Revegetation of riparian mine tailings
by Don Brooke Jackson

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University

Abstract:
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The tailings were amended with combinations of calcium carbonate, calcium hydroxide, manure and fertilizer. Using a randomized complete block experimental design, three grass species, Agrostis stolonifera, Deschampsia cespitosa, and Elymus cinereus were grown in three tailings/amendment media under greenhouse conditions to determine their performance.

Results of the greenhouse trial indicate the riparian tailings' toxic characteristics can be ameliorated with lime and manure amendments and successfully revegetated with grasses. Greenhouse production values indicate that amended tailings are capable of producing sufficient vegetation to provide suitable cover and adequate erosion control stabilization for the deposition sites.

Key words: Revegetation, Tailings, Trace metals, Riparian, Acid mine waste.

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ABSTRACT

Riparian mine tailings deposition sites were identified along Indian Creek in the Elkhorn Mountains near Townsend, Montana. A sample of the tailings was collected for analyses and for use in greenhouse vegetation trials. The tailings have a high sulfide content, are extremely acidic, and are contaminated with elevated levels of lead, arsenic, and zinc.

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CHAPTER 1

INTRODUCTION

Background

The legacy of metal mining in the western United States is thousands of abandoned and unreclaimed mine sites. Acidic drainage and tailings impoundments are two of the most common problems emanating from abandoned mine sites. These problems are serious hazards to human and ecosystem health.

Acid mine drainage is a persistent problem at thousands of sites that were abandoned before the enactment of water pollution laws, or at sites mined by companies that have gone bankrupt. More than 6,400 kilometers of rivers and streams in the United States are adversely affected by acid mine drainage, mostly from mines that have been abandoned for many years (Kleinmann 1990). The effect of acidic discharges can be quite severe. Extremely acidic effluent, with pH commonly below 2.3, may leach trace metals from surrounding strata (Caruccio et al. 1988). If the acidity from acid mine drainage is great enough to negate a stream's natural buffering and/or dilution capacity, the aquatic ecosystem may be decimated and water rendered useless for domestic or commercial uses (Biesecker and George 1966, Caruccio et al. 1988). Detrimental impacts on aquatic environments can be widespread, with effects not only at the point of entry, but also damaging habitat for several kilometers downstream (Perry and Kleinmann 1991).

Tailings are the residue of raw materials or waste separated during the processing of mineral ores (Tver 1981). More specifically, tailings are those portions of washed ore that are regarded as too deficient to be treated further (American Geological Institute 1976). Mine tailings constitute a large proportion of the ore which was originally mined, and therefore present a massive disposal problem with potential environmental hazards. Ritcey (1989) identified the following environmental problems which may result from tailings: contamination of streams by acidic waters containing high concentrations of metals and other substances; contamination of streams due to surface runoff from the impounded tailings; air and water contamination due to wind erosion of dried tailings; catastrophic dam failure with release of fine tailings or other substrates; physical and aesthetic effects on the environment; difficulty of establishing vegetative cover to permanently stabilize tailings.

Problem

The inactive Park Mines complex is located in the headwaters of the North Fork of Indian Creek. This drainage is located in the Elkhorn Mountains approximately fourteen kilometers west-northwest of Townsend, Montana (Figure 1). The Park Mining District produced significant quantities of gold and silver with lead as an important byproduct. Gold was removed from placer deposits along Wilson and Indian Creeks as early as 1858. Lode deposits were discovered in the 1870's which led to intensive prospecting and development of the Marietta Mines from 1880 to 1906 (Reed 1951). Sporadic small scale mining occurred in the Park District from 1906 to 1942. The Marietta Mine was active again in the 1940's and 1950's. Data are available for only five of those years. It shows production of 1,185

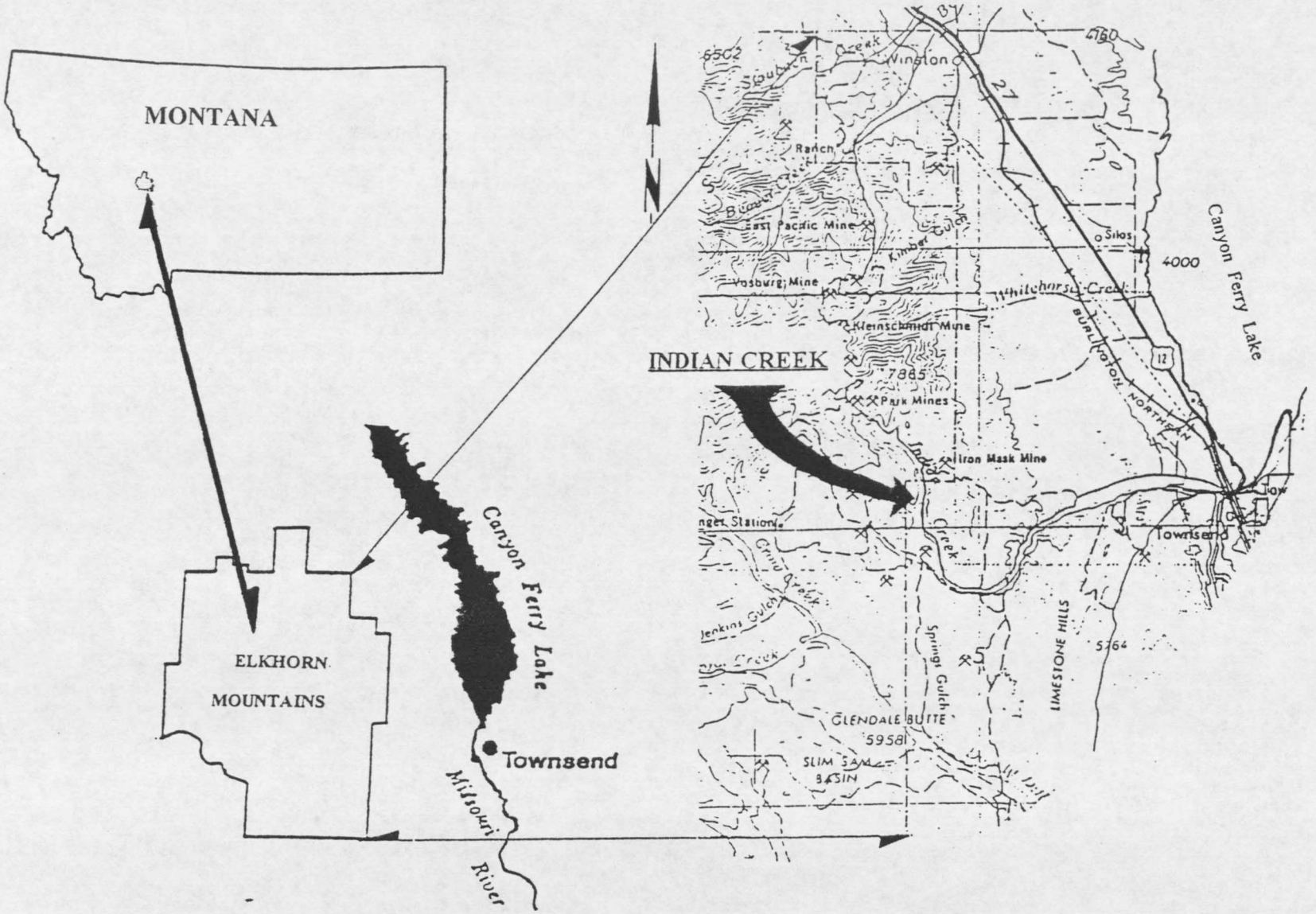

Figure 1. Indian Creek and Elkhorn Mountains Vicinity Maps.

metric tons of ore which resulted in 54 kilograms of gold and 164 kilograms of silver. In addition, 440 kilograms of copper, 9,578 kilograms of zinc, and 13,994 kilograms of lead were produced (Schell 1963). Substantial tonnage and production were reported for numerous other years, but no numbers were given. Mining operations ceased in 1961 or 1962. As a preliminary step in evaluating the heap leaching potential of the Marietta Mines, the six largest waste rock dumps were estimated to contain 53,675 metric tons (Sanguinetti 1986). The total volume of waste rock dumps has been estimated at 49,696 cubic meters (Montana DSL 1995).

The Park Mines complex has been ranked as the 18th most hazardous abandoned mine site in Montana by the Abandoned Mines and Reclamation Bureau (Montana DSL 1994a). This ranking is based on the following site-specific criteria: the quantity, toxicity, and concentrations of hazardous constituents in waste materials at the site; the extent of actual releases, and the potential to release hazardous constituents into the environment; the degree of risk to human health and the environment posed by those hazardous constituents (Montana DSL 1994b). Numerous waste rock dumps and tailings impoundments are associated with the Park Mines. Acid mine drainage flows freely from the former mines. In addition, fluvial action and flood events have resulted in the breaching of dams which formerly impounded tailings and metal laden acidic effluent. This has resulted in tailings being washed downstream and deposited along the stream banks of Indian Creek. These riparian deposition sites do not currently support vegetation. The deposits are extremely acidic and contain elevated concentrations of trace metals.

One reclamation strategy is the *in situ* mitigation of metal contaminants by reducing

their mobility and toxicity. For metal immobilization of acidic tailings, *in situ* mitigation has typically concentrated on the technology of neutralizing acidity and raising the pH with lime amendments (Montana DHES 1993). The neutralization strategy was the focus of this research, a greenhouse bench study using Indian Creek tailings material.

Purpose and Objectives

This study was undertaken to provide assistance to the Bureau of Land Management and Forest Service in determining the best techniques for rehabilitation of stream side tailings deposition sites along the North Fork of Indian Creek. The primary research included the following three specific objectives: 1) determination of the location and extent of tailings deposits along the North Fork of Indian Creek; 2) evaluation of chemical and organic amendments necessary to remediate the limiting plant growth factors in the tailings; and 3) determining the performance of three grass species in amended tailings.

CHAPTER 2

LITERATURE REVIEW

Acid Mine Drainage

Problem

Metal contaminated streams flow rusty orange from many abandoned historic mines. These acid streams serve as a constant reminder of the danger this pollution poses (Lange 1993). Extreme cases of metal contamination from acid mine drainage are the Berkeley Pit and upper Clark Fork River superfund sites near Butte, Montana. Metal concentrations of some riparian soils in this area are lethal to vegetation. Acid mine drainage (AMD) [1] may be the most serious long term threat to environmental quality that results from mining activity. AMD jeopardizes surface water and groundwater quality as well as riparian resources. In the United States the problem is common to the eastern Appalachian coal mining regions as well as western surface and underground mines. Acid drainage problems are associated with coal and hard rock mining activity when water and oxygen come in contact with tailings impoundments, mine shafts, open pits, and waste rock. It has also occurred with highway road cuts and tunnels where iron disulfide enriched strata are exposed to the atmosphere (Caruccio et al. 1988).

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[1] In many publications, AMD is also referred to as acid rock drainage (ARD).

Drainage affected by AMD may have pH values as low as 2.0 and dissolved sulfate concentrations of 400 ppm to 12,000 ppm and iron concentrations of 50 ppm to 500 ppm (Corbett and Growitz 1967). The low pH of AMD effluent may leach metals from strata over which it flows resulting in elevated levels of aluminum, copper, manganese, nickel, and zinc (Chen 1982; Grim and Hill 1974; Sengputa 1993). The metals can accumulate in sediments of streams and lakes and subsequently enter the food chain where they bioaccumulate (Smith and Frey 1971). At high enough concentrations these metals may be toxic to virtually all aquatic and terrestrial plant and animal species.

The water quality of drainage associated with a mine will depend on the abundance and balance of sulfide and calcareous minerals contained within the disturbed geologic strata. Sulfide enriched, carbonate deficient strata oxidize to produce acidic soils and water. The low pH enhances iron bacteria growth which increases ferric iron concentrations and sulfide oxidation. The inorganic reactions and *Thiobacillus* spp. interact in a synergism to accelerate the acid production. Conversely, calcareous enriched, sulfide deficient strata produce alkaline conditions which slow net acid production by reducing the solubility of iron and restricting iron catalyzing bacteria viability (Caruccio 1969).

Chemistry

Acid mine drainage results when iron sulfide minerals are present in an oxidizing environment and calcareous minerals are either absent or in low concentrations. Although numerous other mineral forms of iron sulfides exist, pyrite, FeS_2 is the most common, being

found in both coal and hardrock mine environments. The following three reactions (Singer and Stumm 1970) for the oxidation of FeS_2 by oxygen and water show the potential for acid H^+ production (Reactions 1-3):

$$FeS_2 + 3.5O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad [1]$$

$$Fe^{2+} + 0.25O_2 + H^+ \Rightarrow Fe^{3+} + 0.5H_2O \quad [2]$$

$$Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3 + 3H^+ \quad [3]$$

These can be summarized with the following single reaction (Reaction 4):

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \Rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad [4]$$

A net of four moles of hydrogen are produced for each mole of iron disulfide oxidized. A mine producing thousands of tons of waste rock and tailings with high concentrations of FeS_2 has the potential to generate tremendous quantities of acid.

Crystallography variations, particle size, and mineral purity all affect mineral stability (Caruccio et al. 1988). FeS_2 may occur as marcasite (orthorhombic) or pyrite (isometric-pyritohedral). Marcasite has a greater free energy and therefore is less stable than pyrite (Caruccio et al. 1988). Particle size affects the relative rate that a mineral will oxidize because finer particles have more surface area resulting in more reactivity and increased acid production (Caruccio 1973). However, Jennings and Dollhopf (1995a) found that particle morphology exerts dominant control on oxidation, while particle size influences the rate of sulfide oxidation to a lesser degree. The physical property variations, such as cleavage planes, steps, fractures, dislocations, and defects create a greater reactive surface area which exerts a greater influence than total surface area on the rate of sulfide oxidation (Jennings and Dollhopf 1995a).

Iron oxidizing bacteria also greatly increase the rate of ferrous iron oxidation to ferric iron (Equation 2). Two species, *Thiobacillus thiooxidans* and *Thiobacillus ferrooxidans*, have been described as important biological catalysts for oxidation (Beck and Brown 1968). These bacteria thrive in low pH waters and derive their metabolic energy from the oxidation of iron and/or sulfur (Caruccio et al. 1988). The increased production of ferric iron, Fe^{3+}, accelerates the generation of acid by oxidizing iron disulfide. This is shown in Reaction 5 (Clark 1966):

$$FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad [5]$$

This reaction occurs very rapidly (Singer and Stumm 1970), and becomes the dominant process when pH falls below 3.5 in the soil solution system.

Other factors which influence the oxidation rates of iron disulfide include temperature, oxygen concentration, water partial pressure, pH, adsorbed impurities, and flushing frequency (Caruccio et al. 1988). A temperature increase of 10°C will double the oxidation rate with a constant relative saturation of water (Smith and Shumate 1970). A higher oxygen content of the environment enhances the rate of sulfide oxidation (Clark 1966). The rate of oxidation also increases with higher partial pressure of water and with higher pH values (Smith and Shumate 1970). The abiotic oxidation rate increases slowly up to pH 3 and rapidly as pH exceeds 6. However, oxidation rates under biotic conditions are at a maximum between pH 2.4 and 3.6, with a rapid decrease above 3.6 (Caruccio et al. 1988).

There is conflicting evidence as to the effect of adsorbed impurities on the oxidation rate of iron disulfide. Significant increases in oxidation rates have been attributed to trace

quantities of copper and cobalt, as well as anions which form complexes with ferric iron (Stumm and Morgan 1970). However, Smith and Shumate (1970) found chromium, copper, manganese, nickel, chloride, nitrate, and humic acid to have no effect on oxidation rates. Calcium carbonate present in appreciable quantities will inhibit oxidation and retard acid formation (Caruccio et al. 1981). But carbonates present in concentrations below a critical alkalinity threshold level will slightly raise the pH. This will cause a more rapid ferrous oxidation, accelerated FeS_2 oxidation, and increased acidity (Burt and Caruccio 1986).

An investigation of the various flushing frequencies from coal and rock samples showed an increase of the rate of acid production as the leaching interval was increased (Geidel 1979). However, the cumulative or total amount of acidity produced was independent of flushing frequency.

Lead in the Environment

Lead occurs naturally in trace amounts in virtually all environments. Natural sources include weathering of mineral deposits, emissions from active volcanoes, vegetation, and forest fires. Cook (1977) estimated the emission of lead from natural sources to be about 210,000 tons annually. The local, regional, and planetary biogeochemical cycles of lead have been affected by man to a greater degree than those of any other toxic element (Jaworski 1987). Few areas on earth are now free of anthropogenic lead.

Lead can exist in three oxidation states, 0, +2, and +4. In aqueous solutions it exists primarily in the +2 valence state. Lead is relatively inert, being the stable end product formed by the radioactive decay of uranium. Antimony, arsenic, cadmium, copper, lead,

mercury, selenium, silver, and zinc are classified geochemically as chalcophile elements. These elements, though rare in overall abundance, are relatively easy to obtain commercially because they are concentrated in easily accessible sulfide deposits (Brooks 1977). The average abundance of lead in the earth's crust is 15 ppm (Heinrichs et al. 1980) with sandstones averaging 7 ppm (Bowen 1966) and granitics averaging 30 ppm (Lovering 1976). There are more than 200 minerals containing lead, but only three, galena (PbS), cerussite ($PbCO_3$) and anglesite ($PbSO_4$), are abundant enough to form economically minable deposits.

Kabata-Pendias and Pendias (1992) report the mean concentration of total soil lead to range from 10 to 67 ppm. Soil samples collected from nearly a thousand locations in the United States had a mean total lead content of 16 ppm with only 6 percent of the samples containing more than 30 ppm (Shacklette et al. 1971). Davies (1983) found a mean of 42 ppm total lead for England and Wales soils and concluded that concentrations greater than 110 ppm have arisen from contamination.

Toxicity

Lead is toxic to both animals and humans, especially to young children. As a result of worldwide accumulation, lead presents a more serious health and environmental hazard than does any other element (Jaworski 1987). One of the most important biochemical effects of lead is the interference in the synthesis of heme which results in impairment of hemoglobin in animals and cytochromes in plants. Ultimately, lead prevents the utilization of oxygen in life-sustaining energy production from glucose (Manahan 1984). There is no known physiological requirement for lead in animals. Lead is not an essential plant element.

Lead in Plants

The phytotoxicity of lead is very low compared to other trace metals (Chino 1981). Research has thus focused less on determining plant lead toxicity levels and more on the introduction of lead into the food chain. Plants may accumulate lead via soil or atmospheric pathways. Vegetation may contain considerably more than recommended forage limits of lead for livestock without any apparent damage to the plants (John and Van Laerhoven 1972). Phytotoxic levels of total soil lead have been reported from 100 ppm to 1000 ppm (EPA 1987). The lead hazard phytotoxic level for the Helena Valley was reported to be 1000 ppm, but considerable damage may occur at much lower levels to sensitive crops or to plants grown in acidic soils with higher available lead (EPA 1987).

Soil System

Lead uptake from soil is passive. The process proceeds rapidly until exchange sites in the root-free space equilibrate with the solution concentration (Zimdahl and Arvik 1973). Opinions conflict as to whether lead can be translocated from roots to stem and foliage (Keaton 1937; Marten and Hammond 1966). Motto et al. (1970) concluded that most lead taken up by plants accumulates in the root system, and Jones et al. (1973) concluded that movement of lead into shoots from roots is restricted. High vegetable crop lead levels were not correlated with high soil lead levels Chumbley and Unwin (1982).

However, most research has shown that lead can be absorbed and translocated by plants. Rolfe (1973) showed that lead uptake and concentrations in roots, shoots, and leaves of eight tree species were proportionate to soil lead levels. Lead levels in corn foliage

increases with increasing levels of soil lead (Baumhardt and Welch 1972; Miller and Koeppe 1970). Arvik and Zimdahl (1974) found the plant uptake of lead is passive, and increases with increasing soil lead concentration. There is clear evidence of elevated levels of lead in different plants grown in soils contaminated by mining activities (Davies 1978; Johnson et al. 1978; Johnson and Proctor 1977; Ragaini et al.1977). Tree-ring analysis of lead concentrations is being used as a tool for the study of both temporal and spatial dimensions of historical lead emissions (Eklund 1995; Guyette 1991). Tree rings have also been used to document changes in groundwater chemistry down gradient from point sources of metal contamination (King 1995). Plants which hyperaccumulate lead and other metals are being used in the emerging field of phytoremediation. These plants decontaminate soil by phytoextraction and water via rhizofiltration (Chase 1995).

It is also possible for lead to be transformed and fixed by microorganisms (Summers and Silver 1978; Tornabene and Edwards 1972). Bacteria and microfungi are frequently found in extremely metal contaminated environments, both natural and man-made. Microbes exhibit great powers to immobilize trace metals. They accumulate and bio-concentrate elements from substrates that contain only trace quantities of metals, as well as substrates with highly concentrated levels of metals (Lepp 1992).

The mobility and phytoavailability of lead in the soil system are affected by specific adsorption and exchange adsorption on mineral matrices, by the precipitation of relatively insoluble compounds of which lead is a constituent, and by the formation of relatively stable ions or chelates resulting from interaction with organic matter. Factors which affect the above include soil texture, organic matter, cation exchange capacity, soil pH, and clay

mineralogy. These are discussed individually below.

Soil texture, particularly clay content, has been correlated with increased sorption of lead. Lead and other metals have a strong affinity to the clay fraction, compared to the sand and silt fractions. This was demonstrated by LeRiche and Weir (1963) who ranked lead's affinity for soil fractions as clay > silt > sand.

A high clay and/or organic matter content generally indicate a high cation exchange capacity (CEC) and therefore, higher binding capacity for metal cations such as lead. Karamanos et al. (1976) found lead concentrations to be highest in soil solutions obtained from soils with low clay and organic matter contents. Numerous other investigations have shown that clay and organic matter are the dominant constituents contributing to lead adsorption (Hasset, 1974; Riffaldi et al. 1976; Salim and Cooksey 1980; Soldatini et al. 1976). Organic amendments often decrease cation toxicities in acid soils (Bohn et al. 1985). Metal cations may be strongly adsorbed by solid-phase organic matter or complexed by high molecular weight humic acids. Lead fixation, via reactions involving insoluble organic matter, is partly responsible for the accumulation of lead in surface horizons with a high organic matter content (Zimdahl and Skogerboe 1977). The adsorption of one Pb^{2+} ion onto humic acid or peat occurs through the release of two H^{+} ions from the organic matter (Bunzl 1974; Bunzl et al. 1976).

In addition to CEC, clay, and organic matter, soil pH is an important influence on the capacity of soils to immobilize lead. Soil pH is probably the single most important factor affecting the solubility, mobility, and phytoavailability of lead (Adriano 1986). The application of lime to lead contaminated soils was shown to decrease the uptake of lead by

six crop species (Cox and Rains 1972; John and Van Laerhoven 1972). MacLean et al. (1969) suggested that lime reduced the uptake of lead in oats and alfalfa via reducing its solubility due to the greater capacity of organic matter to complex lead with increasing pH. Zimdahl and Skogerboe (1977) reported a decrease in the lead content of plant roots with increases in pH. Miller et al. (1975a; 1975b) found that higher pH values reduced the uptake of lead in soybean and corn plants. The stability constants of lead complexes increase with increasing pH and with decreasing Eh.

Clay mineralology also influences the retention of lead in soil systems. Illite and zeolite adsorb little lead, while montmorillonite and kaolinite serve as adsorption nuclei for lead over a wide pH range (Scrudato and Estes 1975). Similarly, Lagerwerff and Brower (1973) found lead to be more strongly adsorbed by kaolinitic and montmorillonitic soils than by an illitic soil.

Arsenic in the Environment

Chemistry

Arsenic is commonly identified with toxic or potentially toxic metals, but in view of its chemical and physical properties, it is more suitably termed a metalloid (Peterson et al.1981). Arsenic is rarely encountered in natural environments as a free element, but is more commonly a component of sulfidic ores (NAS 1977). The valence states of arsenic are -3 (AsH_3), 0 (As), +3 (As_2O_3), and +5 (As_2O_5). Elemental arsenic, As^0, and arsine, As^{3-}, are characteristic of strongly reducing environments, with As^{3-} only occurring at very low redox values. Arsines and methylarsines, characteristic of the -3 oxidation state, are

generally unstable in air. Arsenic commonly exists in either the pentavalent or trivalent state. Arsenate, As^{5+}, is the stable oxidation state in aerobic environments, and arsenite, As^{3+}, is the dominant form under moderately reducing conditions (Deuel and Swoboda 1972). Arsenic forms covalent bonds with most nonmetals and metals and forms stable organic compounds in the As^{3+} and As^{5+} states. Arsenic and phosphorous share many similar chemical properties. They belong to the same chemical group and are assumed to react similarly in soils. Their acids have comparable dissociation constants and their salts have similar solubility products. Because of their chemical similarities, arsenic compounds compete with their phosphorous counterparts for chemical binding sites. Arsenic and phosphorous both form insoluble compounds with aluminum, iron, and calcium.

Sources

Arsenic is ubiquitous in the natural environment and is contained in over 200 minerals. It is highly associated with many metal deposits and therefore is used as an indicator in geochemical prospecting. Arsenic occurs in most of the major rock types at an average concentration of 0.5 to 2.5 ppm (Kabata-Pendias and Pendias 1992). Only in argillaceous sediments is arsenic concentrated at higher levels (averaging 13 ppm). Arsenic levels in soils seldom exceed 10 ppm if they have not been contaminated or treated with arsenical pesticides or defoliants (Adriano 1986). The mean concentration of arsenic in 910 samples of soils and other surficial materials throughout the continental United States was found to be 7.4 ppm (Shacklette et al. 1974).

Chilvers and Peterson (1987) estimated the ratio of natural to anthropogenic

atmospheric inputs of arsenic to be 60:40. Volcanism and volatilization account for 97 percent of natural emissions of arsenic. Copper smelting accounts for 40 percent of the human atmospheric input. Arsenic can be present in coal as arsenopyrite. Consequently, the combustion of coal, and other fossil fuels, introduces arsenic into the environment, as do chemical works based on sulfur and phosphorous minerals, geothermal power plants, and agricultural burning. Mine tailings are another anthropogenic source of arsenic. Overburden materials and waste rock containing arsenopyrite release arsenic when the pyrite is oxidized through exposure to oxygen, water, and bacteria. Arsenic also accumulates as a waste product of gold and lead refining and other non-ferrous metal production.

Arsenic in Plants

There is no evidence that arsenic is essential for plant or animal growth. Although some investigations have shown enhanced plant growth with very low levels of arsenic (Liebig et al. 1959; Woolson et al. 1971), it can be attributed to increased phosphorous availability from displacement of phosphate ions by arsenate ions (Jacobs et al. 1970). Because arsenic behaves very much like phosphate in the plant-soil system, it can enter into reactions in place of phosphorous (Bhumbla and Keefer 1994). There is strong evidence that arsenate is absorbed by plants in a manner similar to phosphate uptake (Bieleski and Ferguson 1983).

Though arsenic is phytotoxic, some grass species, such as *Agrostis tenuis* and *Agrostis stolonifera* are capable of tolerating and accumulating high concentrations of arsenic (Benson et al 1981; Porter and Peterson 1975). Crop plants have various degrees of

tolerance to soil arsenic (Adriano 1986). The potential for phytotoxicity is not accurately reflected by total soil arsenic levels (Adriano 1986; Woolson et al. 1971). Extractable soil arsenic is a better indicator, but the most reliable extraction technique has not been clearly defined (Munshower 1994). In a literature survey (EPA 1987), concentrations of 50 ppm extractable soil arsenic and 100 ppm total soil arsenic were cited as the phytotoxic levels. The extractable level was based on numerous studies with various extraction methods. The authors noted that a phytotoxic concentration as low as 10 ppm may be appropriate in some circumstances. The total level was based primarily on data of Woolson et al. (1973) and Steevens et al. (1972).

Soil System

The oxidation state of arsenic governs its reactions in soils. Arsenite, As^{3+}, the reduced state, is more soluble and mobile than arsenate, As^{5+}, the oxidized state (Deuel and Swoboda 1972). Arsenite is much more toxic than arsenate. Arsenate is more readily sorbed onto clay minerals (Frost and Griffin 1977).

The availability of arsenic is dependent on soil texture, pH, phosphate and fertility levels, plant species, soil mineralogy, redox conditions, and adsorption reactions (Wauchope 1975; 1983; Bhumbla and Keefer 1994). Sand and silt fractions offer little capacity for arsenic sorption due to their low surface area and predominance of quartz (Dickens and Hiltbold 1967). The clay fraction is the main sorber of arsenic ions (Jacobs et al. 1970). The most active soil components contributing to arsenic sorption and retention are oxides of aluminum, iron and manganese, and organic matter (Bhumbla and Keefer 1994).

Decomposition of organic matter yields organic substances that adsorb arsenic. Substances with aluminum, iron or calcium may form sparingly soluble arsenic compounds which are unavailable for plant uptake (Bhumbla and Keefer 1994). Hydroxy aluminum on the external surfaces of micaceous minerals are especially significant in arsenic retention (Huang 1975).

An inverse relationship exists between clay content and arsenic mobility and resultant phytotoxicity. Both hydrous iron and aluminum oxides vary directly with clay content, consequently, the water-soluble fraction of arsenic is highest in soils with low clay content and lowest in soils with a high clay content (Akins and Lewis 1976). Arsenite and arsenateare better adsorbed by montmorillonite than kaolinite (Frost and Griffin 1977), probably because montmorillonite has two and a half times more edge surface area than kaolinite. Montmorillonite also contains interlayer hydroxy aluminum polymers which could account for its higher adsorption of arsenic.

Soil pH and Arsenic

Everett (1962) reported that the high pH of grassland soils results in low plant uptake of arsenic. Soil pH influences the activity of aluminum in clays and hydrous oxides of soil colloids. Hiltbold (1975) found the quantity of these colloids, rather than the pH effect, is the governing factor in their adsorptive capacity. Elkhatib et al. (1984) found that soil pH influences the concentration of arsenic being adsorbed at the surface of aluminum and iron oxides, but the Eh and amount of oxides are the main parameters controlling sorption rate. Goldberg and Glaubig (1988) studied arsenate sorption as a function of pH on calcite and

two clay minerals. Arsenate sorption on calcite ($CaCO_3$) increased from pH 6 to 10, peaked between pH 10 and 12, and decreased above pH 12. Arsenate sorption on montmorillonite and kaolinite increased at low pH, peaked at pH 5.5, and decreased at higher pH. Their results indicate that carbonates play an important role in arsenate sorption of calcareous soils at higher pH levels. Jiang and Singh (1994) found no significant effects of liming on arsenic uptake by barley or ryegrass. However, the lime amendments only raised soil pH levels to 6.5 from pH 5.6 in a sand, and from pH 4.9 in a loam. In studies with sediments and soil suspended in solution, Masscheleyn et al. (1991a; 1991b) found arsenic to be increasingly mobilized by increasing pH and decreasing Eh levels. They concluded that arsenic contaminated wastes should be maintained with high redox and nonalkaline conditions to minimize arsenic solubility and mobilization. Marin et al. (1993) studied arsenic absorption by rice (*Oryza sativa* L.) under selected pH and redox conditions with effects of arsenic solubility and speciation. Most arsenic was present as arsenite below 0 mV redox potential. Arsenic availability increased with lower soil pH and with increasing amounts of soluble arsenite (lower soil redox). They concluded that a decrease in pH and/or a decrease in soil redox level results in increased arsenic availability to plants.

Zinc in the Environment

Chemistry

Zinc is divalent in all of its compounds. Zinc is the 24th most abundant element in the earth's crust, with an average value of 70 ppm (Krauskopf 1979). Zinc occurs in the soil primarily as the single sulfide mineral sphalerite, ZnS. It also occurs as $ZnCO_3$, smithsonite,

and as [Zn_4 $(OH)_2$ $Si_2O_7 \cdot H_2O$], hemimorphite. Zinc may also substitute for Mg^{2+} in silicates. Zinc is present in the soil exclusively in the divalent form (Barber 1995). Weathering processes, particularly in acidic oxidizing environments, solubilize zinc minerals producing mobile Zn^{2+}. Zinc is easily adsorbed by organic and mineral components and therefore, accumulates in soil surface horizons. Mean total zinc concentration for world-wide surface soils is 64 ppm (Kabata-Pendias and Pendias 1992).

Soil System

Zinc and other trace metals are partitioned into various forms based on the ways the elements are bound in soil and held against extraction by different chemical agents. The forms may include water-soluble, exchangeable, extractable, occluded by hydrous oxides, precipitates, immobilized in biota and residues, and lattice structure constituents of primary and secondary minerals. Zinc and other trace elements vary in their plant availability depending on the distribution of different forms or fractions between the soil matrix and soil solution. The water-soluble and exchangeable fractions of zinc are readily available to plants. In the other forms it is either unavailable or not readily available. Exchangeable zinc cations are electrostaticly attracted and adsorbed to negative sites on colloidal mineral solids and organic matter. Zinc fixed within mineral lattices is available only via mineral weathering. Sedberry and Reddy (1976) found the vast majority of the zinc fraction to be in the residual form (86.4%) with lesser amounts in the organic (4.4%), chelated (2.6%), exchangeable (0.9%), and water-soluble (1.7%) fractions. Hickey and Kittrick (1984) showed that the majority of zinc in heavily polluted soil is associated with iron and

manganese oxide formation. Sims and Patrick (1978) determined that higher concentrations of zinc are found in exchangeable or organic form at lower pH and Eh values than at higher pH and Eh values. They concluded that zinc in the oxalate and residual forms increases at higher pH. This indicates that the zinc precipitated and occluded as oxides and hydroxides is solubilized by low pH and soil saturation. MacLean and Langille's (1976) analyses of 434 soils showed a decrease in extractable zinc with increasing clay content, increasing soil pH levels, and decreasing soil organic matter. Stream studies of trace metals show zinc speciation changes downstream from mine wastes are largely the result of pH increases downstream from the contamination sources (Amacher et al. 1995). Pagenkopf's (1980) analysis of zinc species' distributions indicates that a sizable fraction of total zinc is complexed by carbonate at pH 7 or higher.

Zinc in Mine Tailings

Recent investigations have questioned the quantity and type of organic and vegetative cover layers used to reclaim tailings. Greenhouse studies by Banks et al. (1994) indicate that revegetation of mine tailings may increase the leaching of Zn, especially if the soil microflora has not been fully restored. Ribet et al. (1995) concluded that organic acids from organic carbon-rich material used to cover tailings may reductively dissolve Fe(III)-(oxy)hydroxides. This results in the mobilization of trace metals previously adsorbed on or coprecipitated with the Fe(III)-(oxy)hydroxides. The research of Burckhard et al. (1995) shows that the establishment of vegetation on tailings may increase the quantity of trace metals leached, and thereby increase groundwater contamination. They concluded that the

presence of rhizosphere organic acids increased the mobility of zinc from contaminated mine tailings.

Acid-Base Account

The acid-base account (ABA) is determined by subtracting the potential acidity (PA) from the neutralization potential (NP) (Equation 1).

$$ABA = NP - PA \quad [1]$$

Neutralization potential (NP) accounts for the alkaline carbonates, exchangeable bases, weatherable silicates, and other mineral sources which have the capability over time to neutralize the potential acidity. Potential acidity (PA) accounts for the acidity produced over time by the oxidation of the mineral fractions of sulfur. The organic sulfur component is not considered acid producing. The sulfur fractions can be differentiated into residual sulfur and the sulfur forms extractable by hot water, hydrochloric acid (HCl), and nitric acid (HNO_3). The total sulfur content is equal to the sum of all the sulfur fractions (Equation 2):

Total S = H_2O Extractable S + HCl Extractable S + HNO_3 Extractable S + Residual S [2]

The potential acidity has been determined by different methods (Smith et al. 1974; Sobek et al. 1978; Schafer et al. 1987). The accuracy of any method relies on the ability to distinguish acid producing from nonacid producing sulfur forms. The Sobek method is commonly used for analysis of coal deposits. The Schafer method is used for analysis of materials emanating from hardrock mining. A study of the two methods by Jennings and Dollhopf (1995b) found neither method to be entirely accurate. Their results indicate that a knowledge of the specific mineralogy of the sulfur compounds is necessary to accurately

determine potential acidity.

From the stoichiometry of the complete oxidation of FeS_2 it can be calculated that it will require 31.25 tons of $CaCO_3$ to completely neutralize the potential quantity of sulfuric acid produced by 1% sulfur, all as pyrite, in 1,000 tons of waste material (Smith et al. 1974). This is shown in Equation 3:

$$\text{PA, tons } CaCO_3 \text{ /1000 t} = (\text{Total S\%})31.25 \quad [3]$$

This method quantifies the potential acidity if the sulfur is present exclusively as pyrite. The acid-base account units, tons of $CaCO_3$ per thousand tons of waste material, are related to site remediation. One thousand tons is the approximate mass of an acre furrow slice, i.e. one acre of soil six inches deep or 0.4 hectare of soil 15 cm deep.

The Sobek (1978) method counts only the nitric acid extractable sulfur component as potentially acid producing sulfides (Equation 4):

$$\text{PA, tons } CaCO_3 \text{ /1000 t} = (HNO_3 \text{ extractable S\%})31.25 \quad [4]$$

This method does not use a hot water extraction. The hydrochloric acid extractable sulfur fraction is considered to be composed of non-acid producing sulfates and the residual sulfur fraction is considered to be composed of non-acid producing organically bound sulfur (Casagrande et al. 1989).

The Schafer (1987) method (Equation 5) counts the nitric acid extractable sulfur and the residual sulfur components as potentially acid producing sulfides. In addition, the hydrochloric acid extractable sulfur is considered potentially acid producing. The water extractable sulfur component is not considered acid producing.

$$\text{PA,tons } CaCO_3\text{/1000 t} = (HNO_3 \text{ Extractable S\% + Residual S\%})31.25 + (\text{HCl Extractable S\%})23.44 \quad [5]$$

The Sobek and Schafer methods both use the stoichiometry of the complete oxidation of FeS_2 to calculate 31.25 tons of $CaCO_3$ required to neutralize each 1% of pyritic sulfur in 1,000 tons of waste material. Similarly, the Schafer method calculates 23.44 tons of $CaCO_3$ are required to fully neutralize the potential acidity produced by the complete oxidation of each 1% of sulfur as jarosite, $KFe_3(SO_4)_2(OH)_6$ in 1,000 tons of waste material.

Lime Requirement

The application of lime amendments is a common agricultural practice designed to raise soil pH, increase basic cations, and decrease the levels of potentially toxic elements available in acid soils (Caruccio et al. 1988). The lime requirement is calculated to determine the quantity of lime amendments required to raise the pH to 11 and neutralize acid waste material in perpetuity (Montana DHES 1993). Raising the pH to 11 also immobilizes trace metals into precipitates, and hydroxide and carbonate complexes. The following Equation (6) is used:

Lime Requirement, tons $CaCO_3$ /1000 t = (Active Acidity + Potential Acidity) x Displacement Factor [6]

The active acidity accounts for the indigenous soil acidity. It is commonly measured by an agricultural lime requirement test such as the SMP Buffer method (Shoemaker et al. 1961) and is reported in units of tons $CaCO_3$ per 1000 tons of soil.

The displacement factor, generally 1.1 to 1.3, is a multiplier used to correct for the lack of complete quantitative displacement when the lime is incorporated into the waste material. Because lime moves slowly in the profile and is beneficial only in the immediate vicinity of application (Dollhopf 1992), the displacement factor is used to increase the

$CaCO_3$ application. It is based on a judgement of how thoroughly the lime will be incorporated and mixed into the soil profile.

The addition of $CaCO_3$ alone is not adequate to meet the goal of raising the system pH to 11 (Dollhopf 1992). A lime amendment composed solely of $CaCO_3$ is only capable of raising the pH to 8.5 or less. To raise the pH to 11 it is necessary to use hydrated lime, $Ca(OH)_2$, and/or quick lime, CaO, which react over time with CO_2 to form $CaCO_3$. If CaO is applied to a soil system it is hydrolyzed to $Ca(OH)_2$ in the presence of water (Reaction 6):

$$CaO + H_2O \Rightarrow Ca(OH)_2 \quad [6]$$

The addition of either CaO or $Ca(OH)_2$ rapidly raises the pH to 11and each Ca^{2+} ion replaces two adsorbed H^+ ions in the soil system (Reaction 7):

$$Ca(OH)_2 + 2H^+ \Rightarrow Ca^{2+} + 2H_2O \quad [7]$$

With time the following mellowing reactions occur which lower the pH from 11 to 8.5 or less (Reactions 8-11):

$$Ca(OH)_2 \Rightarrow Ca^{2+} + 2OH^- \quad [8]$$

$$OH^- + CO_2 \rightleftharpoons HCO_3^- \quad [9]$$

$$HCO_3^- + OH^- \Rightarrow CO_3^{2-} + H_2O \quad [10]$$

$$CO_3^{2-} + Ca^{2+} \Rightarrow CaCO_3 \quad [11]$$

Transformation to $CaCO_3$ can take six to twelve months to lower the pH in a field situation, however the process may be expedited in a laboratory setting with the addition of CO_2.

The solubility of $CaCO_3$ is also affected by the partial pressure of CO_2 which is relatively constant in the atmosphere but may fluctuate widely in the soil atmosphere due to microbial activity (Thomas and Hargrove 1984). The dissolution of $CaCO_3$ and subsequent

neutralization of soil acidity occurs during the following Reactions (12-14):

$$CaCO_3 + H_2O + CO_2 \Rightarrow Ca(HCO_3)_2 \quad [12]$$

$$Ca(HCO_3)_2 \Rightarrow Ca^{2+} + 2HCO_3^- \quad [13]$$

$$H^+ + HCO_3^- \Rightarrow H_2CO_3 \rightleftharpoons H_2O + CO_2 \quad [14]$$

The $CaCO_3$ equivalence of a liming agent must also be considered in determining the lime requirement. The effectiveness of a liming agent depends on its $CaCO_3$ equivalence (Thomas and Hargrove 1984). It is necessary to use fine liming materials to obtain rapid and effective pH increases because the reaction effectiveness is dependent on the amount of lime surface which makes contact (Tisdale and Nelson 1966). Numerous studies have shown a direct correlation between the effect of particle size and the reaction rate of lime in the soil(Meyer and Volk 1952; Beacher et al. 1952; Motto and Melstead 1960) . The finer the particle size the faster and more effectively it increases pH. Calcium diffusion in the soil is slow; therefore, finely ground lime particles uniformly mixed with the soil provide more particles per unit volume of soil, less distance between particles, and hence, more rapid pH increases (Barber 1984).

CHAPTER 3

SITE DESCRIPTION

Climate

The mean annual precipitation around the North Fork of Indian Creek is 46 to 51 centimeters. Mean annual snowfall is 250 to 500 centimeters. The portion of the mean annual precipitation which falls from May through July is 32.5 to 35 per cent. The mean annual air temperature is 3°C. The mean length of the freeze-free season is 110 to 115 days (Caprio et al. 1990).

Geology

The Park Mine District is northwest of Townsend, Montana in Township 7 North, Range 1 West, Broadwater County. This area is on the eastern flank of the Elkhorn Mountains which extend eastward to the Townsend Valley. To the northwest the Elkhorn Mountains merge into the Boulder Mountains south of Helena, Montana. The geology of this area of the Elkhorn Mountains as mapped by Klepper et al. (1971) is underlain by tuffs, tuff breccias, breccias interlayered with a few lava flows and thin welded tuff beds of the lower member of the Late Cretaceous Elkhorn Mountain Volcanics. The average composition is in the trachyandesite-rhyodacite range. Structurally, there is a broad north trending syncline offset by many steep dipping, north and east trending faults. The area has

several irregular porphyrytic dykes and sills. The predominant vein minerals from the Marietta mines are pyrite, arsenopyrite, galena, quartz, gold, chalcopyrite, sphalerite, and carbonates (siderite, ankerite, and manganocalcite) in a silicified andesite gangue (Reed 1951; Schell 1963).

Physiography and Soil

The area is characterized by subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) and Douglas fir (*Pseutotsuga menziesii* [Mirb.] Franco) climax forests on moderately steep to very steep mountain slopes (35 to 60 percent). It is used primarily for range and recreation. The Ess-Cheadle soil complex is predominant in this portion of the Elkhorns. This soil complex consists of about 50 percent Ess stony loam and very stony loam and 40 percent Cheadle cobbly loam and stony loam, and is characterized by deep soils with cryic temperature regimes (Olsen et al. 1977). Included with these soils are rock outcrops, making up about ten percent of the area. The hazard of soil erosion is severe and runoff is rapid.

The stretch of stream where tailings deposits were found is classified as "B3a" (Rosgen 1994). This classification system designates "B" streams as moderately entrenched, moderate gradient, riffle dominated channels, where rapids predominate with infrequently spaced pools. They have very stable plans and profiles with stable banks. The "3" indicates channel materials composed primarily of cobbles, and "a" designates the slope range of four to ten percent.

Site Reconnaissance

The mine tailings deposits were located and mapped to determine their extent and distribution from the Park Mines to the North Fork's confluence with the West Fork of Indian Creek [Sections 14, 15, 23, 24, 25, 36; Township 7 North, Range 1 West] (Figure 1). Mapping was performed on site with the aid of aerial photographs and topographic maps. Five tailings deposition sites were located on Bureau of Land Management public lands in Sections 25 and 36 (Figure 2). All five are adjacent and upstream to remnants of beaver dams containing many beaver chewed logs and stumps nearby. This indicates that the tailings were deposited in previously existing beaver ponds. The perimeters of the depositions were measured to determine areal extent, and holes were dug to determine depths. The tailings deposits range in size from three to 279 square meters; total areal extent is 604 square meters (Table 1). The depths of tailings range from a thin film to 51 centimeters (Table 1).

Higher upstream, one deposition site is located on the Helena National Forest adjacent to a human-made dam which has been breached. The areal extent of this deposit is approximately 930 square meters. The tailings deposited in the former pond at this site have been eroded by the North Fork of Indian Creek which meanders through the deposit.

Even higher upstream is another human made former pond site containing tailings. This site is located on private land which is part of the Park Mines complex. It also is adjacent to a human-made dam which has been breached, and also is bisected and eroded by the meandering North Fork of Indian Creek.

Still higher upstream, is another human-made pond. This pond currently has its dam

intact. The water in the pond does not appear to support life.

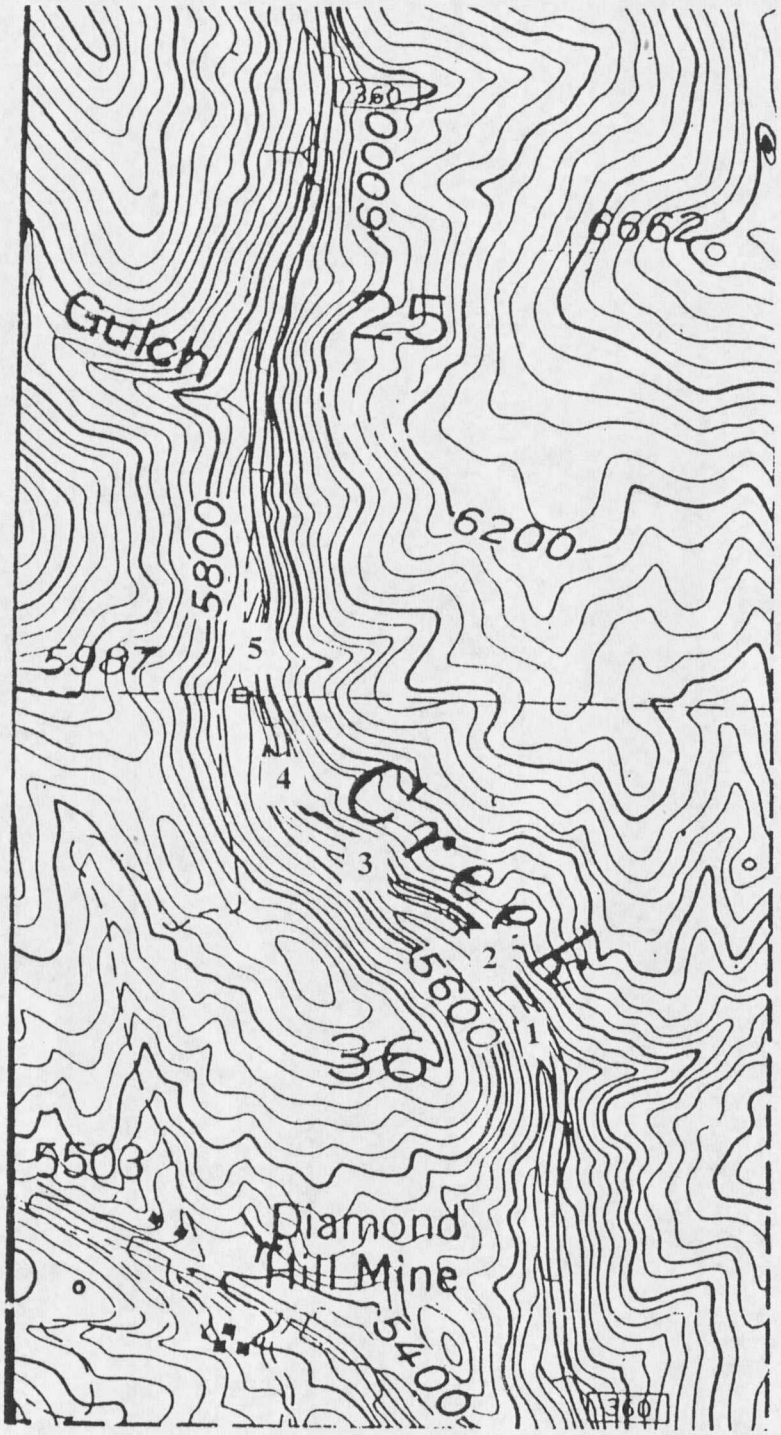

Figure 2. Location of Tailings Deposition Sites 1 through 5 along Indian Creek.

Table 1. Thickness and Areal Distribution of Tailings Along Indian Creek.

Site	Thickness (cm)	Area (m^2)
1	20.3	2.97
2a*	2.5	32.25
	6.4	1.39
	7.6	6.69
	8.9	3.25
	12.7	2.60
2b*	6.4	2.04
	7.6	6.97
	8.9	13.94
	10.2	11.15
	40.6	15.61
3	7.6	11.15
	15.2	9.29
4	5.1	2.79
	15.2	8.36
5a**	7.6	27.88
	50.8	139.4
5b**	17.8	5.58
	40.6	5.58

*Site 2a is located on the east side and Site 2b is on the west side of Indian Creek.

**Site 5a is located in an old stream channel and Site 5b is adjacent to the stream.

Vegetation

The predominant riparian habitat type (Hansen et al. 1995) in the tailings deposit area is Douglas fir /red osier dogwood (*Pseutotsuga menziesii* [Mirb.] Franco /*Cornus stolonifera* Michx.) The cover and composition of vegetation in the vicinity of the tailings sites were identified with two pacing point transects (Evans and Love 1957). The first transect (Table 2) was paced along the stream side near deposition site number 2. The second transect (Table 3) was paced near deposition site number 5 along old channel and bench positions. The transects were 100 paces each. Redtop (*Agrostis stolonifera* L.), a non-native grass, was the dominant species present along both transects.

Table 2. Ground Level Cover at Transect One.

Scientific Name	Common Name	Cover (%)
Achillea millefolium	Common yarrow	1
Agropyron intermedium	Intermediate wheatgrass	1
Agrostis stolonifera	Redtop	46
Alnus viridis	Alder	1
Aster hesperius	Western willow aster	5
Cirsium vulgare	Bull thistle	1
Deschampsia caespitosa	Tufted hairgrass	1
Equisetum spp.	Scouring rush	1
Heracleum sphondylium	Cow parsnip	1
Juncus balticus	Wire rush	7
Juniperus scopulorum	Rocky Mountain juniper	1
Mentha arvensis	Wild mint	1
Potentilla spp.	Cinquefoil	2
Plantago major	Broadleaf plantin	1
Pseudotsuga menziesii	Douglas fir	1
Salix geyeriana	Willow	1
Rock		20
Moss		4
Bareground		2
Wood		1
Cow Manure		1

Table 3. Ground Level Cover at Transect Two.

Scientific Name	Common Name	Cover (%)
Agrostis stolonifera	Redtop	34
Antennaria spp.	Pussytoes	1
Aster hesperius	Western willow aster	2
Carex rostrata	Beaked sedge	1
Cirsium vulgare	Bull thistle	1
Elymus cinereus	Basin wildrye	1
Epilobium glaberrimum	Fireweed	1
Equisetum spp.	Scouring rush	3
Juniperus scopulorum	Rocky Mountain juniper	2
Populus tremuloides	Quaking aspen	2
Rosa spp.	Wild rose	2
Stipa occidentalis	Western needlegrass	1
Litter		25
Rock		18
Water		3
Wood		2
Cow Manure		1

CHAPTER 4

METHODS

Sample Collection and Preparation

Based on the reconnaissance findings, a 225 liter composite bulk sample of tailings was collected from Site 5 (Figure 2). This site is the largest tailings deposit area which is barren of plant life along the Bureau of Land Management segment of Indian Creek. The sample was a composite of tailings collected from ten pits that were dug 50 centimeters deep. All pits were in fluvial tailings deposits; no native subsoil material was sampled.

The bulk sample of tailings material was dried at 48.5°C for 72 hours in the Montana State University Plant Growth Center soil drying ovens. Rock fragments were seperated from soil by hand sieving with a 2 mm opening brass sieve, U.S. Standard Sieve Series No. 10. Soil aggregates and clods were crushed with a rubber tipped pestle and mortar (ASTM 1993) before sieving. The rock fragment (greater than 2 mm particle diameter) content by volume was determined by displacement of an equal volume of water in a container. The sample material less than 2 mm in diameter was thoroughly mixed and a split of the sample was used for analyses. The remaining tailings material was used for soil growth media in greenhouse plant growth trials.

Sample Analyses

The analytical methods used for determining physical and chemical parameters are presented in Table 4. Analyses for pH, electrical conductivity (EC), and particle size distribution were performed at the Reclamation Research Unit Laboratory. The pH and EC were measured on saturation paste extracts with a glass electrode pH meter and a conductivity bridge. Texture (particle size distribution) was determined by the hydrometer method. Analyses for total and extractable quantities of arsenic, cadmium, copper, lead, manganese, and zinc were performed by Energy Labs of Billings MT. Energy Labs also determined the neutralization potential, sulfur fractions, and SMP lime requirement to neutralize active acidity.

Lime Amendments

Based on the results of the sulfur fractions and neutralization potential the potential acidity and acid-base account were calculated using the method of Schafer et al. (1987) (Equation 5). The acid-base account and active acidity (SMP lime requirement) were used with a displacement factor of 1.125 to calculate the lime requirement necessary to raise the pH to 11. A portion of the bulk sample of tailings was amended to raise the pH to 11 in order to produce an adequate growing medium with trace metals immobilized. This was accomplished with sixty percent calcite ($CaCO_3$) at 95% $CaCO_3$ equivalence and forty percent hydrated lime [$Ca(OH)_2$] at 136% $CaCO_3$ equivalence. The calcite was purchased from Montana Limestone of Bridger MT and the hydrated lime was purchased from Dyce

Chemical of Billings MT. The fineness of both the calcite and hydrated lime used was 100 minus mesh (0.15mm).

Table 4. Analytical Procedures for Physical and Chemical Analyses of Tailings.

Parameter	Analytical Method
pH	Saturated paste extract, Sandoval and Power 1978.
Electrical Conductivity (EC)	
Particle Size Distribution	Hydrometer method, Day 1965.
Neutralization Potential	NaOH titration, Sobek et al. 1978.
Lime Requirement for Active Acidity	SMP buffer, McLean 1982.
Hot Water Extractable SO_4	Schafer et al. 1987.
HCl Extractable SO_4	"
HNO_3 Extractable S	"
Total S	"
Total Metals: Arsenic, Cadmium, Copper, Lead, Manganese, Zinc	Nitric acid-hydrogen peroxide digestion, EPA Method 3050 1986.
Extractable Metals: Cadmium, Copper, Lead, Manganese, Zinc	DTPA soil test, Lindsay and Norvell 1978.
Extractable Arsenic	Hot Water Extract, Fine 1965.

Greenhouse Experiment

Design

A greenhouse growth trial was conducted in the Montana State University Plant Growth Center. A randomized complete block experimental design was used. (LeClerg et al. 1962). Each of the nine treatments (3 soil x 3 vegetation) was replicated five times. The soil factors consisted of the following three levels: 1) a control of tailings material with no amendments added, 2) tailings material with lime amendments added, 3) tailings material with lime amendments plus manure added. The vegetation factors consisted of the three grass species, redtop (*Agrostis stolonifera* L.), tufted hairgrass (*Deschampsia cespitosa* [L.] Beauv.) and Great Basin wildrye (*Elymus cinereus* Scribn. & Merr.).

Agrostis stolonifera, *Deschampsia cespitosa*, and *Elymus cinereus* were selected as revegetation species because they are easily grown in poorly drained and acid soils with a high water table (Munshower 1991). Also, *Agrostis stolonifera* and *Deschampsia cespitosa* are easy to establish from seed and have ecotypes with metal tolerant characteristics.

To minimize any variation within the greenhouse environment, each treatment was placed in a random location within the block. In addition, once a week, each block was rotated to a new position and the treatments were re-randomized within the block at that time.

Amendments

The amount of lime added to the tailings + lime and the tailings + lime/manure treatments was equivalent to 142 tons of $CaCO_3$ per 1000 tons waste material, and was

applied in the proportions of $CaCO_3$ and $Ca(OH)_2$ stated previously (Lime Amendments). Thorough mixing of the lime amendments into the tailings raised the pH from 1.82 to 11.46 for the tailings + lime and tailings + lime/manure soil levels. The mellowing reactions, as mentioned previously in Chapter 2, Lime Requirement, then decreased the pH to 7.40. The mellowing was expedited by bubbling carbon dioxide into the amended tailings through a buried and coiled perforated rubber hose. The carbon dioxide rate was 0.70 kg/cm^2 for 19 hours.

Four per cent by dry weight composted steer manure was added to the tailings + lime/manure soil level. The manure was purchased from Ernst Nursery of Bozeman MT.

Before seeding, all treatments had fertilizer incorporated throughout the soil at the following rates: nitrogen--168 kg/ha; phosphorous--34 kg/ha; potassium--224 kg/ha; boron--2.2 kg/ha. The three soil treatments were loaded into PVC growth cylinders. The cylinder dimensions were 10 centimeters in diameter by 38 centimeters in length. The three grass species were surface seeded and tamped down to insure soil contact. After thinning, a maximum of five grass plants per cylinder were grown.

Each growth cylinder was watered at the rate of 50 ml per day for the first 16 days of germination and growth. As the grass plants increased in size, the watering rate was increased to 68 ml per day for 74 days. The grass plants were grown at 25°C with 18 hours of light per day. Night temperature was maintained at 18°C.

Response Variables

The plants were harvested after 90 days and the following variables were measured: 1) above ground production, 2) below ground production, 3) shoot length, 4) root length, 5) vigor, and 6) soil pH. Above ground production was determined by clipping the vegetation in each growing cylinder at soil level, placing the vegetation in paper bags, drying at 43 °C in the Plant Growth Center ovens for 48 hours, and weighing. Below ground production was determined by washing and separating soil from the root mass, placing roots in paper bags, drying at 43 °C for 48 hours, and weighing. Shoot length was measured as the height of the majority of the longest grass shoots. Root length was measured as the maximum rooting depth. Vigor was determined on a qualitative scale of zero through four, ranging from no growth to robust vigorous growth. The pH was measured with saturation paste extracts (Sandoval and Power 1978). In addition, the root to shoot production ratio and total production were calculated from the root and shoot production measurements.

CHAPTER 5

RESULTS AND DISCUSSION

Tailings Physical and Acid Producing Characteristics

The results of tailings analyses for electrical conductivity, pH, and particle size distribution are presented in Table 5. The streamside tailings deposits have suitable textural characteristics for plant growth, i.e. silt loam with seven per cent coarse fragments. However, the electrical conductivity is very high at 16.62 mmhos/cm and the material is extremely acidic with pH of 1.82. An electrical conductivity greater than 8 mmhos/cm or a soil pH less than 5.5 are considered unsuitable for redistributed soil at reclaimed mine sites (MT DEQ 1994). At pH values below 5.5, available metal levels may become so high that they limit plant growth (Munshower 1994). Optimal soil pH ranges for most plants range from 5.5 to 7.5 (Askenasy and Severson 1988).

The acid producing characteristics (Table 5) indicate soil characteristics that are unsuitable for plant growth. The total sulfur content is high at 4.47%. The neutralization potential is nil at <1 ton/1000 tons soil. The HCl extractable, HNO_3 extractable, and residual sulfur fractions indicate a high potential acidity of 102 tons $CaCO_3$/1000 tons as calculated by the Schafer (1987) method with Equation 10 (Chapter 2). In addition the active acidity is very high as indicated by the agricultural lime requirement of 24.3 tons $CaCO_3$/1000 tons soil. The acid-base account is -102 tons $CaCO_3$/1000 tons waste material. This indicates

that as the tailings oxidize there is great potential to generate large amounts of acidity.

Table 5. Laboratory Analyses for Unamended Tailings Physical and Chemical Parameters.

Parameter	**Result**
pH	1.82
EC (mmhos/cm)	16.62
Particle Size Distribution	Fine fraction = 42% sand, 51% silt, 7% clay Rock content (>2mm diameter) by volume = 7%
Textural Class	Silt Loam
Neutralization Potential	<1 ton/1000 tons soil
Potential Acidity	102 tons $CaCO_3$/1000 tons soil
Acid-Base Account	-102 tons $CaCO_3$/1000 tons soil
Active Acidity	24.3 tons $CaCO_3$/1000 tons soil
Total Sulfur	4.47%
Hot H_2O Extractable Sulfur	0.98%
HCl Extractable Sulfur	0.90%
HNO_3 Extractable Sulfur	2.35%
Residual Sulfur	0.24%

Tailings Metal and Arsenic Contents

The tailings deposits have total concentrations of cadmium, copper, and manganese that are not considered toxic to plant growth (Table 6). The analyses for total concentrations show the tailings have elevated levels of lead, arsenic and zinc.

Table 6. Total and Extractable Concentrations for Metals and Arsenic in Tailings.

Element	Extractable (μg/g)	Total (μg/g)
Cadmium	0.7	<1
Copper	9	53
Lead	1.6	4110
Manganese	50.8	72
Zinc	126.1	300
Arsenic	141.0	1570

The total lead level in the tailings of 4,110 μg/g is much higher than mean U.S. soil concentrations of 16 ppm (Shacklette et al. 1971). The extremely low pH and small percentage of clay (Table 5) indicate an increased phytoavailability of metals. This high concentration in an acidic system where the solubility, phytoavailability and uptake of lead are increased, indicates that the deposits are phytotoxic. However, the extractable lead level of 1.6 μg/g is considerably lower than the phytotoxic extractable level of 500 ppm cited by EPA (1987). Lead is easily adsorbed and precipitated at increasing pH with 100% being removed from the soil solution at high pH (McBride 1994). Because the DTPA extraction method buffers the sample to pH 7.3, it is not a reliable estimate of the phytoavailable lead level in an acidic soil system (Neuman 1996).

The tailings total arsenic concentration of 1,570 μg/g is extremely elevated over the mean U.S. soil concentration of 7.4 ppm (Shacklette et al. 1974), and is more than 15 times the phytotoxic soil level of 100 ppm cited by EPA (1987). The extractable arsenic concentration of 141 μg/g is considerably higher than the phytotoxic soil level of 50 ppm

cited by EPA (1987).

The tailings total zinc concentration of 300 μg/g is elevated above the world-wide soil average of 64 ppm (Kabata-Pendias and Pendias 1992) and the U.S. soil average of 54 ppm (Connor and Shacklette 1975), although it is within the range reported by Connor and Shacklette (1975) for U.S. soils of 10 to 300 ppm. Numerous studies report yield reductions for crop species with 100 to 300 ppm total zinc levels (Boawn and Rasmussen 1971; Mitchell et al. 1978; Mortvedt and Giodano 1975; White and Chaney 1980). These studies were with soils having pH ranges of 5.5 to 7.5. Because zinc concentration in soil solution has been shown to increase as much as 30 fold for each unit of pH decrease (McBride and Blasiak 1979; Bar-Yosef 1979) it is likely that a total zinc level of 300 μg/g in an extremely acidic system will be phytotoxic. The phytotoxic extractable soil zinc level of 60 ppm was cited by EPA (1987) with a note that there are arguments to revise the level to 125 ppm. The tailings extractable zinc concentration of 126.1 μg/g is higher than both of these levels.

Plant Growth Response to Treatments

The greenhouse trial had no seed germination in the control soil and therefore, no plant growth in the control soil. The other two soil treatments, tailings plus lime and tailings plus lime/ manure, proved to be adequate growth mediums for all three grass species. Data for these response variables are shown in Appendix C. *Agrostis, Deschampsia,* and *Elymus* seeds germinated and sprouted after six to eight days in both the tailings + lime and tailings + lime/manure soils.

Two way analysis of variance statistical tests were run on SigmaStat (1994) software

for each response variable except vigor with soil and grass factors. Two way analysis of variance tests were also run for each variable except vigor with soil and block factors for each of the grasses individually in order to examine how the soil treatments differed for each grass species. The block factor isolated differences among any of the five repetitions. Significant differences were not found between any of the blocks for any of the variables. Kruskal-Wallis one way analysis of variance on ranks tests (Neter et al.1990) were run for the qualitative response variable vigor with soil, grass, and individual grass species factors. If a statistically significant difference ($p < 0.05$) was detected, a Student-Newman-Keuls pairwise multiple comparison test (Keuls 1952) was used to determine which levels differed from the others. Analysis of variance and multiple comparison results are shown in Appendices A and B.

Soil Treatments

The means of the measured and calculated response variables for soil and grass levels are shown in Table 7. There was a significant ($p<0.05$) increase in all response variables between the control and the tailings + lime, and between the control and the tailings + lime/manure soil levels. This universal positive plant response to the lime amendments indicates the tailings' unsuitable chartacteristics were significantly altered. The trace metals were precipitated or complexed out of solution and the acidity was neutralized. This resulted in a chemically modified soil solution system that is suitable for root viability.

No significant differences in either root or shoot lengths occurred between the tailings + lime and tailings + lime/manure soils. The root weights did not change significantly

between the tailings + lime and tailings + lime/manure soils. The root to shoot ratio decreased significantly from the tailings + lime to the tailings + lime/manure soil. This can be attributed to the increased shoot production of the tailings + lime/manure soil level. The vigor between the tailings + lime and tailings + lime/manure soils did not significantly change. The shoot weights and total weights increased significantly between the tailings + lime and tailings + lime/manure soils.

Table 7. Response Variable Means for Soils* and Grass Species.*

Soil Level	Root weight g/pot	Shoot weight g/pot	Total weight g/pot	Root/ shoot ratio	Shoot length cm	Root length cm	pH	Vigor 0 to 4
Control	0.00a	0.00a	0.00a	0.00a	0.00a	0.00a	1.84a	0.00a
Limed	3.90b	5.90b	9.80b	0.82b	34.8b	35.2b	7.49b	3.43b
Limed/Manure	4.28b	8.81c	13.09c	0.45c	34.5b	35.8b	7.38b	3.90b
Grass Level								
Agrostis	1.99a	4.22a	6.22a	0.60a	23.7a	23.6a	5.53a	2.30a
Deschampsia	0.80b	3.70a	4.50b	0.14b	10.9b	23.4a	5.52a	2.37a
Elymus	5.40c	6.78b	12.17c	0.53a	34.8c	24.0a	5.66a	2.67a

Means followed by the same letter within a column for a given level are not significantly different at the 0.05 probability level.
* Mean of 15 observations (except pH, n=11-15).

The increased production between the tailings + lime and tailings + lime/manure soils indicates a positive response to the addition of manure. The manure amendment rate of 4% by dry weight was used because it is comparable to organic matter levels found in grassland

soils. Organic matter can aid seed germination and establishment by means of improving soil structure, increasing infiltration and lowering soil surface temperatures (Munshower 1994). Organic matter also enhances plant nutrient availability by increasing cation exchange capacity and providing a steady supply of nutrients through decomposition and mineralization (Smith et al. 1987). Manure is one of the more complete sources of organic matter that may be used to amend a disturbed soil (Meek et al. 1982). The positive response to the manure amendment resulted primarily from the *Agrostis* shoot production increase. If a rate of 8% by dry weight manure had been used it is likely that all three species would show increased production over the tailings + lime soil.

Grass Species

The results of the grass level means show the shoot weight of *Elymus* plants were significantly greater than the *Agrostis* and *Deschampsia* plants, which were not significantly different from each other. This can be partially attributed to the large, medium, and small growth stature of *Elymus*, *Agrostis*, and *Deschampsia* respectively. Shoot lengths, root weights and total weights show significant and progressive increases from *Deschampsia* to *Agrostis* to *Elymus*. Again, this can be attributed to the growth stature of the species. No significant differences between species were observed for root length. This can be attributed to the fact that most roots grew the full length of the growth cylinder. The root to shoot ratio was not significantly different for *Agrostis* and *Elymus* but both were significantly greater compared to *Deschampsia*.

Individual Grass Species

The means of the measured and calculated response variables for soil levels within the individual grass species are shown in Table 8. With two exceptions, there was a significant ($p<0.05$) increase in all response variables for all grass species between the control and the tailings + lime, and between the control and the tailings + lime/manure soil levels. The exceptions are 1) no significant differences in shoot weights for *Agrostis* between the control and tailings + lime soil levels, and 2) no significant difference in root to shoot ratios for *Agrostis* between the control and tailings + lime/manure soils. This can be attributed to very low shoot weights for two of the five repetitions of the *Agrostis* x tailings + lime treatment which lowered the mean shoot weight and increased the root to shoot ratio for this treatment.

Root, shoot, and total weights for *Agrostis* all increased significantly between the tailings + lime and tailings + lime/manure soils. This indicates a positive production response to the addition of manure. Neither the shoot and root lengths, nor the vigor for Agrostis changed significantly between the tailings + lime and tailings + lime/manure soils.

Deschampsia plants showed a significant increase in shoot weight between the tailings + lime and tailings + lime/manure soils. This might indicate a positive response to the manure, however it is not indicated by any of the other response variables. Root and total weights, root to shoot ratio, shoot and root lengths, and vigor all remained unchanged between the tailings + lime and tailings + lime/manure soils.

Table 8. Response Variable Means for Individual Grass Species*

Agrostis	Root weight g/pot	Shoot weight g/pot	Total weight g/pot	Root/ shoot ratio	Shoot length cm	Root length cm	pH	Vigor 0 to 4
Control	0.00a	0.00a	0.00a	0.00a	0.00a	0.00a	1.83a	0.00a
Limed	2.12b	1.95a	4.07b	1.43b	35.6b	34.8b	7.45b	3.00b
Limed/Manure	3.86c	10.71b	14.58c	0.37a	35.4b	36.0b	7.31b	3.90b
Deschampsia								
Control	0.00a	0.00a	0.00a	0.00a	0.00a	0.00a	1.84a	0.00a
Limed	1.27b	5.37b	6.64b	0.23b	15.8b	34.8b	7.38b	3.30b
Limed/Manure	1.13b	5.74c	6.87b	0.19b	16.8b	35.4b	7.35b	3.80b
Elymus								
Control	0.00a	0.00a	0.00a	0.00a	0.00a	0.00a	1.84a	0.00a
Limed	8.32b	10.40b	18.70b	0.80b	53.0b	36.0b	7.57b	4.00b
Limed/Manure	7.86b	9.96c	17.82b	0.79b	51.4b	36.0b	7.55b	4.00b

Means followed by the same letter within a column for a given grass specie are not significantly different at the 0.05 probability level.
* Mean of 5 observations (except pH, n=2-5).

Elymus plants had a significant decrease in shoot weights between the tailings + lime and tailings + lime/manure soils. There were no significant differences between tailings + lime and tailings + lime/manure soil levels for any of the other response variables for the *Elymus* plants. This indicates that the addition of manure did not induce a positive production response for the *Elymus* plants.

Plant Production

The plant production in the lime amended soils was suitable to reclaim the tailings. A silty range site in Montana (foothills and mountains, 38 to 48 cm precipitation zone) will normally produce 2,465 kg/ha of above ground plant forage annually (SCS 1981). The mean shoot weight greenhouse production of 5.90 g/pot in the tailings + lime soil and 8.81 g/pot in the tailings + limed/manure soil equate to production of 7,512 kg/ha in the tailings + lime soil and 11,217 kg/ha in the tailings + limed/manure soil. Except the control, the lowest mean shoot weight production in the greenhouse trials was for *Agrostis* in the tailings + lime soil. The greenhouse production of 1.95 g/pot for *Agrostis* equates to production of 2,483 kg/ha. Though field conditions are never as ideal as a greenhouse environment, these production values indicate that tailings amended with lime are capable of producing sufficient vegetation to provide suitable cover and adequate erosion control stabilization for tailings deposition sites.

Soil pH

The liming procedure with $CaCO_3$ and $Ca(OH)_2$ successfully raised the pH of the two amended soils from 1.82 to 11.46. The mellowing with CO_2 successfully lowered the pH to 7.40. After the greenhouse trial the mean pH value for the control was 1.84 (Table 7). The pH levels of tailings + lime and tailings + lime/manure soil levels were increased significantly higher than the tailings control to 7.49 and 7.38, respectively. There was no significant differences between these two levels.

CHAPTER 6

CONCLUSION

Five tailings sites were located in the riparian zone of Indian Creek adjacent to former beaver dams. These sites are not currently supporting vegetation. A sample of the mine tailings deposits was analyzed. The tailings are extremely acidic with pH 1.8 and contain elevated levels of lead (4110 μg/g), arsenic (1570 μg/g), and zinc (300 μg/g). They have a high total sulfur content (4.47%), that yield a potential acidity of 102 tons $CaCO_3$/1000tons waste. The active acidity is also high at 24.3 tons $CaCO_3$/1000tons waste, and the neutralization potential is <1 ton $CaCO_3$/1000 tons waste. The lime requirement to neutralize the tailings with a 1.125 displacement factor is 142 tons of $CaCO_3$/1000 tons waste.

The extreme acidity and metal contamination of the Indian Creek tailings deposits can be successfully ameliorated with $CaCO_3$ and $Ca(OH)_2$ amendments. The greenhouse trial indicates that the riparian tailings deposits along Indian Creek can be successfully revegetated with grass species. Native species such as *Deschampsia cespitosa* and *Elymus cinereus* are less likely to respond to a manure amendment rate of 4% by dry weight. *Agrostis stolonifera* is more likely to respond positively to a manure amendment rate of 4%, and thus gain a greater competitive advantage over *Deschampsia cespitosa* and *Elymus cinereus*.

LITERATURE CITED

Adriano, D.C. 1986. Trace elements in the terrestrial environment. Springer-Verlag New York, Inc. NY. pp. 46-72; 219-262.

Akins, M.B. and R.J. Lewis. 1976. Chemical distribution and gaseous evolution of Arsenic-^{74} added to soils as DSMA-^{74} As. Soil Sci. Soc. Am. Jour. 40(5):655-658.

Amacher, M.C., R.W. Brown, R.C. Sidle and J. Kotuby-Amacher. 1995. Effect of mine waste on element speciation in headwater streams. In: Metal speciation and contamination of soil. H.E. Allen et al., eds. CRC Press. Boca Raton FL. pp.275-309.

American Geological Institute. 1976. Dictionary of geological terms. Anchor Press. NY. p. 424

Arvik, J.H. and R.L. Zimdahl. 1974. The influence of temperature, pH, and metabolic inhibitors on uptake of lead by plant roots. J. Environ. Qual. 3(4):374-376.

Askenasy, P.E. and R.C. Severson. 1988. Chemical procedures applicable to overburden and minesoil. In: Reclamation of surface-mined lands, Vol.1. L.R.Hossner, ed. CRC Press, Boca Raton FL. pp.55-80.

ASTM. 1993. Standard practice for dry preparation of soil samples for particle-size analysis and determination of soil constants. D421-85. Annual Book of ASTM Standards. Vol. 04.08. p.91.

Banks, M.K., A.P. Schwab, G.R. Fleming and B.A. Hetrick. 1994. Effects of plants and soil microflora on leaching of zinc from mine tailings. Chemosphere. 29(8):1691-1699.

Bar-Yosef, B. 1979. pH-dependent Zn adsorption by soils. Soil Sci. Soc. Am. J. 43:1095-1099.

Barber, S.A. 1984. Liming materials and practices. In: Soil acidity and liming. F. Adams, ed.Amer. Soc. Agron. Madison WI. pp.171-209.

Barber, S.A. 1995. Soil nutrient bioavailability: a mechanistic approach. Wiley & Sons. NY. pp. 353-371.

Baumhardt, G.R. and L.F. Welch. 1972. Lead uptake and corn growth with soil-applied lead. J. Environ. Qual. 1(1):92-94.

Beacher, R.L., D. Longnecker and F.G. Merkle. 1952. Influence of form, fineness, and amount of limestone on plant development and certain soil characteristics. Soil Science. 73:75-82.

Beck, J.V. and D.G. Brown. 1968. Direct sulfide oxidation in the solubilization of sulfide ores by *Thiobacillus ferrooxidans.* J. Bacteriology. 96:1433.

Benson, L.M., E.K. Porter and P.J. Peterson. 1981. Arsenic accumulation, tolerance, and genotypic variation in plants on arsenical mine wastes in South-West England. J. Plant Nutr. 3:655-666.

Bhumbla, D.K. and R.F. Keefer. 1994. Arsenic mobilization and bioavailability in soils. In: Arsenic in the environment. Part I. J.O. Nriagu, ed. Wiley & Sons. NY. pp.51-82.

Bieleski, R.L. and I.B. Ferguson. 1983. Physiology and metabolism of phosphate and its compounds. Encycl. Plant Physiol. New Ser. pp.422-449.

Biesecker, J.E. and J.R. George. 1966. Stream quality in Appalachia as related to coal mine drainage, 1965. U.S. Geol. Surv. Circ. 526. Wash. D.C.

Boawn, L.C. and P.E. Rasmussen. 1971. Crop response to excessive zinc fertilization of alkaline soil. Agron. J. 63:874-876.

Bohn, H.L., B.L. McNeal and G.A. O'Connor. 1985. Soil Chemistry. Wiley & Sons. NY. pp.135-152.

Bowen, H.J.M. 1966. Trace Elements in Biochemistry. Academic Press. N.Y.

Brooks, R.R. 1977. Pollution through trace elements. In: Environmental Chemistry. J.O'M. Bockris, ed. Pleneum Press. NY. pp.429-446.

Bunzl, K., 1974. Kinetics of ion exchange in soil organic matter. J. Soil Sci. 25(4):517-532.

Bunzl, K., W. Schmidt and B. Sansoni. 1976. Kinetics of ion exchange in soil organic matter. J. Soil Sci. 27(1):32-41.

Burckhard, S.R., A.P. Schwab and M.K. Banks. 1995. The effects of organic acids on the leaching of heavy metals from mine tailings. J. Haz. Materials. 41:135-145.

Burt, R.A. and F.T. Caruccio. 1986. The effect of limestone treatment on the rate of acid generation from pyritic gangue. Environ. Geochem. Health. 8:71.

Caprio, J.M., J.S. Jacobsen and G.A. Nielsen. 1990. Montana agriculture potential systems. MAPS Mailbox computer software. Montana State Univ. Bozeman MT.

Caruccio, F.T. 1969. Characterization of strip mine drainage by pyrite grain size and chemical quality of existing groundwater. In: Ecology and Reclamation of drastically disturbed sites. Vol. 1. R.J. Hutnick and G. Davis, eds. Gordon & Breach NY. p.193.

Caruccio, F.T. 1973. Estimating the acid potential of coal mine refuse. In: The ecology of resource degradation and renewal. M.J. Chadwick and G.T. Goodman, eds. Blackwell Scientific. Oxford. p. 197.

Caruccio, F.T., G. Geidel and M. Pelletier. 1981. Occurrence and prediction of acid drainages. J. Energy Div. Amer. Soc. Civil Eng. 107:167.

Caruccio, F.T., Hossner, L.R. and Geidel, G. 1988. Pyritic materials: Acid drainage, soil acidity, and liming. In: Reclamation of surface-mined lands, Vol.1. L.R.Hossner, ed. CRC Press, Boca Raton FL. pp.159-189.

Casagrande, D.J., R.B. Finkelman and F.T. Caruccio. 1989. The nonparticipation of organic sulphur in acid mine drainage generation. Env. Geochem. and Health. 11:187-192.

Chase, V. 1995. Phytoremediation: cleansing soil by removing metals. Research & Development. July:29-30.

Chen, H.S. 1982. The response of sulfide-affiliated copper, nickel, and zinc in shale overburdens associated with coals to simulate leaching. Ph. D. Dissertation. U. So. Carolina. Columbia SC.

Chilvers, D.C. and P.J. Peterson. 1987. Global cycling of arsenic. In: Lead, mercury, cadmium and arsenic in the environment. T.C.Hutchinson and K.M. Meema, eds. Wiley & Sons. NY. pp.279-301.

Chino, M. 1981. Metal stress in rice plants. In: Heavy metal pollution in soils of Japan. K. Kitagishi and I. Yamane, eds. Japan Sci. Soc. Press. Tokyo. pp.65-80.

Chumbley, C.G. and R.J. Unwin. 1982. Cadmium and lead content of vegetable crops grown on land with a history of sewage sludge application. Environmental Pollution. (Series B) V.4, pp.231-237.

Clark, C.W. 1966. Oxidation of coal mine pyrite. J. San. Eng. Div., Proc. Am. Soc. Civil Engr. 92: 127

Connor, J.J. and H.T. Shacklette. 1975. Background geochemistry of some rocks, soils, plants, and vegetables in the conterminous United States. USGS Prof. Paper 574-F. Wash. D.C.

Cook, J. 1977. Environmental pollution by heavy metals. Int. J. Environ. Studies. 10(4):253-266.

Corbett, R.B. and D.J. Growitz 1967. Composition of water discharged from bituminous coal mines in northern West Virginia. Econ. Geol. 62:848.

Cox, W.J. and D.W. Rains. 1972. Effect of lime on lead uptake by five plant species. J. Environ. Quality. 1(2):167-169.

Davies, B.E. 1978. Plant available lead and other metals in British garden soils. Sci. Total Environ. 9:243.

Davies, B.E. 1983. A graphical estimation of the normal lead content of some British soils. Geoderma. 29:67-75.

Day, P.R. 1965. Particle fractionation and particle-size analysis. In: Methods of Soil Analysis. C.A. Black, ed. Amer. Soc. of Agron., Mono. 9, Part 1, Madison WI. pp. 562-567.

Deuel, L.E. and A.R. Swoboda. 1972. Arsenic solubility in a reduced environment. Soil Sci. Soc. Am. Proc.36(2):276-278.

Dickens, R. and A.E. Hiltbold. 1967. Movement and persistence of methanearsonates in soil. Weeds. 15(4):299-304.

Dollhopf, D.J. 1992. Deep lime incorporation methods for neutralization of acidic minesoils. Office of Surface Mining. Denver CO. C/N HQ51-GR87/10015. 94 p.

Eklund, M. 1995. Cadmium and lead deposition around a Swedish battery plant as recorded in oak tree rings. J. Environ. Qual. 24(1):126-131.

Elkhatib, E.A., O.L. Bennett and R.J. Wright. 1984. Kinetics of arsenite sorption in soils. Soil Sci. Soc. Am. J. 48:758-762.

Environmental Protection Agency (EPA). 1986. Method 3050. Acid digestion of sediments, sludges and soils. In: Test methods for evaluating soil and waste. SW-846. 3rd Ed. Office of Solid Waste and Emergency Response, Washington, DC.

Environmental Protection Agency (EPA). 1987. Assessment of the toxicity of arsenic, cadmium, lead and zinc in soil, plants, and livestock in the Helena Valley of Montana. EPA Contract 68-01-7251. pp.75-88.

Evans, R.A. and R.M. Love. 1957. The steppoint method of sampling--a practical tool in range research. J. Range Mgmt. 10:208-212.

Everett, C.S. 1962. Effect of phosphorous on the phytotoxicity of tricalcium arsenate as manifested by bluegrass and crabgrass. PhD. Thesis. Rutgers Univ. New Brunswick NJ.

Fine, L.O. 1965. Selenium. Method 80-3.2. In: Methods of soil analysis. ASA Mono. No. 9, Part 2. C.A. Black, ed. Amer. Soc. Agron. Madison WI. pp.1117-1123.

Frost, R.R. and R.A. Griffin. 1977. Effect of pH on adsorption of arsenic and selenium from landfill leachate by clay minerals. Soil Sci. Soc. Am. Proc. 41(1):53-57.

Geidel, G. 1979. Alkaline and acid production ov overburden material: the rate of release. Reclamation Review. 2:101.

Goldberg, S. and R.A. Glaubig. 1988. Anion sorption on a calcareous, montmorillonitic soil--Arsenic. Soil Sci. Soc. Am. J. 52:1297-1300.

Grim, E.C. and R.D. Hill. 1974. Environmental protection in surface mining of coal. U.S. Environ. Protection Agency. Cincinnati OH. EPA-670/2-74-093. p.197.

Guyette, R.P., B.E. Cutter and G.S. Henderson. 1991. Long-term correlations between mining activity and levels of lead and cadmium in tree-rings of eastern red-cedar. J. Environ. Qual. 20(1):146-150.

Hansen, P.L., K. Boggs, B.J. Cook, J. Joy and D.K. Hinckley. 1995. Classification and management of Montana's riparian and wetland sites. Montana Forest & Conservation Experiment Station. Pub. no. 54. Missoula MT 646p.

Hassett, J.J. 1974. Capacity of selected Illinois soils to remove lead from aqueous solution. Comm. Soil Sci. Plant Anal. 5(6):499-505.

Heinrichs, H., B. Schulz-Dobrick, and K.H. Wedepohl. 1980. Terrestrial geochemistry of Cd, Bi, Tl, Pb, Zn and Rb. Geochim. Cosmochim. Acta 44(10):1519-1532.

Hickey, M.G. and J.A. Kittrick. 1984. Chemical partitioning of cadmium, copper, nickel and zinc in soils and sediments containing high levels of heavy metals. J. Environ. Qual. 13(3) :372-376.

Huang, P.M. 1975. Retention of arsenic by hydroxy-aluminum on surface of micaceous mineral colloids. Soil Sci. Soc. Am. Proc. 39(2):271-274.

Jacobs, L.W., J.K. Syers and D.R. Keeney. 1970. Arsenic sorption by soils. Soil Sci. Soc. Am. Proc. 34(5):750-754.

Jaworski, J.F. 1987. Lead. In: Lead, mercury, cadmium and arsenic in the environment. T.C. Hutchinson and K.M. Meema, eds. Wiley & Sons. NY. pp.3-16.

Jennings, S.R. and D.J. Dollhopf. 1995a. Geochemical characterization of sulfide mineral weathering for remediation of acid producing mine wastes. Reclamation Research Unit. Mont. State U. Bozeman MT. Pub. no. 9502. 140 p.

Jennings, S.R. and D.J. Dollhopf. 1995b. Acid-base account effectiveness for determination of mine waste potential acidity. J. Hazardous Materials. 41:161-175.

Jiang, Q.Q. and B.R. Singh. 1994. Effect of different forms and sources of arsenic on crop yield and arsenic concentration. Water Air Soil Pollution. 74:321-343.

John, M.K. and C. Van Laerhoven. 1972. Lead uptake by lettuce and oats as affected by lime, nitrogen, and sources of lead. J. Environ. Quality. 1(2):169-171.

Johnson, M., D. Roberts and N. Firth. 1978. Lead and zinc in the terrestrial environment around derelict metalliferous mines in Wales. Sci. Total Environ. 10:61-78.

Johnson, W.R., and J. Proctor. 1977. A comparative study of metal levels in plants from two contrasting lead mine sites. Plant Soil. 46(1):251-257.

Jones, L.H.P., C.R. Clement, and M.J. Hopper. 1973. Lead uptake from solution by perennial ryegrass and its transport from roots to shoots. Plant Soil. 38(2):403-414.

Kabata-Pendias, A. and H. Pendias. 1992. Trace elements in soils and plants. CRC Press. Boca Raton FL. pp.187-198;203-209.

Karamanos, R.E., J.R. Bettany and J.W.B. Stewart. 1976. The uptake of native and applied lead by alfalfa and bromegrass from soil. Canadian J. Soil Science. 56(4):485-494.

Keaton, C.M. 1937. The influence of lead compounds on the growth of barley. Soil Science. 43(6):401-411.

Keuls, M. 1952. The use of the "studentized range" in conjunction with an analysis of variance. Euphytica. 1:112-122.

King, T.V. 1995. Environmental considerations of active and abandoned mine lands. USGS Bull. No. 2220. Denver CO.

Kleinmann, R.L.P. 1990. Acid mine drainage in the United States. In: Proceedings, First Midwestern Region Reclamation Conference. So. Illinois Univ. Carbondale IL. pp.1-8.

Klepper, M.R., E.T. Ruppel, V.L. Freeman and R.A. Weeks. 1971. Geology and mineral deposits, east flank of the Elkhorn Mountains, Broadwater County, Montana. U.S.G.S. Prof. Paper 665. pp.34-43.

Krauskopf, K.B. 1979. Introduction to geochemistry. McGraw-Hill. NY. 617p.

Lagerwerff, J.V. and D.L. Brower. 1973. Exchange adsorption or precipitation of lead in soils treated with chlorides of aluminum, calcium, and sodium. Soil Sci. Soc. Am. Proc.37(1):11-13.

Lange, T. 1993. What is acid mine drainage? In: Montana's mining boom. No. Plains Res. Council. Billings MT. p.5.

LeClerg, E.L., W.H. Leonard and A.G. Clark. 1962. Field plot technique. Burgess Pub. Minneapolis MN. pp.137-183.

Lepp, N.W. 1992. Uptake and accumulation of metals in bacteria and fungi. In: Biogeochemistry of trace metals. D.C. Adriano, ed. Lewis Pub. Boca Raton FL. pp.277-298.

LeRiche, H.H. and A.H. Weir. 1963. A method of studying trace elements in soil fractions. J Soil Sci. 14(2):225-235.

Liebig, G.F., Bradford, G.R. and A. Vanselow. 1959. Effects of arsenic compounds on citrus plants in solution culture. Soil Science. 88:342-348.

Lindsay, W.L. and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421-428.

Lovering, T.G. 1976. Lead in the environment. USGS Prof. Paper 957. Wash D.C. 90p.

MacLean, A.J., R.L. Halstead and B.J. Finn. 1969. Extractability of added lead in soils and its concentration in plants. Canadian J. Soil Science. 49(3):327-334.

MacLean, K.S. and W.M. Langille. 1976. The extractable trace element content of acid soils and the influence of pH, organic matter and clay content. Commun. Soil Sci. Plant Anal. 7(9):777-785.

Manahan, S.E. 1984. Environmental chemistry. PWS Publishers. Boston MA. pp.496-533.

Marin, A.R., P.H. Masscheleyn and W.H. Patrick. 1993. Soil redox-pH stability of arsenic species and its influence on arsenic uptake by rice. Plant & Soil. 152:245-253.

Marten, G.C. and P.B. Hammond. 1966. Lead uptake by bromegrass from contaminated soils. Agron J. 58:553-554.

Masscheleyn, P.H., R.D. Delaune and W.H. Patrick. 1991a. Arsenic and selenium chemistry as affected by sediment redox potential and pH. J. Environ. Qual. 20:522-527.

Masscheleyn, P.H., R.D. Delaune and W.H. Patrick. 1991b. Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil. Environ. Sci. Technol. 25:1414-1419.

McBride, M.B. 1994. Environmental chemistry of soils. Oxford Press. NY. pp.121-168.

McBride, M.B. and J.J. Blasiak 1979. Zinc and copper solubility as a function of pH in an acid soil. Soil Sci. Soc. Am J. 43:866-870.

McLean, E.O. 1982. Soil pH and Lime Requirement. In: A.L. Page et al., eds. Methods of soil analysis, Part 2, Agron. Mono. 9. ASA and SSSA, Madison WI. pp.199-223.

Meek, B., L. Graham and T. Donovan. 1982. Long-term effects of manure on soil nitrogen, phosphorous, potassium, sodium, organic matter, and water infiltration rate. Soil Sci. Soc. Am. J. 46:1014-

Meyer, T.A. and G.W. Volk. 1952. Effect of particle size of limestones on soil reaction, exchangeable cations, and plant growth. Soil Science. 73(1):37-52.

Miller, J.E., J.J. Hassett and D.E. Koeppe. 1975a. The effect of soil properties and extractable lead levels on the lead uptake by soybeans. Comm. Soil Sci. Plant Anal. 6(4):339-347.

Miller, J.E., J.J. Hassett and D.E. Koeppe. 1975b. The effect of soil lead sorption capacity on the uptake of lead by corn. Comm. Soil Sci. Plant Anal. 6(4):349-358.

Miller, R.J. and D.E. Koeppe. 1970. Trace Subs. Environ. Health 4:186-193.

Mitchell, G.A., F.T. Bingham and A.L.Page. 1978. Yield and metal composition of lettuce and wheat grown on soils amended with sewage sludge enriched with cadmium, copper, nickel and zinc. J. Env. Quality. 7(2):165-171.

Montana Department of Environmental Quality (DEQ). 1994. Soil, overburden and regraded spoil guidelines. Reclamation Division. Coal & Uranium Bureau. Helena MT.

Montana Department of Health and Environmental Sciences (DHES). 1993. Streambank tailings and revegetation studies. STARS Phase III Final Report. Prepared by: Schafer and Assoc. & Reclamation Research Unit. Bozeman MT.

Montana Department of Health and Environmental Sciences (DHES). 1995. Proposed Plan: streamside tailings operable unit. Helena MT. 23p.

Montana Department of State Lands (DSL). 1994a. Abandoned hardrock mine priority sites.Abandoned Mines & Reclamation Bureau. By: Pioneer Tech Services Inc., Butte MT.

Montana Department of State Lands (DSL). 1994b. Abandoned inactive mine scoring system.Abandoned Mines & Reclamation Bureau. By: Pioneer Tech Services Inc., Butte MT.

Montana Department of State Lands (DSL). 1995. Summary report of abandoned hardrock mine priority sites.Abandoned Mines & Reclamation Bureau. By: Pioneer Tech Services Inc., Butte MT.

Mortvedt, J.J. and P.M. Giordano. 1975. Response of corn to zinc and chromium in municipal wastes applied to soil. J. Env. Quality. 4(2):170-174.

Motto, H.L. and S.W. Melstead. 1960. The efficiency of various particle-size fractions of limestone. Soil Sci. Soc. Am. Proc. 24:488-490.

Motto, H.S., R.H. Daines, D.M. Chilko and C.K. Motto. 1970. Lead in soils and plants: Its relationship to traffic volume and proximity to highways. Environ. Sci. Technol. 4(3):231-237.

Munshower, F.F. 1991. Perennial grasses for revegetation of disturbed lands in the northern Great Plains and the intermountain region. Reclamation Research Unit. Mont. State U. Bozeman MT. Pub. no. 9101. 138 p.

Munshower, F.F. 1994. Practical handbook of disturbed land revegetation. CRC Press. Boca Raton FL. 226p.

NAS. 1977. Arsenic. Committee on Medical & Biological Effects of Environmental Pollutants. National Academy of Sciences. Wash. D.C. p.4.

Neter, J., W. Wasserman and M.H. Kutner. 1990. Applied linear statistical models. Irwin Pub. Boston MA. pp. 642-644.

Neuman, D.R. 1996. Personal communication. Reclamation Research Unit. Mont. State U. Bozeman MT.

Olsen, J.A., M.H. Haub and L.C. Bingham. 1977. Soil survey of Broadwater County area, Montana. U.S.D.A. Soil Conservation Service. pp.16-17.

Pagenkopf, G.K. 1980. Zinc speciation and toxicity to fish. In: Zinc in the environment. II:Health effects. J.O. Nriagu, ed. Wiley & Sons. NY. pp.353-361.

Perry, A. and R.L.P. Kleinmann. 1991. The use of constructed wetlands in the treatment of acid mine drainage. Natural Resources Forum. April:178-184.

Peterson, P.J., L.M. Benson and R. Zieve. 1981. Metalloids. In: Effect of heavy metal pollution on plants. N.W. Lepp, ed. Applied Sci. Pub. NJ. pp.279-333.

Porter, E.K. and P.J. Peterson. 1975. Arsenic accumulation by plants on mine waste (United Kingdom). Sci. Total Environ. 4:365-371.

Pugh, C.E., L.R. Hossner and J.B. Dixon. 1984. Oxidation rate of iron sulfides as affected by surface area, morphology, oxygen concentration and autotrophic bacteria. Soil Sci. 137(5):309.

Ragaini, R.C., H.R. Ralston and N. Roberts. 1977. Environmental trace metal contamination in Kellogg, Idaho, near a lead smelting complex. Environ. Sci. Technol. 11(8):773-781.

Reed, G.C. 1951. Mines and mineral deposits (except fuels) Broadwater County, Mont. U.S. Bureau of Mines. Info. Circ. 7592. pp.48-49.

Ribet, I., C.J. Ptacek, D.W. Blowes and J.L. Jambor. 1995. The potential for metal release by reductive dissolution of weathered mine tailings. J. Contaminant Hydrology. 17(3):239-273.

Riffaldi, R., R. Levi-Minzi and G.F. Soldatini. 1976. Pb adsorption by soils. Water, air, soil polluion. 6(1):119-128.

Ritcey, G.M. 1989. Tailings management, problems and solutions in the mining industry. Elsevier Sci. Pub. NY. pp.1-9.

Rolfe G.L. 1973. Lead uptake by selected tree seedlings. J. Environ. Qual. 2(1):153-157.

Rosgen, D.L. 1994. A classification of natural rivers. Catena. 22:169-199.

Salim, R. and B.G.Cooksey. 1980. Kinetics of the adsorption of lead on river-mud. Plant Soil. 54(3):399-417.

Sandoval, F.M. and J.R. Power. 1978. Laboratory methods recommended for chemical analysis of mined-land spoils and overburden in western United States. U.S. Dept. of Agric., Agric. Handbook No. 25. Wash. DC. pp.4-6.

Sanguinetti, M.H. 1986. Report on the Marietta Mine property lode claims (36) contained within sections 10, 11, 14 & 15 Township 7 North, Range 1 West Broadwater County, Montana. Sanguinetti Engineering Ltd. Vancouver BC. p. 26

Schafer and Associates and Reclamation Research Unit. 1987. Laboratory analytical protocol for the Streambank Tailings and Revegetation Study, Silver Bow Creek RI/FS. EPA Region VIII. Doc. No. SBC-STARS-LAP-F-RI-121187.

Schell, E.M. 1963. Ore deposits of the northern part of the Park (Indian Creek) District, Broadwater County, Montana. Mt. Bureau Mines Geol. Butte MT. Bulletin 35. 47p.

Scrudato, R.J. and E.L. Estes. 1975. Clay-lead sorption relations. Env. Geol. 1:167-170.

SCS. 1981. Montana technical guide--Silty 15-19" P.Z. Foothills & Mountains. US Dept. Agriculture. Soil Conservation Service. Section II-E-8.

Sedberry, J.E. and C.N. Reddy. 1976. Water-soluble zinc, exchangeable zinc, chelated zinc, organic zinc, residual mineral zinc, zinc pools. Commun. Soil Sci. Plant Anal. 7(9):787-795.

Sengupta, M. 1993. Environmental impacts of mining. Lewis Pub. Boca Raton FL.pp.325-424.

Shacklette, H.T., J.C. Hamilton, J.G. Boerngen and J.M. Bowles. 1971. Elemental composition of surficial materials in the conterminous U.S.. U.S. Geol. Survey Prof. Paper No. 574-D. Wash. DC.

Shacklette, H.T., J.G. Boerngen and J.R. Keith. 1974. Selenium, fluorine, and arsenic in surficial materials of the conterminous United States. U.S. Geol. Survey Circ. 692. Wash. DC.

Shoemaker, H.E., E.O. McLean and P.F. Pratt. 1961. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminum. Soil Sci. Soc. Am. Proc. 25:274-277.

SigmaStat. 1994. Statistical computer software. Jandel Scientific.

Sims, J.L. and W.H. Patrick. 1978. Soil Sci. Soc. Am. J. 42:258-262.

Singer, P.C. and W. Stumm. 1970. Acidic mine drainage: the rate determining step. Science. 167:1121-1123.

Smith, P.L., E.F. Redente and E. Hooper. 1987. Soil organic matter. In: Reclaiming mine soils and overburden in the western United States. R.D. Williams and G.E. Schuman, eds. Soil Conservation Soc. Amer. pp.185-214.

Smith, R.M., W.E. Grube, T. Arkle, A. Sobek. 1974. Mine spoil potentials for soil and water quality. W. Virginia U. Environ. Protection Agency. EPA-670/2-74-070. p.72.

Smith, R. W. and D.G. Frey. 1971. Acid mine pollution effects on lake biology. Water Poll. Control Res. Series. Environ. Protection Agency. Wash. DC. 18050 EEC. p.6.

Smith, E.E. and K.S. Shumate. 1970. Sulfide to sulfate reaction mechanism. Water Poll. Control Res. Series. Environ. Protection Agency. Wash. DC. 14010 FPS. p.115.

Sobek, A.A., W.A. Schuller, J.R. Freeman and R.S. Smith. 1978. Field and laboratory methods applicable to mine soils. U.S. Env. Prot. Agency. Wash D.C. EPA-600/2-78/054. 203p.

Soldatini, G.F., R. Riffaldi and R. Levi-Minzi. 1976. Pb adsorption by soils. Water Air Soil Pollution. 6(1):111-118.

Steevens, D.R., L.M. Walsh and D.R. Keeney. 1972. Arsenic phytotoxicity on a Plainfield sand as affected by ferric sulfate or aluminum sulfate. J. Environ. Qual. 1(3):301-303.

Stumm, W. and J.J. Morgan. 1970. Aquatic chemistry. Wiley-Interscience. NY. p.583.

Summers, A.O. and S. Silver. 1978. Microbial transformations of metals. Ann. Rev. Microbiol. 32:637-672.

Thomas, G.W. and W.L. Hargrove. 1984. The chemistry of soil acidity. In: Soil acidity and liming. 2nd edit. F. Adams, ed. Am. Soc. Agronomy. Madison WI. pp.3-56.

Tisdale,S.L. and W.L. Nelson. 1966. Soil fertility and fertilizers. Macmillan Co. NY. pp.431-433.

Tornabene, T.G. and H.W. Edwards. 1972. Microbial uptake of lead. Science.176:1334-1335.

Tver, D.F. 1981. Dictionary of dangerous pollutants, ecology, and environment. Industrial Press. NY. p.315.

Wauchope, R. D. 1975. Fixation of arsenical herbicides, phosphate, and arsenate in alluvial soils. J. Environ. Qual. 4(3):355-358.

Wauchope, R. D. 1983. Arsenic--industrial, biomedical, environmental perspectives. W.H. Lederer and R.J. Fensterheim, eds. Rheinhold Pub. NY. pp.348-377.

White, M.C. and R.L. Chaney. 1980. Zinc, cadmium and manganese uptake by soybean from two zinc- and cadmium-amended coastal plain soils. Soil Sci. Soc. Am. J. 44:308-313.

Woolson, E.A., J.H. Axley and P.C. Kearney. 1971. Correlation between available soil arsenic, estimated by six methods, and response to corn (*Zea mays* L.). Soil Sci. Soc. Am. Proc. 35:101-105.

Woolson, E.A., J.H. Axley and P.C. Kearney. 1973. The chemistry and phtotoxicity of arsenic in soils: II. Effects of time and phosphorous. Soil Sci. Soc. Am. Proc. 37:254-259.

Zimdahl, R.L. and J.H. Arvik. 1973. Lead in soils and plants: a literature review. CRC Critical Rev. Environ. Control 3(2):213-224.

Zimdahl, R.L. and R.K. Skogerboe. 1977. Behavior of lead in soil. Environ. Sci. Technology 11(13):1202-1207.

APPENDICES

APPENDIX A

ANALYSIS OF VARIANCE RESULTS FOR GRASS SPECIES

Table 9. Analysis of Variance Results: Agrostis Shoot Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: s wt

Source of Variance	DF	SS	MS
soil	2	326.4	163.20
block	4	19.7	4.91
Residual	8	14.9	1.86
Total	14	361.0	25.78

Source of Variance	F	P
soil	87.55	<0.0001
block	2.64	0.1134

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00000364). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.113).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.303

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.611
2.000	1.95	0.611
3.000	10.72	0.611

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	10.72	3	17.56
3 vs 2	8.78	2	14.38
2 vs 1	1.95	2	3.19

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	Yes
2 vs 1	No

Table 10. Analysis of Variance Results: Agrostis Root Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: r wt

Source of Variance	DF	SS	MS
soil	2	37.33	18.67
block	4	4.57	1.14
Residual	8	8.16	1.02
Total	14	50.06	3.58

Source of Variance	F	P
soil	18.30	0.0010
block	1.12	0.4118

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00104). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.412).

Power of performed test with alpha = 0.0500: for soil : 0.994
Power of performed test with alpha = 0.0500: for block : 0.0647

Least square means for soil

Group	Mean	SEM
1.000	-2.22E-016	0.452
2.000	2.12E+000	0.452
3.000	3.86E+000	0.452

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	3.86	3	8.54
3 vs 2	1.74	2	3.85
2 vs 1	2.12	2	4.69

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	Yes
2 vs 1	Yes

Table 11. Analysis of Variance Results: Agrostis Root to Shoot Ratio.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: rt/s

Source of Variance	DF	SS	MS
soil	2	5.51	2.755
block	4	1.16	0.291
Residual	8	2.33	0.291
Total	14	9.00	0.643

Source of Variance	F	P
soil	9.454	0.0078
block	0.998	0.4617

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00781). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.462).

Power of performed test with alpha = 0.0500: for soil : 0.868
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	1.39E-017	0.241
2.000	1.43E+000	0.241
3.000	3.70E-001	0.241

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	1.430	3	5.92
2 vs 3	1.060	2	4.39
3 vs 1	0.370	2	1.53

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	Yes
3 vs 1	No

Table 12. Analysis of Variance Results: Agrostis Total Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: T wt

Source of Variance	DF	SS	MS
soil	2	566.3	283.13
block	4	42.8	10.71
Residual	8	35.6	4.45
Total	14	644.7	46.05

Source of Variance	F	P
soil	63.56	<0.0001
block	2.40	0.1354

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.0000123). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.135).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.263

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.944
2.000	4.07	0.944
3.000	14.58	0.944

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	14.58	3	15.45
3 vs 2	10.52	2	11.14
2 vs 1	4.07	2	4.31

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	Yes
2 vs 1	Yes

Table 13. Analysis of Variance Results: Agrostis Shoot length

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: s cm

Source of Variance	DF	SS	MS
soil	2	4200.9	2100.5
block	4	118.7	29.7
Residual	8	583.7	73.0
Total	14	4903.3	350.2

Source of Variance	F	P
soil	28.787	0.0002
block	0.407	0.7993

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000222). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.799).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	8.88E-016	3.82
2.000	3.56E+001	3.82
3.000	3.54E+001	3.82

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	35.600	3	9.3191
2 vs 3	0.200	2	0.0524
3 vs 1	35.400	2	9.2667

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 14. Analysis of Variance Results: Agrostis Root Length.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: r cm

Source of Variance	DF	SS	MS
soil	2	4180.80	2090.40
block	4	9.60	2.40
Residual	8	19.20	2.40
Total	14	4209.60	300.69

Source of Variance	F	P
soil	871.000	<0.0001
block	1.000	0.4609
Residual		
Total		

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000000000437). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.461).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	-8.88E-016	0.693
2.000	3.48E+001	0.693
3.000	3.60E+001	0.693

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	36.00	3	51.96
3 vs 2	1.20	2	1.73
2 vs 1	34.80	2	50.23

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	No
2 vs 1	Yes

Table 15. Analysis of Variance Results: Agrostis pH

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: pH

Source of Variance	DF	SS	MS
soil	2	93.0886	46.5443
block	4	0.1378	0.0344
Residual	6	0.0747	0.0124
Total	12	95.6771	7.9731

Source of Variance	F	P
soil	3739.95	<0.0001
block	2.77	0.1279

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000000000515). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.128).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.281

Least square means for soil

Group	Mean	SEM
1.000	1.83	0.0499
2.000	7.45	0.0499
3.000	7.31	0.0706

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	5.616	3	112.57
2 vs 3	0.140	2	2.29
3 vs 1	5.476	2	89.62

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 16. Analysis of Variance Results: Agrostis Vigor

Kruskal-Wallis One Way Analysis of Variance on Ranks

AGROSTIS VIGOR

Group	N	Missing
agrcontrol	5	0
agrlime	5	0
agrlime/m	5	0

Group	Median	25%	75%
agrcontrol	0.00	0.00	0.00
agrlime	3.00	2.00	4.00
agrlime/m	4.00	3.88	4.00

H = 11.4 with 2 degrees of freedom. (P = 0.0034)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.00342)

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Ranks	p	q
agrlime/m vs agrcontrol	44.0	3	4.40
agrlime/m vs agrlime	13.0	2	1.92
agrlime vs agrcontrol	31.0	2	4.58

Comparison	P<0.05
agrlime/m vs agrcontrol	Yes
agrlime/m vs agrlime	No
agrlime vs agrcontrol	Yes

Table 17. Analysis of Variance Results: Deschampsia Shoot Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: s wt

Source of Variance	DF	SS	MS
soil	2	103.202	51.6012
block	4	0.439	0.1098
Residual	8	0.508	0.0635
Total	14	104.150	7.4393

Source of Variance	F	P
soil	812.51	<0.0001
block	1.73	0.2361

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000000000576). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.236).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.152

Least square means for soil

Group	Mean	SEM
1.000	-4.44E-016	0.113
2.000	5.37E+000	0.113
3.000	5.74E+000	0.113

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	5.740	3	50.93
3 vs 2	0.370	2	3.28
2 vs 1	5.370	2	47.65

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	Yes
2 vs 1	Yes

Table 18. Analysis of Variance Results: Deschampsia Root Weight

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: r wt

Source of Variance	DF	SS	MS
soil	2	4.842	2.421
block	4	0.989	0.247
Residual	8	1.120	0.140
Total	14	6.951	0.496

Source of Variance	F	P
soil	17.30	0.0012
block	1.77	0.2287

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00124). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.229).

Power of performed test with alpha = 0.0500: for soil : 0.992
Power of performed test with alpha = 0.0500: for block : 0.157

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.167
2.000	1.27	0.167
3.000	1.13	0.167

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	1.270	3	7.591
2 vs 3	0.142	2	0.849
3 vs 1	1.128	2	6.742

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 19. Analysis of Variance Results: Deschampsia Root to Shoot Ratio.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: rt/s

Source of Variance	DF	SS	MS
soil	2	0.1520	0.07601
block	4	0.0202	0.00504
Residual	8	0.0233	0.00292
Total	14	0.1955	0.01396

Source of Variance	F	P
soil	26.07	0.0003
block	1.73	0.2362

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000313). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.236).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.152

Least square means for soil

Group	Mean	SEM
1.000	1.04E-017	0.0241
2.000	2.30E-001	0.0241
3.000	1.92E-001	0.0241

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	0.2300	3	9.53
2 vs 3	0.0380	2	1.57
3 vs 1	0.1920	2	7.95

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 20. Analysis of Variance Results: Deschampsia Total Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: T wt

Source of Variance	DF	SS	MS
soil	2	152.19	76.093
block	4	2.73	0.684
Residual	8	3.09	0.386
Total	14	158.01	11.286

Source of Variance	F	P
soil	197.17	<0.0001
block	1.77	0.2276

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000000156). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.228).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.158

Least square means for soil

Group	Mean	SEM
1.000	-4.44E-016	0.278
2.000	6.64E+000	0.278
3.000	6.87E+000	0.278

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	6.868	3	24.721
3 vs 2	0.228	2	0.821
2 vs 1	6.640	2	23.900

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	No
2 vs 1	Yes

Table 21. Analysis of Variance Results: Deschampsia Shoot Length.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: s cm

Source of Variance	DF	SS	MS
soil	2	888.1	444.07
block	4	39.1	9.77
Residual	8	74.5	9.32
Total	14	1001.7	71.55

Source of Variance	F	P
soil	47.66	<0.0001
block	1.05	0.4402

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.0000359). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.440).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0560

Least square means for soil

Group	Mean	SEM
1.000	0.00	1.37
2.000	15.80	1.37
3.000	16.80	1.37

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	16.800	3	12.307
3 vs 2	1.000	2	0.733
2 vs 1	15.800	2	11.575

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	No
2 vs 1	Yes

Table 22. Analysis of Variance Results: Deschampsia Root Length.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: r cm

Source of Variance	DF	SS	MS
soil	2	4107.60	2053.80
block	4	9.60	2.40
Residual	8	26.40	3.30
Total	14	4143.60	295.97

Source of Variance	F	P
soil	622.364	<0.0001
block	0.727	0.5977

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00000000166). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.598).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	-3.55E-015	0.812
2.000	3.48E+001	0.812
3.000	3.54E+001	0.812

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	35.400	3	43.574
3 vs 2	0.600	2	0.739
2 vs 1	34.800	2	42.836

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	No
2 vs 1	Yes

Table 23. Analysis of Variance Results: Deschampsia pH.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: pH

Source of Variance	DF	SS	MS
soil	2	81.329	40.6646
block	4	0.106	0.0264
Residual	4	0.363	0.0906
Total	10	83.410	8.3410

Source of Variance	F	P
soil	448.682	<0.0001
block	0.292	0.8701

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.0000197). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.870).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0519

Least square means for soil

Group	Mean	SEM
1.000	1.84	0.135
2.000	7.38	0.196
3.000	7.35	0.196

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	5.5400	3	32.919
2 vs 3	0.0350	2	0.164
3 vs 1	5.5050	2	32.711

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 24. Analysis of Variance Results: Deschampsia Vigor.

Kruskal-Wallis One Way Analysis of Variance on Ranks

DESCHAMPSIA VIGOR

Group	N	Missing
descontrol	5	0
deslime	5	0
deslime/m	5	0

Group	Median	25%	75%
descontrol	0.00	0.00	0.00
deslime	3.00	3.00	3.63
deslime/m	4.00	3.75	4.00

H = 11.4 with 2 degrees of freedom. (P = 0.0034)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.00340)

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Ranks	p	q
deslime/m vs descontrol	44.5	3	4.45
deslime/m vs deslime	14.0	2	2.07
deslime vs descontrol	30.5	2	4.51

Comparison	P<0.05
deslime/m vs descontrol	Yes
deslime/m vs deslime	No
deslime vs descontrol	Yes

Table 25. Analysis of Variance Results: Elymus Shoot Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: s wt

Source of Variance	DF	SS	MS
soil	2	344.916	172.4581
block	4	0.570	0.1426
Residual	8	0.556	0.0695
Total	14	346.043	24.7174

Source of Variance	F	P
soil	2479.69	<0.0001
block	2.05	0.1798

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 6.73E-012). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.180).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.204

Least square means for soil

Group	Mean	SEM
1.000	-6.66E-016	0.118
2.000	1.04E+001	0.118
3.000	9.96E+000	0.118

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	10.372	3	87.94
2 vs 3	0.412	2	3.49
3 vs 1	9.960	2	84.45

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	Yes
3 vs 1	Yes

Table 26. Analysis of Variance Results: Elymus Root Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: r wt

Source of Variance	DF	SS	MS
soil	2	218.81	109.403
block	4	1.57	0.392
Residual	8	12.59	1.574
Total	14	232.97	16.640

Source of Variance	F	P
soil	69.518	<0.0001
block	0.249	0.9022

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00000876). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.902).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.561
2.000	8.32	0.561
3.000	7.86	0.561

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	8.324	3	14.837
2 vs 3	0.464	2	0.827
3 vs 1	7.860	2	14.010

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 27. Analysis of Variance Results: Elymus Root to Shoot Ratio

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: rt/s

Source of Variance	DF	SS	MS
soil	2	2.10724	1.05362
block	4	0.00567	0.00142
Residual	8	0.13009	0.01626
Total	14	2.24300	0.16021

Source of Variance	F	P
soil	64.7916	<0.0001
block	0.0871	0.9840

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.0000114). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.984).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.0570
2.000	0.80	0.0570
3.000	0.79	0.0570

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	0.8020	3	14.063
2 vs 3	0.0140	2	0.245
3 vs 1	0.7880	2	13.817

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 28. Analysis of Variance Results: Elymus Total Weight.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: T wt

Source of Variance	DF	SS	MS
soil	2	1113.10	556.550
block	4	3.83	0.959
Residual	8	13.11	1.639
Total	14	1130.04	80.717

Source of Variance	F	P
soil	339.653	<0.0001
block	0.585	0.6827

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.0000000184). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.683).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.572
2.000	18.70	0.572
3.000	17.82	0.572

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	18.696	3	32.66
2 vs 3	0.876	2	1.53
3 vs 1	17.820	2	31.13

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 29. Analysis of Variance Results: Elymus Shoot Length.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: s cm

Source of Variance	DF	SS	MS
soil	2	9089.20	4544.60
block	4	9.07	2.27
Residual	8	48.13	6.02
Total	14	9146.40	653.31

Source of Variance	F	P
soil	755.335	<0.0001
block	0.377	0.8193

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.000000000770). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.819).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0502

Least square means for soil

Group	Mean	SEM
1.000	-3.55E-015	1.10
2.000	5.30E+001	1.10
3.000	5.14E+001	1.10

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	53.00	3	48.32
2 vs 3	1.60	2	1.46
3 vs 1	51.40	2	46.86

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 30. Analysis of Variance Results: Elymus Root Length.

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: r cm

Source of Variance	DF	SS	MS
soil	2	4320.00	2160.00
block	4	0.00	0.00
Residual	8	0.00	0.00
Total	14	4320.00	308.57

Source of Variance	F	P
soil	>1e20	<0.0001
block	0.00	1.0000

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.00). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 1.000).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0500

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.00
2.000	36.00	0.00
3.000	36.00	0.00

Table 31. Analysis of Variance Results: Elymus pH

Two Way Analysis of Variance
General Linear Model (No Interactions)
Dependent Variable: pH

Source of Variance	DF	SS	MS
soil	2	76.4578	38.22892
block	4	0.0163	0.00407
Residual	4	0.0201	0.00502
Total	10	89.4053	8.94053

Source of Variance	F	P
soil	7607.745	<0.0001
block	0.809	0.5787

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in block. There is a statistically significant difference (p = 0.0000000691). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of block are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.579).

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for block : 0.0519

Least square means for soil

Group	Mean	SEM
1.000	1.84	0.0317
2.000	7.57	0.0388
3.000	7.55	0.0582

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	5.7300	3	161.665
2 vs 3	0.0200	2	0.427
3 vs 1	5.7100	2	121.781

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 32. Analysis of Variance Results: Elymus Vigor

Kruskal-Wallis One Way Analysis of Variance on Ranks

ELYMUS VIGOR

Group	N	Missing
elycontrol	5	0
elylime	5	0
elylime/m	5	0

Group	Median	25%	75%
elycontrol	0.00	0.00	0.00
elylime	4.00	4.00	4.00
elylime/m	4.00	4.00	4.00

H = 14.0 with 2 degrees of freedom. (P = 0.0009)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.000912)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Ranks	p	q
elylime vs elycontrol	37.50	3	3.75
elylime vs elylime/m	0.00	2	0.00
elylime/m vs elycontrol	37.50	2	5.54

Comparison	P<0.05
elylime vs elycontrol	Yes
elylime vs elylime/m	No
elylime/m vs elycontrol	Yes

APPENDIX B

ANALYSES OF VARIANCE RESULTS FOR SOIL AND GRASS

Table 33. Analysis of Variance Results: Soil and Grass Shoot Weight.

Two Way Analysis of Variance
Balanced Design
Dependent Variable: s wt

Source of Variance	DF	SS	MS
soil	2	604.1	302.06
grass	2	81.2	40.61
soil x grass	4	170.4	42.60
Residual	36	36.6	1.02
Total	44	892.4	20.28

Source of Variance	F	P
soil	296.8	<0.0001
grass	39.9	<0.0001
soil x grass	41.9	<0.0001

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 4.27E-023). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are greater than would be expected by chance after allowing for effects of differences in soil. There is a statistically significant difference (p = 0.000000000736). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of soil depends on what level of grass is present. There is a statistically significant interaction between soil and grass. (P = 4.58E-013)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 1.000
Power of performed test with alpha = 0.0500: for soil x grass : 1.000

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.0868
2.000	5.90	0.0868
3.000	8.81	0.0868

Least square means for grass

Group	Mean	SEM
Agrst	4.22	0.0868
Dscha	3.70	0.0868
Elyms	6.78	0.0868

Table 33. Analysis of Variance Results: Soil and Grass Shoot Weight.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	8.81	3	33.8
3 vs 2	2.91	2	11.2
2 vs 1	5.90	2	22.6

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	Yes
2 vs 1	Yes

Comparison	Diff of Means	p	q
Elyms vs Dscha	3.074	3	11.80
Elyms vs Agrst	2.554	2	9.80
Agrst vs Dscha	0.520	2	2.00

Comparison	P<0.05
Elyms vs Dscha	Yes
Elyms vs Agrst	Yes
Agrst vs Dscha	No

Table 34. Analysis of Variance Results: Soil and Grass Root Weight.

Two Way Analysis of Variance
Balanced Design
Dependent Variable: r wt

Source of Variance	DF	SS	MS
soil	2	168.6	84.311
grass	2	170.6	85.287
soil x grass	4	92.4	23.090
Residual	36	29.0	0.805
Total	44	460.5	10.467

Source of Variance	F	P
soil	104.7	<0.0001
grass	105.9	<0.0001
soil x grass	28.7	<0.0001

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 9.93E-016). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are greater than would be expected by chance after allowing for effects of differences in soil. There is a statistically significant difference (p = 8.32E-016). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of soil depends on what level of grass is present. There is a statistically significant interaction between soil and grass. (P = 9.46E-011)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 1.000
Power of performed test with alpha = 0.0500: for soil x grass : 1.000

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.0772
2.000	3.90	0.0772
3.000	4.28	0.0772

Least square means for grass

Group	Mean	SEM
Agrst	1.993	0.0772
Dscha	0.799	0.0772
Elyms	5.395	0.0772

Table 34. Analysis of Variance Results: Soil and Grass Root Weight.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	4.282	3	18.48
3 vs 2	0.377	2	1.63
2 vs 1	3.905	2	16.85

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	No
2 vs 1	Yes

Comparison	Diff of Means	p	q
Elyms vs Dscha	4.60	3	19.83
Elyms vs Agrst	3.40	2	14.68
Agrst vs Dscha	1.19	2	5.15

Comparison	P<0.05
Elyms vs Dscha	Yes
Elyms vs Agrst	Yes
Agrst vs Dscha	Yes

Table 35. Analysis of Variance Results: Soil and Grass Root to Shoot Ratio.

Two Way Analysis of Variance
Balanced Design
Dependent Variable: rt/s

Source of Variance	DF	SS	MS
soil	2	5.07	2.533
grass	2	1.84	0.919
soil x grass	4	2.70	0.675
Residual	36	3.67	0.102
Total	44	13.28	0.302

Source of Variance	F	P
soil	24.83	<0.0001
grass	9.00	0.0007
soil x grass	6.62	0.0004

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 0.000000168). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are greater than would be expected by chance after allowing for effects of differences in soil. There is a statistically significant difference (p = 0.000675). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of soil depends on what level of grass is present. There is a statistically significant interaction between soil and grass. (P = 0.000424)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 0.951
Power of performed test with alpha = 0.0500: for soil x grass : 0.968

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.0275
2.000	0.82	0.0275
3.000	0.45	0.0275

Least square means for grass

Group	Mean	SEM
Agrst	0.600	0.0275
Dscha	0.141	0.0275
Elyms	0.530	0.0275

Table 35. Analysis of Variance Results: Soil and Grass Root to Shoot Ratio.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	0.821	3	9.95
2 vs 3	0.371	2	4.49
3 vs 1	0.450	2	5.46

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	Yes
3 vs 1	Yes

Comparison	Diff of Means	p	q
Agrst vs Dscha	0.4593	3	5.569
Agrst vs Elyms	0.0700	2	0.849
Elyms vs Dscha	0.3893	2	4.720

Comparison	P<0.05
Agrst vs Dscha	Yes
Agrst vs Elyms	No
Elyms vs Dscha	Yes

Table 36. Analysis of Variance Results: Soil and Grass Total Weight.

Two Way Analysis of Variance
Balanced Design
Dependent Variable: T wt

Source of Variance	DF	SS	MS
soil	2	1391.1	695.55
grass	2	486.1	243.07
soil x grass	4	440.4	110.11
Residual	36	101.2	2.81
Total	44	2418.9	54.98

Source of Variance	F	P
soil	247.3	<0.0001
grass	86.4	<0.0001
soil x grass	39.2	<0.0001

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 9.27E-022). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are greater than would be expected by chance after allowing for effects of differences in soil. There is a statistically significant difference (p = 1.80E-014). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of soil depends on what level of grass is present. There is a statistically significant interaction between soil and grass. (P = 1.21E-012)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 1.000
Power of performed test with alpha = 0.0500: for soil x grass : 1.000

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.144
2.000	9.80	0.144
3.000	13.09	0.144

Least square means for grass

Group	Mean	SEM
Agrst	6.22	0.144
Dscha	4.50	0.144
Elyms	12.17	0.144

Table 36. Analysis of Variance Results: Soil and Grass Total Weight.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	13.09	3	30.23
3 vs 2	3.29	2	7.60
2 vs 1	9.80	2	22.63

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	Yes
2 vs 1	Yes

Comparison	Diff of Means	p	q
Elyms vs Dscha	7.67	3	17.71
Elyms vs Agrst	5.96	2	13.76
Agrst vs Dscha	1.71	2	3.96

Comparison	P<0.05
Elyms vs Dscha	Yes
Elyms vs Agrst	Yes
Agrst vs Dscha	Yes

Table 37. Analysis of Variance Results: Soil and Grass Shoot Length.

Two Way Analysis of Variance
Balanced Design
Dependent Variable: s cm

Source of Variance	DF	SS	MS
soil	2	12018.3	6009.2
grass	2	4303.0	2151.5
soil x grass	4	2160.0	540.0
Residual	36	873.2	24.3
Total	44	19354.4	439.9

Source of Variance	F	P
soil	247.7	<0.0001
grass	88.7	<0.0001
soil x grass	22.3	<0.0001

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 9.01E-022). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are greater than would be expected by chance after allowing for effects of differences in soil. There is a statistically significant difference (p = 1.22E-014). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of soil depends on what level of grass is present. There is a statistically significant interaction between soil and grass. (P = 0.00000000255)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 1.000
Power of performed test with alpha = 0.0500: for soil x grass : 1.000

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.424
2.000	34.80	0.424
3.000	34.53	0.424

Least square means for grass

Group	Mean	SEM
Agrst	23.7	0.424
Dscha	10.9	0.424
Elyms	34.8	0.424

Table 37. Analysis of Variance Results: Soil and Grass Shoot Length.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
2 vs 1	34.800	3	27.367
2 vs 3	0.267	2	0.210
3 vs 1	34.533	2	27.157

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Comparison	Diff of Means	p	q
Elyms vs Dscha	23.9	3	18.82
Elyms vs Agrst	11.1	2	8.76
Agrst vs Dscha	12.8	2	10.07

Comparison	P<0.05
Elyms vs Dscha	Yes
Elyms vs Agrst	Yes
Agrst vs Dscha	Yes

Table 38. Analysis of Variance Results: Soil and Grass Root Length.

Two Way Analysis of Variance
Balanced Design
Dependent Variable: r cm

Source of Variance	DF	SS	MS
soil	2	12605.20	6302.600
grass	2	2.80	1.400
soil x grass	4	3.20	0.800
Residual	36	64.80	1.800
Total	44	12676.00	288.091

Source of Variance	F	P
soil	3501.444	<0.0001
grass	0.778	0.4670
soil x grass	0.444	0.7757

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 5.73E-042). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.467).

The effect of different levels of soil does not depend on what level of grass is present. There is not a statistically significant interaction between soil and grass. (P = 0.776)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 0.0500
Power of performed test with alpha = 0.0500: for soil x grass : 0.0500

Least square means for soil

Group	Mean	SEM
1.000	0.00	0.115
2.000	35.20	0.115
3.000	35.80	0.115

Least square means for grass

Group	Mean	SEM
Agrst	23.6	0.115
Dscha	23.4	0.115
Elyms	24.0	0.115

Table 38. Analysis of Variance Results: Soil and Grass Root Length.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Means	p	q
3 vs 1	35.800	3	103.35
3 vs 2	0.600	2	1.73
2 vs 1	35.200	2	101.61

Comparison	P<0.05
3 vs 1	Yes
3 vs 2	No
2 vs 1	Yes

Table 39. Analysis of Variance Results: Soil and Grass pH.

Two Way Analysis of Variance
General Linear Model
Dependent Variable: pH

Source of Variance	DF	SS	MS
soil	2	264.7137	132.3569
grass	2	0.1159	0.0579
soil x grass	4	0.0685	0.0171
Residual	26	0.7171	0.0276
Total	34	269.5856	7.9290

Source of Variance	F	P
soil	4799.127	<0.0001
grass	2.100	0.1427
soil x grass	0.621	0.6514

The difference in the mean values among the different levels of soil are greater than would be expected by chance after allowing for effects of differences in grass. There is a statistically significant difference (p = 4.08E-034). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of grass are not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in soil. There is not a statistically significant difference (p = 0.143).

The effect of different levels of soil does not depend on what level of grass is present. There is not a statistically significant interaction between soil and grass. (P = 0.651)

Power of performed test with alpha = 0.0500: for soil : 1.000
Power of performed test with alpha = 0.0500: for grass : 0.214
Power of performed test with alpha = 0.0500: for soil x grass : 0.0500

Least square means for soil

Group	Mean	SEM
1.000	1.84	0.0429
2.000	7.49	0.0490
3.000	7.38	0.0598

Least square means for grass

Group	Mean	SEM
Agrst	5.53	0.0474
Dscha	5.52	0.0515
Elyms	5.66	0.0540

Table 39. Analysis of Variance Results: Soil and Grass pH.-- Continued

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method)

Comparison	Diff of Means	p	q
2 vs 1	5.650	3	122.71
2 vs 3	0.109	2	1.99
3 vs 1	5.541	2	106.50

Comparison	P<0.05
2 vs 1	Yes
2 vs 3	No
3 vs 1	Yes

Table 40. Analysis of Variance Results: Soil and Grass Vigor.

Kruskal-Wallis One Way Analysis of Variance on Ranks

SOIL--VIGOR

Group	N	Missing
control	15	0
lime	15	0
lime/m	15	0

Group	Median	25%	75%
control	0.00	0.00	0.00
lime	4.00	3.00	4.00
lime/m	4.00	4.00	4.00

H = 35.6 with 2 degrees of freedom. (P = <0.0001)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.0000000183)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Student-Newman-Keuls Method) :

Comparison	Diff of Ranks	p	q
lime/m vs control	378.5	3	7.44
lime/m vs lime	82.0	2	2.41
lime vs control	296.5	2	8.70

Comparison	P<0.05
lime/m vs control	Yes
lime/m vs lime	No
lime vs control	Yes

Table 40. Analysis of Variance Results: Soil and Grass Vigor.-- Continued

Kruskal-Wallis One Way Analysis of Variance on Ranks

GRASS--VIGOR

Group	N	Missing
vig agrs	15	0
vig des	15	0
vig ely	15	0

Group	Median	25%	75%
vig agrs	3.00	0.00	4.00
vig des	3.00	0.00	4.00
vig ely	4.00	0.00	4.00

H = 1.38 with 2 degrees of freedom. (P = 0.5018)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.502)

APPENDIX C

PLANT GROWTH RESPONSE

Table 41. Data for *Agrostis stolonifera* Response Variables

SOIL Block no.	Root weight g/pot	Shoot weight g/pot	Total weight g/pot	Root/ shoot ratio	Shoot length cm	Root length cm	pH	Vigor 0 to 4
Control 1	0	0	0	0	0	0	1.80	0
Control 2	0	0	0	0	0	0	1.84	0
Control 3	0	0	0	0	0	0	1.79	0
Control 4	0	0	0	0	0	0	1.82	0
Control 5	0	0	0	0	0	0	1.91	0
Limed 1	0.16	0.20	0.36	0.80	21	30	7.34	2
Limed 2	0.95	0.31	1.26	3.06	26	36	7.47	2
Limed 3	2.96	3.01	5.97	0.98	46	36	7.54	4
Limed 4	4.65	4.81	9.46	0.97	50	36	7.28	4
Limed 5	1.88	1.40	3.28	1.34	35	36	7.61	3
Limed+Manure 1	3.47	7.26	10.73	0.48	41	36		4
Limed+Manure 2	3.83	9.98	13.81	0.38	34	36	7.13	4
Limed+Manure 3	4.07	12.83	16.90	0.32	33	36		4
Limed+Manure 4	3.70	11.85	15.55	0.31	30	36	7.23	3.5
Limed+Manure 5	4.22	11.70	15.92	0.36	39	36	7.61	4

Table 42. Data for *Deschampsia cespitosa* Response Variables

SOIL	Block no.	Root weight g/pot	Shoot weight g/pot	Total weight g/pot	Root/ shoot ratio	Shoot length cm	Root length cm	pH	Vigor 0 to 4
Control	1	0	0	0	0	0	0	1.77	0
Control	2	0	0	0	0	0	0	1.83	0
Control	3	0	0	0	0	0	0	1.99	0
Control	4	0	0	0	0	0	0	1.82	0
Control	5	0	0	0	0	0	0	1.79	0
Limed	1	2.37	6.14	8.51	0.38	24	36	7.75	4
Limed	2	0.96	5.08	6.04	0.19	14	36		3
Limed	3	0.83	5.11	5.94	0.16	12	30	6.98	3
Limed	4	1.15	5.27	6.42	0.22	16	36		3.5
Limed	5	1.04	5.25	6.29	0.20	13	36	7.58	3
Limed+Manure	1	1.45	5.96	7.41	0.24	17	36		4
Limed+Manure	2	0.96	5.75	6.71	0.17	18	36	7.38	4
Limed+Manure	3	1.31	5.81	7.12	0.22	19	36	7.43	4
Limed+Manure	4	1.36	5.79	7.15	0.23	17	36	7.00	4
Limed+Manure	5	0.56	5.39	5.95	0.10	13	33		3

Table 43. Data for *Elymus cinereus* Response Variables

SOIL	Block no.	Root weight g/pot	Shoot weight g/pot	Total weight g/pot	Root/ shoot ratio	Shoot length cm	Root length cm	pH	Vigor 0 to 4
Control	1	0	0	0	0	0	0	1.81	0
Control	2	0	0	0	0	0	0	1.85	0
Control	3	0	0	0	0	0	0	1.90	0
Control	4	0	0	0	0	0	0	1.84	0
Control	5	0	0	0	0	0	0	1.82	0
Limed	1	9.49	10.16	19.65	0.93	56	36	7.66	4
Limed	2	8.68	10.62	19.30	0.82	54	36	7.65	4
Limed	3	5.65	9.77	15.42	0.58	50	36	7.52	4
Limed	4	9.36	10.33	19.69	0.91	49	36	7.49	4
Limed	5	8.44	10.98	19.42	0.77	56	36		4
Limed+Manure	1	6.97	9.92	16.89	0.70	49	36	7.61	4
Limed+Manure	2	7.90	10.22	18.12	0.77	51	36		4
Limed+Manure	3	8.82	9.55	18.37	0.92	51	36		4
Limed+Manure	4	6.64	10.18	16.82	0.65	54	36	7.48	4
Limed+Manure	5	8.97	9.93	18.90	0.90	52	36		4