GROWTH OF SELECTED PLANTS IN RESPONSE TO TREATMENTS OF ACID COPPER MINE TAILINGS

by

James Edmund Lochner II

A Thesis Submitted to the Faculty of the

SCHOOL OF RENEWABLE NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE
WITH A MAJOR IN RANGE MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 7 8

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in his judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: James E. Hochne

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Gilbert L. Jordan

Gilbert L. Jordan
Professor of Range Management

Aug. 3, 1978
Date

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to his major professor, Dr. Gilbert L. Jordan, for his guidance and assistance in the preparation of this manuscript.

Appreciation is extended to Dr. Phil R. Ogden and Dr. David M. Hendricks for serving on the examining committee, and for their suggestions and critique of the manuscript.

Acknowledgment is made to Dr. Jack L. Stroehlein for providing some of the equipment used in this study, the Tucson Plant Materials Center for supplying seed and soil, the Tucson Wastewater Treatment Plant for supplying sewage sludge, the Phelps Dodge Corporation for supplying mine tailings, and the School of Renewable Natural Resources, University of Arizona for their support and equipment used during the study.

Sincere gratitude is extended to Becci Wallis for her efforts and expertise in the typing of this manuscript.

The author wishes to express his appreciation to his parents, Mr. and Mrs. James E. Lochner, for their financial and moral support throughout his University work. Finally, the author wishes to express his deepest appreciation to his wife, Mary, for her assistance in the collection of data, and for her patience, understanding, and encouragement throughout the graduate program.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

LIST OF ILLUSTRATIONS--Continued

LIST OF ILLUSTRATIONS--Continued

LIST OF TABLES

ABSTRACT

Reducing erosion of copper mine tailings dumps and improving the esthetic value of these areas often requires establishing an effective vegetative cover. The effects of treated tailings on the growth of vegetation was studied in the greenhouse and laboratory. Selected rates of lime, sewage sludge, and topsoil added to tailings were evaluated. Treatments and plant species were evaluated on seedling emergence, rate of top growth and root growth, survival, total vegetative production, and percolate concentration after leaching.

Liming rates of 6.7 metric tons per hectare and less, and sludge rates of 67.2 metric tons per hectare and less provided little improvement in top and root growth of blue panicgrass and balloon pea. Topdressing of tailings with a topsoil layer placed over a mixture of topsoil and tailings appeared to be a highly effective cultural practice. Roots failed to elongate and grow successfully in untreated tailings. When in contact with tailings, roots exhibited signs of heavy metal toxicity.

The general leaching pattern exhibited a relatively high initial concentration of toxic elements in the leachate which gradually decreased upon further leaching. Mixing 740 metric tons of topsoil per hectare with tailings was most effective in reducing heavy metal solubility and toxicity.

INTRODUCTION

The activities of mining operations throughout the United States have frequently resulted in serious disturbances in the enviroment. Waste materials resulting from mining operations are unattractive, a source of air and water pollution, and are often highly prone to erosion. The particle size of most waste heaps is often small enough for it to blow in dry weather on to surrounding areas. Runoff from mine wastes has resulted in severe pollution of downhill land and pastures, endangering the livestock grazing these lands (Griffith 1919). In addition, these wastes have also resulted in contamination of downstream habitats of fish through the effects of suspended particles (Hinesly, Jones, and Sosewitz 1972) and dissolved toxic minerals (Antonovics, Bradshaw, and Turner 1971; Duncan 1972).

Toxic wastes accumulated from copper mining are of special interest in this thesis. The wastes are known as tailings and are deposited in the form of a water slurry in settling basins known as tailings ponds. The water is then decanted leaving the finely grained tailings.

Over 90% of the copper in the United States is produced in five Western states. Arizona produces over 50% of this 90% resulting in about 100 million tons of tailings per year (Nakamura, Aleshin, and Schwartz 1970).

The rate of production of waste materials increases annually as the depth of ore bodies mined becomes greater and ore quality (grade) becomes lower.

For tailings, the normal relationship of moisture, soils, and plants has been drastically altered. In stabilizing these wastes, efforts are directed toward bringing soil material, moisture, and plants back to an ecologically stable and productive situation. Existing means for stabilizing wastes include physical, chemical, and vegetative methods, and combinations of these. Among these, vegetative stabilization is the most promising in minimizing pollution, particularly where the pollution is due to the movement of solid particles, and in improving the appearance of the waste dumps (Dean, Havens, and Valdez 1969, 1971). Due to the combined effects of toxicity, lack of nutrients, and poor physical conditions, tailings are usually void of plant growth and will rarely support plant life unless the wastes are ameliorated to make them more favorable to vegetative establishment and growth.

Vegetative stabilization of mine wastes poses less of a problem in the eastern than in the western United States, primarily due to the amount of precipitation which falls in each region. In arid and semi-arid regions of the West, reclamation is much less efficient because of limited available moisture.

Due to the nature of the geologic strata from which they are derived, copper mine tailings in some western regions are nearly neutral or even basic in their chemical reaction. These wastes generally present no major revegetation problem. However, in some regions tailings are very acid and thus highly unfavorable for plant growth.

Acidic tailings usually require an application of lime or limestone, which is considered essential for neutralizing the acidity and decreasing the availability of most toxic metals in tailings. Laboratory research and field experiments support the general acceptance of treating tailings with lime. Because variations among mine wastes result in variable effects from liming, preliminary experimentation is needed to determine liming effects on tailings and plant growth.

The lack of nutrients in tailings is counteracted by the addition of fertilizer. The combination of rising fertilizer costs, and increasing supplies of municipal wastes has created an interest in the use of sewage sludge as a fertilizer for both agriculture and vegetation stabilization on mine wastes. The use of sewage sludge may be more economically feasible than commercial fertilizers, however, sludges may contain toxic levels of heavy metals and soluble salts, which may limit their use. Therefore, additional research is needed to determine the effects sludge treated tailings have on plant growth.

Tailings that exhibit conditions too extreme to be improved with lime or fertilization, generally require leaching or an application of a layer of topsoil. The use of topsoil has gained universal acceptance among most workers. However, possible confinement of root growth to the topsoil layer may not provide suitable stability of the wastes. Additional research is therefore, needed to study the effects topsoil treated tailings have on plant growth.

Rehabilitation information and guidelines are needed for copper mined areas throughout the arid West. Additional research is needed to increase the probability of successful vegetation establishment on such areas. Continued revision of rehabilitation procedures should ultimately yield suitable guidelines for successful procedures. For this reason, the present study was undertaken.

The objectives of this investigation were (1) to determine through greenhouse studies, the effects of ameliorating tailings with lime, sewage sludge, and topsoil on the establishment and early growth of blue panicgrass (Panicum antidotale), Lehmann lovegrass (Eragrostis lehmaniana), quailbush (Atriplex lentiformis) and balloon pea (Sutherlandia microphilla); and (2) to determine through a laboratory leaching study the effects of the above amendments on the leachate quality of tailings.

LITERATURE REVIEW

Literature deemed important to the study presented in this thesis has been divided into the following categories: (1) nature of tailings, (2) amelioration with lime, (3) amelioration by leaching, (4) amelioration with sewage sludge, (5) amelioration with topsoil, and (6) species selection.

Nature of Tailings

Consideration of esthetics generally favors the use of vegetative stabilization. Such stabilization should produce a self-perpetuating plant cover directly, or foster extrapment and germination of native plant seeds which will form a stable community. However, the successful limitation and perpetuation of vegetation on acid copper mine tailings involves amelioration of a number of unfavorable factors such as poor physical properties, toxic substances, nutrient deficiencies, possible symbotic microorganism deficiences, high acidity, and salinity.

Tailings consist of finely ground host rock and chemically leached material of the ore body from which valuable minerals have been extracted. The solids are usually of small particle size, ranging from 15 to 250 microns that, when windblown, can destroy vegetation by sand blasting.

Organic matter and the structure typical of natural soils is lacking, thus making the tailings a very poor medium for plant growth. Because there is a lack of organic matter, the tailings exhibit little or no buffering capacity to a change in pH, so that a relatively small amount of acidic or basic materials effects large changes in pH. Organic matter tends to adsorb excess anions and cations up to the point of saturation and this acts as a buffer which in normal soils eases the "shock" effect of the addition of chemical materials, and tends to change the soil reaction (Weston 1973).

Steeply sloping sides of the waste piles intensify runoff and erosion and increase the difficulty of successfully establishing a protective stand of vegetation. For this reason, vegetation stabilization usually requires resloping the dam structures for a more gradual relief. Futhermore, the sloping sides receive greatly varying amounts of solar radiation depending on the direction of exposure. Most tailings are light in color and may reflect excessive radiation to plant surfaces, thus intensifying physiological stress. Therefore, vegetation that may be effective on northern and eastern exposures may not be suitable for southern or western exposures.

The reclamation procedure is dictated by the pH rating of the tailings. According to LeRoy and Keller (1972), tailings fall into three categories: (1) normal or neutral pH (6.5 to 8.5); (2) low or acid pH (6.5 to 2.0 or less);

and (3) high or alkaline pH (8.5 to 12.0 or more). James (1966) reported that gold mine tailings in South Africa with a pH of 1.5 were extremely difficult to vegetate.

Sulfide minerals are a common constituent in tailings. When these sulfides are at or near the surface, they are oxidized to form sulfates. Sulfuric acid is formed which reduces the pH of the tailings and thus increases the solubility of copper (Cu), iron (Fe), zinc (Zn) and other metals and minerals to possible toxic levels for plant growth. As reported by Dean, Havens, and Glantz (1974), tailings at the Kennecott Company Utah Copper Division are of such material. Fresh tailings have a pH of 7.8 along with a salinity equivalent to 2.4 atmospheres osmotic concentration and contain approximately 1.3% pyrite. As the pyrites oxidize, the pH may drop from 7.8 to less than 3.0 within one month.

Iron pyrite oxidizes too slowly to have much influence on the physical condition of soil, and is almost ineffective in supplying available nutrients to plants. However, certain oxidized pyrites have been demonstrated to be of agricultural importance when applied to soils or plants where deficiency symptoms are found (McGeorge and Breazeal 1955, Smith 1930). Olson (1950) similarly found that coal mine refuse containing pyrite and ferrous sulfate improved chlorophyll production when applied to an alkaline soil of pH 8.0.

Tailings may contain varying amounts of heavy metals, and in excessive quantities, they are toxic and can cause death of most living organisms (Passow, Rothstein, and Clarkston 1961).

A major problem with growing vegetation on copper tailings is related to low pH and the consequent high levels of soluble toxic metals in the tailings. Peterson and Nielson (1973) noted that the higher concentration of metals in mine tailings were in samples with the lowest pH. For example, when the pH is neutral, water-soluble copper is low. As acidity increases, copper compounds are more soluble resulting in toxic levels to plants. If metals are present in high concentrations, it may be necessary to leach or precipitate these elements and prevent lowering the pH.

Further evidence that the concentration of most elements is related to pH was demonstrated by Galbraith, Williams, and Siems (1971) on old copper mine tailings. These researchers found that the solubility of zinc (Zn), lead (Pb), manganese (Mn), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) decreased with increasing pH. Similar findings were reported by Berg and Vogel (1973), Hodgson (1963), Boyles et al. (1974), and Vogel and Berg (1968). Additional factors found to affect the solubility and availability of heavy metals include the solubility product of the corresponding hydroxides, hardness of water, and absorptive capacity of clay and silt (Duncan 1972).

The availability of most plant nutrients is influenced by soil pH. It is evident that lowering the pH must be prevented to minimize the solubility of heavy metal phytotoxicants. However, as pointed out by Peterson and Nielson (1973), the ideal range for minimum solubility of heavy metals also decreases the solubility of phosphorus (P) in a calcium-sodium system. Galbraith et al. (1971) noted that metal ions enter into solution as metal sulfate and have been found to precipitate at a pH near 6.6. However, working with copper mine tailings with a pH near neutral, Ludeke (1972) observed that the concentration of available Fe, Mg, Zn, and Cu were high enough to adversely affect plant growth. P, Na and K were found to be available in adequate concentrations for satisfactory plant growth. Nitrogen (NO_3-N) and Mn were present in low concentrations.

Sharp changes in vegetation coincide with changes in total concentration of heavy metals. Whitby and Hutchinson (1974) assessed the effects of heavy metal contamination from airborne smelter emissions in Canada on root growth of several species. Extent of radicle elongation in bathing solutions of soil-water extracts was used as a bioassay index of soil toxicity. These workers reported that copper reduced root growth by 30% at 2 ppm (parts per million) and almost completely inhibited elongation at 15 ppm. Root growth was reduced in extracts of soils which had been collected up to a distance of 49.8 km. from the smelter.

Inhibition was greatest in surface soils. Water extracts had metal concentration of up to 142 ppm Ni, and 59.5 Cu.

Dean et al. (1974) reported that the copper content in the sulfide form in tailings containing .07% to .2% copper was not a significant factor on plant growth. These workers observed that 1,000 ppm Cu had little effect, greater than 100 ppm Ni was toxic, and greater than 10 ppm Zn was toxic. When using a composite of these elements, toxic effects became evident at 10 ppm and became pronounced at 100 ppm. At low concentrations, toxicity was independent of osmotic pressure.

Total soluble salt levels can be high enough to be deterrents to plant growth. At Kennecott's Utah Copper Division, difficulty was encountered in growing vegetation in mine tailings (Dean et al. 1973). Duplicate plantings were made in (1) flotation tailings containing water soluble salts but assaying only .05% Cu, mostly as sulfides, and (2) tailings containing little soluble salts but almost .25% copper. Seeded plots were watered with tap water and tailings effluent water. Both germination and plant growth were adversely affected when effluent water was used. Toxicity was shown to be the result of high salt content of the water and tailings. Similar results were observed by Peterson and Nielson (1973). These workers reported that plants usually died when planted in unaltered tailings. The results were attributed to high salinity and severe nitrogen deficiency. The salinity problem was caused by the salty water used in transporting the tailings as a slurry. The condition was further aggravated by the concentrating effect of recycled water. The salt concentration was most severe during the summer months when evaporation from the tailings pond was greatest.

Excess salts affect plants in several ways. These are (1) retarded uptake of water, (2) plasmolysis (the removal of water by osmosis and the death of root cells), (3) limited uptake or availability of certain nutrients, and (4) the toxic effects of concentrations of some salts. In some cases it may be difficult to distinguish whether excess salt or calcium deficiency is the dominant factor affecting plant growth. According to Geraldson (1957), a calcium deficiency in the plant can result from a low calcium ratio in the soil solution.

Plant growth studies on acidic copper mine tailings containing enough salts to produce osmotic concentrations between 2.2 and 2.5 atmospheres, indicated that the osmotic gradient between the plant fluids and the environment around the roots presumably caused plants to become dehydrated (Dean and Havens 1971). The death of the plants was due more to the salt content than to either toxic organic compounds, or metallic elements. Further studies by Dean and associates (1974) were conducted to determine which salts or organic reagents in copper tailings affected plant growth the most. The principal salt found to have caused dehydration was sodium chloride, however, dehydration was produced with all types of salts at the osmotic concentrations considered, which were 2.36 and 2.46 atmospheres.

The effect of salts, other than limiting the availability of moisture to plants, may also be of equal importance in restricting growth by the antagonism of essential nutrients. Toxicity need not involve a direct effect of the salt or ions on surface membranes of plant roots or in the plant tissues. Toxicity may be caused in part, through effects on the uptake or metabolism of essential nutrients. The influence of excessive concentrations of specific salts on plant growth is extremely complex with many physiological principles beyond the scope of this review. The literature is voluminous and diversified. Hayward and Wadleigh (1949) present a review of much of this pertinent literature.

The total concentration as well as the types of dissolved salts involved, influence seed germination and, thus, seedling establishment. Soil salinity affects seed germination by decreasing water availability and by facilitating the entry of ions in sufficient amounts to be toxic. Uhvits (1946) reported that the rate and percent of seed germination decreased by increasing the osmotic pressure. On acidic copper mine tailings, Dean et al.

(1973) reported that the germination rate of tomatoes decreased with increasing concentration of salts until there was no germination at 4.5 atmospheres.

Root systems of most species growing in natural soils or on non - toxic materials are well developed both horizontally and vertically. Where toxic constituents are present, the roots develop only in the surface and near surface soil. Harabin and Greszta (1973) observed that the development of root systems of trees were affected more by the chemical than by the physical properties of toxic spoil material. In a toxic soil environment, tree species exhibited a flat root system. The roots were spread out just below the surface of the soil layer no more than 10 centimeters deep. Stewart, Cottarn, and Hutchings (1940) observed that roots of shadscale penetrated soil having 1,000 to 10,000 ppm salt, but those of sagebrush did not. Results obtained from a greenhouse study to determine potential plant growth on surface-mined spoils in Wyoming indicated that 86.7% of the herbage yield may be accounted for by its dependence on the corresponding amount of root development (Howard, Schuman, and Rauzi 1977).

It is often believed that nutrient deficiency is the cause of vegetative failure on industrial waste land, and deficiency symptoms are often observed among species. However, according to Knab (1965), nutrient deficiency may often be the cause of poor growth, but rarely accounts for the complete absence of vegetation.

Establishing vegetation on open-pit copper mine tailings is additionally difficult because of constraints represented by sharp differences in physical and chemical characteristics of wastes from the same pit. A large degree of segregation through dispersion in the tailings pond create areas of varying densities, textures, porosities, and water contents. Tailings have potentials that are completely different from any of the naturally occurring sites in the area, although they are presently limited by the same climatic factors. The composite of geologic strata removed from the various mines and dumped as overburden have characteristics unique to each location and to each tailings pile. In some instances both acidic and basic conditions are present in different locations of a single tailings accumulation.

Amelioration with Lime

The intensity of acidity in soils is characterized by hydrogen ion activity. Adsorbed hydrogen contributes directly to the hydrogen ion concentration in the soil solution. Aluminum under very acid soil conditions becomes soluble and is present in the form of aluminum or aluminum hydroxy cations.

Aluminum ions in the soil solution contribute to soil acidity through their tendency to hydrolize. The consequent release of hydrogen ions results in a very low pH value in the soil solution.

According to Black (1968, p. 276), increased exchange capacity with increasing pH resulted in the concept that exchange positions are "pH dependent". At low pH values, the numerous hydrogen ions present supress the disconnection of hydrogen from most of the pH dependant sites. At high pH values, fewer hydrogen ions are present, more of the hydrogen disconnects from the sites, and the displacing cations can then be attached in exchangeable form.

The use of lime for alleviating acidic conditions and improving production on agricultural soils is a well known practice, and has been studied extensively (Coleman, Kamprath, and Weed 1959). The mechanisms through which lime reacts with acid soils are extremely complex, and are discussed by Pearson and Adams (1967).

Utilization of lime or limestone is the most widely used practice in neutralizing and upgrading acidic mine wastes, and is considered by most investigators to be essential to the establishment of a vegetative cover in a reasonable length of time (Dean et al. 1973; Goodman, Pitcairn, and Gemmell 1973; Chadwick 1973; Berg 1970).

If sufficient lime is applied to an acid waste, the pH can be raised to levels sufficient to decrease availability of most metals. Since the solubility of nearly all toxic metals increases with a decrease in pH, there is agreement (Webber 1972, Lunt 1953, Patterson 1971, King and Morris 1972, Chaney 1973) that soils must be limed to at least pH 6.5 to reduce the possibilities of metal toxicity. Snaydon and Bradshaw (1961) observed that by incorporating hydrated lime into an acid soil at the rate of 100 grams per square meter, symptoms of heavy metal toxicity were reduced on _Festuca ovina_.

Peterson and Nielson (1973) reported that smaller quantities of heavy metals contained in copper mine tailings were removed when lime was added prior to leaching. The lime appeared effective in tying up the metals. However, the data also suggested that the addition of lime may aggrevate the phosphorus deficiencies that persist in copper tailings. Mihok et al. (1968) reported the precipitation of almost all Fe, Mn, Cu, Pb, and Zn during utilization of ground limestone to neutralize acid mine drainage. These findings are confirmed on mineral soils by Leeper (1947), and Chaiwanakupt and Robertson (1976).

The amount of lime that must be applied to a soil to bring the soil reaction to neutrality or to some other desired pH level, as determined by some specified method, is termed "lime requirement". Field experiments indicate that affected land usually requires an application of lime which is above the lime requirement determined (Griffith 1919). Russell (1973, p. 665) reported that it is commonly necessary to double or triple the lime requirement determined in the laboratory for application under field conditions. Homuth, as reported by Darmer (1973), postulated that 1 milliequivalent of acid per 100 grams of soil requires .8 to 1 metric ton of lime per hectare to achieve neutralization.

Rates of limestone application on mine wastes will vary widely from 3 to 30 tons or more per acre (LeRoy and Keller 1972). The efficiency or rate at which lime reacts with a soil is largely determined by soil pH, limestone particle size, and extent of lime-soil intermixing (Pierre 1930). Cycles of wetting and drying, along with mechanical mixing, appear to enhance the reaction rate.

The rate of reaction is probably influenced significantly by the salt level in the soil. Adsorbed anions such as sulfate can make a significant contribution to the buffer capacity of soils. In acid soils containing adsorbed sulfate, liming decreases the amount of sulfate adsorbed, and appreciable amounts of calcium carbonate can be consumed in producing calcium sulfate (Pearson and Adams 1967).

Vegetation studies were conducted on uranium tailings from Wyoming and Colorado (Dean et al. 1974) with acidities of pH 2.3 and 4.5, respectively. The addition of 70 pounds and 7 pounds of lime per acre, respectively, to the top 12 inches of tailings raised the pH levels high enough to sustain plant growth. Young (1969) reported that applying agricultural limestone at the rate of 3 tons per acre on moderately acid copper mine tailings at Copper Cliff in Canada, increased the pH of the tailings to near neutrality. The use of hydrated lime resulted in a more rapid method of adjusting the tailings pH, and establishing vegetation.

Chenik (1960), conducting research on gold mine tailings in Africa, reported an increase in the pH of tailings from 2.7 to 6.5 by adding 2 tons of lime per morgen (1 morgen = 2.116 acre). A first application of 2 tons of air slaked lime was carried out for a rapid rise in pH. A second application of 2 tons of coarse limestone acted as a stability factor over a longer period of time. However, James (1966) reported that the addition of lime to gold mine tailings with a pH 1.5 failed to provide a suitable pH for plant growth. He concluded that this method of raising the pH value is satisfactory only for tailings of low or moderate acidity.

Greenhouse studies involving lime addition and plant growth on acidic copper mine tailings were conducted by Peterson and Nielson (1973). These workers reported that the addition of lime throughout the study period resulted in no measurable benefit to plant growth. It was thought that the plant growth period was short enough so that little sulfide oxidation occurred. In addition, the water used in this study contained Ca and Mg carbonates and bicarbonates equivalent to .32 tons per acre foot of water. The investigators concluded that leaching with this water which provided lime, reduced the acidity.

Mixing lime with tailings does not usually ensure a good medium for plant growth. Most tailings are more or less deficient in one or more of the common plant nutrients. Liming will raise the pH and make certain cations unavailable but is not effective in providing N, P, or K for plants. Therefore, some kind of fertilization should be incorporated into the waste. Knab (1965) reported that adding combinations of lime and nutrients to tailings has given a much better response than simple liming alone. Knab supported these findings by conducting soil investigations and greenhouse studies which showed that acidity was the primary cause of toxicity, and nutrient deficiencies were the secondary cause for poor plant growth.

Peters (1970) reported that the addition of lime and fertilizer resulted in the best vegetative production on acid siliceous tailings in Ontario, Canada. The application of 3 tons per acre of feed grade limestone sufficiently reduced acidity. This was followed by 400 pounds per acre of a 5-20-20 fertilizer. The combined use of these two amendment materials resulted in maximum vegetative production.

Despite failures in earlier attempts, Sutton (1973), reported that a combination treatment of limestone and fertilizer produced the most plant growth of Korean lovegrass, and weeping lovegrass on toxic coal mine spoils. The spoils were characterized as having a pH of 2.4 and a high soluble salt content of 3,970 pounds per acre. The addition of 2,700 pounds of limestone per acre was sufficient to raise the pH to 4.7 and attain a stand of vegetation. However, subsequent growth was very limited. The addition of 380 pounds per acre of a 12-12-12 fertilizer alone failed to produce any plant growth. The combined use of these two amendments produced the best treatment for plant production.

Amelioration by Leaching

As mentioned earlier, excess soluble salts in tailings are inhibitory to plant growth. Salts can be removed from soil solution mainly by plant uptake, soil utilization (microorganisms and fixation), and leaching. In some instances, provisions must be made to leach at least a portion of the salt from the tailings before plants can be grown. Knab (1965) reported that high concentrations of soluble salts exceeding the osmotic pressure of the roots cannot be eliminated except by leaching or covering the wastes with fertile material. Berg (1970) concluded that a combination of liming and leaching of mine tailings was a successful procedure for establishing vegetation.

The amount of water necessary for desired leaching is dependent on the amount of salt, acidity, soluble toxic metals, water capacity, and moisture content of the tailings (Peterson and Nielson 1973). Following some rather detailed studies, these workers concluded that a minimum leaching is "one water-holding-capacity volume", or one "pore volume", which is the amount of water necessary to completely saturate a given amount of material. Unpublished data obtained by Stroehlein (1977) revealed that levels of water soluble copper and zinc contained in the fifth pore volume extracted from acid copper mine tailings were reduced by 98% and 99%, respectively.

The rate at which water is applied for leaching is also significant. Keller and Alfaro (1966) working with a clay loam salinized with calcium chloride, found that leaching efficiency was improved by decreasing the application rate of water. Ghuman, Verma, and Prihar (1975) worked with leaching columns having chloride salts applied to the soil surface. These workers also found that salts travelled further in columns under slow rates of leaching.

Flooding is not an effective means of leaching salts from tailings. Prolonged flooding compacts the material resulting in unfavorable conditions for plant growth. When flooding is halted, evaporation brings the salts to the surface again (James 1964).

The removal of salts from the upper horizons of soil is a relatively slow process in arid environments but a few methods of leaching are commonly used. One practice used on very acidic gold mine tailings in Africa has been reported to permanently reduce the high acidity by the properly controlled application of water (James 1966, James and Mrost 1965). They indicated that the downward movement of acidic materials can be encouraged by an extremely fine spray of water which forms a mist over the surface and retards evaporation. If application rates do not exceed penetration rates, constituents causing high acidity can be moved to a sufficient depth in a period of three to four weeks to permit vegetative growth. It was concluded that if the acid could be moved downward to contact a slime layer within which it reacts, subsequent evaporative movement will not return the acid to the surface.

Drip irrigation has also been used successfully under arid conditions (Bengson 1975). Drip irrigation supplies water at a slow enough rate to alleviate the hazard of runoff and subsequent erosion. This method is also effective in leaching excess soluble salts from the root zone. Roots can, therefore, grow more deeply into the wastes where soil temperature and moisture conditions are more uniform (Bach 1973). These deeply penetrating roots promote plant survival after the irrigation system is removed.

A disadvantage of drip irrigation for establishing vegetation involves the possible accumulation of salts at the edge of the wetting zone. The drip system only wets a small area and is relatively ineffective for producing a solid vegetative cover.

Amelioration with Sewage Sludge

Sewage sludge consists of the solids remaining after the sewage treatment process. Sludge contains substantial amounts of plant nutrients and other chemical elements potentially beneficial for improving mine tailings. The application of sewage sludge to mine tailings could be beneficial to the revegetation problem as well as the sewage disposal problem.

The use of sewage sludge possesses several advantages. One is that it recycles plant nutrients, primarily N, P, K, Ca, Mg, S, Zn and Cu. Sludge acts as a slow release fertilizer providing nutrients slowly throughout the growing season. Another benefit is its effect on soil physical conditions. It decreases bulk density and improves soil tilth. This increases infiltration and water holding capacity, and consequently reduces the erosive power of water.

Results from several studies have shown that sewage sludge is an excellant fertilizer (Lunt 1959, Hinesly and Sosewitz 1969, Milne and Graveland 1972) with yield increases usually due to the nitrogen and phosphorus in the material (Coker 1966a, 1966b).

Sludges contain all of the nutrient elements essential for plant growth and can contain levels of other elements inhibitory for plant growth. Research by many investigators has indicated that sewage sludge generally contains relatively high amounts of heavy metals (Anderson 1955; Goldstein 1970, Bradford et al. 1975, Berrow and Webber 1972, Webber 1972). According to Dotson (1973), and King and Morris (1972), Zn and Cu are the metals most likely to build to toxic levels as a result of sludge applications on agricultural soils. Lunt (1953) similarly reported that an application of 65 metric tons per hectare resulted in Zn and Cu toxicities which reduced growth rates of beans and oats.

Sewage sludges vary so widely in chemical and physical composition that no truly average value for the content of solids, nutrients, or metals can be given. This heterogeneity occurs from city to city depending upon the treatment process used and major industries, and from day to day in the same city. There is a lack of adequate, definitive information available to set precise guidelines for sludge applications based on its metal content.

A potential limitation of sludge application is the amount of soluble nitrogen present. To prevent excess nitrate concentration in waste drainage from land receiving sludge, the annual loading rate must be adjusted accordingly (Hinesly et al. 1972). In addition, Keeney, Lee and Walsh (1975) reported that if sludge rates are limited to use the nitrogen effectively, heavy metals should not be a problem.

Approximately two-thirds of the nitrogen is tied up in the slowly-available organic form which must be converted to ammonium or nitrate before it becomes available for plant growth. The other one-third is mostly ammonium nitrogen, and is readily available to plants (Keeney et al. 1975). Applied directly to the surface, a large amount of the inorganic ammonium nitrogen in the sludge will volitalize and be lost as ammonia gas.

Sewage sludge can contain relatively high amounts of soluble salts, ranging in concentration from 50,000 ppm to 100,000 ppm. According to Keeney et al. (1975), when large amounts of sludge are applied (greater than 10 tons per acre on agricultural lands), these salts may adversely affect germination and early growth. An application rate of greater than 10 tons per acre might be expected for acid tailings primarily because of the lack of nitrogen in the tailings.

The organic matter content of the soil is of importance in the sense that it is able to form stable complexes with metal ions, thus making them unavailable to plants. Goodman (1974) reported that the organic matter in sewage sludge was able to complex free metal ions making them unavailable to roots.

Leachate quality from acidic mine tailings can be upgraded through the application of sewage sludge into the waste material. Peterson and Gschwind (1972) determined the ameliorating effects of liquid digested sewage sludge on acidic strip-mine spoils by a laboratory column study. The sludge used by these investigators was slightly alkaline in nature and its organic components were able to reduce metal availability by exchange reactions. Acidity decreased, and pH increased to the alkaline side with higher sludge rates. The application rate of 61 metric tons per hectare was the most efficient for water amelioration. Reductions also occurred in Al, Fe, and soluble salts. These workers concluded that the reduction of metal availability through the addition of sewage sludge is an improvement over lime addition which affects mainly the pH dependent metal solubility.

McCormick and Borden (1973) also studied the effects of sewage sludge on acid coal mine spoils. These workers reported that 8 inches of sewage sludge mixed in the upper 12 inches of spoil material produced an increase in the pH of the percolate from 4.2 to 7.2. This rise in pH was attributed to the ammonia and ammonium ion concentration in the sludge-spoil mix. An initial increase in the Ca and K concentrations of the percolate associated with the sludge treatment followed by a gradual decline in concentration suggested a partial saturation of the exchange sites of the colloidal portion of the spoils by ammonia.

Dean and associates (1969) reported that 5 tons per acre of sewage sludge produced better growth than commercial compost in plots prepared with Kennecott copper tailings. Even better responses were obtained when sludge was augmented with mineral fertilizers. Smith and Bradshaw (1970) found that sludge treated tailings resulted in better growth response in tolerant strains of *Festuca rubra* and *Agrostis stolonifera* than from the application of mineral fertilizers.

Sopper (1970), working on acidic strip-mine spoils, reported that best germination and growth resulted from a combination treatment consisting of 2 inches of sewage sludge applied to spoils followed by irrigation equivalent to 2 inches of sewage effluent. The organic residue in the sludge apparently provided the necessary seedbed for germination. Percolate analysis from the study revealed that the control plot had the lowest average values for phosphorus and nitrate-nitrogen, and the highest values for Mn, Fe, and Al. The best treatment, 2 inches of effluent and 2 inches of sludge, ranked highest in P and NO_3-N, and lowest in Mn, Fe, and Al. Levels of K, Ca, Mg, Na, Zn, Cu, and B were relatively higher in the control and apparently resulted from the solublization of the native rock by the high acidity.

Sopper concluded that irrigation of the sludge treated spoils with effluent leached and diluted the salts and solubilities of Mn, Fe, Al, Cu, and Zn.

Lejcher (1973) reported that there is a direct relationship between application rates of sludge and vegetative responses on coal mine spoils. Sludge treatments varied from 77.8 to 303.7 metric tons per hectare with the latter treatment producing a 100% vegetative cover. Lejcher also noted that if sludge application rates are not high enough to neutralize the acidity, some metal concentrations may increase in the runoff.

Layers of sewage sludge burried under a layer of tailings prevents or retards the oxidation of sulfides and the consequent acidification of sulfide-containing tailings. Dean and associates (1974) conducted a series of tests in which 2-inch layers of sludge were placed at depths of 3, 7, 11, and 15 inches in barrels containing an 18-inch depth of tailings. The vegetation appeared healthier in plots with the shallow sludge layers because once the roots penetrated the sludge layer, the plants became healthier and hardier than plants with roots only in the tailings. In another test series, the layering pattern was unchanged but an additional equivalent of 15 tons per acre of sludge was mixed into the top 3 inches of the tailings. The additional sludge-tailings mix appeared to be beneficial to overall plant survival. Roots for the sludge at depths of 7, 11, and 15 inches had grown and remained in the upper 3 inches of tailings containing admixed sludge. Conversely, the main root system for the plot with sludge at 3 inches grew down into and through the sludge layer to within 2 inches of the bottom of the tailings in the barrel. These workers concluded that best results can be achieved with sludge emplaced from the surface down to a depth of 6 to 7 inches.

Amelioration with Topsoil

Various groups have expressed environmental concern that has influenced legislation so that reclamation laws require that topsoil be stockpiled and returned to the overburden surface after mining is completed.

As defined by the Soil Survey Staff (1951, p. 185), "'topsoil' is that material (normally the A, and in some cases, the upper part of the B horizon) which, is acceptable for respreading on the surface of regraded areas to provide a medium for plant growth." Unlike tailings, topsoil usually contains a small but important percentage of organic matter and microorganisms, and is frequently the determining factor in obtaining a cover of seeded plant growth.

According to Cook, Hyde, and Sims (1974), a quality topsoil should have a minimum available moisture holding capacity of 7% (by weight) and be composed of 3 to 20% organic matter. However, soils of the southwestern deserts do not meet these minimum levels. Cook et al. (1974)

recommended that topsoil in arid and semi-arid areas should be 6 to 8 inches deep with a suitable subsoil beneath the topsoil providing at least 18 inches or more of material for a plant growth medium.

Review of available literature has revealed a limited quantity of work dealing with placement of topsoil over tailings. The use of a topsoil layer has seemingly been universally accepted by most workers as a practice that will invariably produce a successful stand of vegetation on mine wastes. However, the spreading of topsoil over vast areas of tailings in a reasonable length of time requires a large labor force and a large capital outlay. In addition, topsoil may be unavailable in some areas, eliminating the possibility of its use. It appears that because of these conditions, the number of experimental studies and field applications utilizing topsoil are limited.

Topsoil treatments have been successful on tailings at the Miami Copper Company in Miami, Arizona (Dean et al. 1969). The tailings were covered with about 4 inches of topsoil obtained from areas adjacent to the tailings. This soil was of a darker color than the tailings and provided some protection from heat reflection. The material was seeded with mixtures of seeds. Seedlings or sprouts of trees and shrubs were also placed by hand. Vigorous growth of planted species and the rapid encroachment of native species resulted.

Topdressing with native topsoils and subsoils appeared to be highly desirable on acidic copper-cobalt tailings in control Idaho (Farmer, Richardson, and Brown 1976). Topsoil was applied at a depth of 8 inches or more, and had a texture of silt loam, a pH of 6.3, and a CEC of 6.0. Coupled with a fertilizer application of granular 18-46-0 fertilizer at a rate of 435 pounds per acre, both ground cover density and vegetative dry weight production increased. Brown and Johnson (1976) reported similar results on acidic tailings in Montana. Plant densities were highest on plots treated with 8 inches of native topsoil, coupled with an application of a 16-16-16 fertilizer.

The use of topsoil is by no means a "cure all" for vegetative stabilization of tailings. Several problems exist with using topsoil as an amendment. Cresswell (1973) encountered the following problems in his work. The first involves the differential permeability between the topsoil and underlying tailings which causes water to accumulate at the soil-sand interface. This water tends to seep downhill following the original sand surface of the tailings structure and may cause a gradual slipping of the overlying topsoil. The second problem is that the plant roots grow preferentially in soil instead of the underlying tailings; therefore, root penetration is limited to the topsoil layer. Weston (1973) does not recommend the use of topsoil because of the restricted root penetration. Smith and Bradshaw

(1972) additionally oppose the use of topsoil because of the large capital outlay required.

Sutton (1973) reported that 6 inches of topsoil material applied over coal mine spoils resulted in the establishment of good vegetative growth. However, he also found that root growth was limited to the topsoil material. Similar results were obtained with 3 inches of topsoil material over a copper mine tailings pond in British Columbia (Anonymous 1972). Furthermore, water and wind consequently eroded the topsoil away within one year, and destroyed the grass cover.

Species Selection

Numerous plant species have been tested for germination and growth in samples of tailings. Many have been found to germinate, grow, and reseed in waste materials that have been adequately prepared to support plant life if environmental conditions are not overly severe (Wesley 1969).

Arid regions of the West are more difficult to stabilize than higher rainfall areas of the East. In the Southwest particularly, precipitation is low, erratic, and unpredictable. Vegetation is subject to great stress from intermittent precipitation, high temperatures, strong winds, and excessive evaporation.

With regard to revegetation, it is important to consider species that are adapted to the soil, climate, elevation, and exposure for a specific site. Species adapted to drought conditions are not necessarily adapted to conditions characteristic of mine tailings in arid environments. Likewise, species which are salt resistant are not necessarily drought tolerant. The review of available literature failed to reveal any plant species which have been proven particularly adapted to mine wastes. However, through some rather detailed studies, Ludeke (1976) considered the possibility of using plant breeding techniques in the selection of adapted barley genotypes for copper mine tailings stabilization. From barley composite crosses, he derived 1200 barley genotypes possessing some adaptation to soil and irrigation water containing high soluble salts, and the environment in southern Arizona.

Species known to be hardy and vigorous when grown under adverse conditions often perform well on tailings. Native species are desirable but are usually low in germination, have poor seedling vigor, and are slow to become established. Once established however, native species may be effective in stabilizing tailings (Nielson and Peterson 1973). Introduced species, on the other hand, often have a high seedling vigor, better soil holding ability, and a greater potential for stabilizing mine wastes (May 1967).

Evaluation of the performance of both domestic and wild plant species has received attention by Dean et al.

(1974). Domestic species were reported to be more reliable germinators than wild species on acid copper mine tailings in Utah. Plants that showed considerable promise include sweet clover, barley, rye, winter wheat, various wheatgrasses (western, crested, intermediate, tall, and pubescent), other grasses (sorghum, lovegrass, Kentucky bluegrass, and orchardgrass), and shrubs such as big sagebrush, rubber rabbit bush, and Siberian pea tree. In addition, *Oryzopsis hymenoides*, a native grass, showed considerable potential as a stabilizing plant.

Certain organisms possess an ability to survive under conditions of heavy metal contamination which prove toxic to other living things. The mechanisms whereby plants combat toxic levels of heavy metals are varied. In higher plants, the tolerance mechanism appears to be designed to keep metal ions away from the active sites of metabolism and chelation in the cell wall. (Antonovics et al. 1971). Galbraith, Williams and Siems (1971) have shown that some plants increase their heavy metal uptake significantly when grown on mine wastes. Others die.

The possibility of using naturally occurring metal tolerant populations of wild species for stabilizing mine wastes has been given consideration by Antonovics et al. (1971), and Smith and Bradshaw (1972). The advantage is that only a lack of nutrients has to be overcome by fertilization. Smith and Bradshaw (1972) reported that ordinary commercial material of the same tolerant species died within one year when planted in heavy metal contaminated mine wastes. As a result of these tests, Agrostis spp. and Festuca spp. are being made available for stabilization of different types of wastes.

Many species of grass and some species of forbs and shrubs show promise for stabilizing mine wastes. Ludeke (1973, pp. 377-410) lists 52 plant species, both native and domestic, that have been tested on copper mine tailings at the Pima Mining Company near Tucson, Arizona. Their response characteristics are discussed in sufficient detail for the list to be used as a guide to selection of plants for vegetating mine wastes in arid and semi-arid climates. Plummer and McArthur (1975) provide a list and discussion of 25 species of shrubby chenopods worthy of consideration for revegetation of mine wastes. Ruffner (1973), and Cook et al. (1974) provide additional information regarding plant species for vegetating mine wastes.

LeRoy and Keller (1972) reported that grasses offer the most effective initial ground cover on copper mine tailings. The grasses become well rooted and will give the necessary protection to slower growing plants. Day and Ludeke (1973) reported that giant bermudagrass, under irrigation and fertilization, has been found effective in providing vegetative cover to stabilize copper mine tailings and to reduce environmental pollution in the Southwest.

However, even though this species is somewhat drought resistant, it is not effectively drought tolerant. When irrigation is removed and moisture becomes limiting, bermudagrass will probably not grow and perpetuate on tailings under climate conditions of the southwest. Day and Ludeke (1973) also reported that the plugged method of planting resulted in more vegetative cover 30 and 180 days after planting than did broadcast seeding. In addition, plants established by plugging developed deeper and more extensive root systems and thus provided more resistance to wind and water erosion than did plants from broadcasting.

Several grass species tested by Vogel and Berg (1968) on acid waste materials included weeping lovegrass (*Eragrostis curvula*), blackwell switchgrass (*Panicum virgatum*), and tall fescue (*Festuca arundinacea*). These investigators reported that weeping lovegrass provided a fast ground cover (70% to 90%) on extremely acid wastes of pH 4.0 to pH 4.5. Blackwell switchgrass required 2 years to establish a satisfactory cover. Tall fescue did not produce a satisfactory cover unless nitrogen fertilizer was applied. These species however, are not considered sufficiently drought tolerant under southwestern conditions.

Seeding mixtures of grasses provides for better adaptability to variable canopy, soil, terrain, and climatic conditions. Mixtures are also more efficient in the use of the total soil profile. Farmer and co-workers (1976) reported that introduced grasses produced good stands under the best conditions, native species provided some cover under adverse conditions, and native and introduced species mixture provided stands across a wide range of intermediate soil conditions on acid tailings in Idaho.

Because tailings generally have little nitrogen and legumes are able to fix nitrogen, legumes may be of special interest in vegetating mine tailings. LeRoy and Keller (1972) reported that *Lotus corniculatus* and *L. uligenosus* have proved to be of outstanding value in reclamation where a wide range of conditions occur on tailings. *Coronillia varia* was the most valuable legume used on very steep banks. Working with several species of legumes, Vogel and Berg (1968) reported that nodulation of legume roots was good in most wastes of pH 5.0 and higher. Plants growing in wastes of pH 4.5 to 4.9 had fewer nodules, and many of these were relatively small. Little or no nodulation occurred on plants growing in wastes below pH 4.5.

Species of interest in the present study presented in this thesis include blue panicgrass (*Panicum antidotale*), Lehmann lovegrass (*Eragrostis lehmaniana*), balloon pea (*Sutherlandia microphilla*), and quailbush (*Atriplex lentiformis*). These species were considered primarily becuase of their ability to withstand droughty conditions. Quailbush was additionally selected because of its ability to withstand high concentrations of salt.

Blue panicgrass has been seeded extensively on rangelands and pasture lands in Arizona (Anderson et al. 1957). This introduced species is characterized as a warm-season, tall growing, long-lived bunchgrass growing from an extensive root system and thick, short, bulbous rhizomes. Once plants are developed, they have been found to exhibit drought tolerance under limited moisture conditions of desert grasslands (Wright 1966, University of Arizona 1969). The literature search failed to reveal any information on the use of this species for vegetating acidic mine wastes.

Lehmann lovegrass, an introduced species, has been widely used to revegetate the drier portions of southwestern ranges (Crider 1945, and Humphrey 1960). This warm-season, perennial bunchgrass is well adapted to semidesert ranges primarily because of its ability to reseed readily, tolerate drought conditions, and produce acceptable forage for livestock. The performance of Lehmann lovegrass on various mine wastes in arid areas has been studied by several investigators. Ludeke (1972) reported that this grass was easily established on copper tailings and could withstand hot dry winds during the summer period. Dean et al. (1969) reported that this species showed considerable promise on acidic copper mine tailings in Nevada. LeRoy and Keller (1972) reported that Lehmann lovegrass provided rapid soil cover on other acid tailings. Chenik (1960) stressed that because of good germination of this species, it was ideal for vegetating acid gold mine tailings in Africa.

Balloon pea is an introduced shrub originating from South Africa. According to Briggs (1973), this species exhibits good germination, is fairly drought tolerant and winter hardy, reseeds readily, and is valuable as a browse species. Information in the literature could not be found regarding growth of this species on acid mine wastes. However, Chenik (1960) reported that _Sutherlandia frutescens_, an indigenous, 4 foot tall, leguminous bush of the same genera as _S_. _microphilla_, performs very well on acidic mine wastes in Africa. In fact, it is difficult to distinguish between these species on a morphological or physiological basis.

Quailbush is a native, salt tolerant shrub usually growing in moist or dry saline soil. As a group, salt bushes exhibit important attributes of adaptation, as well as for improvement of forage and cover. Plummer and McArthur (1975) reported that their ability to establish and grow on salt-bearing, low fertile soils as well as a wide climatic variation, makes them especially suited for planting on mine wastes. Ludeke (1972), in reviewing the usefulness of various species on mine wastes, reported that quailbush is beneficial as a hedge or windbreak where salt tolerant plants are needed.

MATERIALS AND METHODS

Copper mine tailings used in the following investigations were acquired in the fall of 1976 from the Phelps Dodge open-pit copper mine at Morenci, Arizona. These tailings are characterized by a pH slightly above 4.0, the value usually given as the critical value for plant survival and growth (Linstrom 1960, Vogel and Berg 1968). Apache desert shrub is characteristic of the Morenci area. Mean annual precipitation ranges from 11 to 14 inches. The geology of the area as described by Lindgren (1905, p. 55) consists of "pre-Cambrian schists and granite below a Paleozoic series of limestones, shales, and quartzites overlain by Crustaceous shales and sandstones. Masses of granitic dioritic porhyries are intruded into all of these rocks." The minerals in the mine veins from which the tailings originate are primarily pyrite (iron disulfide), chalcopyrite (copper-iron sulfide), sphalerite (zinc sulfide), galena (lead sulfide), gold (elemental), silver (elemental), and quartz.

Topsoil and seed species were acquired from the Soil Conservation Service, Tucson Plant Materials Center. The topsoil, a loam, was of the Grabe series, and is classified in soil taxonomy as a Typic Torrifluvent (Soil Survey Staff 1975, p. 189). Sewage sludge was acquired from the City of Tucson, Wastewater Treatment Plant. All studies conducted in this investigation were performed at The University of Arizona under greenhouse and laboratory conditions. The entire experiment consisted of a preliminary investigation, and three additional separate studies. Chemical and physical analyses of materials and samples were performed by the University of Arizona Soils and Water Testing Laboratory.

Preliminary Investigation

A preliminary investigation was conducted to determine the appropriate amount of lime required to neutralize the tailings. Hydrated lime was used in all the investigations. Liming rates were determined using a soil-lime incubation method described by McLean (1973, p. 89). This test involved preparing samples of saturated paste with tailings and distilled water. Samples were limed at rates ranging from 1.1 to 17.9 metric tons per hectare. Samples were allowed to incubate for 4 hours, after which the pH was determined using a glass electrode pH meter. The pH was again determined after a 28 hour incubation period. Results of these tests are presented in Figure 1. These tests revealed that an application of approximately 4 metric tons of calcium hydroxide per hectare would be required to raise the pH of the tailings to neutrality. After 28 hours incubation, a reduction in pH of the saturated paste samples occurred at liming rates above 4.5 metric tons per hectare.

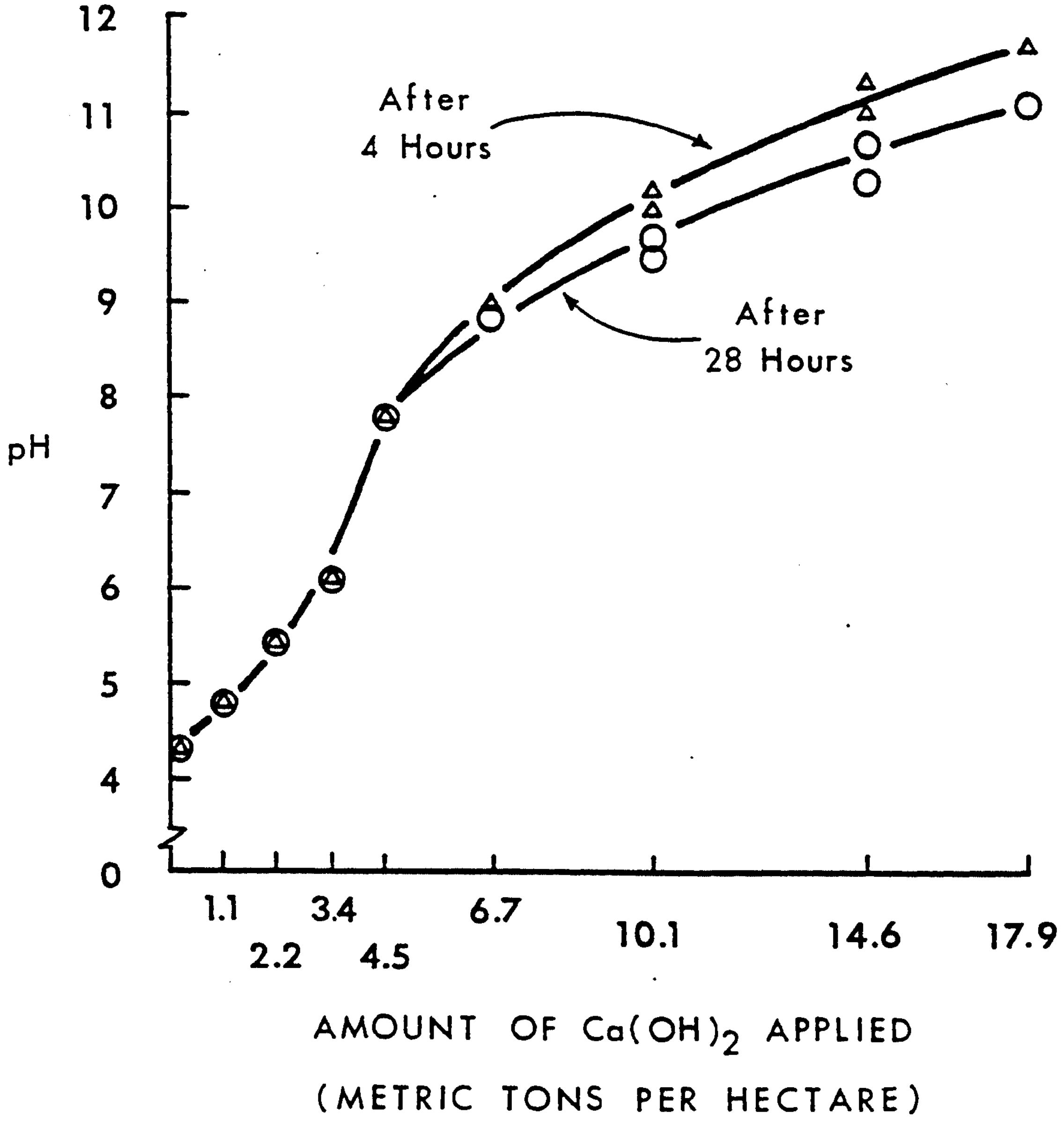

Figure 1. PH of saturated paste samples prepared with copper mine tailings and distilled water under various liming rates with $Ca(OH)_2$ incubated for 4 hours and 28 hours.

Study I

A greenhouse study was undertaken to determine the effects of lime, topsoil material, and sewage sludge on the establishment and early growth of blue panicgrass and balloon pea.

Tailings, topsoil, and sewage sludge were all air dried, and passed through a 2 mm sieve. Treatment formulation was based on the assumption that an acre-furrow slice of tailings is equivalent to 908,000 kg (2 million pounds) of soil. Grabe loam was applied as a topsoil, and also as a soil-tailings mix. Sewage sludge and lime were applied as a tailings-sludge, and a tailings-lime mix. The three amendment materials were applied as single, and combination treatments to 4 kg of tailings in 20cm clay pots. The treatments were replicated three times.

Numerous treatments will be discussed in the following sections. Upon the first discussion of each treatment, a description and treatment symbol will be given. Thereafter, each treatment will be referred to by it's symbol. Each symbol contains letters and numbers. Letters refer to the type of amendment used. Numbers refer to the rate (metric tons per hectare) at which each amendment was applied. The treatments and symbols used are as follows:

1. Control
2. 1.1 metric tons of lime per hectare mixed throughout the tailings (1.1(L))

3. 3.4 metric tons of lime per hectare mixed throughout the tailings (3.4(L))
4. 4.5 metric tons of lime per hectare mixed throughout the tailings (4.5(L))
5. 6.7 metric tons of lime per hectare mixed throughout the tailings (6.7(L))
6. 22.4 metric tons of sewage sludge per hectare mixed throughout the tailings (22.4(SS))
7. 44.8 metric tons of sewage sludge per hectare mixed throughout the tailings (44.8(SS))
8. 67.2 metric tons of sewage sludge per hectare mixed throughout the tailings (67.2(SS))
9. 4.5 metric tons of lime per hectare plus 44.8 metric tons of sewage sludge per hectare mixed throughout the tailings (4.5(L)-44.8(SS))
10. 740 metric tons of topsoil per hectare mixed throughout the tailings (740(MS))
11. 740 metric tons of topsoil per hectare applied as overburden (740(TS))
12. 370 metric tons of topsoil per hectare applied over 370 metric tons of topsoil per hectare mixed throughout the tailings (370(TS) over 370(MS))
13. 740 metric tons of topsoil per hectare plus 4.5 metric tons of lime per hectare mixed throughout the tailings (740(MS)-4.5(L))

14. 740 metric tons of topsoil per hectare plus 44.8 metric tons of sewage sludge per hectare mixed throughout the tailings (740(MS)-44.8(SS))
15. 740 metric tons of topsoil per hectare plus 4.5 metric tons of lime per hectare plus 44.8 metric tons of sewage sludge per hectare all mixed throughout the tailings (740(MS)-4.5(L)-44.8(SS)).

One species was seeded per pot. Pots were seeded with blue panicgrass and balloon pea at rates of 1,076 seeds per square meter (35 seeds per pot) and 323 seeds per square meter (10 seeds per pot), respectively. Pots were watered throughout the study to maintain a moist growth medium.

Seedling emergence and maximum height (cm) were recorded over an 18-week growing period. Observations were recorded at 1-week intervals thereafter. Thus, a total of 12 observations were made throughout the study. At the end of 18 weeks, plants were removed from the pots by washing the material from the roots. Both top and root growth were oven dried and weighed seperately.

Study II

A second greenhouse study was conducted to determine the effect of treated tailings, and a subsurface layer of untreated tailings on root growth of two grass species and two shrub species. This study was concurrent with Study I.

This study was conducted in containers measuring 11.5 cm X 51 cm X 84 cm. One side of the container had a glass window to allow visual observation of root growth. Sand (used only as a filler) was placed in the bottom 38 cm of each box. Next was added 25 cm of untreated tailings, above which were placed the treated layers. Three replications of treatments were used at the following rates of application:

1. Control
2. 3.4 metric tons of lime per hectare mixed throughout 10.2 cm (1,480 metric tons per hectare) of tailings (3.4(L))
3. 4.5 metric tons of lime per hectare mixed throughout 10.2 cm of tailings (4.5(L))
4. 22.4 metric tons of sewage sludge per hectare mixed throughout 10.2 cm of tailings (22.4(SS))
5. 67.2 metric tons of sewage sludge per hectare mixed throughout 10.2 cm of tailings (67.2(SS))
6. 1,480 metric tons of topsoil per hectare (10.2 cm of topsoil) (1,480(TS))
7. 740 metric tons of topsoil per hectare (5 cm) mixed throughout upper 5 cm of tailings (1 to 1 soil:tailings mixture) (740(MS))
8. 740 metric tons of topsoil per hectare over 370 metric tons of topsoil per hectare (2.5 cm) mixed thoroughly with 370 metric tons per hectare of

tailings (5 cm layer of topsoil over a 5 cm layer of 1 to 1 soil:tailings mixture) (740(TS) over 370(MS))

9. 740 metric tons of topsoil per hectare over 4.5 metric tons of lime per hectare mixed thoroughly with 370 metric tons per hectare of tailings (740(TS) over 4.5(L))

Two shrubs species, and two grass species were seeded in each treatment. Shrubs included balloon pea (*Sutherlandia microphilla*) and quailbush (*Atriplex lentiformis*). Grasses included blue panicgrass (*Panicum antidotale*) and Lehmann lovegrass (*Eragrostis lehmaniana*). Species were randomly arranged in the boxes.

Data on maximum root depth were taken at 1-week intervals for the first 8 weeks, then at 2-week intervals thereafter to the eighteenth week. A total of 13 observations were made during the growing period.

Study III

A leaching study was undertaken in the laboratory to determine the effects of topsoil material, sewage sludge, and lime on the leachate quality of tailings.

Tubular plastic leaching columns measuring 50.8 cm in height, and 10.2 cm in diameter were used. Amendments were mixed throughly with 4 kg of tailings. The treatments were in triplicate, consisting of the following rates:

1. Control
2. 4.5 metric tons of lime per hectare (4.5(L))
3. 44.8 metric tons of sewage sludge per hectare (44.8(SS))
4. 740 metric tons of topsoil per hectare (740(MS))
5. 4.5 metric tons of lime per hectare plus 44.8 metric tons of sewage sludge per hectare (4.5(L)-44.8(SS))
6. 740 metric tons of topsoil per hectare plus 4.5 metric tons of lime per hectare plus 44.8 metric tons of sewage sludge per hectare (740(MS)-4.5(L)-44.8(SS))

The columns were leached with distilled water for 30 days at a rate of 400 ml per day. This rate was considered to be a satisfactory amount, approximately equivalent to 51 mm per day which can be readily achieved under drip irrigation. The leachate was collected after the first, second, fourth, seventh, fourteenth, twenty-seventh, and thirtieth days. These sample dates, respectively, correspond to 0.4, 0.8, 1.6, 2.4, 5.6, 10.8, and 12.0 liters of cumulative amount of water passed through the columns. Leachate analyses were performed by the University of Arizona Soils and Water Testing Laboratory for pH and concentrations of total soluble salts, SO_4, Zn, Cu, Fe, Mn, Mg, Na, Ca, and K.

Statistical Analysis

All studies employed randomized split-plot designs with sample dates treated as subplots. First order effects were amendment rates. Second order effects were sample dates. Analysis of variance of the data was conducted by the University of Arizona Agriculture Experiment Station, Statistical Analysis Center. Separate tests between means for significant differences were made using the least significant difference method at the 5% level described by Steel and Torrie (1960, pp. 106-7).

RESULTS AND DISCUSSION

The results obtained here should not be considered necessarily analogous to results expected under field conditions. Therefore, conclusive comparisons of some treatments could only be made among treatments within a particular study but not between studies. However, trends and complementary results will be indicated.

Physical and chemical analyses of tailings, topsoil, and sewage sludge are presented in Table 1. Tailings were strongly acidic, and soluble salts were present in moderate amounts. Nitrogen and phosphorus were present in very low amounts, probably inadequate for satisfactory plant growth. The CEC of the tailings suggests that the absorptive capacity and retention of cations by this material is low. The textural class of the tailings based on percentages of sand, silt and clay was sandy loam.

The topsoil was slightly alkaline, and soluble salts were present in slight amounts. Nitrogen and phosphorus were at levels adequate for satisfactory growth of most plants. The CEC was higher than in the tailings, and may provide some adsorption and complexing ability of metal cations if incorporated into the tailings. The textural class of the topsoil was loam.

Table 1. Chemical analyses of tailings, topsoil, and sewage sludge used in these studies.

Constituent	Tailings	Topsoil	Sewage Sludge
pH	4.3	7.7	6.4
CEC (meq/100g)	4.47	16.10	
Soluble salts (ppm)	3,034.50	1,603.00	10,658.70
EC X 10^3 (mmhos/cm)	4.34	2.29	15.23
P (ppm)	.25	9.50	
Total Nitrogen (ppm)	3.10	102.00	10,210.00
NO_3-N (ppm)			285.70
% Sand	71.50	38.00	
% Silt	19.50	46.00	
% Clay	9.00	16.00	

	Acid Sol.	Water Sol.	Acid Sol.	Water Sol.	Acid Sol.	Water Sol.
	ppm					
Copper (Cu)	1,480	470.00	140	.10	395	.78
Iron (Fe)	34,100	.28	34,000	.17	4,989	.56
Zinc (Zn)	250	114.50	144	---	1,032	.66
Manganese (Mn)	140	63.70	660	.06	227	.44
Magnesium (Mg)	2,700	264.00	10,400	39.00	4,223	77.30
Calcium (Ca)	38,800	445.00	17,600	350.00	21,337	250.30
Potassium (K)	3,310	18.00	10,000	120.00	3,730	82.30
Sodium (Na)					1,093	121.70
Sulfate (SO_4)						289.00

The sewage sludge was slightly acidic with extremely high levels of soluble salts. Total nitrogen and the readily available form of nitrate nitrogen (NO_3-N) were at levels adequate for satisfactory plant growth. Prior knowledge of the CEC of the sludge would have been desirable in predicting the ameliorating potential of the sludge. However, because of the organic nature of the sludge, the CEC was expected to be high. According to McLean (1973), the CEC of soil organic matter varies from 70 to 250 meq/100g. Thus, the CEC of the sludge may be high enough to provide considerable adsorption and complexing ability of heavy metal cations.

Acid soluble concentrations of nutrients were higher than the water soluble primarily because acid soluble included exchangeable and non-exchangeable nutrient forms. Therefore, water soluble levels may be more representative of nutrients immediately available to plants than acid soluble levels. However, water soluble analyses gives no indication of reserve supply. Tailings were very high in Cu. Coupled with the low pH, Cu should be considered very toxic. High levels of Zn and Mn were also present. Fe was probably sufficient for adequate plant growth, and K may have been low.

Water soluble heavy metals in the topsoil were at levels acceptable for adequate growth of most plants. Water soluble Zn, however, was not detectable in the topsoil.

Sewage sludge contained very high acid soluble levels of Zn. Water soluble levels of Zn, Cu, Fe and Mn were probably within acceptable limits for adequate plant growth.

Study I

This study was designed to test the effects of 14 tailings amendments on the vegetative growth of blue panicgrass and balloon pea. These 14 treatments were described under the methods section.

Data consisted of seedling emergence, rate of growth, and survival. Upon termination of the growing period, additional data included weight of top growth and weight of root growth. Analysis of variance on the data indicated a significant difference among treatments, species, and treatment and species interactions with respect to seedling survival, weight of top growth, and weight of root growth (Appendix Table A-1). There was also a highly significant difference among treatments and among treatment and date interactions with respect to average maximum height of both blue panicgrass and balloon pea (Appendix Table A-2).

Seedling emergence of blue panicgrass was evident after the first week in several treatments (Appendix Table A-3). All treatments resulted in a higher rate of seedling emergence, rate of growth, survival, and total vegetative yield than the control. An average seedling emergence of 85% over all treatments was reached by the eight week. From the eighth week to term, survival decreased. The control reached a 40% emergence by the sixth week. However, all plants died by the fourteenth week. Symptoms leading to death were observed shortly after emergence. Symptoms included tip burning, chlorosis, lack of vigor, and stunting.

Seedling emergence was most rapid in 44.8(SS), attaining 97% by the fifth week. However, this treatment did not have the highest survival of seedlings. Survival was greatest in 740(MS)-4.5(L)-44.8(SS) with 91%.

Plant growth was more vigorous in the treatments having a layer of topsoil (Appendix Table A-4). Initial rate of top growth was greatest in 740(TS) up to week 6. By the sixth week chlorosis and signs of drying of the older leaves became progressively more severe. From week 6 to term, 370(TS) over 370(MS) produced the highest rate of growth followed by 740(TS). With no topsoil layer, but with soil in the tailings (740(MS)), growth was very poor as compared to 740(TS) and 370(TS) over 370(MS) (Figure 2).

Upon the removal of plants from the pots after the 18-week growing period, plants growing in 740(TS) exhibited a matted root system restricted to the topsoil layer. The roots of plants grown in 740(MS) were observed to extend slightly deeper in the soil-tailings mix than in the 740(MS) treatment. The 740(MS) treatment was very nearly a 1 to 4 soil:tailings mixture. Root systems of plants grown in 370(TS) over 370(MS) extended throughout the entire

Figure 2. Blue panicgrass grown for 18 weeks in the greenhouse in 4 kilograms of tailings treated with soil. -- A=Control, B=740(TS), C=740(MS), D=370(TS) over 370(MS).

depth of the pot, and the soil:tailings mixture was very nearly 1 to 8. Thus, roots grew poorly in the 1 to 4 mixture but grew well in the 1 to 8 mixture with the added influence of a layer of topsoil (Figure 3).

The addition of lime and sewage sludge to 740(MS) improved growth rate and survival compared to 740(MS) alone. The most productive was 740(MS)-4.5(L)-44.8(SS) followed by 740(MS)-44.8(SS) and 740(MS)-4.5(L) (Figure 4). Root growth and top growth of these three treatments was greater than that of 740(MS). Root growth extended throughout the treated area in 740(MS)-4.5(L)-44.8(SS) and 740(MS)-4.5(L), and to a lesser extent in 740(MS)-44.8(SS) (Figure 5).

Treatments that received lime alone, and sludge alone resulted in very poor, stunted growth. Sewage sludge appeared to improve growing conditions slightly more than lime (Figure 6). Tip burning and chlorosis was severe throughout the growing period.

Differences in vegetative yield among treatments are shown in Figure 7. The 370(TS) over 370(MS) treatment was significantly greater in yield than 740(TS) and 740(MS)-4.5(L)-44.8(SS). All other treatments were significantly poorer at the 5% level.

Seedling emergence of balloon pea was evident after the first week for several treatments. Though some treatments did not result in a greater initial emergence and early growth than the control, survival was higher in the

Figure 3. Comparative root growth of blue panicgrass grown in tailings treated with soil. -- A=740(MS), B=740(TS), C=370(TS) over 370(MS).

Figure 4. Blue panicgrass grown in tailings treated with combinations of soil, lime, and sewage sludge. -- A=740(MS)-4.5(L), B=740(MS)-44.8(SS), C=740(MS)-4.5(L)-44.8(SS).

Figure 5. Comparative root growth of blue panicgrass grown in tailings treated with combinations of soil, lime, and sewage sludge. -- A=740(MS)-4.5(L), B=740(MS)-44.8(SS), C=740(MS)-4.5(L)-44.8(SS).

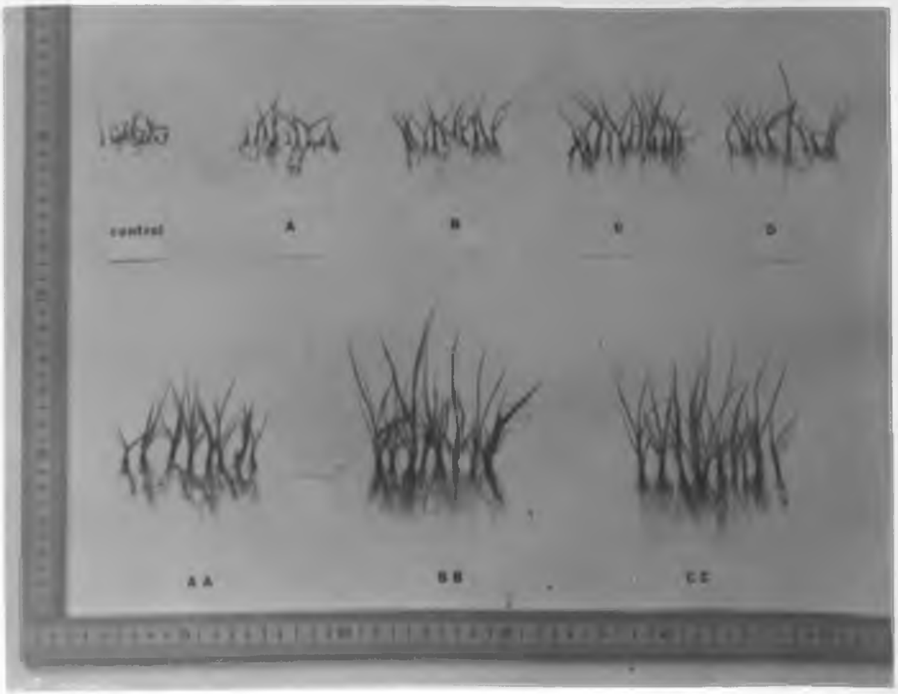

Figure 6. Comparative growth of blue panicgrass grown in tailings treated with lime, and sewage sludge. -- A=1.1(L), B=3.4(L), C=4.5(L), D=6.7(L), AA=22.4(SS), BB=44.8(SS), CC=67.2(SS).

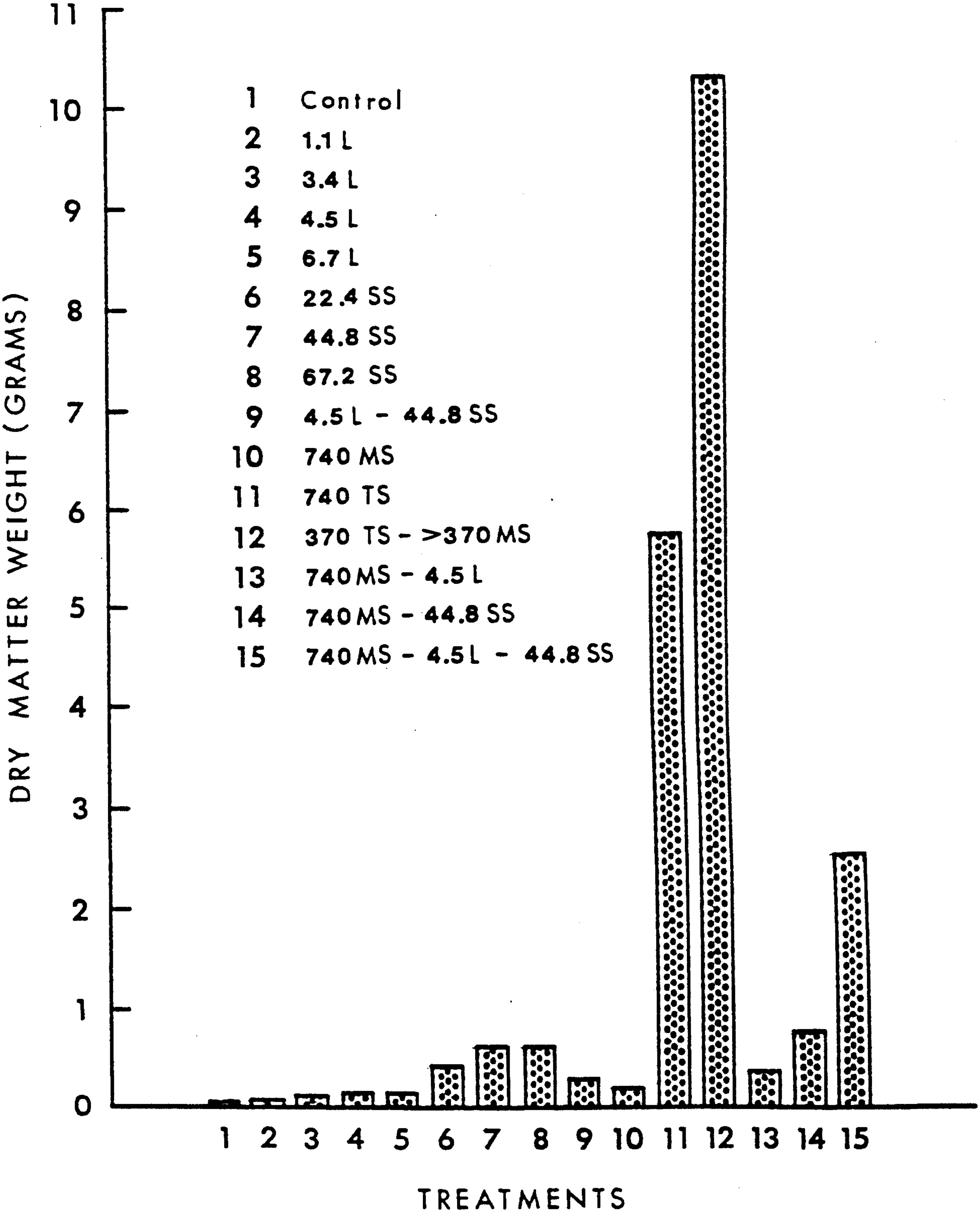

Figure 7. Total dry matter production of blue panicgrass grown for 18 weeks in pots containing 4 kilograms of tailings treated with lime, sewage sludge, and topsoil.

treated tailings (Appendix Table A-5). An average seedling emergence of 76% over all treatments was reached by the sixth week. Thereafter, survival decreased to 60% by week 18. Untreated tailings were not totally detrimental to balloon pea. The control attained a 65% emergence by the sixth week. Survival decreased to 17% by week 18. Plant symptoms similar to those observed on blue panicgrass, were noted shortly after emergence.

A maximum seedling emergence of 93% for balloon pea occurred in 740(MS)-4.5(L) on the fourteenth week, which also had the highest survival rate of 87%.

Treatments having a layer of soil on the tailings maintained a higher growth rate (Appendix Table A-6). The highest rate of growth was maintained by 740(TS). Plants grown in this treatment appeared very healthy with only a slight lack of green color in the older leaves. The next highest rate of growth and overall plant height was given by 370(TS) over 370(MS). Poor seedling emergence, growth rate, and survival occurred in 740(MS) (Figure 8).

Careful removal of plants from the pots after the growing period revealed that balloon pea grown in 740(TS) exhibited a matted root system restricted to the topsoil layer. Roots of plants grown in 740(MS) were found to extend slightly deeper in the 1 to 4 soil:tailings mix than in the control. However, plants grown in 740(MS) were extremely reduced in size. Root systems of plants grown

Figure 8. Balloon pea grown in tailings treated with soil. -- A=Control, B=740(TS), C=740(MS), D=370(TS) over 370(MS).

in 370(TS) over 370(MS) extended throughout the entire depth of the underlying 1 to 8 soil:tailings mixture, with a higher concentration of roots in the topsoil layer (Figure 9). Thus, roots grew poorly in the 1 to 4 mixture, but grew well in the 1 to 8 mixture with the added influence of a layer of topsoil.

The incorporation of lime and sludge into 740(MS) improved growth rate and survival as compared to 740(MS). The most productive was 740(MS)-4.5(L)-44.8(SS) followed by 740(MS)-4.5(L) and 740(MS)-44.8(SS) (Figure 10). In addition to being the least productive of these three treatments, 740(MS)-44.8(SS) exhibited more severe signs of chlorosis. Root growth and top growth of these three treatments was greater than that of 740(MS). Root growth extended throughout the depth of the treated area in 740(MS)-4.5(L) and 740(MS)-4.5(L)-44.8(SS). A poorer depth of root growth was attained in 740(MS)-44.8(SS).

The application of lime alone and sludge alone produced a very poor growth rate and average plant height. Only very slight differences were observed in growth rates and plant heights between lime and sludge treatments (Figure 11). Plant growth was severely stunted in these treatments. Chlorosis and tip burning of the leaves were evident early, and became severe throughout the growing period.

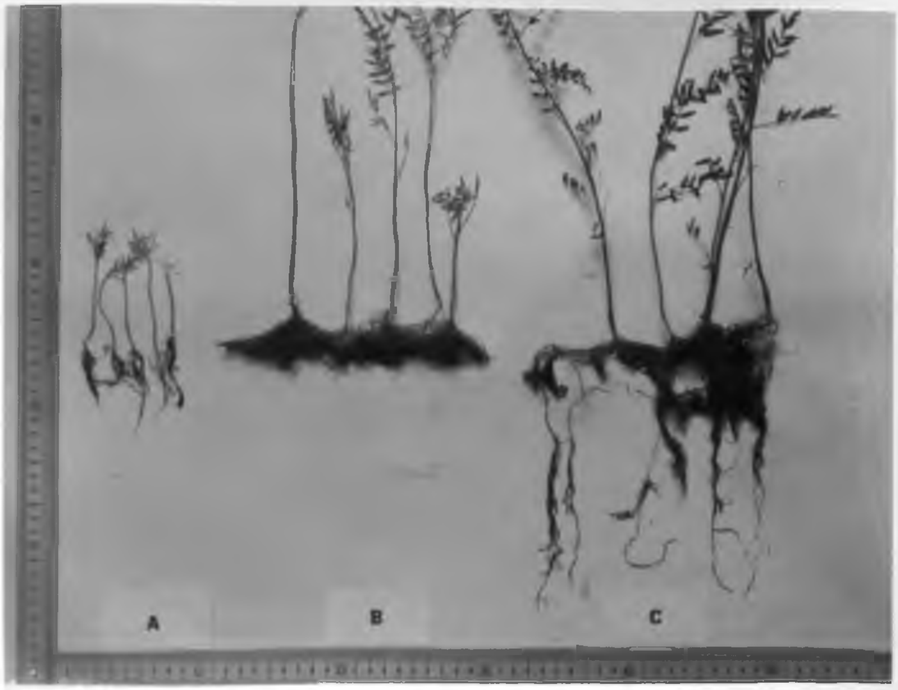

Figure 9. Comparative root growth of balloon pea grown in tailings treated with soil. -- A=740(MS), B=740(TS), C=370(TS) over 370(MS).

Figure 10. Balloon pea grown in tailings treated with combinations of soil, lime, and sewage sludge. -- A=740(MS)-4.5(L), B=740(MS)-44.8(SS), C=740(MS)-4.5(L)-44.8(SS).

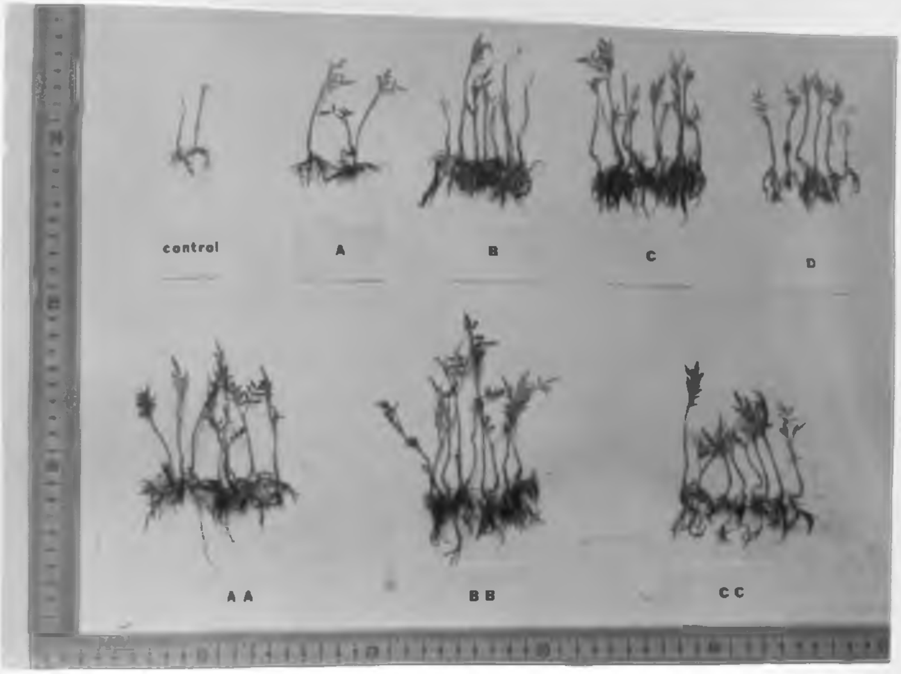

Figure 11. Comparative growth of balloon pea grown in tailings treated with lime, and sewage sludge. -- A=1.1(L), B=3.4(L), C=4.5(L), AA==22.4(SS), BB=44.8(SS), CC=67.2(SS).

All treatments yielded more dry matter than the control, but only two treatments, 740(TS) and 370(TS) over 370 (MS), were significantly better at the 5% level (Figure 12).

Several instances occurred when an increase or decrease in the weight of root growth did not correlate with respective increases or decreases in the weight of top growth (Appendix Table A-7). Variations in the calculated shoot:root ratios suggest that top and root growth reacted somewhat differently to toxic factors inhibiting production. A high shoot:root ratio infers that root mass is efficient in water and nutrient absorption, thus supporting good top development. Such is the case in 740(MS) for blue panicgrass and 370(TS) over 370(MS) for balloon pea. If top growth was increased by reducing toxicity of heavy metals and salts, and root growth was not affected, it would appear that top growth is more sensitive to toxicity than root growth. A low shoot: root ratio suggests that tops are affected more by toxic substances than roots are. Thus, roots are able to absorb nutrients and utilize them for their production while top growth is inhibited. This may be exibited to some extent by 740(MS)-4.5(L) for balloon pea.

Study II

This study was designed to test the effects of eight tailings amendments on the depth of root growth of blue panicgrass, Lehmann lovegrass, balloon pea, and quailbush in

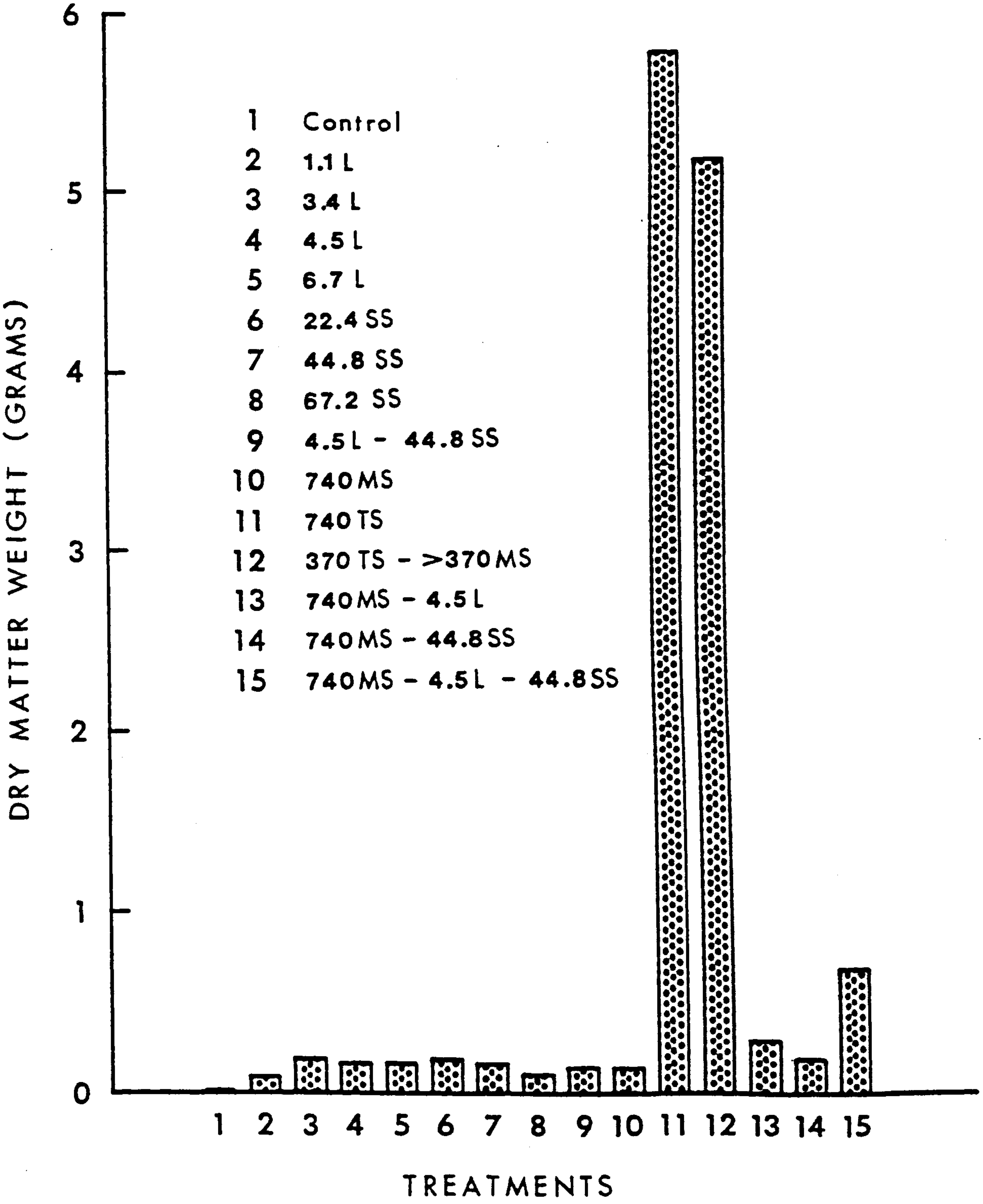

Figure 12. Total dry matter production of balloon pea grown for 18 weeks in pots containing 4 kilograms of tailings treated with lime, sewage sludge, and topsoil.

the greenhouse over an 18-week growing period. These treatments were described in the methods section.

Analysis of variance on the data indicated a highly significant difference among treatments, dates, and species (Appendix Table A-8). The control failed to produce any growth.

Root systems were limited to the upper treated layers and failed to grow into the underlying layer of untreated tailings. Roots that grew throughout the treated tailings and came into contact with raw tailings incurred severe root damage. The symptoms included blackening of the root tips followed by darkening of the root system, lack of root hairs, and cessation of elongation. These symptoms suggest toxicity from heavy metals. Root elongation ceased and lateral roots became more pronounced in the more favorably treated layers. Bennett (1974) reported similar symptoms in cases of heavy metal toxicity. Berg and Vogel (1973) suggested that stubby roots and lack of laterals are observed only in cases of severe toxicity of heavy metals.

Visible root growth was not observed until the second week in several treatments. The four treatments receiving soil produced the only surviving vegetation by the eighteenth week. Both top and root growth of all species grown in treatments receiving lime and sludge alone took on a stunted appearance. By the tenth week all seedlings died.

Comparisons in maximum root elongation due to treatment and species are expressed in Table 2 and Figure 13. The four soil treatments, 1,480(TS), 740(MS), 740(TS) over 370(MS), and 740(MS) over 4.5(L), resulted in considerably deeper root growth for all species. The highest rate of root elongation as well as the deepest root growth was produced with 10.2 centimeters of topsoil (1,480(TS)) as shown in Appendix Table A-9. Over the growing period, a zone of illuviation was formed just below the topsoil layer in 1,480(TS) (Figure 14). The leaching of minerals as well as the translocation of soil particles into the upper portion of the tailings probably allowed some root growth to extend beyond the topsoil layer. Several roots of blue panicgrass and balloon pea penetrated the zone of illuviation.

A lower rate of root elongation as well as a lesser total root depth was produced in 740(MS) than in 1,480(TS). This was a 1 to 1 soil:tailings mixture. Roots of blue panicgrass and balloon pea grew in the 1 to 1 soil:tailings layer down to slightly above the untreated tailings layer (Figure 15). Lehmann lovegrass and quailbush appeared to be the most affected, failing to elongate through the full depth of the treated layer.

Total depth and rate of root elongation was higher in 740(TS) over 370(MS) with the added influence of a layer of topsoil than in 740(MS). Root growth of species grown in 740(TS) over 370(MS) is shown in Figure 16. In both

Table 2. Maximum root elongation of blue panicgrass, Lehmann lovegrass, balloon pea, and quailbush grown in planter boxes containing copper mine tailings treated with selected rates of lime, sewage sludge, and topsoil.

	Species				
Treatments	Blue panicgrass	Lehmann lovegrass	Balloon pea	Quailbush	Mean
	cm				
Control	--	--	--	--	--
1.1(L)	3.6	2.1	3.6	1.6	2.7
4.5(L)	4.8	1.8	5.4	2.2	3.6
22.4(SS)	.2	--	.3	.7	.3
67.2(SS)	2.0	1.2	2.6	.7	1.6
1,480(TS)	11.0	10.7	10.9	10.9	10.9
740(MS)	10.4	5.7	9.9	6.3	8.1
740(TS) over 370(MS)	10.7	9.3	10.9	10.0	10.2
740(TS) over 4.5(L)	7.2	7.4	7.6	7.1	7.3
Mean	6.2	4.8	6.4	4.9	5.6

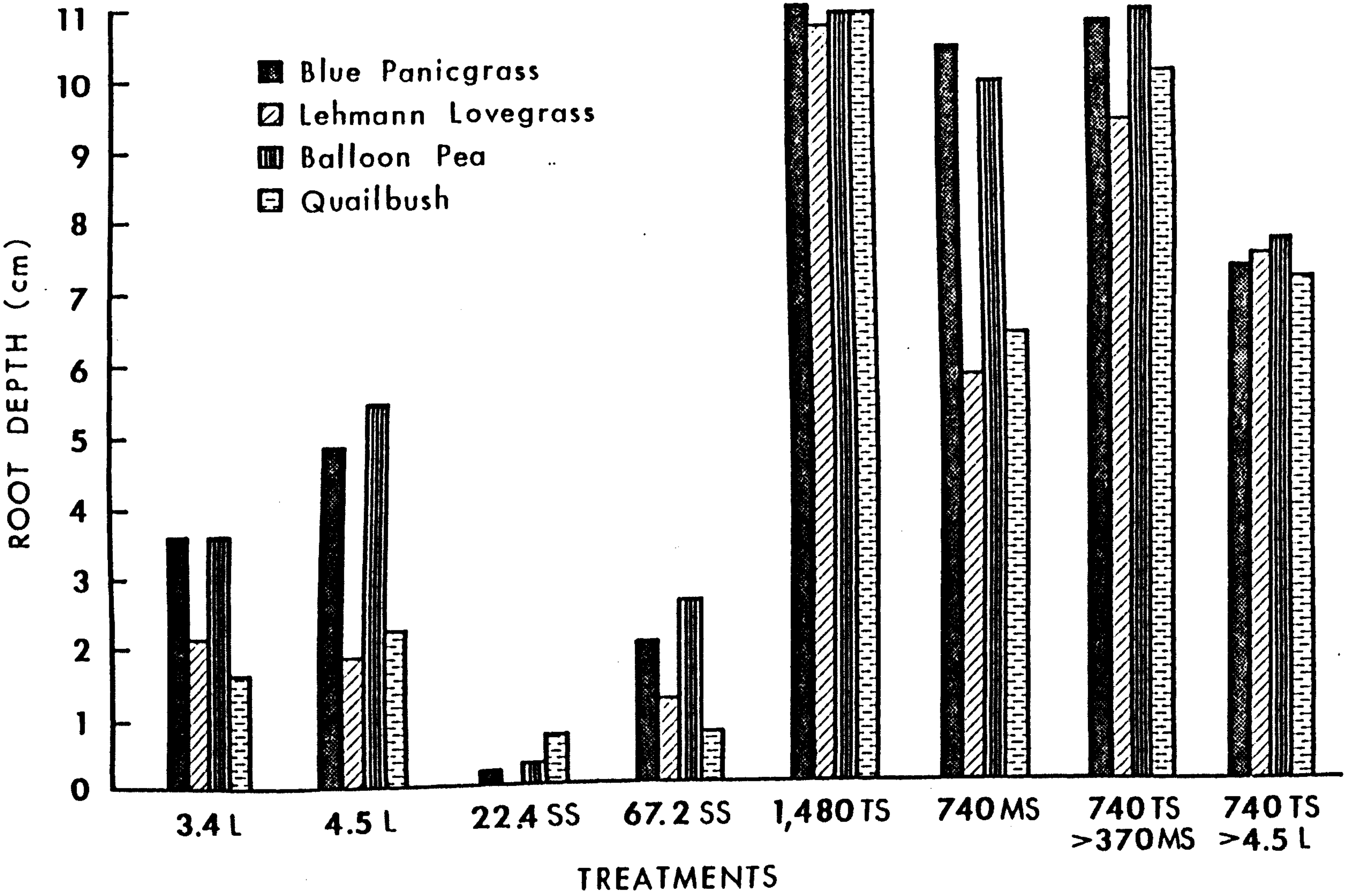

Figure 13. Effects of treating tailings with lime, sewage sludge, and soil on maximum root depth of blue panicgrass, Lehmann lovegrass, balloon pea, and quailbush grown in planter boxes.

Figure 14. Root growth of Lehmann lovegrass, balloon pea, blue panicgrass, and quailbush (left to right) in a 10.2 cm layer of topsoil(1,480(MS)) placed over a layer of tailings in planter boxes.

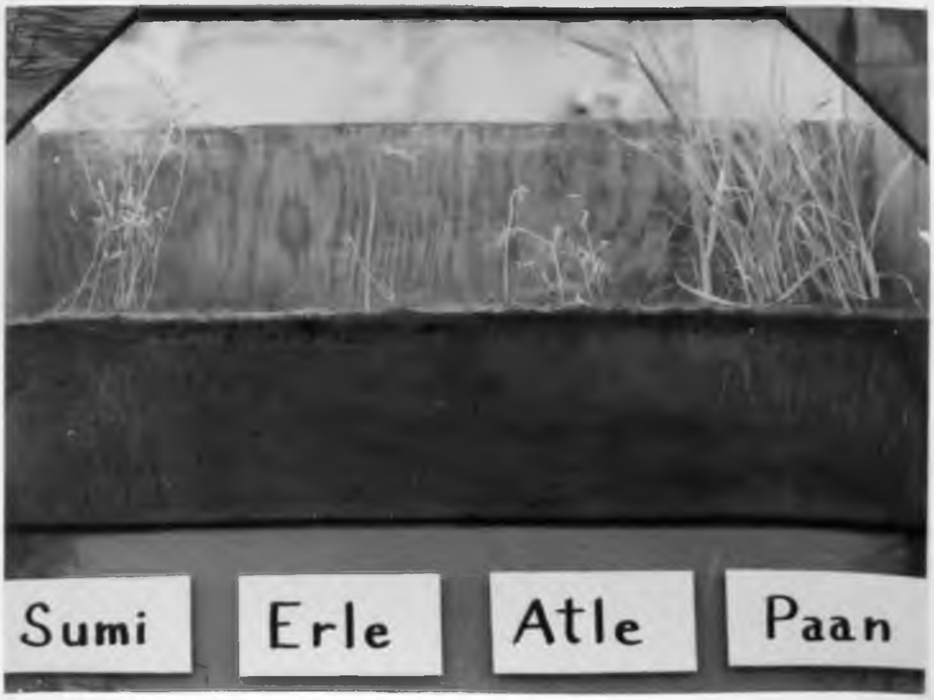

Figure 15. Root growth of balloon pea, Lehmann lovegrass, quailbush, and blue panicgrass (left to right) grown in a 10.2 cm layer of 1 to 1 soil:tailings mixture (740(MS)) placed over a layer of tailings.

Figure 16. Root growth of balloon pea, blue panicgrass, quailbush, and Lehmann lovegrass(left to right) in a treatment that received 51mm of topsoil over a 51mm layer of a 1 to 1 soil:tailings mixture (740(TS) over 740(MS)) placed over a layer of tailings.

740(MS) and 740(TS) over 370(MS), the rate of root elongation was slowed by the 1 to 1 soil:tailings layer as compared to 1,480(TS).

The 740(MS) over 4.5(L) treatment produced somewhat similar root elongation results for all species (Figure 17). Compared to the overlying 1 to 1 soil:tailings mix layer, root elongation was hindered to some extent by the underlying lime treated layer. Roots that penetrated the lime treated layer became darkened and ceased to elongate. This suggest that this rate of liming was inadequate to prevent heavy metal toxicity.

The two sewage sludge treatments, 22.4(SS) and 67.2 (SS), produced the least amount and the lowest rate of root elongation with 67.2(SS) producing a slightly higher rate of elongation than 22.4(SS). Roots of plants grown in these treatments became damaged shortly after germination.

Of the two lime treatments, 3.4(L) and 4.5(L), 4.5(L) produced better root elongation. Root cessation in these treatments generally occurred around the eighth week.

Variations in maximum root elongation were slight between blue panicgrass and balloon pea (Table 2). These two species did, however, have a higher root elongation for all treatments than Lehmann lovegrass and quailbush. Maximum root elongation and rate of elongation were consistantly greater in blue panicgrass than in Lehmann lovegrass, and also consistantly greater in balloon pea than in quailbush.

Figure 17. Root growth of balloon pea, blue panicgrass, quailbush, and Lehmann lovegrass (left to right) grown in 51mm of topsoil over a 51mm layer of tailings treated with 4.5 metric tons of lime per hectare placed over a layer of tailings.

Study III

This study was conducted to test the effects of soil, lime, and sewage sludge on the relative mobility of metalic ions by monitoring the leachate quality of the tailings (Appendix Tables A-10 through A-15).

Analysis of variance on the data indicate a highly significant difference among treatments and sample dates as well as treatment and date interactions with respect to pH, total soluble salts, Cu, Zn, Fe, Mg, Mn, Na, K, and SO_4 (Appendix Table A-16). Variations in the concentration of Ca were not significantly different among treatments, and treatment and date interactions.

The general leaching pattern exhibited a relatively high initial concentration of soluble salts, which rather rapidly decreased with additional leaching. This general trend was exhibited by total soluble salts, and ions of Cu, Zn, Fe, Mg, Mn, Na, K, and SO_4 (Figures 18 through 26). The effects of treatments were most evident in the change of the initial concentration of the various elements. This change was due to adsorption, complexing, or changes in solubility.

Total soluble salts were leached readily from the control and sewage sludge treatment, with the highest concentrations eluded in the first volume of leachate. The addition of lime, with or without sewage sludge, only slightly decreased the solubility. Although sewage sludge increased solubility initially, it did not have an appreciable effect. Soil was most effective in reducing the availability of total soluble salts (Figure 18).

Copper was readily leached from the control and sewage sludge treatment. The addition of lime, with or without sewage sludge, was effective in decreasing the solubility of copper, and consequently a lower concentration appeared in the leachate. The effectiveness of soil in decreasing the availability of copper was outstanding. Very small amounts were obtained in the leachate under the soil treatments (Figure 19).

Zinc was very similar to copper in leaching behavior. It was readily leached from the control and the sewage sludge treatment. The addition of lime with or without sewage sludge, decreased the solubility of zinc. Again, soil proved to be very effective in complexing this element, and very little was obtained in the leachate from soil treatments (Figure 20).

Iron was not easily removed from the control until several leachings occurred. Lime, sewage sludge, and soil were all relatively effective in complexing or changing the solubility of iron. Concentrations of iron in treated tailings were small from the initial leachates (Figure 21).

Magnesium was easily leached from the control. The mobility of Mg was not appreciably changed by additions of lime or sewage sludge. High concentrations of Mg were

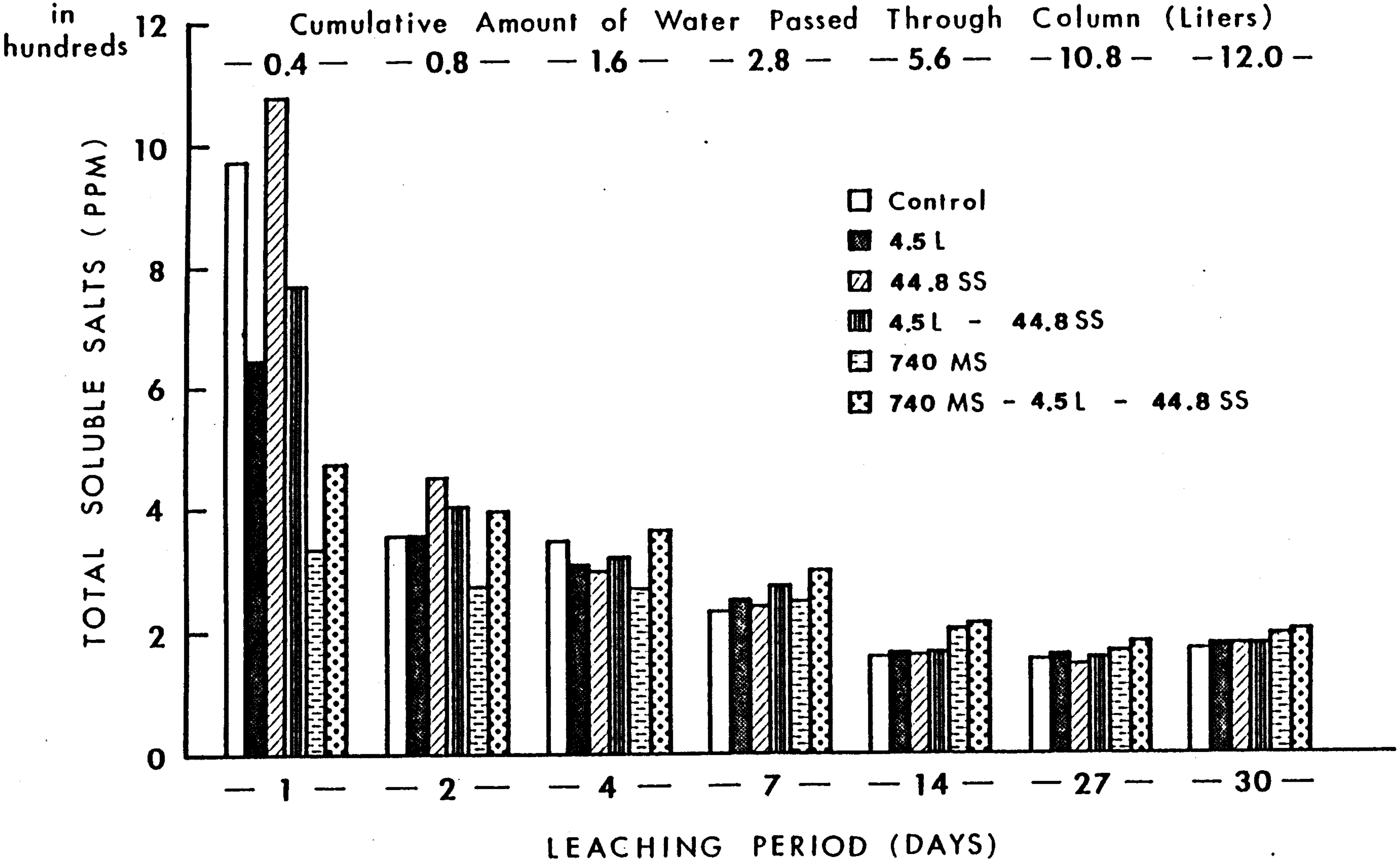

Figure 18. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of total soluble salts at various sample dates over a 30-day leaching period.

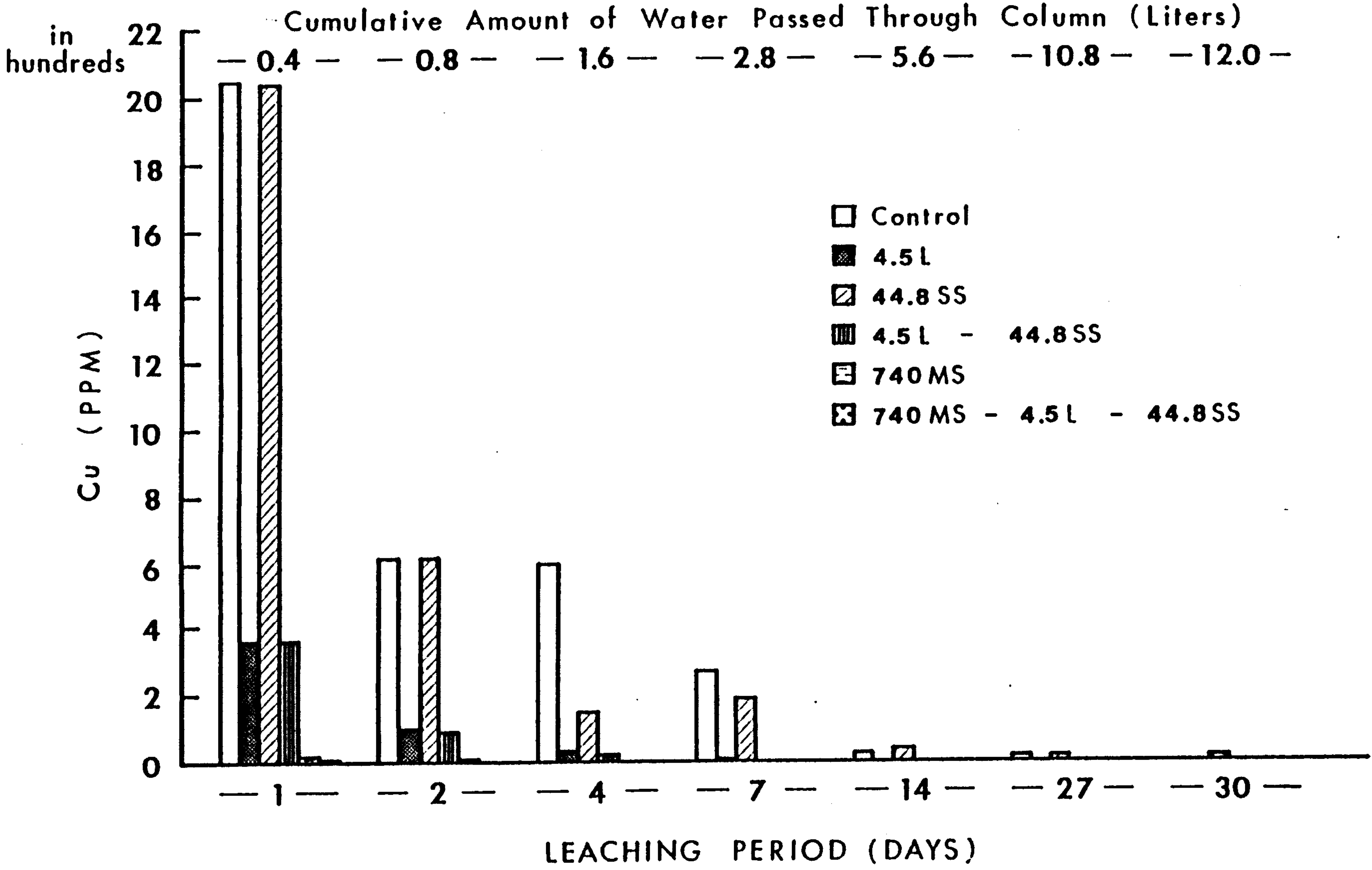

Figure 19. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of copper at various sample dates over a 30-day leaching period.

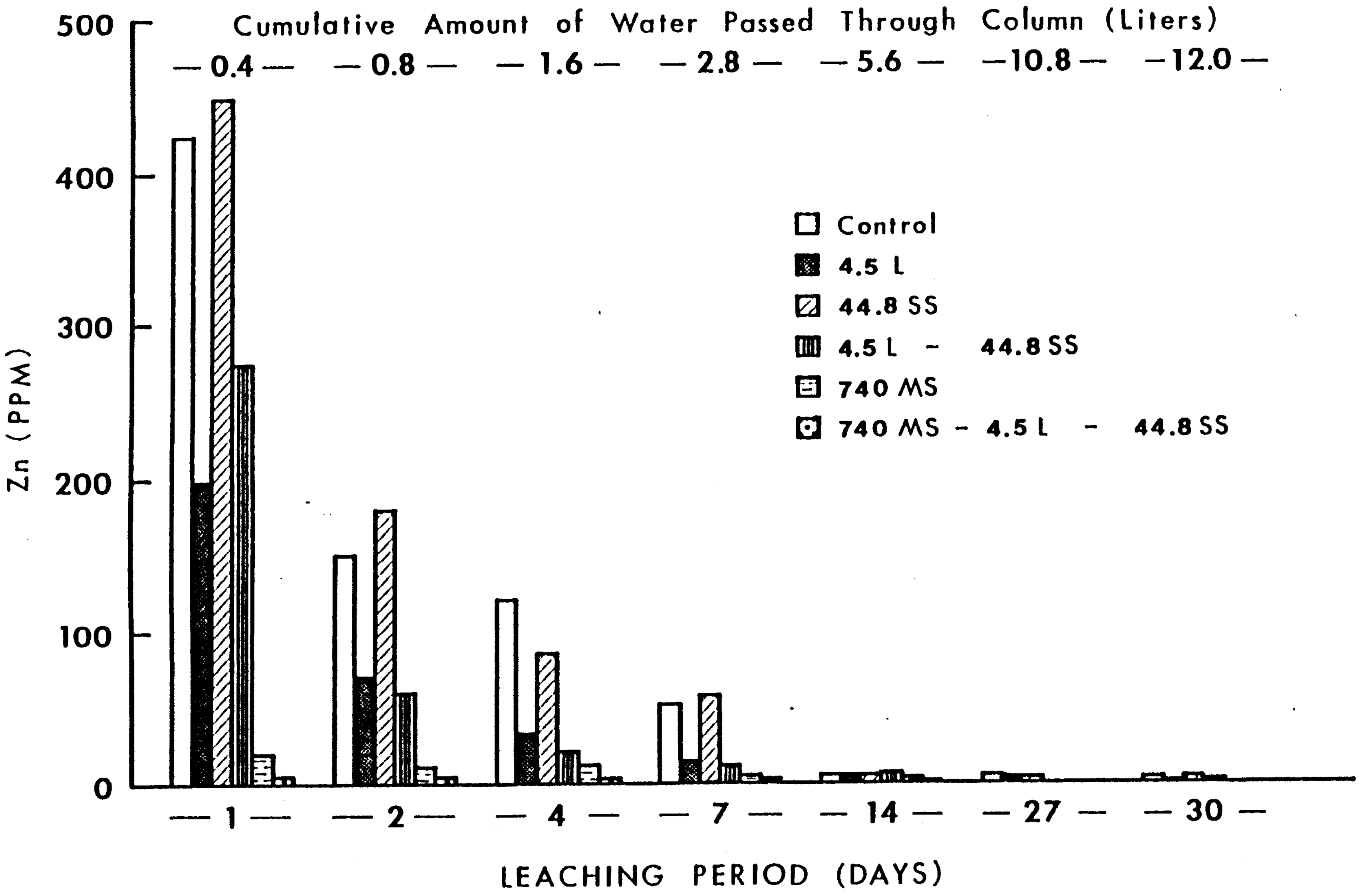

Figure 20. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of zinc at various sample dates over a 30-day leaching period.

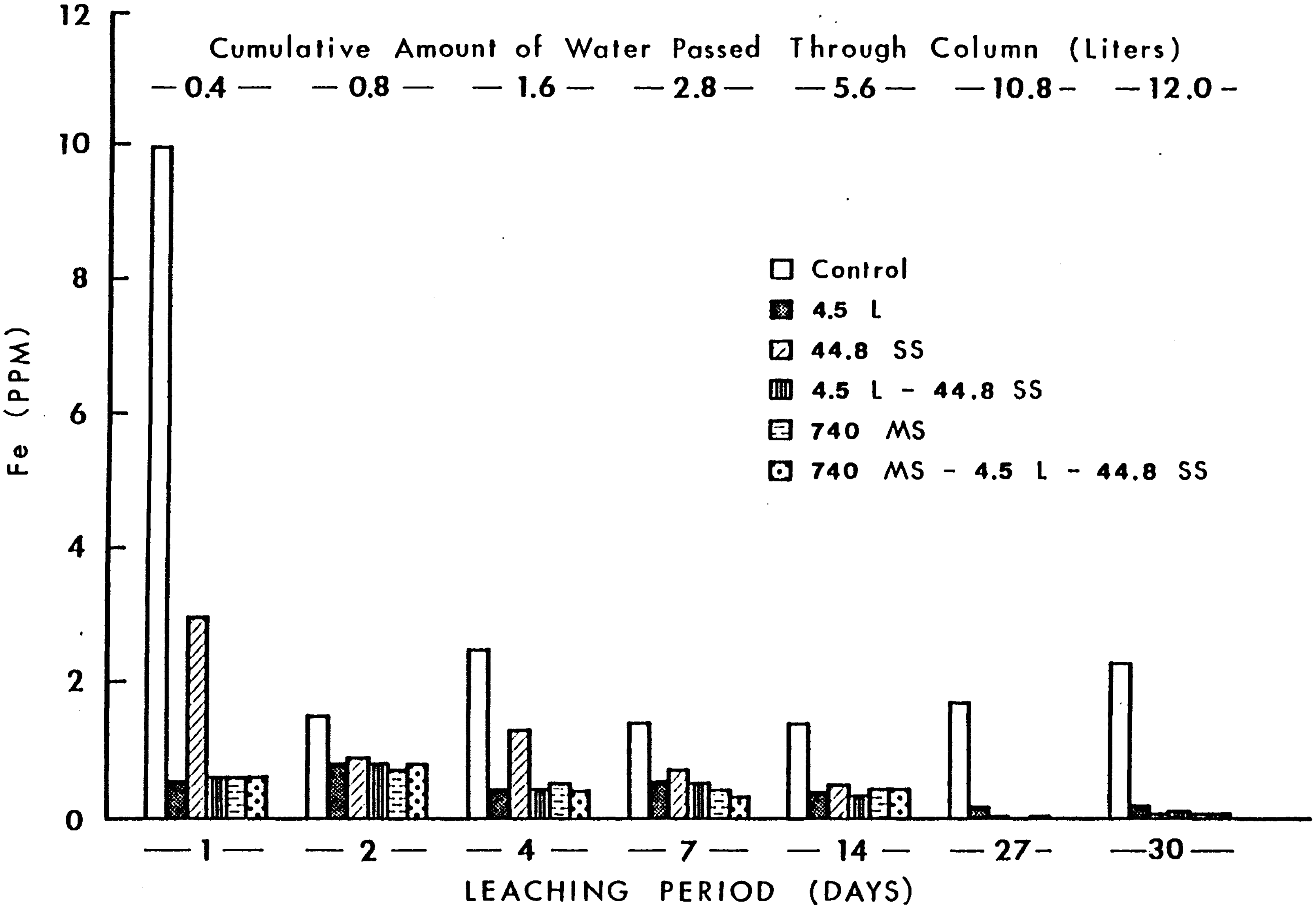

Figure 21. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of iron at various sample dates over a 30-day period.

also initially leached under these treatments. The particular soil treatments were moderately effective in complexing, and consequently reducing the initial concentration of Mg (Figure 22).

As with Cu and Zn, manganese was readily leached from the control and the sewage sludge treatment, with the highest concentrations being eluded in the first volume of leachate. Lime, with or without sewage sludge, only slightly decreased the solubility of Mn. Adding soil was most effective in complexing, and decreasing the solubility of this element (Figure 23).

Sodium was readily leached from the control. Lime and soil used separately, did not appreciably increase the solubility of Na. Sewage sludge, with or without lime, markedly increased the quantity of Na leached. When lime, sewage sludge, and soil were used together, the results appeared to be somewhat addative, and appreciably increased the leachate concentration of Na (Figure 24).

Potassium was readily leached from the control. The addition of lime complexed, and decreased K solubility. Sewage sludge did not have an appreciable affect on the concentration of K in the leachate. However, lime and sewage sludge together did effectively increase K solubility, and the concentration in the initial leachate. The addition of soil was effective in increasing K solubility. (Figure 25).

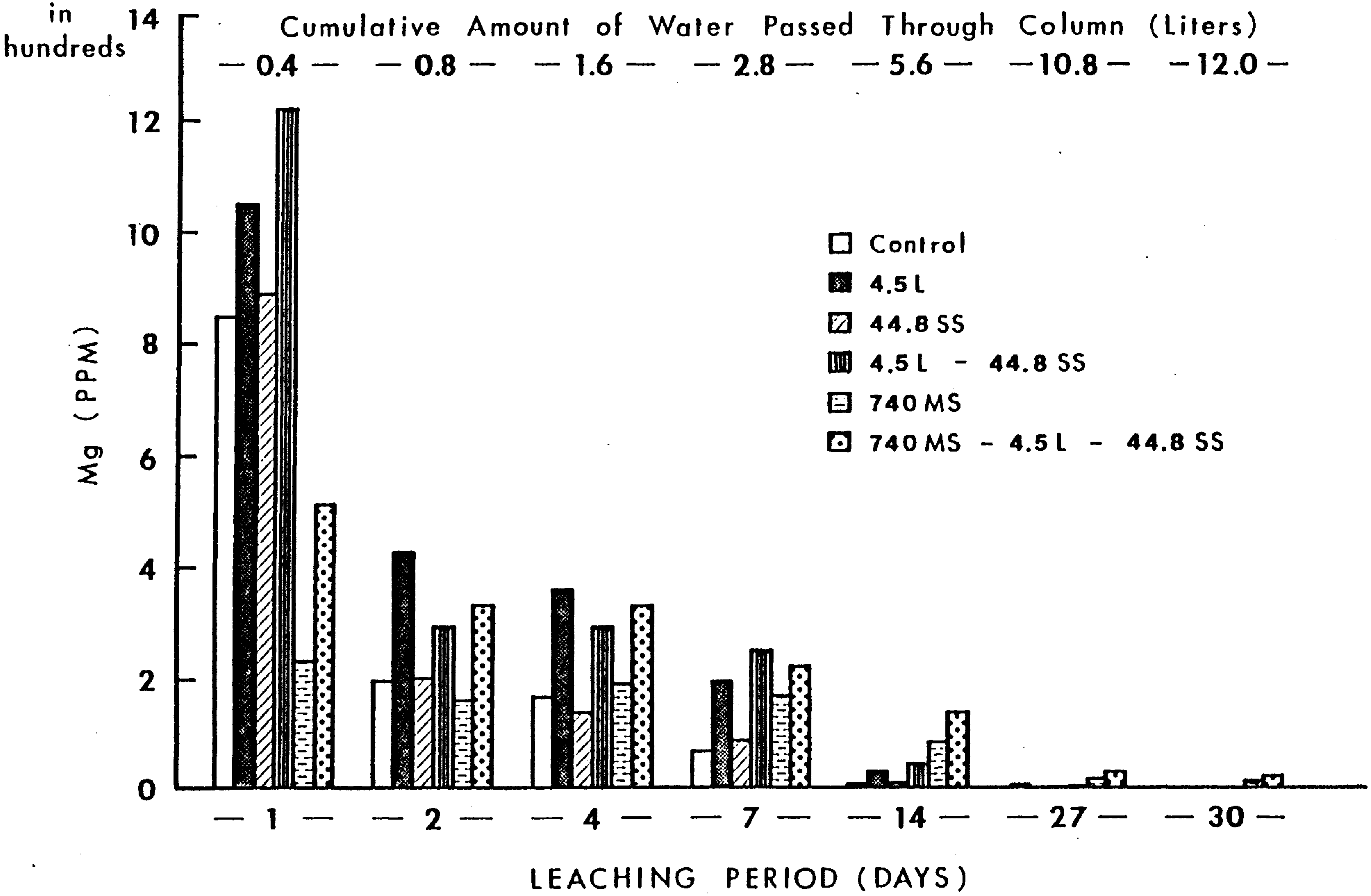

Figure 22. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of magnesium at various sample dates over a 30-day leaching period.

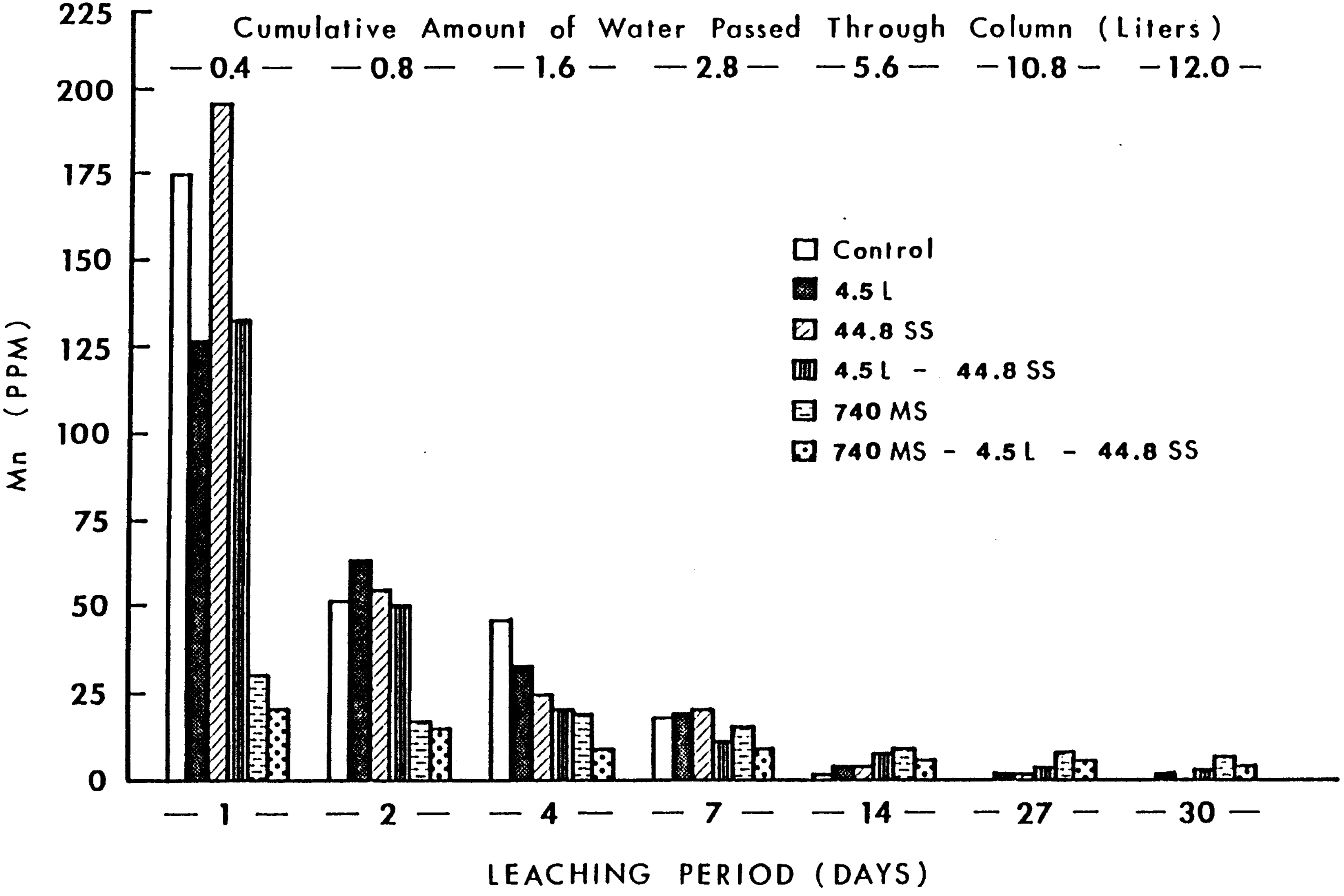

Figure 23. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of manganese at various sample dates over a 30-day leaching period.

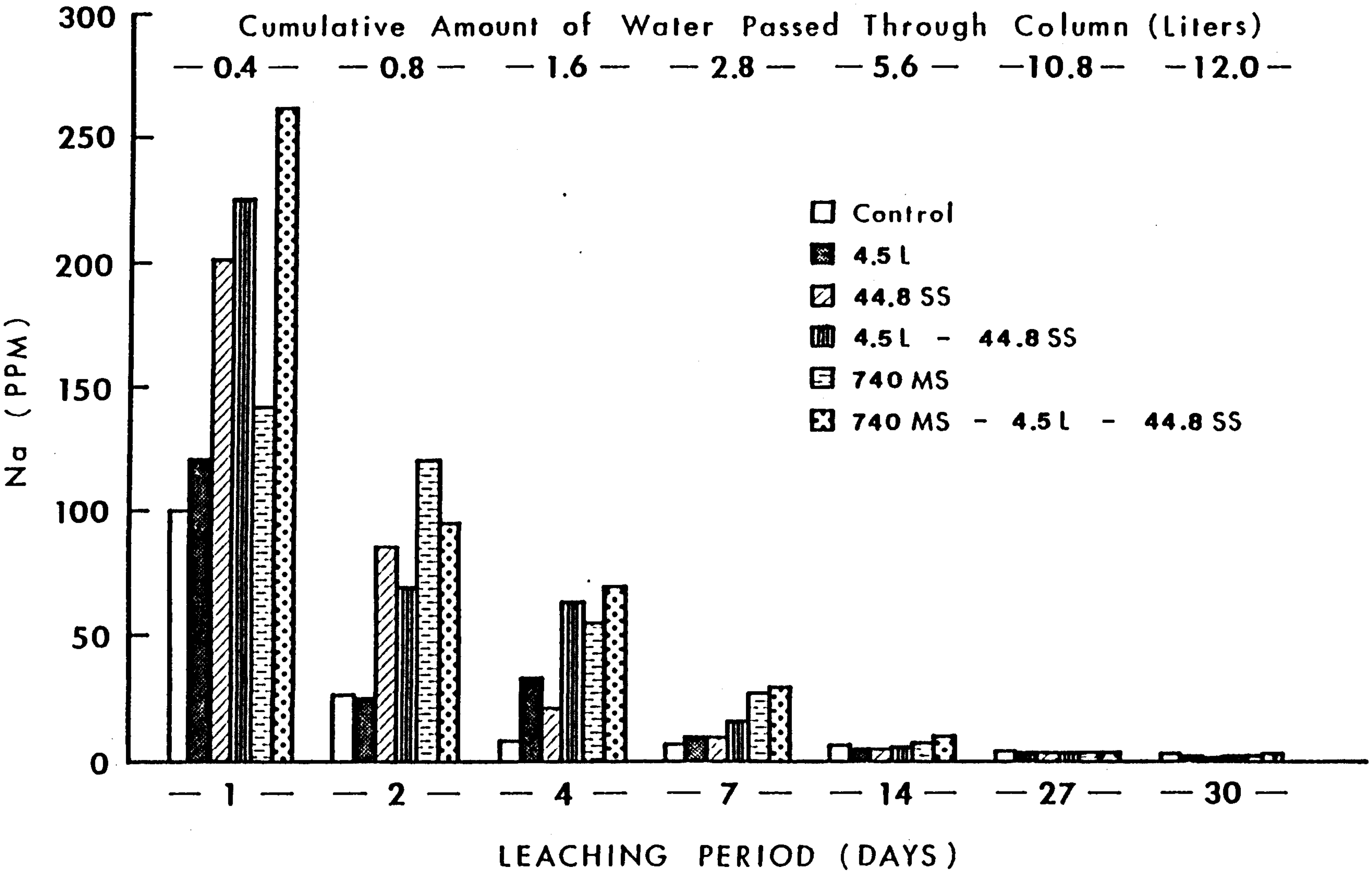

Figure 24. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of sodium at various sample dates over a 30-day leaching period.

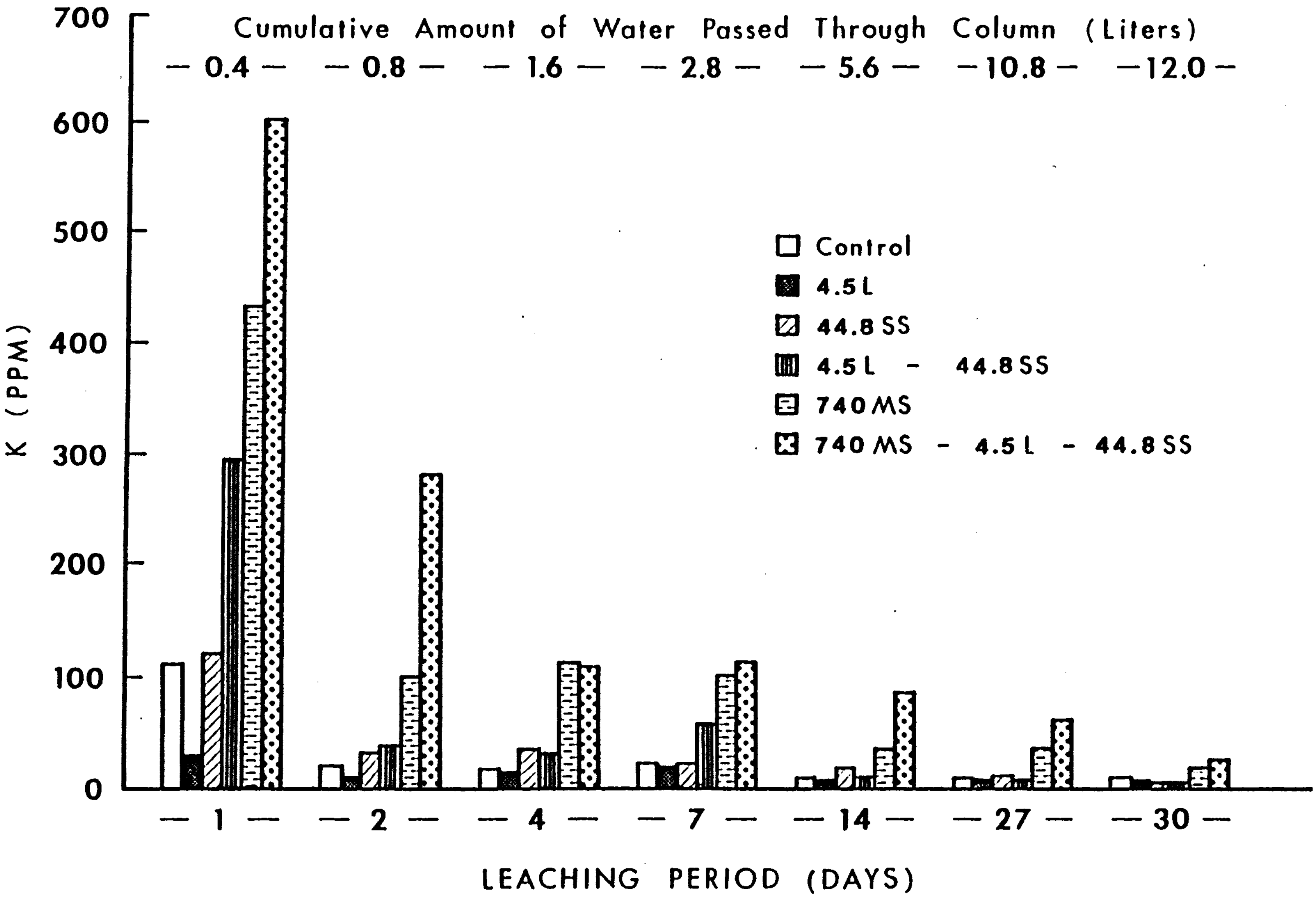

Figure 25. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of potassium at various sample dates over a 30-day leaching period.

Sulfate was easily leached from the control and the sewage sludge treatment, with high concentrations eluded in the first volume of leachate. The solubility of sulfate did not differ appreciably from the control when sewage sludge was added. Lime alone, and with sewage sludge, effectively decreased sulfate solubility in the first volume of leachate. Sulfate was not easily leached from the soil treatments until several leachings occurred (Figure 26).

Exceptions to the general leaching pattern included pH levels, and Ca concentrations. The pH of the leachate from the control was initially 3.7, and significantly increased to 4.7 with additional leaching. This rise reflects the benefits that may be obtained by simply leaching the tailings. Lime, sewage sludge, or soil were all effective in increasing pH. Lime, with or without sewage sludge, produced a moderate initial increase in pH. The addition of sewage sludge alone, resulted in only a slight increase. The soil treatments were most effective in increasing the pH of the leachate (Figure 27).

Calcium became more readily soluble with successive leaching. Additions of lime, sewage sludge, or soil did not appreciably change the solubility of Ca (Figure 28).

If the leachate were considered analogous to the soil solution, its chemical quality reflects the conditions plants would encounter if grown in these tailings. Initial leachate analysis of the control suggested that the

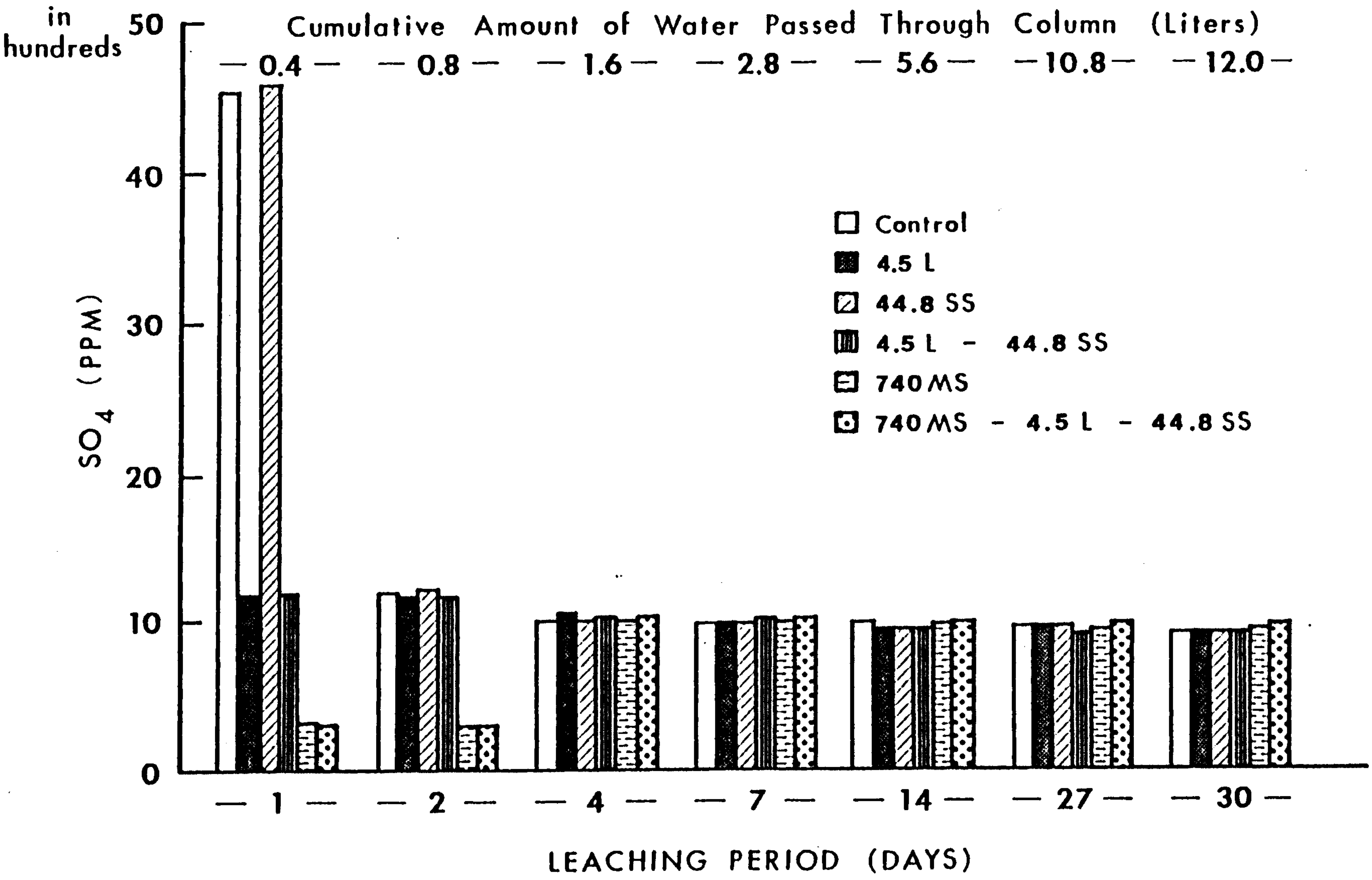

Figure 26. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of sulfate at various sample dates over a 30-day leaching period.

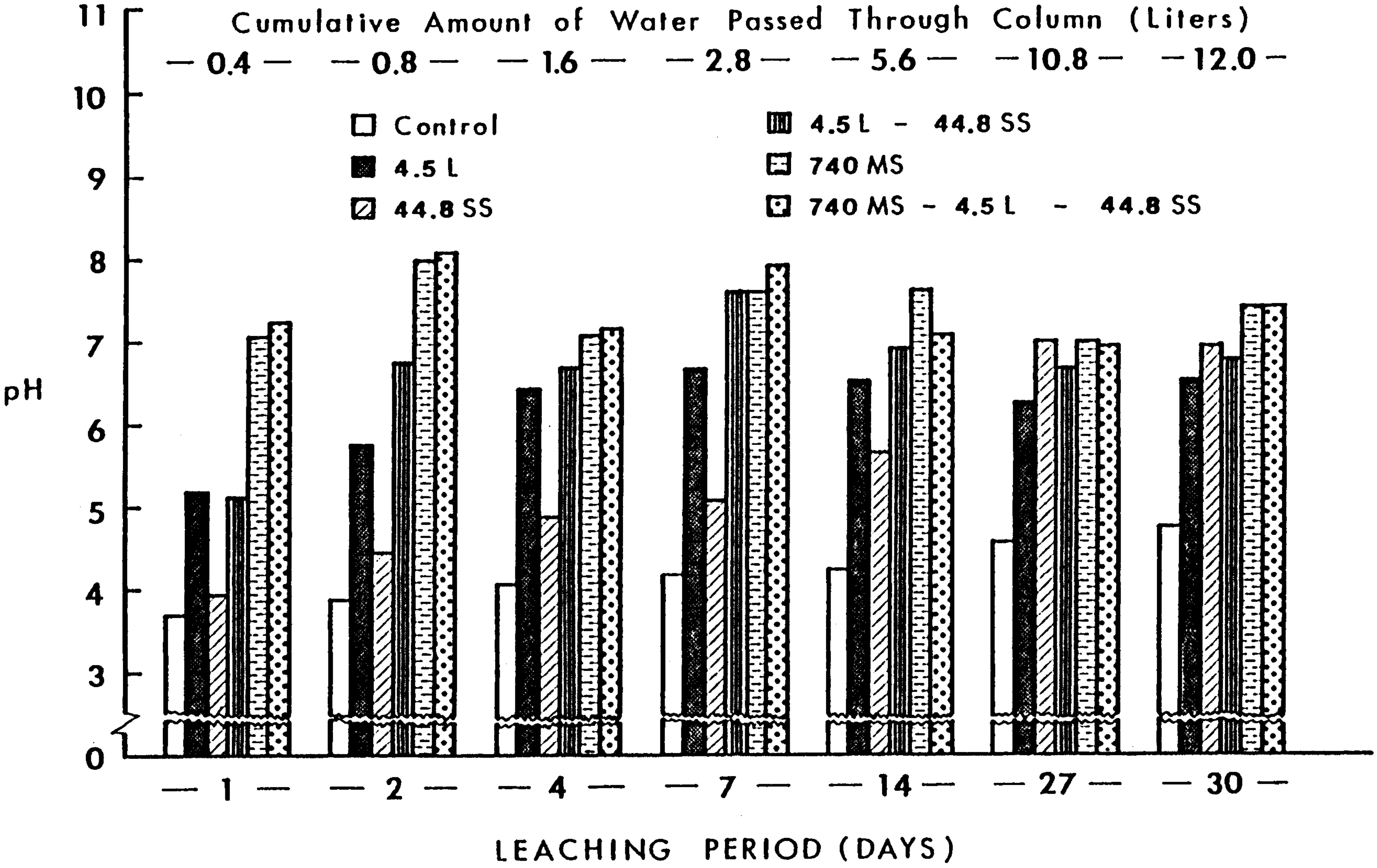

Figure 27. Effects of lime, sewage sludge, and soil treated tailings on the pH of the leachate collected at various sample dates over a 30-day leaching period.

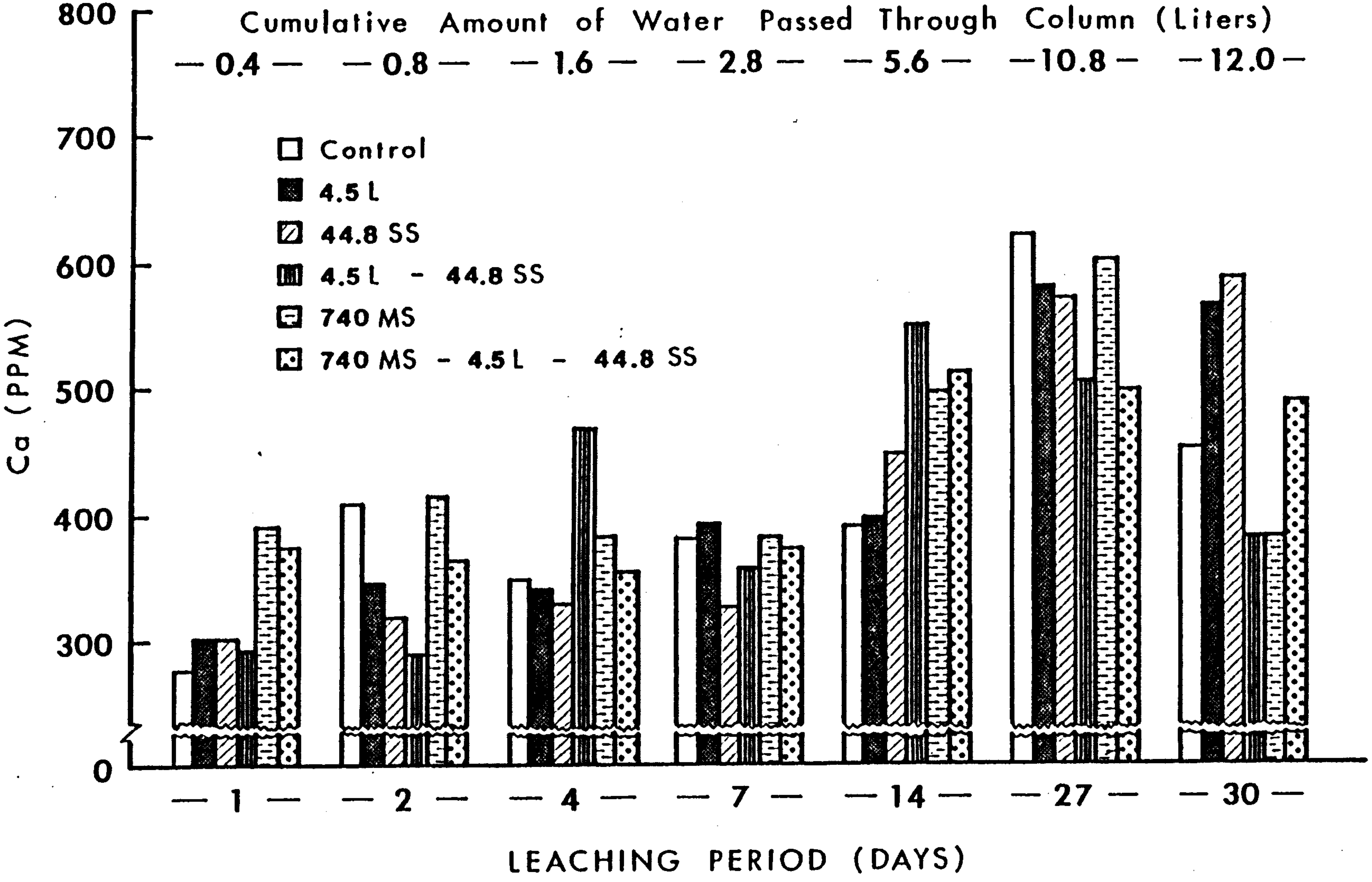

Figure 28. Effects of lime, sewage sludge, and soil treated tailings on the leachate concentration of calcium at various sample dates over a 30-day leaching period.

concentration of total soluble salts may restrict growth of all but highly tolerant species. Concentrations of Cu, Zn, and Fe were also initially toxic. Heavy metal concentrations in the leachate decreased with sucessive leachings to possible acceptable levels by the end of the leaching period. This may suggest the importance and benefit of leaching tailings to remove large amounts of toxic metals before planting.

The leachate from the lime treatment was moderately to strongly affected with total soluble salts. Although lime substantially reduced concentrations of Cu and Zn, the levels were still potentially toxic to most plants. Iron was present at possible acceptable levels.

Similar to the control, sewage sludge produced a very high concentration of total soluble salts, potentially restricting the growth of most plants. Levels of Cu, Zn, and Mn may be considered highly toxic. The Fe concentration in the leachate was possibly acceptable for plant growth. However, it has been reported that high levels of Cu and Zn may induce iron deficiency (Smith and Specht 1953; Hewitt 1952, 1953; Dotson 1973; DeKock 1956).

Leachate was only slightly affected with total soluble salts from the soil treatment. Concentrations of Cu, Zn, Fe, and Mn were present at acceptable levels for plant growth.

In addition to the preceeding results of leachate concentration, the total weight of each constituent leached on the various sample dates was calculated (Appendix Table A-17), and percent change from the control was then determined from these values as shown in Appendix Table A-18. These values indicated that the soil treatment produced the greatest reductions in leachate constituents. These reductions may be accounted for by the complexing ability of the CEC from the clay, silt, and organic matter fractions of the soil.

The reductions of heavy metal solubility from the addition of lime, were probably due in part by the direct effect of lime in the formation of complexes and insoluble hydroxides. The consequent poor plant growth may have been due in part to the lack of nitrogen, and to the possible presence of exchangeable forms of heavy metals not easily leached. Even though nitrogen fertilizers were not supplemented, it is anticipated that plant growth would have been improved with its use.

Reductions in concentrations of Cu and Fe by the sewage sludge treatment might have been due to the formation of stable complexed with the organic matter in the sludge, thus decreasing effective concentration of these metals in the tailings. Conversely, the increased mobility of other metals may have resulted from the formation of soluble metal chelates by the organic matter in the sludge.

The higher concentrations of metals were generally found in the samples with the lower pH values. Supporting evidence was reported by Struthers (1964) who found that the concentration of Fe, Al, and Mn in the leachate of strip-mine spoils have generally been found to be related to the pH of the leachate. Massey and Barnhisel (1972) showed the same trend for Cu, Zn, and Ni. In addition, Peterson and Nielson (1973) found that concentrations of Fe, Al, Mn, Zn, Cu, and Ni from mine tailings were generally higher in extracts of low pH.

It should be noted that Mg is relatively more mobile than Ca, and that a higher concentration of Mg than Ca might be expected in the leachate. However, Ca was originally present in the tailings at a much higher concentration than Mg. Therefore, a greater quantity of Ca was leached out.

Total amounts of soluble salts, Zn, Cu, and Mn leached from the control over the 30-day period were higher than values obtained from the initial analysis of the tailings. This might be accounted for by the equalibriating action of these elements by exchange positions between leaching volumes, thus producing higher levels of availability for water extraction.

SUMMARY AND CONCLUSIONS

Tailings used in the foregoing studies exhibit harsh conditions for plant growth. The low pH of the tailings appear to be caused by the oxidation of sulfides. Total soluble salts, Cu, Zn, and Mn were present in toxic concentrations. Nitrogen and phosphorus were too low for adequate plant growth. Results obtained from greenhouse studies indicate that untreated tailings were totally detrimental to blue panicgrass seedlings 12 weeks after emergence while tailings were less detrimental to balloon pea. Blue panicgrass, balloon pea, Lehmann lovegrass and quailbush show promise for vegetating and stabilizing copper mine tailings used in this investigation.

Treating tailings with lime, sewage sludge, and topsoil increased seedling emergence, growth rate, survival and vegetative yield of blue panicgrass and balloon pea. These species generally responded similarly to tailings treatments.

Liming rates of 6.7 metric tons per hectare and less resulted in very poor vegetative growth of blue panicgrass and balloon pea. The addition of lime effectively reduced heavy metal solubility, and consequently decreased metal concentrations in the leachate. This was probably due to the formation of complexes and insoluble hydroxides.

Even though metal solubility was reduced, restricted plant growth occurred probably because these metal ions may have been available to plants in exchangeable forms not readily leached. In addition, the variation in watering rates between the leaching study and the greenhouse study probably accounted for different leaching rates of heavy metals, with a smaller concentration of toxic elements leached in the greenhouse study.

Application of sewage sludge at rates of 67.2 metric tons per hectare and less also resulted in very poor plant growth. Sludge addition decreased soluble Cu and Fe probably by the formation of stable complexes with the organic matter in the sludge. However, the resulting poor plant growth may have been caused by the increased solubility of other heavy metals, probably by the formation of soluble metal chelates with the organic matter in the sludge.

Soil greatly increased plant growth when added as a topsoil layer over the tailings. Resulting root growth exhibited a matted system restricted to the topsoil layer. A topsoil layer placed over a 1:8 soil:tailings mixture proved highly beneficial to top growth and root growth. A 1:4 soil:tailings mixture alone produced poor plant growth. However, growth greatly improved when lime and sludge were added to the soil:tailings mix. The poor plant growth in the soil:tailings mixture alone is not easily explained because soil was very effective in reducing toxic levels of heavy metals and other constituents. Even though heavy metals decreased in solubility, they may have still been readily available to plants in exchangeable forms not easily leached. Another explanation might be the variation in watering rates between the greenhouse and leaching study.

Additions of lime, sewage sludge, and topsoil produced many significant changes in the leachate. Simply leaching untreated tailings considerably reduced heavy metal concentration. The general leaching pattern was a high initial increase in concentration followed by a gradual decrease with further leaching. The higher concentrations of metals were generally found in the samples with the lowest pH.

Although a layer of topsoil proved beneficial in the greenhouse, care might be exercised in using a topsoil layer in the field, especially on sloping tailings banks. Due to the differential permiability of the topsoil and tailings, water may accumulate at the soil-sand interface causing a gradual slippage of the topsoil layer. In addition, root growth restricted to the topsoil layer may not prevent this downhill slippage. However, by mixing the soil with the tailings, roots may penetrate deeper into the tailings thus binding and holding the tailings and topsoil in place. Employing a practice of mixing the topsoil and tailings may therefore, prove more beneficial in the field, especially on steep slopes.

Because of great differences in growth characteristics among plant species, it was difficult to interpret the data from plant damage due to the toxicity of various salts or ions. Factors other than toxicity of a single heavy metal apparently limited plant growth. Observations of leaves and roots often showed numerous probable deficiency and toxicity symptoms.

The adverse effects of heavy metals on the root system probably greatly influenced absorption and translocation of other ions and made it difficult to establish critical limits for the various plant nutrients as well as toxicants. There is considerable accumulation of data in the literature on deficiency levels for many elements and plants, but little data on limits toxic to various plants, and on interacting toxicities.

Soluble and or exchangeable ions are selectively removed by erosion and it may be expected that runoff from tailings will contain appreciable heavy metals. The quality of tailings leachate shows the deleterious compositional changes that ground water can experience when it is recharged from mine tailings. If this leachate were considered analagous to the soil solution, the unusually harsh conditions plants would encounter are evident.

The conditions which may restrict plant growth on tailings are evidently complex. The results from the foregoing greenhouse and laboratory investigations are not necessarily assured under field conditions. Physical problems encountered in the greenhouse will ultimately be more severe under field conditions. Field sites are harsh, low in precipitation and humidity, subject to temperature extremes, and high damaging winds.

APPENDIX A

TABULAR DATA

Table A-1. Analysis of variance of the effects of various treatments on the weight of root growth and top growth, and rate of top growth of blue panicgrass and balloon pea grown in copper mine tailings.

		Weight of root growth		Weight of top growth		Number of plants survived	
Source	df	Mean Squares	F Value	Mean Squares	F Value	Mean Squares	F Value
Block (B)	2	.128	1.502	.086	.253	50.144	1.706
Treatment (T)	14	4.078	47.997**	13.278	39.027**	150.373	5.115**
Species (S)	1	1.347	15.853**	2.663	7.826**	7128.900	142.502**
T X S	14	.497	5.849**	.913	2.682**	90.948	3.094**
Error A	58	.085		.248		31.302	

** Denotes significance at the 1% level.

Table A-2. Analysis of variance of the effects of various treatments and sample dates on the mean maximum plant height of blue panicgrass and balloon pea grown in copper mine tailings.

	Blue panicgrass			Balloon pea		
Source	df	Mean Squares	F Value	df	Mean Squares	F Value
Block (B)	2	1.642	.849	2	1.675	.091
Treatment (T)	14	137.510	71.860**	14	264.622	14.391**
Error A (B X T)	27	1.914	2.720	28	18.388	7.187
Date (D)	11	94.843	134.795**	11	310.468	121.340**
Error B (T X D)	143	9.072	12.894**	140	29.094	11.371**

** Denotes significance at the 1% level.

Table A-3 Percent seedling emergence and survival of blue panicgrass grown in pots containing 4 kilograms of tailings treated with lime, sewage sludge, and topsoil.

	Growing period (weeks)											
Treatments	1	2	3	4	5	6	8	10	12	14	16	18
	%											
Control	--	1	6	26	39	40	36	13	9	--	--	--
1.1(L)	--	52	57	66	72	75	74	64	34	31	27	25
3.4(L)	--	86	91	91	95	97	95	78	57	72	69	67
4.5(L)	--	69	74	79	91	92	91	86	75	72	69	67
6.7(L)	--	48	56	63	83	88	89	85	71	71	63	60
22.4(SS)	--	51	62	71	73	74	76	66	65	65	65	65
44.8(SS)	13	91	91	94	97	97	97	94	93	93	91	91
67.2(SS)	--	61	80	88	91	91	89	88	83	81	77	76
4.5(L)-44.8(SS)	--	72	80	89	94	93	93	92	91	89	88	86
740(MS)	--	85	89	89	91	91	91	91	91	91	91	89
740(TS)	9	34	42	58	65	71	83	82	80	79	79	77
370(TS) over 370(MS)	1	18	42	65	73	74	74	69	69	65	63	63
740(MS)-4.5(L)	--	19	35	63	85	84	97	86	86	86	86	86
740(MS)-44.8(SS)	4	28	29	55	89	91	89	86	86	84	84	84
740(MS)-4.5(L)-44.8(SS)	--	31	41	65	89	94	96	96	96	95	95	95
Mean	2	50	58	71	82	83	85	78	72	71	69	68

Table A-4. Average maximum height of blue panicgrass grown in treated tailings.

Treatments	Growing period (weeks)											
	1	2	3	4	5	6	8	10	12	14	16	18
	cm											
Control	--	.1	.2	.3	.9	1.4	1.8	2.2	2.0	2.2	1.8	1.7
1.1(L)	--	.3	.8	.8	1.4	1.7	2.4	2.6	2.7	2.5	1.9	1.9
3.4(L)	--	.4	.8	1.1	1.4	1.9	2.4	2.4	2.3	2.2	1.6	1.4
4.5(L)	--	.3	.7	1.0	2.0	2.4	2.9	2.8	2.6	2.2	1.7	1.4
6.7(L)	--	.5	.8	.9	1.5	2.0	2.6	2.7	2.5	2.5	1.8	1.6
22.4(SS)	--	.2	.5	.7	1.4	1.8	2.5	2.9	2.9	2.9	2.9	2.3
44.8(SS)	.1	.4	.7	1.1	2.2	2.7	3.2	3.2	3.1	3.2	3.3	4.1
67.2(SS)	--	.3	.6	.9	1.8	2.4	3.4	3.2	3.3	3.7	4.0	4.8
4.5(L)-44.8(SS)	--	.5	1.1	1.5	2.2	2.6	2.8	2.8	2.6	2.6	2.0	2.1
740(MS)	--	.7	1.2	1.7	2.4	2.7	2.9	2.9	2.6	2.5	1.7	1.6
740(TS)	.3	1.0	2.0	2.4	3.8	4.9	7.8	9.4	9.7	12.3	11.6	12.1
370(TS) over 370(MS)	.1	.4	.9	1.7	3.4	4.9	8.8	12.2	13.7	14.8	15.3	17.9
740(MS)-4.5(L)	--	.4	.6	.8	1.6	2.2	2.5	2.8	2.8	2.7	2.3	2.6
740(MS)-44.8(SS)	.1	.8	.8	1.0	2.0	2.6	3.1	3.2	3.1	3.2	3.0	4.1
740(MS)-4.5(L)-44.8(SS)	--	.9	1.4	2.0	2.4	2.7	2.1	2.6	4.0	4.3	4.7	8.2

Table A-5. Percent seedling emergence and survival of balloon pea grown in pots containing 4 kilograms of tailings treated with lime, sewage sludge, and topsoil.

	Growing period (weeks)											
Treatments	1	2	3	4	5	6	8	10	12	14	16	18
	%											
Control	7	23	47	50	60	63	53	37	17	13	17	17
1.1(L)	3	23	40	60	60	70	70	37	37	43	43	40
3.4(L)	--	20	20	70	77	77	70	67	67	77	77	73
4.5(L)	--	30	43	53	70	80	73	67	70	70	67	70
6.7(L)	--	7	23	63	80	80	80	67	63	63	63	63
22.4(SS)	7	40	40	53	63	67	60	47	43	60	60	60
44.8(SS)	--	7	27	43	77	80	77	50	43	50	50	50
67.2(SS)	3	7	10	30	60	70	67	37	37	40	40	40
4.5(L)-44.8(SS)	--	13	27	57	80	87	67	57	57	63	60	57
740(MS)	--	--	--	30	73	73	50	47	50	57	57	57
740(TS)	--	17	23	67	83	80	80	80	73	70	80	80
370(TS) over 370(MS)	--	20	23	47	63	70	67	67	67	67	67	67
740(MS)-4.5(L)	--	--	17	53	80	77	80	77	77	93	87	87
740(MS)-44.8(SS)	--	3	17	67	87	87	87	83	83	90	70	73
740(MS)-4.5(L)-44.8(SS)	--	7	17	83	87	83	83	87	83	87	77	73
Mean	1	14	25	55	73	76	71	60	58	63	61	60

Table A-6. Average maximum height of balloon pea grown in treated tailings.

Treatments	Growing period (weeks)											
	1	2	3	4	5	6	8	10	12	14	16	18
	cm											
Control	.1	.3	.3	.5	.5	.8	1.6	2.2	2.5	2.4	2.9	2.1
1.1(L)	.1	.3	.4	.7	.9	1.5	2.7	4.5	4.8	3.3	3.6	4.4
3.4(L)	--	.2	.7	.6	1.2	2.4	4.5	5.2	5.4	4.5	4.6	4.7
4.5(L)	--	.3	.5	.7	.9	1.4	2.9	2.9	4.2	4.4	4.7	4.6
6.7(L)	--	.2	.5	.7	1.2	2.0	3.8	4.9	5.2	5.0	4.8	4.7
22.4(SS)	.1	.5	.7	.7	1.5	2.1	3.7	4.2	4.9	3.3	4.0	4.7
44.8(SS)	--	.5	.4	.6	1.0	1.7	3.2	4.2	5.2	4.7	5.2	5.5
67.2(SS)	.1	.6	.6	.5	.8	1.1	2.7	3.3	3.9	4.2	4.3	4.6
4.5(L)-44.8(SS)	--	.4	.5	.5	1.0	1.5	3.4	4.3	4.4	6.5	4.1	4.0
740(MS)	--	--	--	.4	.9	1.5	4.0	4.8	4.8	4.6	4.8	5.0
740(TS)	--	.7	1.1	1.4	2.8	4.7	8.9	13.1	18.4	22.6	26.8	31.6
370(TS) over 370(MS)	--	.6	.7	.9	1.8	2.8	5.7	7.9	11.2	51.5	20.6	29.6
740(MS)-4.5(L)	--	--	.5	.7	1.5	2.5	3.8	4.3	4.4	3.6	3.9	4.5
740(MS)-44.8(SS)	--	.3	.4	.6	1.6	2.6	3.7	4.0	4.2	3.9	3.8	4.0
740(MS)-4.5(L)-44.8(SS)	--	.1	.9	.7	1.9	2.9	4.3	4.6	4.9	4.9	5.7	7.2

Table A-7. Total oven-dry weight of top growth and root growth, and shoot:root ratios of blue panicgrass and balloon pea grown for 18 weeks in 20 centimeter pots containing 4 kg. of tailings treated with lime, sewage sludge, and topsoil.

	Blue panicgrass			Balloon pea		
Treatments	top weight	root weight	shoot: root	top weight	root weight	shoot: root
	---- gms ----			---- gms ----		
Control	.01	.01	1.00	.01	.01	1.00
1.1(L)	.04	1.00	.06	.06	.04	1.50
3.4(L)	.06	.04	1.50	.10	.01	1.00
4.5(L)	.08	.05	1.60	.09	.08	1.13
6.7(L)	.08	.05	1.60	.08	.08	1.00
22.4(SS)	.22	.22	1.00	.11	.09	1.22
44.8(SS)	.37	.25	1.58	.10	.07	1.43
67.2(SS)	.38	.24	1.58	.07	.04	1.75
4.5(L)-44.8(SS)	.17	.14	1.21	.07	.07	1.00
740(MS)	.14	.10	1.40	.07	.07	1.00
740(TS)	3.57	2.12	1.68	3.76	2.02	1.86
370(TS) over 370(MS)	6.44	5.88	1.66	3.51	1.66	2.11
740(MS)-4.5(L)	.23	.15	1.53	.13	.17	.76
740(MS)-44.8(SS)	.46	.32	1.44	.10	.09	1.11
740(MS)-4.5(L) -44.8(SS)	1.54	.95	1.62	.39	.29	1.34

Table A-8. Analysis of variance of the effects of treated copper mine tailings and growing period on maximum root elongation of blue panicgrass, Lehmann lovegrass, balloon pea, and quailbush.

Source	df	Mean Squares	F Value
Block (B)	2	54.592	4.718*
Treatment (T)	8	1419.807	122.696**
Species (S)	3	301.844	26.085**
T X S	24	25.703	2.221**
Error A	70	11.572	
Date (D)	12	358.818	353.010**
W X T	96	29.147	28.674**
W X S	36	5.228	5.143**
W X T X S	288	3.073	3.025**
Error B	864	1.016	

* Denotes significance at the 5% level.
** Denotes significance at the 1% level.

Table A-9. Maximum depth of root growth of blue panicgrass, Lehmann lovegrass, balloon pea, and quailbush grown for 18 weeks in tailings treated with lime, sewage sludge, and soil.

		Growing period (weeks)											
Treatment	Species	2	3	4	5	6	7	8	10	12	14	16	18
		cm											
3.4(L)	blue panicgrass	---	.3	1.0	2.0	2.6	3.5	3.6	3.6	3.6	3.6	3.6	3.6
	Lehmann lovegrass	---	.4	.5	.8	.9	1.4	1.9	2.1	2.1	2.1	2.1	2.1
	balloon pea	.5	.8	.8	2.4	2.7	3.6	3.6	3.6	3.6	3.6	3.6	3.6
	quailbush	---	.8	.9	1.0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
4.5(L)	blue panicgrass	---	.6	.6	2.5	3.0	3.8	4.4	4.7	4.8	4.8	4.8	4.8
	Lehmann lovegrass	---	---	.1	.1	.7	1.0	1.6	1.8	1.8	1.8	1.8	1.8
	balloon pea	.3	.9	1.4	2.7	3.9	4.6	5.1	5.4	5.4	5.4	5.4	5.4
	quailbush	---	.1	.5	1.0	1.6	2.2	2.2	2.2	2.2	2.2	2.2	2.2
22.4(SS)	blue panicgrass	---	---	---	.2	.2	.2	.2	.2	.2	.2	.2	.2
	Lehmann lovegrass	---	---	---	---	---	---	---	---	---	---	---	---
	balloon pea	---	---	---	.3	.3	.3	.3	.3	.3	.3	.3	.3
	quailbush	---	---	---	.2	.2	.2	.7	.7	.7	.7	.7	.7
67.2(SS)	blue panicgrass	---	---	---	---	.6	.6	1.4	2.0	2.0	2.0	2.0	2.0
	Lehmann lovegrass	---	---	---	---	---	---	1.2	1.2	1.2	1.2	1.2	1.2
	balloon pea	---	---	---	1.1	1.4	2.4	2.6	2.6	2.6	2.6	2.6	2.6
	quailbush	---	---	---	---	---	---	---	.7	.7	.7	.7	.7
1,480(TS)	blue panicgrass	1.2	7.2	9.8	10.7	10.7	11.1	11.1	11.1	11.1	11.1	11.1	11.1
	Lehmann lovegrass	---	---	---	.7	1.8	7.6	10.5	10.5	10.7	10.7	10.7	10.7
	balloon pea	1.2	2.1	10.8	10.8	10.8	10.8	10.9	10.9	10.9	10.9	10.9	10.9
	quailbush	---	---	2.3	6.1	9.0	9.5	10.9	10.9	10.9	10.9	10.9	10.9
740(MS)	blue panicgrass	---	1.7	4.5	7.5	8.8	9.8	9.8	10.4	10.4	10.4	10.4	10.4
	Lehmann lovegrass	---	---	.7	2.5	3.4	3.9	3.9	4.8	5.3	5.7	5.7	5.7
	balloon pea	1.6	3.1	4.8	5.1	6.4	8.8	9.4	9.9	9.9	9.9	9.9	9.9
	quailbush	---	---	2.3	6.1	9.0	9.5	10.9	10.9	10.9	10.9	10.9	10.9
740(TS) over 370(MS)	blue panicgrass	2.6	6.5	8.4	10.3	10.6	10.6	10.6	10.7	10.7	10.7	10.7	10.7
	Lehmann lovegrass	---	.6	1.3	3.4	5.5	6.4	9.1	9.2	9.3	9.3	9.3	9.3
	balloon pea	3.0	5.6	8.5	10.3	10.4	10.8	10.9	10.9	10.9	10.9	10.9	10.9
	quailbush	.9	1.9	2.0	3.4	5.2	7.7	9.1	9.8	10.1	10.1	10.1	10.1
740(TS) over 4.5(L)	blue panicgrass	3.7	5.8	5.9	6.2	6.5	6.9	6.9	7.2	7.2	7.2	7.2	7.2
	Lehmann lovegrass	---	---	3.0	4.3	5.2	6.8	7.2	7.4	7.4	7.4	7.4	7.4
	balloon pea	3.8	6.0	6.1	6.3	6.4	6.6	7.0	7.4	7.6	7.6	7.6	7.6
	quailbush	---	3.9	5.5	5.9	6.1	6.4	6.6	7.1	7.1	7.1	7.1	7.1

Table A-10. Concentration of constituents leached at various sample dates from the control column containing 4 kilograms of tailings.

		Constituents									
Days Leached	pH	Soluble Salts	SO_4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		ppm									
1	3.7	9,692	4,540	426.7	2,048.0	10.0	853	176.0	101	280	112
2	3.9	3,639	1,188	149.3	616.7	1.5	195	52.0	28	413	22
4	4.0	3,469	1,010	117.3	597.3	2.5	168	46.7	7	347	18
7	4.1	2,267	996	53.3	272.0	1.9	69	18.3	7	380	22
14	4.2	1,610	990	4.3	23.3	1.9	7	2.0	5	390	8
27	4.5	1,542	958	4.7	11.3	2.7	1	.3	4	619	9
30	4.7	1,677	926	--	6.3	2.3	1	--	3	450	8
Total		23,895	10,608	751.6	3,574.9	22.8	1,294	295.3	155	2,879	198

Table A-11. Concentration of constituents leached at various sample dates from column containing 4 kilograms of tailings treated with 4.5 metric tons per hectare of lime mixed thoroughly throughout the column.

		Constituents									
Days Leached	pH	Soluble Salts	SO_4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		ppm									
1	5.2	6,348	1,180	202.7	362.7	.5	1,056	126.7	221	303	28
2	5.7	3,605	1,162	69.3	98.7	.8	427	64.0	24	347	9
4	6.3	3,106	1,042	32.0	25.0	.4	359	33.3	32	340	3
7	6.6	2,397	1,008	13.3	10.0	.5	200	19.0	9	393	19
14	6.4	1,621	948	4.0	3.7	.4	39	4.3	5	397	6
27	6.2	1,553	948	4.0	2.3	.1	5	1.0	3	577	7
30	6.4	1,723	936	3.0	2.0	.1	4	2.3	2	560	6
Total		20,351	7,224	328.3	504.4	2.8	1,890	249.0	296	2,917	88

Table A-12. Concentration of constituents leached at various sample dates from column containing 4 kilograms of tailings treated with 44.8 metric tons per hectare of sewage sludge mixed thoroughly throughout the column.

Days Leached	pH	Soluble Salts	SO_4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		Constituents									
		ppm									
1	3.9	10,769	4,580	448.0	2,048.0	3.0	891	196.3	200	303	120
2	4.4	4,444	1,210	181.3	618.7	.9	204	55.3	84	320	33
4	4.8	2,925	1,018	85.3	151.1	1.3	139	25.3	20	327	35
7	5.0	2,346	978	58.7	186.7	.7	88	21.3	9	327	22
14	5.6	1,593	940	4.1	43.5	.5	11	4.5	5	447	18
27	5.9	1,485	944	2.0	15.0	.03	3	1.0	3	563	10
30	5.9	1,710	928	1.0	13.8	.07	1	--	1	587	5
Total		25,272	10,598	780.4	3,076.8	6.5	1,337	303.7	322	2,874	242

Table A-13. Concentration of constituents leached at various sample dates from column containing 4 kilograms of tailings treated with 4.5 metric tons per hectare of lime, and 44.8 metric tons per hectare of sewage sludge mixed thoroughly throughout the column.

		Constituents									
Days Leached	pH	Soluble Salts	SO4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		ppm									
1	5.1	7,651	1,180	277.3	369.1	.6	1,227	133.3	244	293	295
2	6.7	3,899	1,180	58.7	88.8	.8	292	50.7	68	290	37
4	6.6	3,197	1,036	18.7	10.7	.4	291	21.3	63	467	31
7	7.5	2,675	1,014	10.7	4.7	.5	255	12.3	15	357	57
14	6.8	1,655	952	5.0	2.3	.3	48	8.0	5	550	9
27	6.6	1,508	918	2.3	1.0	--	5	3.3	3	503	7
30	6.7	1,736	938	2.3	1.0	.1	3	2.3	2	380	5
Total		22,351	7,218	375.0	477.6	2.7	2,121	231.2	380	2,840	441

Table A-14. Concentration of constituents leached at various sample dates from column containing 4 kilograms of tailings treated with 740 metric tons per hectare of topsoil material mixed thoroughly throughout the column.

		Constituents									
Days Leached	pH	Soluble Salts	SO_4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		ppm									
1	7.0	3,299	301	18.0	17.3	.6	228	30.7	140	393	433
2	8.0	2,698	308	9.3	9.0	.7	161	17.3	120	415	100
4	7.0	2,271	1,006	9.0	4.7	.5	189	20.3	56	380	112
7	7.5	2,392	1,004	4.0	1.3	.4	168	16.3	26	380	101
14	7.5	1,961	970	1.7	1.8	.4	89	9.4	7	493	35
27	6.6	1,632	932	1.0	1.7	.03	19	7.7	3	600	38
30	7.8	1,884	950	1.0	.3	.06	15	6.8	2	380	17
Total		16,587	5,471	44.0	36.1	2.7	869	108.5	354	3,041	836

Table A-15. Concentration of constituents leached at various sample dates from column containing 4 kilograms of tailings treated with 740 metric tons per hectare of topsoil material, 4.5 metric tons per hectare of lime, and 44.8 metric tons per hectare of sewage sludge mixed thoroughly throughout the column.

		Constituents									
Days Leached	pH	Soluble Salts	SO_4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		ppm									
1	7.2	4,670	300	6.3	7.3	.6	512	20.7	263	377	603
2	8.0	3,854	305	2.7	4.0	.8	329	15.0	94	360	279
4	7.1	3,650	1,026	2.4	2.0	.4	332	9.3	69	353	109
7	7.8	2,868	1,012	1.4	1.3	.3	227	8.7	28	370	113
14	7.0	2,074	1,002	1.0	1.0	.4	141	5.7	9	410	86
27	6.8	1,723	974	.3	---	--	37	5.3	3	497	62
30	7.3	1,923	972	---	---	.06	28	3.3	3	490	25
Total		20,762	5,591	14.2	15.6	2.6	1,606	68.0	469	2,857	1,277

Table A-16. Analysis of variance of the effects of treating tailings with lime, sewage sludge, and soil on the leachate concentration of total soluble salts, SO_4, Zn, Cu, Fe, Mg, Mn, Na, Ca, K, and pH value from 4 kilograms of tailings.

Source	pH			Soluble salts			SO_4			Zn		
	d.f	Mean Square	F Value	d.f	Mean Square	F Value	d.f	Mean Square	F Value	d.f	Mean Square	F Value
Treatment (T)	5	32.65	391.13**	5	3,996,680.19	129.37**	5	2,204,418.45	699.83**	5	46,959.26	45.76**
Error A	12	.08		12	30,892.61		12	3,149.95		12	1,026.24	
Date (D)	6	2.50	30.12**	6	67,179,311.31	719.58**	6	2,845,438.39	3,118.07**	6	121,854.34	123.84**
T X D	30	.63	7.61**	30	3,752,946.45	40.20**	30	1,742,852.56	1,909.84**	30	14,661.63	14.90**
Error B	70	.08		72	93,359.50		71	912.57		72	983.97	

Source	Cu			Fe			Mg			Mn		
	d.f	Mean Square	F Value	d.f	Mean Square	F Value	d.f	Mean Square	F Value	d.f	Mean Square	F Value
Treatment (T)	5	1,104,564.74	312.51**	5	26.80	272.05**	5	100,047.27	20.44**	5	4,157.73	66.41**
Error A	12	3,534.49		12	.10		12	4,894.08		12	62.61	
Date (D)	6	1,502,362.97	504.53**	6	9.46	30.00**	6	1,347,083.15	233.06**	6	28,497.41	301.92**
T X D	30	367,789.29	123.51**	30	4.26	13.52**	30	63,453.19	10.98**	30	2,308.15	24.45**
Error B	72	2,977.78		70	.32		71	5,779.27		72	94.39	

Source	Na			Ca			K		
	d.f	Mean Square	F Value	d.f	Mean Square	F Value	d.f	Mean Square	F Value
Treatment (T)	5	4,606.67	9.48**	5	2,576.63	.66	5	89,687.49	16.94**
Error A	12	485.80		12	3,892.63		12	5,293.76	
Date (D)	6	83,318.29	180.79**	6	123,207.97	15.54**	6	138,808.30	29.91**
T X D	30	1,945.49	4.22**	30	10,702.97	1.35	30	17,388.74	3.75**
Error B	71	460.85		70	7,929.23		72	4,640.26	

** Denotes significance at the 1% level.

Table A-17. Total amount of constituents leached (by weight) in seven leaching periods from columns containing 4 kilograms of tailings treated with lime, sewage sludge, and topsoil.

		Constituents									
Treatments	pH 1/	Soluble Salts	SO_4	Zn	Cu	Fe	Mg	Mn	Na	Ca	K
		mg									
Control	4.7	9,558	4,243	301	1,430	9.12	518	118	62	1,152	80
4.5(L)	6.4	8,141	2,890	131	202	1.12	756	100	115	1,167	36
44.8(SS)	5.9	10,109	4,239	312	1,231	2.06	534	122	129	1,150	97
4.5(L)-44.8(SS)	6.7	8,928	2,887	150	191	1.08	848	92	152	1,136	176
740(MS)	7.8	6,635	2,188	18	14	1.08	348	44	142	1,206	334
740(MS)-4.5(L) -44.8(SS)	7.3	8,305	2,236	6	6	1.04	642	27	188	1,143	511

1/ pH value in last volume of leachate.

Table A-18. Percent of constituents leached (by weight) from columns containing 4 kilograms of tailings treated with lime, sewage sludge, and soil based on the actual total weight of constituents leached from the control column containing untreated tailings.

Constituents	Treatments					
	Control	4.5(L)	44.8(SS)	4.5(L)-44.8(SS)	740(MS)	740(MS)-4.5(L)-44.8(SS)
pH 1/	4.7 a	6.4 b	5.9 c	6.7 b	7.8 d	7.3 d
	--mg--	%				
Soluble Salts	9,558 ac	85 b	106 a	93 c	69 d	87 bd
SO_4	4,243 a	68 b	100 a	68 b	52 c	53 c
Zn	301 ab	44 c	104 a	50 bc	6 c	2 c
Cu	1,430 a	14 b	86 a	13 b	1 b	.4 b
Fe	9.12 a	12 b	29 b	12 b	12 b	11 b
Mg	518 ac	146 ac	103 ac	164 a	67 bc	124 ab
Mn	118 a	85 a	104 a	78 a	37 b	23 b
Na	62 a	185 ab	208 ab	245 ab	229 ab	303 b
Ca	1,152 a	101 a	100 a	99 a	105 a	99 a
K	80 a	45 a	121 a	202 ab	418 ab	638 b

Note: Percentages within each constituent followed by the same letter are not significantly different at the 5% level.
1/ pH values in last volume of leachate.

LIST OF REFERENCES

Anderson, D.L., L.P. Hamilton, H.G. Reynolds, and R.R. Humphrey. 1957. Reseeding desert grassland ranges in southern Arizona. University of Arizona Agri. Exp. Sta. Bull. 249. 31 p.

Anderson, M.S. 1955. Sewage sludge for soil improvement. U.S. Dept. Agri. Circ. 972: 14-17.

Anonymous. 1972. Reclamation and environmental control. Western Miner 45: 50-52.

Antonovics, J., A.D. Bradshaw, and R.G. Turner. 1971. Heavy metal tolerance in plants, p. 2-72, in Advances in ecological research. Vol. 7. J.B. Cragg (ed.). Academic Press, London. 254 p.

Bach, D.A. 1973. The use of drip irrigation for vegetating mine waste areas, p. 563-570, in Tailing disposal today, C.L. Alpin and G.O. Argall Jr. (eds.). Proc., 1st International Tailing Symposium, Tucson, Arizona. Miller Freeman Publishers, San Francisco. 861 p.

Bengson, Stuart A. 1975. Drip irrigation for revegetating steep slopes in an arid environment. Progressive Agri. in Arizona 27: 3-5, 12.

Bennett, A.C. 1974. Toxic effects of aqueous ammonia, copper, zinc, lead, boron, and manganese on root growth, p. 669-680, in The plant root and its environment, E.W. Carson (ed.). University Press of Virginia, Charlottesville. 691 p.

Berg, W.A. 1970. How to promote plants in mine wastes. Mining Eng. 22: 67-68.

Berg, W.A., and W.G. Vogel. 1973. Toxicity of acid coal-mine spoils to plants, p. 57-68, in Ecology and reclamation of devastated lands. Vol. 1. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 538 p.

Berrow, M.L., and J. Webber. 1972. Trace elements in sewage sludges. J. Sci. Food Agri. 23: 93-100.

Black, C.A. 1968. Soil-plant relationships, 2nd. ed. John Wiley and Sons, Inc., New York. 792 p.

Boyles, J.M., D. Cain, W. Alley, and R.W. Klusman. 1974. Impact of Argo Tunnel acid mine drainage, Clear Creek County, Colo., p. 41-53, in Water problems related to mining, R.F. Hadley and D.T. Snow (eds.). Proc., 18th American Water Resources Assoc., Minneapolis. 236 p.

Bradford, G.R., A.L. Page, L.J. Lund, and W. Olmstead. 1975. Trace element concentrations of sewage sludge treatment plant effluents and sludges; their interactions with soils and uptake by plants. J. Environ. Qual. 4: 123-127.

Briggs, Jim. 1973. Legumes, shrubs and forb species for cover and beautification. Ann. Tech. Rep. U.S. Dept. Agri., Soil Cons. Serv. p. 3-11.

Brown, R.W., and R.S. Johnson. 1976. Revegetation of an alpine mine disturbance; Beartooth Plateau, Montana. U.S. Dept. Agri., Forest Serv. Res. Note INT-206. 8 p.

Chadwick, M.J. 1973. Amendment trials of coal spoils in the north of England, p. 175-188, in Ecology and reclamation of devastated lands. Vol. 2. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization, Penn. State. Gordon and Breach, New York. 504 p.

Chaiwanakupt, P., and W.K. Robertson. 1976. Leaching of phosphate and selected cations from sandy soils as affected by lime. Agron. J. 68: 507-511.

Chaney, R.L. 1973. Crop and food chain effects of toxic elements in sewages and effluents, p. 129-141, in Proc. of the Joint Conf. on Recycling Municipal Sludges and Effluents on Land. Champaign, Ill. Natl. Assoc. State Univ. and Land Grant Colleges, Wash. D.C.

Chenik, D. 1960. The promotion of a vegetative cover on mine slime dams and sand dumps. J.S. Afr. Inst. Mining Metall. 60: 525-555.

Coker, E.G. 1966a. The value of liquid digested sewage sludge. I. The effects of liquid sewage sludge on growth and composition of grass-clover swards in south-east England. J. Agri. Sci. 67: 91-97.

Coker, E.G. 1966b. The value of liquid digested sewage sludge. III. The results of an experiment on barley. J. Agri. Sci. 67: 105-107.

Coleman, N.T., E.J. Kamprath, and S.B. Weed. 1959. Liming. Adv. Agron. 10: 475-522.

Cook, W.C., R.M. Hyde, and P.L. Sims. 1974. Revegetation guidelines for surface mined areas. Range Sci. Dept. Ser. No. 16, Colorado State University, Fort Collins. 73 p.

Cresswell, C.F. 1973. Changes in vegetational composition, nutritional status, soils, and microbial populations with the establishment of vegetation on gold-mine dumps on the Withwatersrand, p. 335-359, in Ecology and reclamation of devastated lands. Vol. 2. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 504 p.

Crider, F.J. 1945. Three introduced lovegrasses for soil conservation. U.S. Dept. Agri. Circ. 730. 90 p.

Darmer, Gerhard. 1973. Grasses and herbs for revegetating phytotoxic material, p. 91-101, in Ecology and reclamation of devastated lands. Vol. 2. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 504 p.

Day, A.D., and K.L. Ludeke. 1973. Stabilizing copper mine tailing disposal berms with giant bermudagrass. J. Environ. Qual. 2: 314-315.

Dean, K.C., and R. Havens. 1971. Stabilizing mineral wastes Eng. Mining J. 12: 99-103.

Dean, K.C., R. Havens, and M.W. Glantz. 1974. Methods and costs for stabilizing fine-sized mineral wastes. U.S. Bur. Mines R.I. 7896. 26 p.

Dean, K.C., R. Havens, K.T. Harper, and J.B. Rosenbaum. 1973. Vegetative stabilization of mill mineral wastes, p. 119-136, in Ecology and reclamation of devastated lands. Vol. 2. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 504 p.

Dean, K.C., R. Havens, and E.G. Valdez. 1969. Stabilization of mineral wastes, Indust. Water Eng. 6: 30-33.

Dean, K.C., R. Havens, and E.G. Valdez. 1971. U.S.B.M. finds many ways to stabilize mineral wastes. Mining Eng. J. 23: 61-63.

DeKock, P.C. 1956. Heavy metal toxicity and ion chlorosis. Ann. Bot. N.S. 20: 133-141.

Dotson, G.K. 1973. Constraints to spreading sewage sludge on cropland. News of environmental research in Cincinnati, advanced waste treatment. U.S. Environ. Protection Agency. 4 p.

Duncan, D.W. 1972. Environmental problems associated with the disposal of mining and milling wastes. Western Miner 45: 14-16, 19-20.

Farmer, E.E., B.Z. Richardson, and R.W. Brown. 1976. Revegetation of acid mining wastes in central Idaho. U.S. Dept. Agri., Forest Serv. Res. Paper INT-178. 17 p.

Galbraith, J.H., R.E. Williams, and P.L. Siems. 1971. Migration and leaching of metals from old mine tailings deposits. Ground Water J. 10: 33-44.

Geraldson, C.M. 1957. Soil soluble salts -- determination of and association with plant growth. Proc., Florida State Hort. Soc. 70: 121-126.

Ghuman, B.S., S.M. Verma, and S.S. Prihar. 1975. Effects of application rate, initial soil wetness, and redistribution time on salt displacement by water. Soil Sci. Soc. Am. Proc. 39: 7-10.

Goldstein, J. 1970. Transporting wastes to build soils. Compost Sci. 11: 22-24.

Goodman, Gordon T. 1974. Ecological aspects of the reclamation of derelict land, p. 251-264, in Conservation in practice, A. Warren and F.B. Goldsmith (eds.). John Wiley and Sons, Ltd. 512 p.

Goodman, G.T., C.E. Pitcairn, and R.P. Gemmell. 1976. Ecological factors affecting growth on sites contaminated with heavy metals, p. 149-173, in Ecology and reclamation of devastated lands. Vol. 2. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 504 p.

Griffith, J.W. 1919. Influence of mines upon land and livestock in Cardiganshire. J. Agri. Sci., Cambridge. 9: 366-395.

Harabin, Zdzislaw, and Jan Greszta. 1973. Abnormalities in the roots of trees growing on toxic dump material, p. 413-428, in Ecology and reclamation of devastated lands. Vol. 1. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Organization Advanced Study, Penn. State. Gordon and Breach, New York. 538 p.

Hayward, H.E., and C.B. Wadleigh. 1949. Plant growth on saline and alkaline soils. Adv. Agron. 1: 1-38.

Hewitt, E.J. 1952. Metal interrelationships in plant nutrition. I. Effects on some metal toxicities on sugar beet, tomatoe, oat, potatoe, and marrowstem kale grown in sand cultures. J. Exp. Bot. 4: 59-64.

Hewitt, E.J. 1953. The importance of trace elements in crop nutrition. Brit. Agri. Bull. 6: 222-229.

Hinesly, T.D., R.L. Jones, and B. Sosewitz. 1972. Use of waste treatment plant solids for mined land reclamation. Mining Cong. J. 58: 66-73.

Hinesly, T.D., M. Sosewitz. 1969. Digested sludge disposal on cropland. J. Water Poll. Contr. Fed. 41: 822-830.

Hodgson, J.F. 1963. Chemistry of the micronutrient elements in soils. Adv. Agron. 15: 119-161.

Howard, G.S., G.E. Schuman, and F. Rauzi. 1977. Growth of selected plants on Wyoming surface-mined soils and flyash. J. Range Manage. 30: 306-310.

Humphrey, Robert R. 1960. Arizona range grasses, their description, forage value, and management. University of Arizona Agri. Exp. Sta. Bull. 298. 104 p.

James, A.L. 1964. Stabilization of surfaces of mine tailings dumps. S. Afr. Mining Eng. J. 75: 1021-1029.

James, A.L. 1966. Stabilizing mine dumps with vegetation. Endeavor 25: 154-157.

James, A.L., and M. Mrost. 1965. Control of acidity of tailings dams and dumps as precursor to stabilization of vegetation. J.S. Afr. Inst. Mining Metall. 65: 488-495.

Keeney, D.R., K.W. Lee, and L.M. Walsh. 1975. Guide lines for the application of waste water sludge to agricultural land in Wisconsin. Dept. of Nat. Res., Madison, Wisconsin. Tech. Bull. 88. 36 p.

Keller, J., and J.F. Alfaro. 1966. Effects of water application rate on leaching. Soil Sci. 102: 107-114.

King, L.D., and H.D. Morris. 1972. The effects on soil pH, Mn, Zn, and growth and chemical composition of rye (*Seceale cereale* L.). J. Exp. Qual. 1: 425-429.

Knab, Wilhelm. 1965. Observations on world-wide efforts to reclaim industrial wasteland, p. 263-296, in Ecology and the industrial society, G.T. Goodman, R.W. Edwards, and J.M. Lambert (eds.). A symposium of the British Ecological Society. John Wiley and Sons, New York. 395 p.

Leeper, G.W. 1947. The forms and reactions of manganese in the soil. Soil Sci. 63: 79-94.

Lejcher, T.P. 1973. Utilizing treated municipal wastes for strip mine reclamation. Mining Eng. 25: 49-50.

LeRoy, Jean-Claude, and Herman Keller. 1972. How to reclaim mined areas, tailings ponds, and dumps into valuable land. World Mining 8: 34-42.

Lindgren, W. 1905. The copper deposits at the Clifton-Morenci district, Arizona. U.S. Geo. Surv. Prof. Paper 43. 375 p.

Linstrom, G.T. 1960. Forestation of strip mined land in the central states. U.S. Dept. Agri. Handbook 166. 74 p.

Ludeke, Kenneth L. 1972. Soil properties of soil materials in copper mine tailings disposal berms. M.S. Thesis, University of Arizona, 45 p.

Ludeke, Kenneth L. 1973. Vegetative stabilization of copper mine tailings disposal berms of Pima Mining Company, p. 377-410, in Tailing disposal today, C.L. Alpin and G.O. Argall Jr. (eds.). Proc., 1st International Tailing Disposal Symposium, Tucson, Arizona. Miller Freeman Publishers, San Francisco. 861 p.

Ludeke, Kenneth L. 1976. Evaluation and selection of spring barley (*Hordeum vulgare* L.) for the revegetation and stabilization of copper tailing disposal berms. Ph.D. Dissertation, University of Arizona. 58 p.

Lunt, H.A. 1953. The case of sludge as a soil improver. Water Sewage Works 100: 295-301.

Lunt, H.A. 1959. Digested sewage sludge for soil improvement. Conn. (New Haven) Agri. Exp. Sta. Bull. 622. 30 p.

Massey, H.F., and R.I. Barnhisel. 1972. Copper, nickel, and zinc released from acid coal mine spoil materials of eastern Kentucky. Soil Sci. 113: 207-212.

May, M. 1967. Mine reclamation in the western states. Mining Cong. J. 53: 101-105.

McCormick, Larry H., and F. Yates Borden. 1973. Percolate from spoils treated with sewage effluent and sludge, p. 239-250, in Ecology and reclamation of devastated lands. Vol. 1. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Organization Advanced Study, Penn. State. Gordon and Breach, New York. 538 p.

McGeorge, W.Y., and E.L. Breazeal. 1955. The value of pyrite and pyrrhotite as soil conditioners. University of Arizona Agri. Exp. Sta. Rep. 124. 18 p.

McLean, E.O. 1973. Testing soils for pH and lime requirement, p. 77-95, in Soil testing and plant analysis, L.M. Walsh and J.D. Beaton (eds.). Soil Sci. Soc. Am., Madison, Wis. 491 p.

Mihok, E.A., M. Duel, D.E. Chamberlain, and J.G. Selmeczi. 1968. Mine water research -- the limestone neutralization process. U.S. Bur. Mines R.I. 7191. 20 p.

Milne, R.A., and D.N. Graveland. 1972. Sewage sludge as a fertilizer. Can. J. Soil Sci. 52: 270-273.

Nakamura, H.H., E. Aleshin, and M.A. Schwartz. 1970. Utilization of copper, lead, zinc, and iron ore tailings, p. 140-148. Proc., 2nd Mineral Waste Utilization Symp. U.S. Bur. Mines, and I.I.T., Res. Inst., Chicago, Ill. 373 p.

Nielson, Rex F., and H.B. Peterson. 1973. Establishing vegetation on mine tailings wastes, p. 103-115, in Ecology and reclamation of devastated lands. Vol. 2. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 504 p.

Olson, R.V. 1950. Effects of acidification, iron oxide addition, and other soil treatments on sorghum chlorosis and iron absorption. Proc. Soil Sci. Soc. Am. 15: 97-101.

Passow, H., A. Rothstein, and T.W. Clarkston. 1961. The general pharmacology of three heavy metals. Pharmac. Rev. 13: 185-224.

Patterson, J.B.E. 1971. Metal toxicities arising from industry, p. 193-207, in Trace elements in soils and crops, J. Webber (ed.). Min. Agri., Fish Food Tech. Bull. 21. Her Majesty's Stationery Office, London. 217 p.

Pearson, Robert W., and Fred Adams. 1967. Soil acidity and liming. No. 12 in the series Agronomy. Am. Soc. Agron., Madison, Wis. 274 p.

Peters, T.A. 1970. Utilizing vegetation to stabilize mine tailings. J. Soil Water Cons. 25: 65-66.

Peterson, H.B., and R.F. Nielson. 1973. Toxicities and deficiencies in mine tailings, p. 15-25, in Ecology and reclamation of devastated lands. Vol. 1. R.J. Hutnik and G. Davis (eds.). Proc., North Atlantic Treaty Organization Advanced Study, Penn. State. Gordon and Breach, New York. 538 p.

Peterson, J.R., and John Gschwind. 1972. Leachate quality from acidic mine spoil fertilized with liquid digested sewage sludge. J. Environ. Qual. 1: 410-412.

Pierre, W.H. 1930. Neutralizing values and rates of reaction with acid soils of different grades and kinds of liming materials. Soil Sci. 29: 137-158.

Plummer, A. Perry, and E. Durant McArthur. 1975. Woody chenopods for reclamation of depleted and spoiled areas on arid ranges. Unpublished paper presented at the 28th Annual Society for Range Management meeting, Feb. 10-14, Mexico City. U.S. Dept. Agri., Intermountain Forest and Range Exp. Sta., Ephrain, Utah. 19 p.

Ruffner, J.D. 1973. Projecting the use of new plant materials for special reclamation projects, p. 233-242, in Research and applied technology symposium on mined land reclamation. Natl. Coal Assoc., Bituminous Coal Res., Inc., Monroeville, Penn. 355 p.

Russell, E.W. 1973. Soil conditions and plant growth. 10th ed. Longman Group Limited, London. 849 p.

Smith, H.V. 1930. The effects on plant growth of treated soils with copper carrying pyrite. J. Am. Soc. Agron. 22: 903-915.

Smith, R.A.H., and A.D. Bradshaw. 1970. Reclamation of toxic metaliferous wastes using tolerant populations of grass. Nature 227: 376-377.

Smith, R.A.H., and A.D. Bradshaw. 1972. Stabilization of toxic mine wastes by the use of tolerant plant populations. Trans. Sec. A., Inst. Mining Metall. 81: A230-A238.

Smith, P.F., and A.W. Specht. 1953. Heavy Metal nutrition and iron chlorosis of citrus seedlings. Plant Physiol. 28: 371-382.

Snaydon, R.W., and A.D. Bradshaw. 1961. Differential response to calcium within the species *Festuce ovina* L. New Phytol. 60: 219-234.

Soil Survey Staff. 1951. Soil survey manual, U.S. Dept. Agri. Handbook No. 18. U.S. Dept. Agri. Gov't. Printing Office, Wash. 503 p.

Soil Survey Staff. 1975. Soil Taxonomy, U.S. Dept.Agri. Handbook No. 436. U.S. Dept. Agri. Gov't. Printing Office, Wash. 754 p.

Sopper, E.W. 1970. Revegetation of strip mine spoil banks through irrigation with municipal sewage effluent and sludge. Compost Sci. 10: 6-11.

Steel, Robert C.D., and James H. Torrie. 1960. Principles and procedures of statistics. McGraw-Hill Book Co. 481 p.

Stewart, G., W.P. Cottarn, and S.S. Hutchings. 1940. Influence of unrestricted grazing on northern salt desert plant association in western Utah. J. Agri. Res. 60: 289-316.

Stroehlein, Jack L. 1977. Sludge/acid tailings report. Unpublished report. Dept. Soils, Water and Engineering, University of Arizona, Tucson. 8 p.

Struthers, P.H. 1964. Chemical weathering of strip-mine spoils. Ohio J. Soil Sci. 64: 125-131.

Sutton, P. 1973. Establishment of vegetation on toxic mine spoils, p. 153-158, in Research and applied technology symposium on mined land reclamation. Natl. Coal Assoc., Bituminous Coal Res., Inc., Monroeville, Penn. 355 p.

University of Arizona. 1969. Guide to improvement of Arizona rangeland. University of Arizona Agri. Exp. Sta. Bull. A-58. 93 p.

Uhvits, Rachel. 1946. Effects of osmotic pressure on water absorption and germination of alfalfa seed. Am. J. Bot. 33: 278-285.

Vogel, W.G., and W.A. Berg. 1968. Grasses and legumes for cover on acid strip-mine spoils. J. Soil Water Cons. 23: 89-90.

Webber, J. 1972. Effects of toxic metals in sewage on crops. Water Poll. Cont. 71: 404-413.

Wesley, P.G. 1969. Miners and conservationists discuss ecology in the arid environment. World Mining 6: 28-29.

Weston, S. 1973. Report on developments in reclaiming waste dumps and tailing ponds. Western Miner 46: 29-37.

Whitby, L.M., and T.C. Hutchinson. 1974. Heavy Metal pollution in the Sudburg mining and smelting region of Canada. II. Soil toxicity tests. Environ. Cons. 1; 191-199.

Wright, L.N. 1966. Blue panicgrass for Arizona and the southwest. Arizona Agri. Exp. Sta. Tech. Bull. 173. 27 p.

Young, C.A. 1969. The use of vegetation to stabilize mine tailings areas at Copper Cliff. Can. Mining J. 90: 43-46.