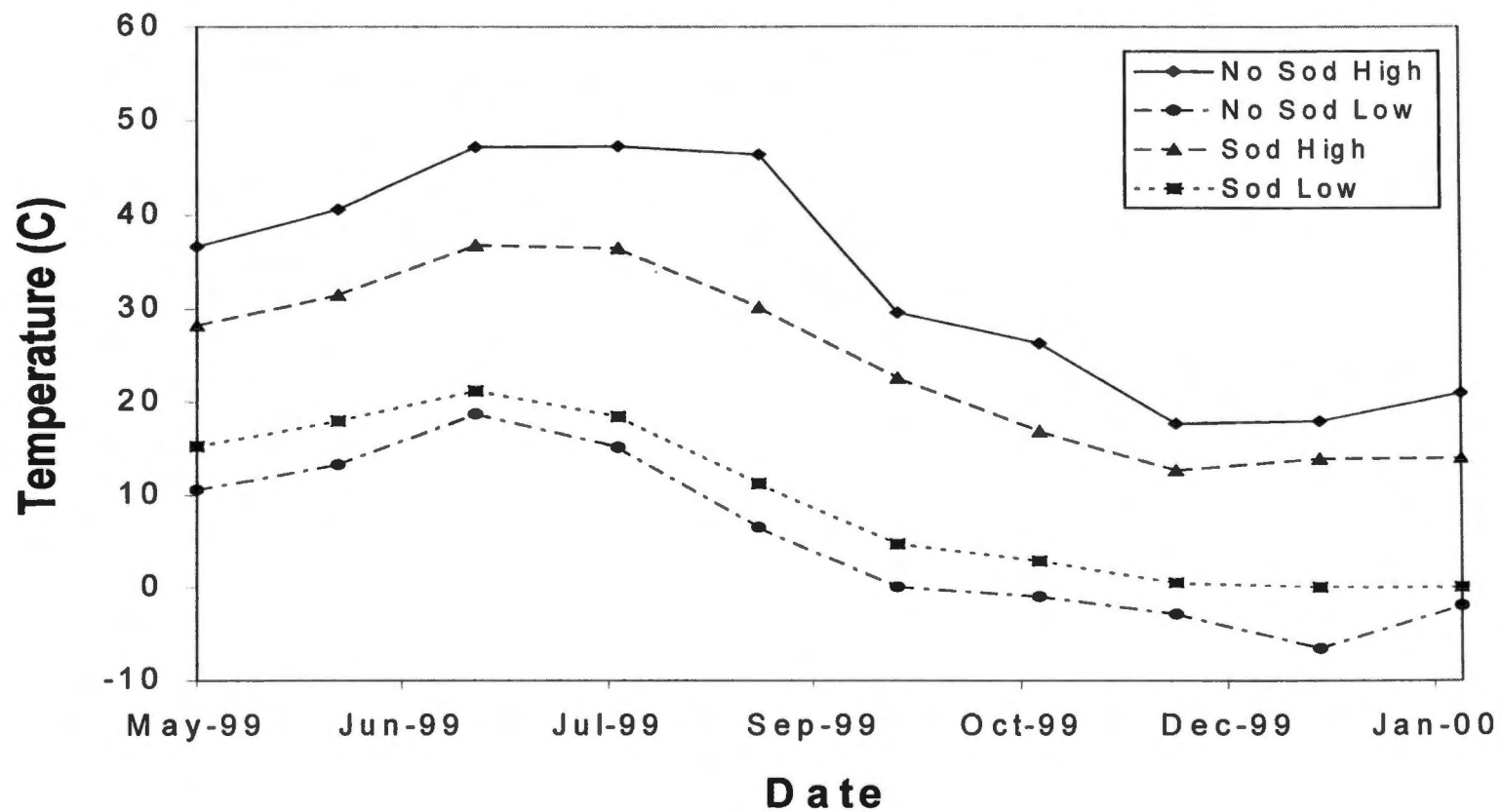


Figure 3.9. High and low temperatures for cover (Sod) and no cover (No Sod) at a depth of 7 cm.

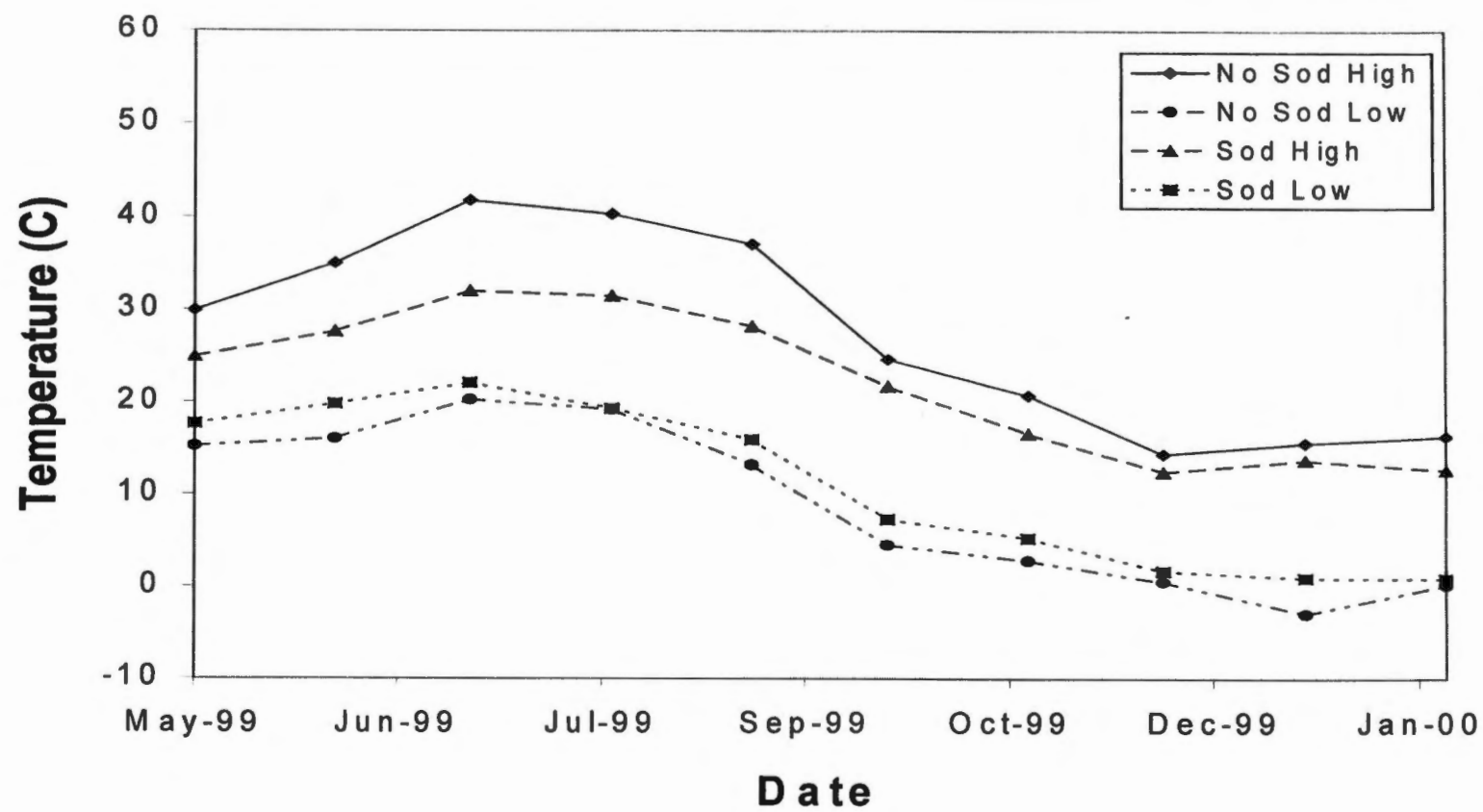


Figure 3.10. High and low temperatures for cover (Sod) and no cover (No Sod) at a depth of 15 cm.

Previous studies have indicated that biosolids provide equal or better long-term benefits compared to traditional fertilizers (Vogel, 1981; Wolt, 1985). Field observations in Mar 99 revealed that vegetation on the biosolids plot was much greener and dense compared to vegetation on the non-biosolids plot. Although not measured, the biosolids may also have provided more available N to the vegetation as it continued to decompose. Biosolids act similarly to slow release fertilizers with approximately 15% of the nutrients released the first year, 15% the second, 10% the third, and 5% the fourth and fifth years (Barnhisel and Hower, 1997). The application of biosolids increases soil organic matter and moisture holding capacity (Henry and Brown, 1992). The greener color seen in the vegetation on the biosolids plot may have also been caused by increased water holding capacity, as vegetation on the non-biosolids plot appeared very dry.

During the Mar 99 visit, vegetation on the P control, 56 kg P ha⁻¹, and 112 kg P ha⁻¹ had noticeable purpling on the leaves, characteristic of P deficiencies. Additionally, sporadic vegetation on both plots showed yellowing of the leaves in older tissue, indicating a deficiency in N. Tall fescue populations were noticeably higher during the Mar 99 count as compared to the initial plant count. Figure 3.11 shows differences between the non-biosolids plot and the biosolids plot. Phosphorus control sections on both plots still had very little or no vegetation. The biosolids plot had thicker cover with most of the vegetation as winter wheat and tall fescue. Legume establishment was still noticeably low on both the non-

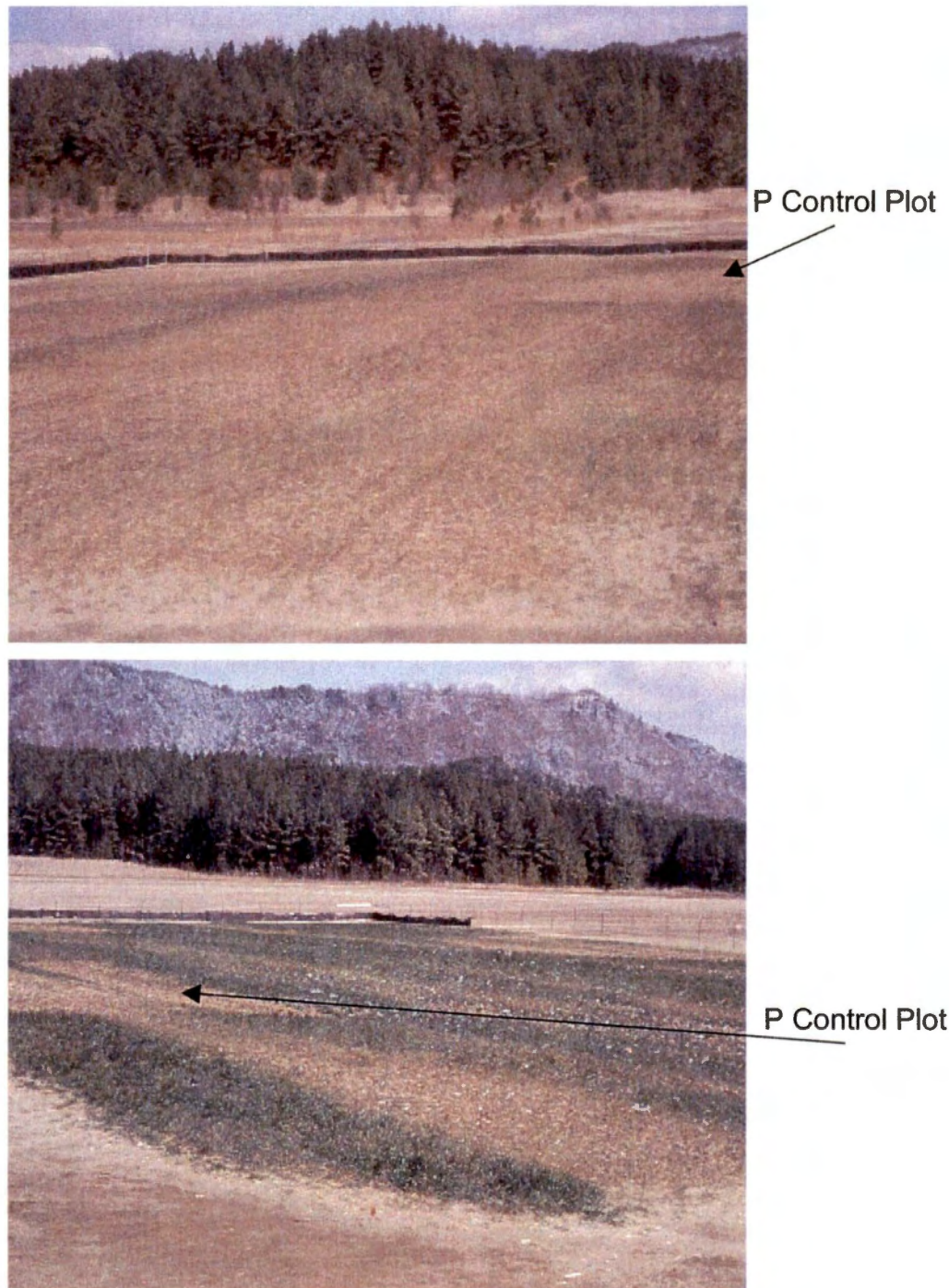


Figure 3.11. Picture showing P control plots on non-biosolids (top) and biosolids (bottom) plots during the March 99 (3rd) monitoring visit.

biosolids and biosolid plot. Field observations revealed that kobe lespedeza and birdsfoot trefoil counts were a little higher than sericea and Korean lespedeza.

By Jun 99, winter wheat populations decreased as ryegrass (*Lolium* sp.), an invasive species, began to appear in thicker stands. The establishment of ryegrass may have come from the straw applied during pretreatments. Tall fescue populations continued to respond well. As birdsfoot trefoil populations noticeably decreased, kobe and Korean lespedeza continued to grow well on both plots, with slightly higher populations on the non-biosolids plot. Growth of annual lespedezas usually increases during summer months, if soil moisture is adequate (Offutt *et al.*, 1974). Competition from grasses was noticeable higher on the biosolids plot. Grasses have an inherent capability of absorbing more available N than legumes in similar conditions (Munoz and Weaver, 1999). Available N supplied by the biosolids most likely stimulated the higher growth of grasses.

Field observations for Oct 99 revealed that both kobe and Korean lespedeza continued to give favorable results compared to birdsfoot trefoil and sericea lespedeza. Ryegrass, winter wheat, and tall fescue continued to make up the majority of the vegetation on both plots. Vegetation on some plots on the non-biosolids plot was noticeably higher with kobe and Korean lespedeza. Around the edges of both the non-biosolids plot and the biosolids plot, the establishment of vegetation aided in the decrease of the erosion of tailings

material while P control plots having little or no vegetation still had erosion problems.

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 cocklebur (*Xanthium pensylvanicum*), and ryegrass (*Lolium* sp.).

Statistical Analysis of Vegetation

Statistical analysis were performed on the plant counts, vegetative cover estimates, and biomass weights. Plant counts were separated into two groups, total plant counts and legume counts. Total plant counts included grasses, legumes, and other invading species. Legume counts included only legumes and omitted grasses and other invading species.

Phosphorus treatments significantly affected total plant counts for the Nov 98, Mar 99, and Oct 99 (1st, 2nd, and 4th) plant counts (Table 3.12). This was evident in field observations as plots receiving P treatments had noticeably more vegetation growing on them. During the Nov 98 (1st) plant counts, there were significant differences between P control plots and plots receiving 56 kg P ha⁻¹ applications (Table 3.13). Most of this vegetation was comprised of winter wheat and tall fescue with some legumes.

In the Mar 99 (2nd) plant counts, there were significant differences in total plant counts between the control plots and plots receiving P applications (Table

Table 3.12. ANOVA table for total plant counts per sampling period.

Source of Variation	Nov 98	Mar 99	Jun 99	Oct 99
Plant Mix (M)	NS	NS	NS	NS
Biosolids (B)	NS	NS	NS	NS
B*M	NS	NS	NS	NS
P Treatment (P)	*	***	NS	***
M*P	NS	NS	NS	NS
B*P	NS	NS	NS	NS
B*M*P	NS	NS	NS	NS

*, **, *** Significant at $P=0.05$, 0.01 , 0.001 levels, respectively.

NS, Nonsignificant

Table 3.13. Mean plant counts affected by phosphorus treatments for Nov 98.

Phosphorus Treatment	Plant Counts (0.09 m ²)
0 kg P ha ⁻¹	6.9 b*
56 kg P ha ⁻¹	10.2 a
112 kg P ha ⁻¹	9.0 ab
224 kg P ha ⁻¹	8.8 ab

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

3.14). However, there were no significant differences within P applications. Plant counts decreased from the Nov 98 (1st) to Mar 99 (2nd) monitoring visits. This may have been caused by the droughty conditions in the region between these two sampling dates. Due to noticeably low success rates in all legumes on the non-biosolids and biosolids plots, both grass/legume seeding and N application were repeated after the Mar 99 monitoring samples were taken. Although cover estimates were not completed until Jun 99, vegetation was noticeably thicker on both plots in Mar 99 compared to Nov 98.

By the Oct 99 (4th) plant counts, average counts decreased again (Table 3.15). However, these decreases in plant counts were offset by an increase in vegetative cover. While some plots had plant counts that were lower than others, vegetative cover was higher. Significant differences still existed between the P control plots and P applications.

Legume counts were significantly affected by P treatments in the Nov 98 (1st) plant counts (Table 3.16). Mar 99 (2nd) legume counts were significantly affected by plant mix while both plant mix and biosolids by phosphorus treatment affected the Jun 99 (3rd) plant counts. There were no significant effects on the Oct 99 (4th) legume counts.

The Nov 98 (1st) legume counts revealed a significant difference between the P control plots and the 56 and 112 kg P ha⁻¹ application plots (Table 3.17). There were no significant differences between the 224 kg P ha⁻¹ plot and the control, 56 or 112 kg P ha⁻¹ application plots. According to field observations,

Table 3.14. Mean plant counts affected by phosphorus treatments for Mar 99.

Phosphorus Treatment	Plant Counts (0.09 m ²)
0 kg P ha ⁻¹	3.1 b*
56 kg P ha ⁻¹	6.1 a
112 kg P ha ⁻¹	5.8 a
224 kg P ha ⁻¹	5.7 a

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

Table 3.15. Mean plant counts affected by phosphorus treatments for Oct 99.

Phosphorus Treatment	Plant Counts (0.09 m ²)
0 kg P ha ⁻¹	2.4 b*
56 kg P ha ⁻¹	4.1 a
112 kg P ha ⁻¹	4.4 a
224 kg P ha ⁻¹	4.4 a

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

Table 3.16. ANOVA table for legume counts per sampling period.

Source of Variation	Nov 98	Mar 99	Jun 99	Oct 99
Plant Mix (M)	NS	*	*	NS
Biosolids (B)	NS	NS	NS	NS
B*M	NS	NS	NS	NS
P Treatment (P)	*	NS	NS	NS
M*P	NS	NS	NS	NS
B*P	NS	NS	*	NS
B*M*P	NS	NS	NS	NS

*, **, *** Significant at $P=0.05$, 0.01, 0.001 levels, respectively.

NS, Nonsignificant

Table 3.17. Mean legume counts affected by phosphorus treatments for Nov 98.

Phosphorus Treatment	Legume Counts (0.09 m ²)
0 kg P ha ⁻¹	9.2 b*
56 kg P ha ⁻¹	14.6 a
112 kg P ha ⁻¹	13.6 a
224 kg P ha ⁻¹	12.1 ab

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

kobe lespedeza populations were higher than other legumes during the Nov 98 (1st) legume counts.

The Mar 99 (2nd) legume counts revealed significant differences between birdsfoot trefoil and the lespedezas with threefold increases in birdsfoot counts compared to other legumes (Table 3.18). This corresponded to visual observations as birdsfoot trefoil populations were noticeably higher on both the non-biosolids and biosolids plots during visits to the tailings pond in late winter.

By the Jun 99 (3rd) legume counts, Korean lespedeza counts were significantly higher than birdsfoot trefoil and sericea lespedeza while there were no significant differences between kobe lespedeza, sericea lespedeza, and birdsfoot trefoil (Table 3.19). The decline in birdsfoot trefoil success was most likely due to the warmer summer temperatures.

Legume counts affected by P treatment and biosolids applications corresponded to field observations. On the non-biosolids plot, legume counts were lower on the plot receiving the 224 kg P ha⁻¹ application (Table 3.20). However, there were no significant differences between the control, 56, or 112 kg P ha⁻¹ applications on the non-biosolids plot. On the biosolids plot, there were no significant differences in legume counts over all P applications (Table 3.20). Legume counts on the P control plots were higher on the non-biosolids plot as compared to the biosolids plot. However, with the application of P, there were no significant differences in legume populations between the non-biosolids and biosolids plot (Table 3.20).

Table 3.18. Mean legume counts affected by plant mix for Mar 99.

Plant Mix	Legume Counts (0.09m ²)
Birdsfoot trefoil/Tall fescue	3.8 a*
Sericea lespedeza/Tall fescue	0.4 b
Kobe lespedeza/Tall fescue	0.6 b
Korean lespedeza/Tall fescue	0.2 b

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

Table 3.19. Mean legume counts affected by plant mix for Jun 99.

Plant Mix	Legume Counts (0.09 m ²)
Birdsfoot trefoil/Tall fescue	5.5 b*
Sericea lespedeza/Tall fescue	3.8 b
Kobe lespedeza/Tall fescue	12.4 ab
Korean lespedeza/Tall fescue	15.9 a

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

Table 3.20. Mean legume counts affected by biosolids application and phosphorus treatments for Jun 99.

Biosolids Application	Phosphorus Treatment	Legume Counts (0.09 m ²)
Non-biosolids	0 kg P ha ⁻¹	14.0 a*
	56 kg P ha ⁻¹	11.3 ab
	112 kg P ha ⁻¹	11.1 ab
	224 kg P ha ⁻¹	5.0 c
Biosolids	0 kg P ha ⁻¹	8.0 bc
	56 kg P ha ⁻¹	8.9 abc
	112 kg P ha ⁻¹	7.0 bc
	224 kg P ha ⁻¹	10.0 abc

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

As stated earlier, some plots may have lower plant counts but higher vegetative cover compared to other plots. Therefore, percent cover estimates were completed during the Jun 99 and Oct 99 (3rd and 4th) plant counts. Vegetative cover was significantly affected by P treatment during the Jun 99 (3rd) plant counts and by P treatment and biosolids application by P treatment during the Oct 99 (4th) plant counts (Table 3.21).

The Jun 99 (3rd) vegetative cover estimates were significantly higher on plots receiving 112 and 224 kg P ha⁻¹ applications as compared to P control plots by almost twofold (Table 3.22). On the biosolids plot, most of the vegetation was noticeably ryegrass and fescue. Similar results were also found on the Oct 99 (4th) cover estimates, as plots receiving P applications were higher than P control plots with the 112 kg P ha⁻¹ application having the highest cover (Table 3.23). This helps support the theory that the tailings material was deficient in P as percent cover was increased with the application of P.

Cover estimates for Oct 99 (4th) were significantly affected by both biosolids application and P treatments (Table 3.24). On the non-biosolids plot, there were no significant differences in percent cover over all levels of P application (Table 3.24). On the biosolids plot, only the plot receiving the 112 kg P ha⁻¹ application had significantly higher vegetative cover compared to all levels of P application on the non-biosolids plot with estimates being almost twofold.

Vegetation clippings were taken during the final (4th) plant counts. Biomass weights were significantly affected by biosolids application alone (Table

Table 3.21. ANOVA table for percent vegetative cover estimates per sampling period.

Source of Variation	Jun 99	Oct 99
Plant Mix (M)	NS	NS
Biosolids (B)	NS	NS
B*M	NS	NS
P Treatment (P)	***	***
M*P	NS	NS
B*P	NS	***
B*M*P	NS	NS

*, **, *** Significant at $P=0.05$, 0.01, 0.001 levels, respectively.
 NS, Nonsignificant

Table 3.22. Mean percent vegetative cover estimates affected by phosphorus treatments for Jun 99.

Phosphorus Treatment	Vegetative Cover (%)
0 kg P ha ⁻¹	24.5 c*
56 kg P ha ⁻¹	35.3 b
112 kg P ha ⁻¹	48.2 a
224 kg P ha ⁻¹	44.1 a

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

Table 3.23. Mean percent vegetative cover estimates affected by phosphorus treatments for Oct 99.

Phosphorus Treatment	Vegetative Cover (%)
0 kg P ha ⁻¹	29.5 b*
56 kg P ha ⁻¹	40.7 a
112 kg P ha ⁻¹	47.4 a
224 kg P ha ⁻¹	45.2 a

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

Table 3.24. 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

NS, Nonsignificant

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

3.25). When biosolids were applied to the tailings, biomass weights increased threefold (Table 3.26).

Revegetation Recommendation

Using the data contained in the research report, a revegetation plan was devised for the copper mine tailings. Prior to soil amendments, chemical and physical characteristics were relatively uniform throughout the two one-acre test plots. As these research plots were only a small representation of the entire tailings area, variation in characteristics, such as soil pH and plant nutrients may 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, the 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 was applied to both plots, it is not possible to determine if N was also a limiting nutrient. Therefore, with the application of biosolids, the addition of mineral N may not be necessary. Although tailings within the two fertility plots contained sufficient amounts of K, K should still be added at a rate of 56 kg K ha^{-1} to 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.

Table 3.25. ANOVA table for plant biomass weight per sampling period.

Source of Variation	Oct 99
Plant Mix (M)	NS
Biosolids (B)	***
B*M	NS
P Treatment (P)	NS
M*P	NS
B*P	NS
B*M*P	NS

*, **, *** Significant at $P=0.05$, 0.01 , 0.001 levels, respectively.

NS, Nonsignificant

Table 3.26. Mean biomass weights affected by biosolids application for Oct 99.

Biosolids Application	Weights (g m ⁻²)
Non-biosolids	17.0 b*
Biosolids	67.8 a

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

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 P deficient mine tailings, revegetation projects have been successful (Hossner and Hons, 1992; Gemmell, 1977; Ludeke *et al.*, 1974). During the Mar 99 and Oct 99 (3rd and 4th) plant counts were significantly higher when amended with phosphorus (Tables 3.14 and 3.15). 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). Similar results were observed as legume populations during the Nov 98 (1st) visit were higher on plots receiving 56 and 112 kg P ha⁻¹ applications (Table 3.17). Additionally, percent vegetative cover was higher during the Jun 99 (3rd) visit on plots receiving the 112 and 224 kg P ha⁻¹ applications and higher during the Oct 99 (4th) visit within all 3 levels of P treatments (Tables 3.22 and 3.23).

The application of biosolids to the tailings material yielded positive results. While legume populations did not differ in comparing the non-biosolids plot and the biosolids plot during the Jun 99 (3rd) counts, the addition of biosolids and the amendment of 112 kg P ha⁻¹ did increase vegetative cover estimates during the Oct 99 (4th) visit (Table 3.24). Other studies on minesoils have also shown that vegetative cover is increased with the amendment of biosolids alone (Pichtel *et al.*, 1994; Sopper, 1992; Joost *et al.*, 1987) and the combined amendments of biosolids and P (Walker *et al.*, 1996). Biomass samples taken during the final

visit were higher on the biosolids plot correlating to the noticeably higher establishment of grasses.

Significant effects from grass/legume mixes were only found during the Mar and Jun 99 (2nd and 3rd) visits. In Mar 99 (2nd counts), birdsfoot trefoil populations were than the other 3 legumes (Table 3.18). However, as warmer months approached, kobe and Korean lespedeza counts were higher (Table 3.19). While there were no differences in kobe and Korean lespedeza populations, Korean lespedeza was higher than both birdsfoot trefoil and sericea lespedeza. Temperatures may have been too warm for the establishment of birdsfoot but it is unknown why sericea did poorly. 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).

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.

Once these amendments are applied, 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 pond may be used for recreational purposes such as golf courses or ball fields, or lay dormant for wildlife habitat.

Conclusions

1. Both plots had minute amounts pyritic sulfur ($<0.1\%$) and high amounts of CaCO_3 resulting in an excess of neutralizing bases. Paste pH on both the non-biosolids and biosolids plot ranged from 6.0 to 6.7 prior to soil amendments. Paste pH increased over time to a high of 7.4 on both plots with average values higher on the biosolids plot.
2. Exchangeable Al and total acidity were low in both plots correlating to the high paste pH.
3. Exchangeable Ca was high due to the presents of free carbonates contained in the tailings material from the milling process. Cation exchange capacity was low on both plots with values reaching a high of only $2.61 \text{ cmol kg}^{-1}$. This resulted in a high base saturation on both plots ($> 100\%$).
4. Most of the C contained in the tailings material was bound as CaCO_3 . Total C in the non-biosolids plot remained unchanged while total C increased over time with the addition of biosolids. Final fertility samples revealed that organic C remained unchanged while the biosolids plot had increases in organic C, again correlating to the addition of biosolids.

5. Although not statistically different, moisture retention averages were noticeably higher during final fertility samples on plots receiving biosolids application. This was also observed in field observations as the vegetation on the non-biosolids plot appeared drier compared to vegetation on the biosolids plot.
6. Plant available Ca was high on 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 while Na was low. While plant available Cu was found to be low, Zn concentrations were relatively high, most likely due to the nature of the ore.
7. Total N concentrations were low on initial samples on both plots. Increases in N on both research plots in Nov 98 and Jun 99 (2nd and 4th) fertility attributed to N fertilizer applications. Samples from the Oct 99 (5th) sampling period revealed a decrease in total N on the biosolids plot. This may have resulted from the increased uptake of N by grasses, which were better established on the biosolids plot. There were no significant differences in total N between the non-biosolids plot and the biosolids plot in final fertility samples.
8. Phosphorus appeared to be a limiting nutrient in the tailings material. Phosphorus control plots had very little or no vegetation growing on them. Concentrations of available P increased corresponding to P treatments. Over time, P concentrations were higher on the biosolids plot due to the

slow release of P as organic matter continued to decompose. Phosphorus applications significantly increased total plant counts, legume counts, and vegetative cover estimates. For successful revegetation on the mine tailings, P should be applied at a rate of 112 kg P ha⁻¹ (10 lb P acre⁻¹).

9. The biosolids applied on the tailings material did not contain heavy metals in amounts that may limit vegetative growth. While legume populations were not significantly affected by the application of biosolids, percent vegetative cover (when coupled with the effects of P) and biomass weights were higher. Therefore, biosolids should be applied for successful revegetation of the mine tailings.
10. Legume counts revealed that Korean and kobe lespedeza had higher success rates compared to sericea lespedeza and birdsfoot trefoil. Korean and/or kobe lespedeza should be used in the seeding mix of grass/legumes for the successful establishment of vegetation on the mine tailings.

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APPENDICES

Appendix A. Abbreviations for Soil Morphology

Appendix A: Definitions of Abbreviations used in Soil Morphology

I. Soil Texture

COS	Course sand
FS	Fine sand
LS	Loamy sand
MS	Medium sand
S	Sand
VCOS	Very course sand
VFS	Very fine sand

II. Soil Structure

SLS SG	Structureless single grain
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III. Boundary

C	Clear
---	-------

IV. Consistency

L	Loose
---	-------

Appendix B. Morphology and Laboratory Data for Site 1

Soil Profile Description for Site 1

Landscape position: flood plain

Slope: 4%

Parent material: mine tailings pond

Vegetation: none

Drainage: somewhat excessively drained

Classification: mixed, mesic Typic Udipsamment

- C1 - 0 to 30 cm; dark grayish brown (2.5Y 4/2) sand; structureless single grain; loose; clear boundary.
- C2 - 30 to 50 cm; dark yellowish brown (10YR 4/4) sand; structureless single grain; loose; clear boundary.
- C3 - 50 to 70 cm; dark yellowish brown (10YR 4/6) sand; structureless single grain; loose; clear boundary.
- C4 - 70 to 90 cm; yellowish red (5YR 4/6) loamy sand; structureless single grain; loose; clear boundary.

Sampling depth, pH, organic mater, organic carbon, and total carbon for Site 1.

Sample #	Horizon	Depth (cm)	pH (1:1 H ₂ O)	pH (1:2 CaCl ₂)	O.M. (Walkley-Black)	O.C. (Walkley-Black)	Total Carbon
						%	
9817	C1	0 – 30	7.2	7.3	0.25	0.15	1.71
9818	C2	30 – 50	7.4	7.4	0.19	0.11	2.19
9819	C3	50 – 70	7.4	7.3	0.54	0.31	1.43
9820	C4	70 - 90	7.6	7.4	0.09	0.05	1.26

Particle size distribution for Site 1.

Horizon	Depth (cm)	-----Size Class and Particle Diameter (microns)-----							
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50	SAND 2000 - 50	SILT 50 - 2	CLAY < 2
C1	0 - 30	0	10	19	43	16	88	11	1
C2	30 - 50	0	15	15	43	14	87	12	1
C3	50 - 70	3	24	14	38	10	88	12	0
C4	70 -90	0	17	17	40	13	85	13	2

Cation exchange capacity (pH 7), ammonium acetate extractable bases, potassium chloride extractable aluminum and acidity, base saturation, citrate-dithionite extractable iron, and hydroxylamine manganese for Site 1.

Horizon	CEC (NH ₄ OAc)	Ca	Exchangeable Bases Mg	Na	K	(KCl) Al	Total Acidity (KCl)	Base Saturation (NH ₄ OAc) pH 7	Free Iron	Manganese
			cmol kg ⁻¹					%		mg kg ⁻¹
C1	.92	22.25	1.50	.04	0.00	0.01	0.20	> 100	1.76	825
C2	.65	59.92	11.60	.03	0.00	0.00	0.08	> 100	2.26	1040
C3	.80	67.52	5.86	.02	0.00	0.00	0.04	> 100	4.42	704
C4	.65	87.85	15.54	.04	0.00	0.00	0.04	> 100	2.63	715

Sulfur fractionation analyzed by an independent laboratory for Site 1.

Horizon	Depth (cm)	Total Sulfur	Pyritic Sulfur	Sulfate Sulfur	Organic Sulfur
		-----	-----	-----	-----
C1	0 – 30	1.79	-.189	1.54	.439
C2	30 – 50	8.22	-.070	6.57	1.72
C3	50 – 70	1.94	-.047	1.81	.177
C4	70 – 90	2.76	.099	2.42	.241

Acid-base account data analyzed by an independent laboratory for Site 1. **Calculated from total sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃	Neutralization Potential Equivalent Tons	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 30	4	2.5Y 6/2	1.79	55.94	219.47		163.53	7.5
C2	30 – 50	4	10YR 4/4	8.22	256.88	211.79	45.09		5.9
C3	50 – 70	4	10YR 6/3	1.94	60.63	166.34		105.71	7.3
C4	70 – 90	3	10YR 5/4	2.76	86.25	109.25		23.00	6.5

Acid-base account data analyzed by an independent laboratory for Site 1. **Calculated from pyritic sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃ Equivalent Tons	Neutralization Potential 1000 Tons ⁻¹	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 30	4	2.5Y 6/2	< .001	.03	219.47		219.44	7.5
C2	30 – 50	4	10YR 4/4	< .001	.03	211.79		211.76	5.9
C3	50 – 70	4	10YR 6/3	< .001	.03	166.34		166.31	7.3
C4	70 - 90	3	10YR 5/4	.099	3.09	109.25		106.16	6.5

Total elemental analysis of selected elements for Site 1.

Horizon	Depth (cm)	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	As	Mg	Mn
		-----mg kg ⁻¹ -----											
C1	0 – 30	24619	134	68429	3	21	21	898	65737	5922	70	41944	3973
C2	30 – 50	20356	108	79701	2	18	81	904	62001	5313	62	41870	4257
C3	50 – 70	23203	115	66203	3	25	113	967	70830	6206	60	34796	3643
C4	70 - 90	28257	129	56050	3	16	41	587	48458	7290	62	36045	3020

Total elemental analysis of selected elements for Site 1, continued.

Horizon	Depth (cm)	Mo	Na	Ni	P	Pb	S mg kg ⁻¹	Si	Sr	Ti	Zn	Zr
C1	0 – 30	7	8190	73	166	105	16540	28194	209	1361	1734	5
C2	30 – 50	6	5993	91	93	103	17011	31613	210	1092	1075	4
C3	50 – 70	6	6659	82	231	105	27454	22300	181	1279	2235	9
C4	70 - 90	6	9007	52	242	88	13089	35779	174	1475	1909	16

Appendix C. Morphology and Laboratory Data for Site 2

Soil Profile Description for Site 2

Landscape position: flood plain

Slope: 4%

Parent material: mine tailings pond

Vegetation: none

Drainage: somewhat excessively drained

Classification: mixed, mesic Typic Udipsamment

- C1 - 0 to 30 cm; dark grayish brown (10YR 4/2) sand; structureless single grain; loose; clear boundary.
- C2 - 30 to 55 cm; dark yellowish brown (10YR 4/4) sand; structureless single grain; loose; clear boundary.
- C3 - 55 to 100 cm; dark yellowish brown (10YR 4/6) sand; structureless single grain; loose; clear boundary.
- C4 - 100 to 125 cm; dark red (2.5YR 3/6) loamy sand; structureless single grain; loose; clear boundary.
- C5a - 125 to 150 cm; reddish black (2.5YR 2.5/0) sand; structureless single grain; loose; clear boundary.
- C5b - 125 to 150 cm; dark olive gray (5Y 3/2) sand; structureless single grain; loose; clear boundary.

Sampling depth, pH, organic mater, organic carbon, and total carbon for Site 2.

Sample #	Horizon	Depth (cm)	pH (1:1 H ₂ O)	pH (1:2 CaCl ₂)	O.M.	O.C.	Total Carbon
					(Walkley-Black)		
					-----%		
9821	C1	0 – 30	8.2	7.6	0.41	0.24	1.54
9822	C2	30 – 55	8.0	7.6	0.73	0.42	1.72
9823	C3	55 – 100	7.4	7.2	0.63	0.37	1.84
9824	C4	100 – 125	6.6	6.8	0.06	0.04	1.57
9825	C5	125 - 150	7.0	7.1	0.09	0.05	1.66

Particle size distribution for Site 2.

Horizon	Depth (cm)	-----Size Class and Particle Diameter (microns)-----							
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50	SAND 2000 - 50	SILT 50 - 2	CLAY < 2
C1	0 - 30	0	5	11	53	22	91	9	0
C2	30 - 55	0	13	21	43	14	92	8	0
C3	55 - 100	1	16	14	41	14	87	11	2
C4	100 - 125	0	7	13	42	18	81	12	7
C5	125 - 150	1	20	15	46	11	92	7	1

Cation exchange capacity (pH 7), ammonium acetate extractable bases, potassium chloride extractable aluminum and acidity, base saturation, citrate-dithionite extractable iron, and hydroxylamine manganese for Site 2.

Horizon	CEC (NH ₄ OAc)	Ca	Exchangeable Bases Mg	Na	K	(KCl) Al	Total Acidity (KCl)	Base Saturation (NH ₄ OAc) pH 7	Free Iron	Manganese
			cmol kg ⁻¹					%		mg kg ⁻¹
C1	0.77	12.31	1.81	0.03	0.00	0.00	0.04	> 100	1.21	979
C2	1.42	15.53	0.14	0.03	0.00	0.00	0.08	> 100	1.61	748
C3	0.72	73.32	0.08	0.05	0.01	0.00	0.08	> 100	2.85	913
C4	1.48	156.17	1.67	0.04	0.02	0.00	0.08	> 100	4.19	660
C5	0.72	48.18	3.07	0.03	0.02	0.00	0.08	> 100	0.97	809

Sulfur fractionation analyzed by an independent laboratory for Site 2.

Horizon	Depth (cm)	Total Sulfur	Pyritic Sulfur	Sulfate Sulfur	Organic Sulfur
			%		
C1	0 – 30	.944	.028	.584	.332
C2	30 – 55	2.85	-1.14	2.66	1.33
C3	55 – 100	8.26	0.00	5.90	2.36
C4	100 – 125	5.63	.330	4.18	1.12
C5a	125 – 150	3.26	-1.27	2.86	1.67
C5b	125 - 150	2.78	-1.16	2.51	1.43

Acid-base account data analyzed by an independent laboratory for Site 2. **Calculated from total sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃	Neutralization Potential Equivalent Tons	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 30	4	2.5Y 6/3	.944	29.50	174.02		144.52	7.9
C2	30 – 55	5	10YR 6/3	2.85	89.06	245.73		156.67	7.2
C3	55 – 100	5	10YR 5/4	8.26	258.13	323.45		65.33	6.7
C4	100 – 125	4	7.5YR 5/4	5.63	175.94	143.43	32.51		6.5
C5a	125 - 150	5	2.5Y 5/3	3.26	101.88	217.31		115.43	6.6
C5b	125 - 150	4	2.5Y 6/2	2.78	86.88	233.02		146.15	7.1

Acid-base account data analyzed by an independent laboratory for Site 2. **Calculated from pyritic sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃	Neutralization Potential Equivalent Tons	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 30	4	2.5Y 6/3	.028	.88	174.02		173.14	7.9
C2	30 – 55	5	10YR 6/3	< .001	.03	245.73		245.70	7.2
C3	55 – 100	5	10YR 5/4	< .001	.03	323.45		323.42	6.7
C4	100 – 125	4	7.5YR 5/4	.330	10.31	143.43		133.12	6.5
C5a	125 - 150	5	2.5Y 5/3	< .001	.03	217.31		217.28	6.6
C5b	125 - 150	4	2.5Y 6/2	< .001	.03	233.02		232.99	7.1

Total elemental analysis of selected elements for Site 2.

Horizon	Depth (cm)	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	As	Mg	Mn
		-----mg kg ⁻¹ -----											
C1	0 – 30	32206	118	64731	3	14	51	405	47132	7184	60	43799	3584
C2	30 – 55	22775	89	59918	3	17	122	678	55141	5406	60	37676	3450
C3	55 – 100	22011	98	72297	3	27	55	1033	92130	5480	62	35053	3732
C4	100 – 125	19227	107	76351	3	20	31	700	52209	5239	62	37176	3678
C5	125 - 150	25904	127	60722	3	20	51	871	55249	7079	62	36155	3516

Total elemental analysis of selected elements for Site 2, continued.

Horizon	Depth (cm)	Mo	Na	Ni	P	Pb	S mg kg ⁻¹	Si	Sr	Ti	Zn	Zr
C1	0 – 30	6	9693	48	312	80	6831	20307	224	1375	1407	4
C2	30 – 55	6	6950	78	289	85	11113	22604	192	1194	1458	6
C3	55 – 100	6	6811	79	237	104	32614	22175	217	1306	2979	4
C4	100 – 125	6	6034	35	355	96	25143	17120	167	1185	939	8
C5	125 – 150	6	8611	73	199	106	18248	32892	203	1354	2829	6

Appendix D. Morphology and Laboratory Data for Site 3

Soil Profile Description for Site 3

Landscape position: flood plain

Slope: 1.5%

Parent material: mine tailings pond

Vegetation: none

Drainage: well drained

Classification: mixed, mesic Typic Udipsamment

- C1 - 0 to 5 cm; reddish brown (2.5YR 4/4) loamy sand; structureless single grain; loose; clear boundary.
- C2 - 5 to 32 cm; yellowish red (5YR 4/6) loamy sand; structureless single grain; loose; clear boundary.
- C3 - 32 to 79 cm; light olive brown (2.5Y 5/6) loamy sand; structureless single grain; loose; clear boundary.
- C4 - 79 to 130 cm; olive (5Y 4/6) loamy sand; structureless single grain; loose; clear boundary.
- Cg - 130+ cm; dark greenish gray (5BG 4/1) sand; structureless single grain; loose; clear boundary.

Sampling depth, pH, organic mater, organic carbon, and total carbon for Site 3.

Sample #	Horizon	Depth (cm)	pH (1:1 H ₂ O)	pH (1:2 CaCl ₂)	O.M. (Walkley-Black)	O.C.	Total Carbon
					-----%		
9826	C1	0 – 5	7.8	7.5	1.89	1.10	1.74
9827	C2	5 – 32	7.0	7.1	0.35	0.20	1.52
9828	C3	32 – 79	7.6	7.4	0.19	0.11	1.05
9829	C4	79 – 130	7.4	7.4	0.32	0.18	1.02
9830	Cg	130+	7.4	7.1	0.19	0.11	1.30

Particle size distribution for site 3.

Horizon	Depth (cm)	Size Class and Particle Diameter (microns)							
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50	SAND 2000 - 50	SILT 50 - 2	CLAY < 2
C1	0 - 5	0	2	5	44	31	83	15	1
C2	5 - 32	0	6	7	49	20	82	15	3
C3	32 - 79	0	4	10	52	20	86	12	2
C4	79 - 130	0	3	6	56	21	86	13	1
Cg	130+	0	5	10	50	24	89	11	0

Cation exchange capacity (pH 7), ammonium acetate extractable bases, potassium chloride extractable aluminum and acidity, base saturation, citrate-dithionite extractable iron, and hydroxylamine manganese for Site 3.

Horizon	CEC (NH ₄ OAc)	Ca	Exchangeable Bases Mg	Na	K	(KCl) Al	Total Acidity (KCl)	Base Saturation (NH ₄ OAc) pH 7	Free Iron	Manganese
			cmol kg ⁻¹					%		mg kg ⁻¹
C1	2.03	16.19	0.73	0.02	0.00	0.00	0.08	> 100	2.69	1095
C2	1.68	160.21	1.16	0.06	0.00	0.00	0.04	> 100	3.47	1056
C3	1.09	92.07	0.78	0.04	0.00	0.00	0.08	> 100	2.13	627
C4	0.96	84.68	0.80	0.07	0.00	0.00	0.08	> 100	1.82	567
Cg	0.60	45.64	1.52	0.05	0.02	0.00	0.04	> 100	1.10	798

Sulfur fractionation analyzed by an independent laboratory for Site 3.

Horizon	Depth (cm)	Total Sulfur	Pyritic Sulfur	Sulfate Sulfur	Organic Sulfur
			-----%		
C1	0 – 5	2.06	-.980	1.70	1.34
C2	5 – 32	3.43	-.036	3.11	.356
C3	32 – 79	1.31	.064	1.24	.006
C4	79 – 130	1.73	.142	1.54	.048
Cg	130+	1.56	-.570	1.41	.720

Acid-base account data analyzed by an independent laboratory for Site 3. **Calculated from total sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃ Equivalent Tons	Neutralization Potential 1000 Tons ⁻¹	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 5	4	10YR 5/4	2.06	64.38	208.08		143.71	7.8
C2	5 – 32	4	7.5YR 5/4	3.43	107.19	148.11		40.92	6.8
C3	32 – 79	4	2.5Y 6/4	1.31	40.94	109.97		69.03	7.6
C4	79 – 130	4	2.5Y 6/4	1.73	54.06	112.73		58.67	6.8
Cg	130+	4	2.5Y 6/2	1.56	48.75	172.10		123.35	7.4

Acid-base account data analyzed by an independent laboratory for Site 3. **Calculated from pyritic sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃	Neutralization Potential Equivalent Tons	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 5	4	10YR 5/4	< .001	.03	208.08		208.05	7.8
C2	5 – 32	4	7.5YR 5/4	< .001	.03	148.11		148.08	6.8
C3	32 – 79	4	2.5Y 6/4	.064	2.00	109.97		107.97	7.6
C4	79 – 130	4	2.5Y 6/4	.142	4.44	112.73		108.29	6.8
Cg	130+	4	2.5Y 6/2	< .001	.03	172.10		172.07	7.4

Total elemental analysis of selected elements for Site 3.

Horizon	Depth (cm)	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	As	Mg	Mn
		mg kg ⁻¹											
C1	0 – 5	25660	128	65018	2	23	54	750	71667	6674	62	39103	4330
C2	5 – 32	21763	109	79193	2	17	88	767	62035	6620	60	37737	4204
C3	32 – 79	32566	152	56014	2	16	66	423	46920	9335	62	41237	3099
C4	79 – 130	31883	209	52092	3	18	32	417	40490	9308	62	37381	3084
Cg	130+	30845	170	55645	2	17	43	973	41473	8736	62	40157	3673

Total elemental analysis of selected elements for Site 3, continued.

Horizon	Depth (cm)	Mo	Na	Ni	P	Pb	S mg kg ⁻¹	Si	Sr	Ti	Zn	Zr
C1	0 – 5	6	8111	68	416	99	14241	27217	221	1317	1911	4
C2	5 – 32	6	6760	86	254	96	22657	22308	219	984	1980	4
C3	32 – 79	6	9208	65	260	85	10074	25039	190	1521	1375	7
C4	79 – 130	6	9569	47	278	94	9386	28096	189	1403	1545	11
Cg	130+	6	10387	50	160	108	12576	24074	207	1291	1376	12

Appendix E. Morphology and Laboratory Data for Site 4

Soil Profile Description for Site 4

Landscape position: flood plain

Slope: 4%

Parent material: mine tailings pond

Vegetation: none

Drainage: somewhat excessively drained

Classification: mixed, mesic Typic Udipsamment

- C1 - 0 to 15 cm; dark grayish brown (2.5Y 4/2) loamy sand; structureless single grain; loose; clear boundary.
- C2 - 15 to 40 cm; dark yellowish brown (10YR 3/6) loamy sand; structureless single grain; loose; clear boundary.
- C3 - 40 to 60 cm; dark reddish brown (5YR 3/4) loamy sand; structureless single grain; loose; clear boundary.
- C4 - 60 to 85 cm; yellowish red (5YR 4/6) loamy sand; structureless single grain; loose; clear boundary.
- C5 - 85 to 110 cm; red (2.5YR 4/6) loamy sand; structureless single grain; loose; clear boundary.
- C6 - 110 to 130 cm; dark brown (7.5YR 3/2) loamy sand; structureless single grain; loose; clear boundary.
- C1' - 0 to 20 cm; yellowish red (5YR 4/6) loamy sand; structureless single grain; loose; clear boundary.

Sampling depth, pH, organic mater, organic carbon, and total carbon for Site 4.

Sample #	Horizon	Depth (cm)	pH (1:1 H ₂ O)	pH (1:2 CaCl ₂)	O.M. (Walkley-Black)	O.C.	Total Carbon
						%	
9831	C1	0 – 15	7.6	7.3	0.54	0.31	1.09
9832	C2	15 – 40	6.6	6.5	1.33	0.77	0.67
9833	C3	40 – 60	3.0	3.2	0.00	0.00	0.18
9834	C4	60 – 85	3.0	3.0	0.00	0.00	0.14
9835	C5	85 – 110	3.8	4.3	NA	NA	NA
9836	C6	110 – 130	3.6	3.8	NA	NA	NA
9837	C1'	0 - 20	1.9	1.9	0.57	0.33	0.09

Particle size distribution for site 4.

Horizon	Depth (cm)	Size Class and Particle Diameter (microns)							
		VCOS 2000 - 1000	COS 1000 - 500	MS 500 - 250	FS 250 - 100	VFS 100 - 50	SAND 2000 - 50	SILT 50 - 2	CLAY < 2
C1	0 - 15	1	10	11	39	25	86	14	0
C2	15 - 40	6	23	15	26	10	80	19	1
C3	40 - 60	6	21	12	23	10	72	26	2
C4	60 - 85	13	20	10	26	9	78	19	3
C5	85 - 110	2	18	14	31	11	76	21	3
C6	110 - 130	NA	NA	NA	NA	NA	NA	NA	NA
C1'	0 - 20	7	31	10	20	7	75	22	3

Cation exchange capacity (pH 7), ammonium acetate extractable bases, potassium chloride extractable aluminum and acidity, base saturation, citrate dithionite extractable iron, and hydroxylamine manganese for Site 4.

Horizon	CEC (NH ₄ OAc)	Ca	Exchangeable Bases Mg	Na	K	(KCl) Al	Total Acidity (KCl)	Base Saturation (NH ₄ OAc) pH 7	Free Iron	Manganese
			cmol kg ⁻¹					%		mg kg ⁻¹
C1	0.91	81.26	0.63	0.03	0.00	0.00	0.04	> 100	2.76	721
C2	1.55	153.15	1.82	0.03	0.00	0.00	0.08	> 100	7.56	350
C3	2.48	121.55	1.90	0.04	0.00	0.48	1.27	> 100	10.83	133
C4	2.34	197.74	1.29	0.04	0.00	7.86	9.77	> 100	9.27	52
C5	NA	NA	NA	NA	NA	0.99	3.83	NA	NA	345
C6	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
C1'	2.50	167.57	4.02	0.03	0.01	5.47	9.95	> 100	11.58	36

Sulfur fractionation analyzed by an independent laboratory for Site 4.

Horizon	Depth (cm)	Total Sulfur	Pyritic Sulfur %	Sulfate Sulfur	Organic Sulfur
C1	0 – 15	4.16	-.530	3.63	1.06
C2	15 – 40	7.10	.060	4.84	2.20
C3	40 – 60	4.84	.160	4.35	.330
C4	60 – 85	4.19	.214	3.90	.076
C5	85 – 110	6.91	.400	5.43	1.08
C6	110 – 130	7.14	.757	5.65	.733
C1'	0 - 20	7.42	-.430	5.63	2.22

Acid-base account data analyzed by an independent laboratory for Site 4. Calculated from total sulfur values only.

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃	Neutralization Potential Equivalent Tons	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 15	3	2.5Y 5/3	4.16	130.00	144.39		14.39	6.9
C2	15 – 40	3	10YR 4/4	7.10	221.88	110.69	111.18		6.2
C3	40 – 60	1	10YR 4/6	4.84	151.25	40.46	110.79		4.7
C4	60 – 85	2	10YR 5/6	4.19	130.94	59.48	71.46		4.8
C5	85 – 110	1	10YR 5/4	6.91	215.94	40.77	175.17		4.0
C6	110 – 130	1	2.5Y 4/4	7.14	223.13	30.90	192.23		4.0
C1'	0 – 20	0	10YR 4/6	7.42	231.88	-3.62	235.49		3.1

Acid-base account data analyzed by an independent laboratory for Site 4. **Calculated from pyritic sulfur values only.**

Horizon	Depth (cm)	Fizz Test	Color	Sulfur %	Max Acidity From % Sulfur -----CaCO ₃	Neutralization Potential Equivalent Tons	Max Needed (pH 7) 1000 Tons ⁻¹	Excess CaCO ₃ Material-----	Paste pH
C1	0 – 15	3	2.5Y 5/3	< .001	.03	144.39		144.36	6.9
C2	15 – 40	3	10YR 4/4	.060	1.88	110.69		118.81	6.2
C3	40 – 60	1	10YR 4/6	.160	5.00	40.46		35.46	4.7
C4	60 – 85	2	10YR 5/6	.214	6.69	59.48		52.79	4.8
C5	85 – 110	1	10YR 5/4	.400	12.5	40.77		28.27	4.0
C6	110 – 130	1	2.5Y 4/4	.757	23.66	30.90		7.24	4.0
C1'	0 – 20	0	10YR 4/6	< .001	.03	-3.62	3.65		3.1

Total elemental analysis of selected elements for Site 4.

Horizon	Depth (cm)	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	K	As	Mg	Mn
-----mg kg ⁻¹ -----													
C1	0 – 15	22622	123	58704	4	27	25	1845	88954	5550	67	40700	4839
C2	15 – 40	21109	106	56894	4	32	30	3077	94560	4811	67	32653	3960
C3	40 – 60	16131	99	54533	2	22	14	1336	110174	4682	67	21960	2539
C4	60 – 85	17081	147	60630	3	21	19	3209	93387	4375	66	24035	2330
C5	85 – 110	18002	134	59470	4	35	29	3067	91252	4653	67	26462	3167
C6	110 – 130	17518	110	61492	8	72	29	2687	111742	4324	67	22916	3302
C1'	0 - 20	17352	104	50441	2	21	40	1072	122614	4544	66	23414	2338

Total elemental analysis of selected elements for Site 4, continued.

Horizon	Depth (cm)	Mo	Na	Ni	P	Pb	S	Si	Sr	Ti	Zn	Zr
							mg kg ⁻¹					
C1	0 – 15	7	7980	47	279	206	29197	23766	166	1227	3614	4
C2	15 – 40	7	7535	53	201	261	44588	21333	145	1114	4599	4
C3	40 – 60	7	8837	42	74	467	34106	21267	154	1132	1126	4
C4	60 – 85	7	7070	52	231	309	40472	22621	168	967	1058	4
C5	85 – 110	7	7488	70	190	254	42321	17235	164	1056	2545	4
C6	110 – 130	7	5592	79	151	216	53427	21643	181	896	4224	4
C1'	0 - 20	7	7555	64	88	244	42551	22925	112	869	921	4

Appendix F. Laboratory Data for Fertility Samples

Percent sulfur (S) for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample %	4 th Sample	5 th Sample
A1	1.87	2.47	1.24	2.80	2.35
A2	1.87	2.43	1.87	2.40	2.77
A3	1.08	2.01	1.77	2.49	2.45
A4	1.08	1.35	2.08	2.79	2.40
A5	1.85	1.89	1.23	1.30	1.84
A6	1.85	1.52	2.19	2.52	2.26
A7	1.36	1.01	1.83	2.30	2.59
A8	1.36	1.64	1.71	2.36	2.85
A9	0.91	0.66	1.65	1.34	1.87
A10	0.91	1.51	1.45	1.87	2.60
A11	1.71	2.50	2.30	2.70	2.79
A12	1.71	2.09	1.98	2.48	2.78
A13	0.89	0.94	1.16	0.85	1.41
A14	0.89	1.29	1.43	1.14	1.68
A15	1.33	0.94	0.85	1.44	2.27
A16	1.33	2.36	1.83	1.94	2.84
B1	1.40	1.57	2.16	1.73	2.13
B2	1.40	2.28	2.06	2.03	2.28
B3	2.03	2.54	2.85	2.34	2.66
B4	2.03	3.81	3.30	2.99	3.68
B5	1.69	1.54	2.40	2.15	2.59
B6	1.69	1.65	2.10	1.63	2.18
B7	1.77	2.12	2.21	2.26	2.60
B8	1.77	3.08	3.43	3.05	3.17
B9	1.86	1.53	2.89	2.32	2.86
B10	1.86	2.16	3.16	2.72	3.01
B11	1.56	2.64	2.80	2.94	2.89
B12	1.56	2.38	3.38	2.96	2.45
B13	2.02	2.20	2.59	2.07	2.69
B14	2.02	3.20	3.87	2.68	3.46
B15	2.39	2.53	3.83	2.82	3.31
B16	2.39	3.20	3.15	3.02	3.15

Sulfur fractionation for fertility samples

Block	Sulfate Sulfur	Pyritic (Sulfide) Sulfur %	Organic Sulfur
A1	0.00	0.00	1.97
A2	0.00	0.00	1.97
A3	0.00	0.00	1.50
A4	0.00	0.00	1.50
A5	.904	0.00	1.14
A6	.904	0.00	1.14
A7	0.00	.088	1.45
A8	0.00	.088	1.45
A9	.540	0.00	.651
A10	.540	0.00	.651
A11	.338	.076	1.30
A12	.338	.076	1.30
A13	.158	0.00	.926
A14	.158	0.00	.926
A15	.182	.085	1.07
A16	.182	.085	1.07
B1	0.00	0.00	1.72
B2	0.00	0.00	1.72
B3	.280	0.00	2.02
B4	.280	0.00	2.02
B5	.183	0.00	1.77
B6	.183	0.00	1.77
B7	0.00	0.00	2.71
B8	0.00	0.00	2.71
B9	.361	0.00	2.02
B10	.361	0.00	2.02
B11	0.00	0.00	2.95
B12	0.00	0.00	2.95
B13	0.00	0.00	2.86
B14	0.00	0.00	2.86
B15	0.00	0.00	3.62
B16	0.00	0.00	3.62

Exchangeable magnesium (NH₄OAc) for fertility samples.

Block	1 st Sample	2 nd Sample
	cmol kg ⁻¹	
A1	0.60	0.38
A2	0.60	0.54
A3	0.83	0.62
A4	0.83	0.78
A5	0.60	0.41
A6	0.60	0.45
A7	0.85	0.47
A8	0.85	0.72
A9	0.54	0.45
A10	0.54	0.41
A11	0.85	0.57
A12	0.85	0.71
A13	0.62	0.56
A14	0.62	0.47
A15	0.60	0.44
A16	0.60	0.45
B1	0.64	0.46
B2	0.64	0.42
B3	0.72	0.39
B4	0.72	0.47
B5	1.16	0.45
B6	1.16	0.40
B7	0.81	0.40
B8	0.81	0.48
B9	0.91	0.50
B10	0.91	0.48
B11	0.86	0.48
B12	0.86	0.45
B13	1.04	0.56
B14	1.04	0.45
B15	0.90	0.00
B16	0.90	0.00

Exchangeable potassium (NH₄OAc) for fertility samples.

Block	1 st Sample	2 nd Sample
	cmol kg ⁻¹	
A1	0.00	0.00
A2	0.00	0.00
A3	0.00	0.01
A4	0.00	0.01
A5	0.00	0.00
A6	0.00	0.00
A7	0.00	0.02
A8	0.00	0.01
A9	0.00	0.00
A10	0.00	0.00
A11	0.00	0.00
A12	0.00	0.00
A13	0.00	0.00
A14	0.00	0.00
A15	0.00	0.00
A16	0.00	0.00
B1	0.00	0.00
B2	0.00	0.00
B3	0.00	0.00
B4	0.00	0.00
B5	0.00	0.00
B6	0.00	0.00
B7	0.00	0.00
B8	0.00	0.00
B9	0.00	0.00
B10	0.00	0.00
B11	0.00	0.00
B12	0.00	0.00
B13	0.00	0.01
B14	0.00	0.00
B15	0.00	0.00
B16	0.00	0.00

Exchangeable sodium (NH_4OAc) for fertility samples.

Block	1 st Sample	2 nd Sample
	cmol kg ⁻¹	
A1	0.06	0.07
A2	0.06	0.05
A3	0.01	0.11
A4	0.01	0.12
A5	0.11	0.04
A6	0.11	0.06
A7	0.01	0.20
A8	0.01	0.06
A9	0.08	0.15
A10	0.08	0.10
A11	0.01	0.06
A12	0.01	0.02
A13	0.07	0.04
A14	0.07	0.03
A15	0.00	0.08
A16	0.00	0.02
B1	0.01	0.04
B2	0.01	0.08
B3	0.03	0.06
B4	0.03	0.04
B5	0.01	0.05
B6	0.01	0.07
B7	0.01	0.12
B8	0.01	0.03
B9	0.02	0.19
B10	0.02	0.04
B11	0.00	0.03
B12	0.00	0.01
B13	0.06	0.04
B14	0.06	0.03
B15	0.02	0.00
B16	0.02	0.00

Percent total carbon for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample %	4 th Sample	5 th Sample
A1	1.41	1.81	1.82	1.82	1.90
A2	1.41	1.82	1.84	2.04	1.78
A3	1.23	1.38	1.60	1.53	1.42
A4	1.23	1.40	1.41	1.38	1.45
A5	1.36	1.41	1.49	1.48	1.43
A6	1.36	1.27	1.36	1.36	1.41
A7	1.21	1.37	1.51	1.52	1.47
A8	1.21	1.19	1.35	1.36	1.33
A9	1.11	1.19	1.47	1.38	1.26
A10	1.11	1.04	1.18	1.24	1.34
A11	1.19	1.31	1.33	1.24	1.32
A12	1.19	1.18	1.37	1.21	1.34
A13	1.26	1.22	1.49	1.30	1.38
A14	1.26	1.32	1.42	1.34	1.39
A15	1.41	1.36	1.44	1.32	1.50
A16	1.41	1.45	1.43	1.55	1.48
B1	1.89	1.75	1.81	1.81	1.85
B2	1.89	1.90	1.84	1.86	2.02
B3	1.65	1.75	2.10	2.06	1.80
B4	1.65	1.43	1.77	1.64	1.60
B5	1.15	1.49	1.60	1.40	1.61
B6	1.15	1.56	1.77	1.83	1.64
B7	1.82	1.89	2.09	1.92	1.87
B8	1.82	2.34	2.39	2.08	1.75
B9	1.28	1.69	1.73	1.48	1.51
B10	1.28	1.48	1.59	1.45	1.37
B11	1.51	1.66	1.41	1.42	1.49
B12	1.51	1.88	1.85	1.92	1.68
B13	1.29	1.36	1.56	1.45	1.70
B14	1.29	1.77	1.80	1.65	1.79
B15	1.74	1.76	1.91	1.71	1.73
B16	1.74	1.47	1.66	1.60	1.46

Percent organic carbon for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample %	4 th Sample	5 th Sample
A1	0.41	0.10	0.45	0.42	0.30
A2	0.41	0.13	0.41	0.08	0.45
A3	0.32	0.02	0.38	0.15	0.49
A4	0.32	0.13	0.34	0.23	0.34
A5	0.32	0.02	0.26	-0.04	0.26
A6	0.32	0.15	0.32	0.22	0.28
A7	0.46	0.42	0.00	0.21	0.43
A8	0.46	0.17	0.32	0.30	0.37
A9	0.34	0.10	0.41	0.15	0.30
A10	0.34	0.21	0.41	0.15	0.30
A11	0.37	0.21	0.39	0.30	0.52
A12	0.37	0.21	0.41	0.67	0.56
A13	0.42	0.13	0.32	0.26	0.47
A14	0.42	0.15	0.47	0.15	0.49
A15	0.29	0.15	0.42	0.22	0.37
A16	0.29	0.11	0.15	0.26	0.47
B1	0.25	0.34	0.60	0.30	0.45
B2	0.25	2.13	0.83	0.30	0.30
B3	0.22	0.15	0.26	0.37	0.37
B4	0.22	0.36	0.19	0.49	0.56
B5	0.27	0.23	0.60	0.41	0.45
B6	0.27	0.30	0.49	0.45	0.53
B7	0.27	0.51	0.41	0.56	0.61
B8	0.27	0.59	0.34	0.54	0.95
B9	0.32	0.30	0.26	0.60	0.53
B10	0.32	0.21	0.30	0.52	0.53
B11	0.24	0.32	0.38	0.52	0.87
B12	0.24	0.32	0.36	0.64	0.30
B13	0.39	0.36	0.26	0.58	0.53
B14	0.39	0.70	0.39	0.30	0.36
B15	0.29	0.51	0.23	0.22	0.49
B16	0.29	1.20	0.26	0.52	0.27

Total nitrogen for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	416	544	281	666	1461
A2	416	474	237	800	795
A3	434	493	531	704	1515
A4	434	470	308	659	1855
A5	413	447	819	832	2244
A6	413	430	693	1322	3049
A7	492	384	1177	1255	2388
A8	492	465	1190	1227	1673
A9	386	380	1897	981	1673
A10	386	6813	1838	1557	1919
A11	421	2093	1990	1322	1819
A12	421	1408	1613	1872	2275
A13	399	1449	2233	2282	1784
A14	399	2160	11300	1962	2134
A15	403	2305	2003	2996	1389
A16	403	3460	543	3134	520
B1	412	3387	617	2937	1629
B2	412	3327	562	1993	1636
B3	386	4239	530	1942	1602
B4	386	2290	472	2038	1587
B5	542	951	622	1414	1974
B6	542	1026	499	2732	1307
B7	388	710	460	3327	1462
B8	388	830	519	3752	480
B9	555	756	447	3362	406
B10	555	627	507	3209	389
B11	372	737	760	3159	395
B12	372	746	694	1881	956
B13	441	939	1010	1054	598
B14	441	769	908	831	458
B15	404	638	927	1896	461
B16	404	419	904	2258	345

Plant available (double-acid extractable) calcium for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	13470	13074	17528	13963	14768
A2	13470	13642	15381	13664	14627
A3	15372	14449	15876	15965	14535
A4	15372	15963	14898	14237	15262
A5	26869	13706	16094	22524	16561
A6	26869	14969	15562	16543	13852
A7	15461	16505	14657	15150	15502
A8	15461	13383	15251	14909	13507
A9	16930	12194	15110	15634	12847
A10	16930	12057	14889	13520	12449
A11	12989	13061	15463	24716	12931
A12	12989	13090	15120	12976	13504
A13	15190	11244	14495	12564	13017
A14	15190	12720	15736	14697	12494
A15	15432	11481	15857	13661	14273
A16	15432	15312	15731	13684	12841
B1	15958	16233	15953	15160	14251
B2	15958	16763	15721	15069	13654
B3	15847	12228	17384	14638	16096
B4	15847	15983	16099	14209	14114
B5	17570	18023	16064	13634	13285
B6	17570	16229	15271	14325	14177
B7	14685	12620	14937	14275	14288
B8	14685	11435	15831	13923	14442
B9	17473	11710	15817	13664	14188
B10	17473	14479	15464	14828	13995
B11	15545	14638	16400	15270	15732
B12	15545	15923	14086	14074	14090
B13	15100	15673	13096	11982	14146
B14	15100	14989	13807	12134	12867
B15	15392	15261	13406	14605	14424
B16	15392	15382	14757	15190	13895

Plant available (double-acid extractable) copper for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	54.77	81.13	20.28	76.58	134.65
A2	54.77	60.29	31.88	53.91	165.00
A3	40.81	55.44	82.45	35.94	63.45
A4	40.81	45.92	61.26	83.71	62.84
A5	39.90	72.05	102.56	66.83	117.36
A6	39.90	70.45	53.47	75.52	93.89
A7	53.58	92.61	73.41	64.66	146.48
A8	53.58	68.86	61.37	48.88	165.33
A9	62.67	53.69	86.10	80.14	87.56
A10	62.67	63.95	83.76	86.44	147.72
A11	75.13	74.11	104.50	117.79	108.03
A12	75.13	74.03	101.45	117.97	143.22
A13	91.30	66.57	105.39	106.48	130.27
A14	91.30	69.59	88.88	106.38	119.53
A15	72.78	55.66	79.75	58.94	119.88
A16	72.78	73.52	88.61	51.94	160.19
B1	8.36	10.36	4.05	31.27	45.32
B2	8.36	41.25	34.05	43.21	35.32
B3	34.21	31.93	19.42	46.58	40.32
B4	34.21	53.58	36.63	5.95	80.31
B5	37.94	36.12	48.55	7.87	17.78
B6	37.94	29.86	5.93	6.68	56.33
B7	42.68	36.59	1.01	3.51	20.63
B8	42.68	49.64	3.67	32.76	97.99
B9	52.14	64.58	23.98	82.99	118.62
B10	52.14	47.14	63.93	78.77	92.18
B11	37.14	34.88	18.30	85.83	42.32
B12	37.14	37.94	30.19	86.88	24.94
B13	43.34	72.42	84.43	137.67	65.28
B14	43.34	69.11	72.02	108.90	103.73
B15	37.29	61.71	67.62	110.66	124.05
B16	37.29	51.05	54.12	76.69	98.98

Plant available (double-acid extractable) iron for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	78.88	174.88	51.91	134.21	225.81
A2	78.88	156.73	40.43	229.08	238.84
A3	130.46	282.20	211.55	156.89	89.47
A4	130.46	195.18	199.80	380.36	68.81
A5	158.17	261.03	250.40	86.77	78.38
A6	158.17	205.32	121.04	77.92	93.46
A7	169.05	212.02	244.98	118.67	271.93
A8	169.05	321.97	161.38	101.25	376.11
A9	287.05	260.81	216.07	206.39	387.97
A10	287.05	313.32	329.34	229.42	498.72
A11	303.93	256.89	160.38	342.95	92.29
A12	303.93	253.66	235.01	377.47	101.64
A13	339.62	347.41	284.00	167.97	51.17
A14	339.62	271.19	92.07	205.10	55.66
A15	137.55	307.82	235.51	189.76	101.88
A16	137.55	274.23	198.61	102.24	260.02
B1	53.02	130.39	136.68	245.26	246.07
B2	53.02	200.68	117.20	202.47	79.82
B3	156.20	235.85	87.08	176.04	60.26
B4	156.20	306.38	126.06	116.17	137.39
B5	240.45	277.42	211.58	112.30	96.39
B6	240.45	234.16	68.39	103.75	222.87
B7	166.21	270.04	1.06	30.13	29.36
B8	166.21	272.05	10.38	101.89	198.40
B9	140.47	287.63	42.24	52.27	394.93
B10	140.47	253.39	250.42	178.04	180.31
B11	140.20	246.90	109.35	206.44	142.69
B12	140.20	59.37	27.55	182.86	115.01
B13	121.99	237.75	274.23	277.98	41.33
B14	121.99	121.37	308.39	326.36	100.54
B15	138.38	203.06	270.50	388.96	144.91
B16	138.38	227.68	312.22	196.01	367.14

Plant available (double-acid extractable) potassium for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	132.90	162.91	140.09	318.39	294.94
A2	132.90	160.59	113.51	367.61	242.57
A3	179.08	172.42	194.09	340.96	247.23
A4	179.08	177.57	178.50	348.22	279.53
A5	157.06	204.05	206.33	295.82	276.98
A6	157.06	177.16	236.84	266.05	327.26
A7	155.71	158.88	176.50	278.18	330.11
A8	155.71	203.06	166.87	252.91	306.18
A9	259.77	178.86	186.17	394.66	432.19
A10	259.77	197.91	254.22	342.71	287.68
A11	200.75	169.64	189.86	379.18	330.00
A12	200.75	158.73	194.69	308.17	263.45
A13	200.21	206.00	201.89	349.14	243.56
A14	200.21	173.82	168.08	310.17	289.46
A15	177.30	167.31	182.49	349.72	359.64
A16	177.30	171.94	204.72	359.85	425.24
B1	165.22	111.10	175.83	303.98	302.83
B2	165.22	111.20	250.77	319.31	274.13
B3	138.71	91.19	174.28	281.78	257.14
B4	138.71	117.22	179.30	298.81	282.56
B5	191.68	122.73	227.33	268.88	297.72
B6	191.68	122.95	196.84	244.87	351.54
B7	183.59	133.59	170.19	359.36	306.21
B8	183.59	81.90	103.78	280.48	348.30
B9	153.89	80.49	104.06	225.90	337.31
B10	153.89	118.29	171.61	320.03	268.66
B11	180.54	130.45	194.30	277.95	348.26
B12	180.54	123.34	162.81	289.46	259.75
B13	150.48	132.68	186.27	219.34	231.92
B14	150.48	87.91	159.98	224.41	253.33
B15	156.75	69.30	141.62	249.59	263.14
B16	156.75	109.78	163.24	265.03	308.07

Plant available (double-acid extractable) magnesium for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	310.85	302.40	362.30	433.58	417.48
A2	310.85	315.75	318.89	468.86	436.59
A3	471.67	406.81	389.08	533.17	443.51
A4	471.67	450.79	418.31	474.58	449.23
A5	667.94	345.42	393.56	628.74	470.73
A6	667.94	391.32	402.59	486.96	405.41
A7	441.75	402.59	394.34	455.61	509.02
A8	441.75	416.12	418.31	438.74	519.11
A9	449.67	350.69	469.93	576.57	501.97
A10	449.67	348.84	488.94	460.74	414.64
A11	425.21	368.10	473.69	907.19	499.98
A12	425.21	399.96	522.10	545.08	588.83
A13	437.73	382.55	474.76	590.85	529.14
A14	437.73	369.00	431.27	568.38	506.01
A15	387.07	311.47	417.13	555.30	452.58
A16	387.07	369.39	438.87	543.15	457.81
B1	388.85	335.99	382.51	504.00	419.15
B2	388.85	337.67	383.76	456.42	370.47
B3	427.23	299.18	409.81	438.74	457.72
B4	427.23	421.67	399.96	445.29	462.75
B5	621.46	469.72	477.89	447.77	457.62
B6	621.46	455.61	370.94	361.15	471.54
B7	404.00	323.85	322.47	391.32	409.81
B8	404.00	259.03	329.65	401.38	478.69
B9	502.98	301.00	329.26	392.55	544.08
B10	502.98	392.78	438.21	501.98	477.89
B11	465.53	371.47	419.00	511.02	574.27
B12	465.53	356.41	329.30	404.40	408.00
B13	433.29	401.38	351.17	410.88	382.51
B14	433.29	325.29	361.72	416.95	408.04
B15	475.71	354.51	362.87	496.92	480.81
B16	475.71	450.57	431.42	497.96	509.05

Plant available (double-acid extractable) manganese for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	582.32	531.56	531.70	694.29	592.29
A2	582.32	566.97	555.26	659.23	641.59
A3	689.37	590.38	577.77	757.62	726.09
A4	689.37	637.48	640.79	716.10	705.39
A5	621.20	450.12	543.22	695.28	691.07
A6	621.20	610.37	544.10	664.15	660.22
A7	658.91	600.41	432.77	652.21	723.44
A8	658.91	605.88	514.76	664.37	777.14
A9	532.36	396.13	534.50	648.58	714.01
A10	532.36	514.22	600.08	691.23	680.88
A11	629.31	561.60	716.54	666.48	799.09
A12	629.31	575.52	650.03	633.81	855.80
A13	558.53	444.74	565.70	663.63	645.21
A14	558.53	414.51	575.19	667.78	712.04
A15	603.13	433.52	567.27	688.27	763.08
A16	603.13	499.63	589.29	739.49	736.87
B1	607.20	548.57	624.68	592.64	572.77
B2	607.20	556.11	572.26	670.47	707.78
B3	649.99	363.79	546.40	624.24	809.77
B4	649.99	614.51	598.29	742.22	858.53
B5	667.54	514.76	570.45	693.90	762.32
B6	667.54	584.36	588.09	643.78	746.03
B7	649.44	378.17	590.31	610.48	737.48
B8	649.44	311.96	594.74	703.06	830.84
B9	644.49	423.77	578.38	658.80	771.64
B10	644.49	498.27	621.42	679.61	683.62
B11	669.92	485.71	596.40	706.36	795.37
B12	669.92	565.42	594.61	716.86	744.73
B13	653.18	584.40	573.26	701.55	725.28
B14	653.18	546.39	563.53	621.75	687.50
B15	679.80	585.31	487.43	672.43	821.16
B16	679.80	659.45	585.57	754.88	772.31

Plant available (double-acid extractable) sodium for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample	4 th Sample	5 th Sample
	mg kg ⁻¹				
A1	12.59	16.97	15.51	20.21	13.08
A2	12.59	15.10	13.99	17.42	11.46
A3	15.67	16.44	12.58	20.86	12.97
A4	15.67	15.58	10.11	15.43	13.84
A5	13.26	17.49	10.73	15.46	14.89
A6	13.26	19.24	7.21	14.49	12.96
A7	16.28	15.92	13.89	14.88	16.27
A8	16.28	16.24	12.69	14.77	11.88
A9	14.34	26.62	10.26	22.70	17.31
A10	14.34	13.96	29.50	15.33	11.29
A11	19.73	15.20	15.92	14.01	13.58
A12	19.73	13.34	13.05	21.53	12.73
A13	15.04	14.57	11.55	18.75	12.74
A14	15.04	14.31	10.36	17.74	13.40
A15	14.90	13.25	11.19	24.09	11.47
A16	14.90	15.37	14.18	19.21	12.98
B1	13.57	16.11	13.23	15.41	10.26
B2	13.57	12.02	13.39	11.99	5.77
B3	14.85	12.30	13.74	15.67	9.04
B4	14.85	13.94	15.03	14.04	14.06
B5	14.17	13.25	18.18	12.72	14.42
B6	14.17	17.78	15.32	11.83	7.92
B7	15.65	13.32	18.51	13.00	9.53
B8	15.65	15.06	24.41	13.38	7.63
B9	13.89	11.97	16.30	11.33	8.08
B10	13.89	26.04	15.86	10.78	8.44
B11	15.32	16.26	16.57	14.80	8.85
B12	15.32	15.27	12.00	12.40	10.55
B13	14.86	16.15	11.95	15.73	12.04
B14	14.86	12.81	12.72	10.93	10.58
B15	13.27	11.57	12.87	12.92	12.16
B16	13.27	13.66	18.15	13.45	11.67

Plant available (double-acid extractable) zinc for fertility samples.

Block	1 st Sample	2 nd Sample	3 rd Sample mg kg ⁻¹	4 th Sample	5 th Sample
A1	207.51	253.04	191.45	393.44	370.98
A2	207.51	244.25	268.32	318.41	470.46
A3	197.45	211.60	274.67	97.07	367.98
A4	197.45	197.91	237.35	340.71	349.66
A5	169.74	161.92	231.70	273.90	458.33
A6	169.74	194.14	219.23	334.58	333.83
A7	215.74	287.25	219.23	358.10	431.67
A8	215.74	235.62	217.80	285.83	387.31
A9	123.80	135.21	174.38	240.97	276.43
A10	123.80	188.86	204.15	221.21	339.73
A11	193.16	201.45	277.09	294.10	336.12
A12	193.16	221.65	277.19	355.32	548.79
A13	191.35	168.86	233.06	313.39	374.15
A14	191.35	157.27	220.77	278.62	337.34
A15	177.62	124.05	169.40	186.25	305.63
A16	177.62	184.62	214.00	310.32	405.56
B1	134.09	136.34	153.19	215.08	247.06
B2	134.09	171.55	198.72	240.72	292.17
B3	142.01	107.05	186.61	213.88	306.44
B4	142.01	191.35	188.65	222.98	311.92
B5	199.01	186.85	259.80	248.87	332.20
B6	199.01	178.39	201.01	278.83	342.15
B7	169.95	156.95	163.12	250.24	329.24
B8	169.95	160.19	173.40	232.16	331.10
B9	220.44	218.04	249.26	354.93	392.09
B10	220.44	208.76	239.84	353.23	397.36
B11	235.10	291.51	239.60	383.14	421.96
B12	235.10	186.32	210.92	388.73	337.62
B13	238.04	245.31	274.01	426.11	355.59
B14	238.04	275.33	293.66	329.34	443.30
B15	240.90	233.09	214.73	304.70	434.07
B16	240.90	225.16	219.89	309.73	356.34

Extractable phosphorus (Sodium bicarbonate) for fertility samples.

Block	P Treat	1 st Sample	2 nd Sample	3 rd Sample	4 th Sample	5 th Sample
				mg kg ⁻¹		
A1	0	0.00	0.41	3.54	0.00	0.00
A2	1	0.00	1.60	6.68	0.24	3.71
A3	2	0.00	2.46	8.16	4.11	4.98
A4	3	0.00	5.70	10.73	11.98	7.39
A5	1	1.49	6.03	5.81	1.33	3.71
A6	2	1.49	6.68	7.43	3.51	1.65
A7	3	0.00	6.57	15.43	13.07	9.58
A8	0	0.00	1.71	3.00	0.00	0.27
A9	2	0.00	11.67	9.48	13.07	8.43
A10	0	0.00	3.22	3.43	0.00	0.00
A11	1	0.00	3.54	9.48	4.72	2.68
A12	3	0.00	10.56	18.56	20.46	12.45
A13	1	0.00	3.87	6.89	3.51	6.24
A14	3	0.00	18.45	33.83	12.59	13.60
A15	0	0.00	4.08	1.33	0.24	0.50
A16	2	0.00	6.57	8.16	7.26	6.70
B1	2	0.00	8.73	5.58	22.88	7.51
B2	0	0.00	4.73	4.53	3.63	2.68
B3	3	0.84	13.81	15.73	20.46	12.54
B4	1	0.84	5.92	3.36	3.63	1.08
B5	3	0.00	6.68	19.27	16.82	24.13
B6	1	0.00	9.56	12.84	15.86	3.53
B7	2	1.17	7.34	11.78	11.86	11.17
B8	0	1.17	14.89	10.50	4.98	0.80
B9	0	0.00	3.00	5.16	8.43	6.53
B10	1	0.00	5.59	4.62	6.53	0.94
B11	3	1.27	11.10	11.21	15.90	10.92
B12	2	1.27	6.03	8.84	4.98	9.40
B13	3	1.38	5.92	6.78	11.88	7.08
B14	2	1.38	5.92	4.51	7.16	2.30
B15	0	0.00	2.35	10.13	2.68	3.67
B16	1	0.00	1.92	4.62	6.24	0.26

Total aluminum for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	22098.0	21304.0
A2	22098.0	20060.0
A3	22310.0	20204.0
A4	22310.0	21706.0
A5	24068.0	24900.0
A6	24068.0	22681.0
A7	22212.0	23241.0
A8	22212.0	22261.0
A9	25161.0	25155.0
A10	25161.0	23478.0
A11	21648.0	23727.0
A12	21648.0	21632.0
A13	25664.0	25640.0
A14	25664.0	24772.0
A15	23244.0	23963.0
A16	23244.0	22795.0
B1	22530.0	19736.0
B2	22530.0	20754.0
B3	17132.0	19102.0
B4	17132.0	17820.0
B5	20139.0	21460.0
B6	20139.0	19467.0
B7	19678.0	20373.0
B8	19678.0	19441.0
B9	21111.0	20728.0
B10	21111.0	20091.0
B11	24494.0	19342.0
B12	24494.0	18683.0
B13	23750.0	22823.0
B14	23750.0	22800.0
B15	18816.0	20550.0
B16	18816.0	19250.0

Total arsenic for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	50.0	50.0
A2	50.0	50.0
A3	50.0	50.0
A4	50.0	50.0
A5	50.0	50.0
A6	50.0	50.0
A7	50.0	50.0
A8	50.0	50.0
A9	50.0	50.0
A10	50.0	50.0
A11	50.0	50.0
A12	50.0	50.0
A13	50.0	50.0
A14	50.0	50.0
A15	50.0	50.0
A16	50.0	50.0
B1	50.0	50.0
B2	50.0	50.0
B3	50.0	50.0
B4	50.0	50.0
B5	50.0	50.0
B6	50.0	50.0
B7	50.0	50.0
B8	50.0	50.0
B9	50.0	50.0
B10	50.0	50.0
B11	50.0	50.0
B12	50.0	50.0
B13	50.0	50.0
B14	50.0	50.0
B15	50.0	50.0
B16	50.0	50.0

Total barium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	97.3	114.4
A2	97.1	108.5
A3	100.1	111.2
A4	100.5	99.1
A5	114.5	119.0
A6	114.2	103.9
A7	92.0	114.5
A8	92.4	109.4
A9	115.2	113.6
A10	115.6	107.2
A11	86.1	98.1
A12	86.4	126.1
A13	122.0	150.4
A14	122.3	146.0
A15	91.2	129.7
A16	91.1	126.8
B1	104.1	106.6
B2	104.4	110.2
B3	82.7	117.4
B4	82.5	104.4
B5	85.6	90.8
B6	85.7	112.6
B7	83.1	106.7
B8	83.0	111.5
B9	94.5	114.5
B10	94.5	99.4
B11	104.6	85.5
B12	104.2	95.7
B13	100.4	102.4
B14	100.1	97.1
B15	80.5	83.6
B16	80.1	85.2

Total calcium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	66775.0	65839.0
A2	66775.0	67499.0
A3	58505.0	67368.0
A4	58505.0	62090.0
A5	65295.0	64983.0
A6	65295.0	63953.0
A7	59103.0	59106.0
A8	59103.0	61360.0
A9	51577.0	50430.0
A10	51577.0	60278.0
A11	63900.0	59270.0
A12	63900.0	59176.0
A13	55058.0	48094.0
A14	55058.0	50566.0
A15	54310.0	54926.0
A16	54310.0	60261.0
B1	62685.0	66710.0
B2	62685.0	68834.0
B3	66311.0	71369.0
B4	66311.0	61916.0
B5	59819.0	58204.0
B6	59819.0	60010.0
B7	67000.0	65465.0
B8	67000.0	64560.0
B9	57460.0	58308.0
B10	57460.0	61313.0
B11	54047.0	59984.0
B12	54047.0	65066.0
B13	57020.0	56395.0
B14	57020.0	58670.0
B15	61659.0	65405.0
B16	61659.0	65875.0

Total cadmium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	2.0	2.0
A2	2.2	2.0
A3	2.1	2.0
A4	2.0	2.2
A5	2.0	2.1
A6	2.1	2.1
A7	2.0	2.2
A8	2.5	2.1
A9	2.0	2.1
A10	2.1	2.2
A11	2.0	2.0
A12	2.0	2.1
A13	2.1	2.5
A14	2.0	2.2
A15	2.5	2.1
A16	2.2	2.0
B1	2.0	2.2
B2	2.6	2.1
B3	2.1	2.2
B4	2.2	2.1
B5	2.0	2.0
B6	2.4	2.0
B7	2.0	2.1
B8	2.0	2.0
B9	2.3	2.3
B10	2.0	2.1
B11	2.1	2.0
B12	2.2	2.2
B13	2.1	2.0
B14	2.0	2.3
B15	2.0	2.1
B16	2.5	2.0

Total chromium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	12.2	12.2
A2	12.1	10.1
A3	13.0	9.1
A4	13.2	11.5
A5	14.3	13.4
A6	14.4	12.2
A7	12.0	10.1
A8	12.2	15.0
A9	13.5	14.2
A10	13.1	12.3
A11	13.0	13.4
A12	13.6	10.0
A13	16.4	11.2
A14	16.8	11.1
A15	14.0	14.4
A16	14.6	9.2
B1	14.7	10.4
B2	14.5	13.1
B3	8.6	12.0
B4	8.1	7.0
B5	12.5	14.3
B6	12.3	10.4
B7	14.1	14.2
B8	14.5	10.3
B9	14.3	9.4
B10	14.7	9.2
B11	17.0	9.3
B12	17.2	7.4
B13	13.3	9.5
B14	13.1	9.1
B15	11.5	8.3
B16	11.3	9.4

Total cobalt for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	16.0	26.4
A2	16.6	23.2
A3	18.3	21.1
A4	18.3	21.0
A5	23.6	16.1
A6	23.3	20.6
A7	23.2	21.4
A8	23.1	17.2
A9	17.0	19.3
A10	17.4	16.1
A11	18.3	17.1
A12	18.4	15.2
A13	19.6	15.0
A14	19.2	15.0
A15	17.1	15.2
A16	17.3	22.1
B1	20.5	17.4
B2	20.1	18.0
B3	16.5	20.0
B4	16.6	22.1
B5	20.1	15.2
B6	20.5	17.2
B7	19.1	17.3
B8	19.0	22.1
B9	18.4	18.2
B10	18.3	24.0
B11	14.0	25.3
B12	14.1	21.1
B13	19.0	22.1
B14	19.3	22.0
B15	20.5	20.2
B16	20.1	25.0

Total copper for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	800.0	947.0
A2	800.0	1104.0
A3	703.0	983.0
A4	703.0	868.0
A5	815.0	749.0
A6	815.0	697.0
A7	815.0	1032.0
A8	815.0	845.0
A9	596.0	548.0
A10	596.0	723.0
A11	851.0	872.0
A12	851.0	1010.0
A13	737.0	756.0
A14	737.0	603.0
A15	602.0	678.0
A16	602.0	982.0
B1	699.0	695.0
B2	699.0	827.0
B3	887.0	952.0
B4	887.0	1113.0
B5	705.0	558.0
B6	705.0	813.0
B7	973.0	931.0
B8	973.0	1141.0
B9	812.0	1003.0
B10	812.0	850.0
B11	592.0	981.0
B12	592.0	913.0
B13	957.0	842.0
B14	957.0	1215.0
B15	789.0	890.0
B16	789.0	1060.0

Total iron for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	61167.0	64373.0
A2	61167.0	81706.0
A3	67776.0	78044.0
A4	67776.0	64147.0
A5	61217.0	52725.0
A6	61217.0	52449.0
A7	63964.0	68673.0
A8	63964.0	61983.0
A9	56179.0	45123.0
A10	56179.0	63247.0
A11	63074.0	58937.0
A12	63074.0	66423.0
A13	66930.0	55802.0
A14	66930.0	51351.0
A15	57473.0	51459.0
A16	57473.0	79578.0
B1	57780.0	68979.0
B2	57780.0	68498.0
B3	64844.0	68986.0
B4	64844.0	85174.0
B5	75448.0	58693.0
B6	75448.0	73253.0
B7	75538.0	67915.0
B8	75538.0	83438.0
B9	66974.0	70117.0
B10	66974.0	69353.0
B11	50113.0	93466.0
B12	50113.0	86271.0
B13	71360.0	83387.0
B14	71360.0	96770.0
B15	83563.0	71028.0
B16	83563.0	98185.0

Total lead for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	114.3	122.4
A2	114.4	135.2
A3	124.2	121.3
A4	124.1	132.0
A5	122.3	109.1
A6	122.0	111.5
A7	120.5	118.1
A8	120.0	104.0
A9	112.1	140.2
A10	112.6	100.1
A11	115.2	93.3
A12	115.4	122.0
A13	115.5	99.4
A14	115.0	84.0
A15	102.6	84.2
A16	102.4	106.0
B1	115.4	94.2
B2	115.0	103.3
B3	98.2	104.1
B4	98.6	116.4
B5	128.7	93.2
B6	128.8	100.3
B7	121.0	97.0
B8	121.3	115.5
B9	114.5	120.4
B10	114.0	109.2
B11	106.5	134.6
B12	106.3	109.0
B13	108.3	107.1
B14	108.4	138.0
B15	112.5	118.5
B16	112.6	143.3

Total magnesium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	41174.0	39830.0
A2	41174.0	37428.0
A3	36141.0	36023.0
A4	36141.0	37796.0
A5	41196.0	40182.0
A6	41196.0	38032.0
A7	37540.0	37376.0
A8	37540.0	36020.0
A9	40115.0	38218.0
A10	40115.0	38651.0
A11	38207.0	38671.0
A12	38207.0	36958.0
A13	43446.0	39995.0
A14	43446.0	40104.0
A15	38720.0	41969.0
A16	38720.0	40051.0
B1	38258.0	37273.0
B2	38258.0	39258.0
B3	34584.0	37848.0
B4	34584.0	33956.0
B5	35979.0	37853.0
B6	35979.0	37086.0
B7	37719.0	40651.0
B8	37719.0	37306.0
B9	36049.0	36482.0
B10	36049.0	34272.0
B11	37573.0	33556.0
B12	37573.0	36463.0
B13	39373.0	38128.0
B14	39373.0	36722.0
B15	36580.0	38203.0
B16	36580.0	35162.0

Total manganese for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	4055.0	4091.0
A2	4055.0	4223.0
A3	3691.0	4167.0
A4	3691.0	3866.0
A5	3745.0	3577.0
A6	3745.0	3410.0
A7	3556.0	3761.0
A8	3556.0	3493.0
A9	3513.0	3012.0
A10	3513.0	3527.0
A11	3493.0	3420.0
A12	3493.0	3537.0
A13	3858.0	3299.0
A14	3858.0	3180.0
A15	3313.0	3426.0
A16	3313.0	3740.0
B1	3994.0	4143.0
B2	3994.0	4208.0
B3	3848.0	4189.0
B4	3848.0	3966.0
B5	3744.0	3639.0
B6	3744.0	3986.0
B7	4223.0	4318.0
B8	4223.0	4235.0
B9	3642.0	3720.0
B10	3642.0	3707.0
B11	3118.0	3987.0
B12	3118.0	4125.0
B13	3662.0	3630.0
B14	3662.0	3934.0
B15	3955.0	4008.0
B16	3955.0	4162.0

Total nickel for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	64.2	50.3
A2	64.1	58.1
A3	48.3	53.0
A4	48.0	50.5
A5	57.1	60.3
A6	57.0	51.1
A7	59.2	53.4
A8	59.5	57.0
A9	61.4	46.5
A10	61.0	57.0
A11	46.5	54.5
A12	46.0	37.0
A13	60.1	55.4
A14	60.4	46.4
A15	52.5	49.6
A16	52.0	59.1
B1	53.2	49.4
B2	53.0	51.5
B3	38.4	45.7
B4	38.0	53.0
B5	51.3	43.3
B6	51.0	48.1
B7	57.5	46.0
B8	57.0	61.6
B9	55.1	48.1
B10	55.6	60.1
B11	59.0	64.4
B12	59.4	58.3
B13	56.07	60.0
B14	56.4	73.5
B15	59.0	48.7
B16	59.5	68.0

Total phosphorus for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	83.2	139.1
A2	83.1	345.2
A3	123.0	259.4
A4	123.1	194.2.
A5	164.5	221.3
A6	164.1	149.0
A7	107.6	219.0
A8	107.0	133.1
A9	113.1	169.5
A10	113.2	218.2
A11	101.3	147.6
A12	101.4	225.7
A13	284.5	244.1
A14	284.0	194.4
A15	216.1	169.2
A16	216.3	337.3
B1	159.5	332.4
B2	159.1	223.1
B3	78.4	254.2
B4	78.6	235.3
B5	115.0	107.1
B6	115.4	189.0
B7	129.5	207.6
B8	129.0	260.4
B9	102.1	112.2
B10	102.0	99.3
B11	65.3	310.4
B12	65.4	182.0
B13	69.0	161.2
B14	69.2	204.4
B15	182.0	122.5
B16	182.3	146.9

Total potassium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	5754.0	5906.0
A2	5754.0	5193.0
A3	5853.0	5601.0
A4	5853.0	5397.0
A5	6349.0	6008.0
A6	6349.0	5804.0
A7	5357.0	5601.0
A8	5357.0	6008.0
A9	5159.0	5702.0
A10	5159.0	5470.0
A11	5357.0	5470.0
A12	5357.0	5470.0
A13	5655.0	6068.0
A14	5655.0	5641.0
A15	4960.0	5299.0
A16	4960.0	5385.0
B1	6052.0	5128.0
B2	6052.0	5897.0
B3	5128.0	5470.0
B4	5128.0	4530.0
B5	5060.0	6410.0
B6	5060.0	5470.0
B7	5357.0	5897.0
B8	5357.0	5556.0
B9	5853.0	5128.0
B10	5853.0	4822.0
B11	4861.0	4569.0
B12	4861.0	4484.0
B13	5952.0	5415.0
B14	5952.0	4738.0
B15	4464.0	4906.0
B16	4464.0	4653.0

Total sodium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	6061.0	5696.0
A2	6061.0	5483.0
A3	6168.0	5572.0
A4	6168.0	6510.0
A5	6911.0	6989.0
A6	6911.0	7694.0
A7	6490.0	6606.0
A8	6490.0	6095.0
A9	7022.0	7392.0
A10	7022.0	6558.0
A11	6124.0	6985.0
A12	6124.0	6424.0
A13	6897.0	7099.0
A14	6897.0	7854.0
A15	6805.0	6957.0
A16	6805.0	6388.0
B1	6243.0	6292.0
B2	6243.0	5760.0
B3	5000.0	5338.0
B4	5000.0	5202.0
B5	5908.0	5904.0
B6	5908.0	6020.0
B7	7374.0	5885.0
B8	7374.0	5305.0
B9	5624.0	7097.0
B10	5624.0	5737.0
B11	7045.0	5909.0
B12	7045.0	5428.0
B13	6344.0	8568.0
B14	6344.0	5987.0
B15	5524.0	5462.0
B16	5524.0	5134.0

Total silicon for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	71434.0	56083.0
A2	71434.0	33498.0
A3	48639.0	40714.0
A4	48639.0	24101.0
A5	74657.0	32229.0
A6	74657.0	31507.0
A7	53239.0	25568.0
A8	53239.0	25980.0
A9	67162.0	31829.0
A10	67162.0	35825.0
A11	70547.0	44479.0
A12	70547.0	71653.0
A13	68408.0	54987.0
A14	68408.0	60594.0
A15	40670.0	59210.0
A16	40670.0	40002.0
B1	51061.0	40488.0
B2	51061.0	46860.0
B3	30781.0	49214.0
B4	30781.0	67364.0
B5	58837.0	48373.0
B6	58837.0	57484.0
B7	62897.0	43419.0
B8	62897.0	47902.0
B9	29926.0	54630.0
B10	29926.0	57600.0
B11	72814.0	50708.0
B12	72814.0	47279.0
B13	51701.0	46382.0
B14	51701.0	68030.0
B15	45249.0	53888.0
B16	45249.0	72229.0

Total strontium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	194.2	473.3
A2	194.1	206.5
A3	167.0	184.1
A4	167.3	198.4
A5	189.0	211.0
A6	189.6	189.2
A7	170.4	203.2
A8	170.5	179.0
A9	165.0	179.3
A10	165.0	181.1
A11	165.5	194.1
A12	165.1	175.0
A13	169.2	166.5
A14	169.0	173.3
A15	173.3	185.2
A16	173.1	193.4
B1	203.4	200.1
B2	203.1	208.2
B3	190.2	201.0
B4	190.3	174.5
B5	163.1	174.7
B6	163.2	178.3
B7	201.3	209.1
B8	201.4	203.2
B9	163.5	195.6
B10	163.3	178.4
B11	171.4	167.2
B12	171.2	191.3
B13	172.0	156.4
B14	172.1	190.4
B15	173.3	183.2
B16	173.1	175.3

Total sulfur for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	17560.0	18365.0
A2	17560.0	25661.0
A3	21788.0	27476.0
A4	21788.0	20438.0
A5	18339.0	15201.0
A6	18339.0	18970.0
A7	21535.0	20258.0
A8	21535.0	27000.0
A9	13603.0	10013.0
A10	13603.0	18843.0
A11	25694.0	17844.0
A12	25694.0	22902.0
A13	10923.0	10144.0
A14	10923.0	11165.0
A15	13418.0	10937.0
A16	13418.0	22144.0
B1	12787.0	22084.0
B2	12787.0	20588.0
B3	25486.0	20459.0
B4	25486.0	28253.0
B5	23457.0	15980.0
B6	23457.0	17354.0
B7	23046.0	16510.0
B8	23046.0	18235.0
B9	20483.0	17317.0
B10	20483.0	21670.0
B11	13564.0	18856.0
B12	13564.0	25733.0
B13	19476.0	23173.0
B14	19476.0	28291.0
B15	24391.0	18893.0
B16	24391.0	33467.0

Total titanium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	1151.0	1171.0
A2	1151.0	1184.0
A3	1060.0	1195.0
A4	1060.0	1053.0
A5	1369.0	1277.0
A6	1369.0	1051.0
A7	1108.0	1122.0
A8	1108.0	1049.0
A9	1551.0	1377.0
A10	1551.0	1261.0
A11	1022.0	1207.0
A12	1022.0	1093.0
A13	1768.0	1590.0
A14	1768.0	1714.0
A15	1264.0	1453.0
A16	1264.0	1560.0
B1	949.0	1042.0
B2	949.0	959.0
B3	834.0	891.0
B4	834.0	1034.0
B5	970.0	957.0
B6	970.0	1016.0
B7	966.0	1012.0
B8	966.0	1043.0
B9	915.0	1038.0
B10	915.0	914.0
B11	1137.0	1142.0
B12	1137.0	1013.0
B13	1114.0	1181.0
B14	1114.0	1194.0
B15	884.0	949.0
B16	884.0	991.0

Total zinc for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	2089.0	2276.0
A2	2089.0	2832.0
A3	2138.0	2562.0
A4	2138.0	2026.0
A5	2098.0	1990.0
A6	2098.0	2151.0
A7	2222.0	2350.0
A8	2222.0	1958.0
A9	2052.0	1326.0
A10	2052.0	2101.0
A11	2217.0	1829.0
A12	2217.0	2036.0
A13	1846.0	1457.0
A14	1846.0	1566.0
A15	1708.0	1674.0
A16	1708.0	2348.0
B1	1478.0	1936.0
B2	1478.0	1946.0
B3	1875.0	2320.0
B4	1875.0	2390.0
B5	2269.0	1908.0
B6	2269.0	2175.0
B7	2153.0	1743.0
B8	2153.0	2338.0
B9	2065.0	1940.0
B10	2065.0	2099.0
B11	1562.0	2876.0
B12	1562.0	2105.0
B13	1977.0	2238.0
B14	1977.0	2673.0
B15	2281.0	2249.0
B16	2281.0	2487.0

Total zirconium for fertility samples.

Block	1 st Sample	2 nd Sample
	mg kg ⁻¹	
A1	3.1	3.2
A2	3.2	3.2
A3	3.0	3.1
A4	3.3	3.2
A5	4.0	3.3
A6	4.1	3.1
A7	3.2	3.0
A8	3.6	3.2
A9	10.1	8.3
A10	10.0	5.1
A11	3.1	5.0
A12	3.2	5.4
A13	8.4	10.2
A14	8.3	15.4
A15	4.1	13.0
A16	4.2	8.2
B1	3.6	4.4
B2	3.3	3.2
B3	3.1	3.3
B4	3.0	3.1
B5	3.1	3.0
B6	3.5	4.2
B7	3.3	3.0
B8	3.1	3.3
B9	3.2	3.4
B10	3.3	3.2
B11	3.4	3.2
B12	3.0	3.0
B13	3.2	3.2
B14	3.1	3.3
B15	4.3	3.2
B16	4.2	3.4

VITA

Thomas E. Cook was born in Nashville, Tennessee on 24 January 1972. He graduated from McGavock Comprehensive High School in Nashville, Tennessee in May of 1990. Following graduation, he attended Middle Tennessee State University majoring in voice performance while working part-time with the Kroger Company.

In August 1995, he transferred to the University of Tennessee, Knoxville. In May 1998, he received his Bachelor of Science in Agriculture in Plant and Soil Sciences emphasizing in Environmental Science. He began work on a Master of Science degree in Plant and Soil Sciences with an emphasis in Soil Science in August 1998 where he served as Graduate Research Assistant.

Upon completion of his Master of Science degree in August 2000, he will be relocating to Denver, CO where he will be working as an environmental scientist for Camp, Dresser, and McKee Federal Programs Corporation.

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