The effect of land application of neutralized cyanide solution on soil salinity and sodicity
by Lih-An Yang

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Land Rehabilitation
Montana State University
© Copyright by Lih-An Yang (1996)

Abstract:
Heap leach operations commonly dispose of neutralized cyanide solution by means of land application. Although the reduction of cyanide is achieved by cyanide neutralization, the treated solution may contain high levels of salts, particularly sodium chloride. The purpose of this study is to examine the impact of land application on soil salinity and sodicity.

Three land application areas of different soil textures were investigated between 1992 and 1994. The soils were sandy clay loam, sandy loam, and stony loamy sand. Saturation paste extract solutions were measured for electrical conductivity, pH, sodium adsorption ratio, and chloride concentrations. The mean levels of these four parameters before, immediately after, and several months after land application were compared for each site. In addition, large soil columns were constructed to simulate land application and examine the vertical distribution patterns of the same four parameters.

Results indicate that in the sandy clay loam land application significantly raised the mean electrical conductivity, sodium adsorption ratio and chloride concentration, all of which stayed elevated one year after land application. In the sandy loam, salinity was increased by land application but returned to the control level six and a half months later. Mean sodium adsorption ratio and chloride concentration were also increased by land application, and remained elevated at this site after precipitation leaching. In the stony loamy sand, the mean electrical conductivity and chloride concentration remained elevated approximately three months after land application. A column study affirmed that leaching from precipitation events was able to greatly reduce solute concentrations but not the sodium adsorption ratios of the soils. The pH data indicated an acidifying trend after the land application sites have been inactive for a period of time.

Although one land application did not cause soil salinity and sodicity hazards, repeated discharges at the same site may result in excessive salt, exchangeable sodium and chloride levels. Soil structural damage associated with sodicity may also escalate as solutes are leached. Leaching was more rapid in sandy soil than in clayey soils. Depending on site-specific factors such as vegetation and groundwater table, sandy soil may be more suitable than clayey soils for receiving land applications.

THE EFFECT OF LAND APPLICATION OF NEUTRALIZED CYANIDE SOLUTION ON SOIL SALINITY AND SODICITY

by

Lih-An Yang

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Rehabilitation

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

May 1996

N378
Y166

APPROVAL

of a thesis submitted by

Lih-An Yang

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citation, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Dr. Frank Munshower Frank Munshower 18 april'96

Date

Approved for the Department of Animal and Range Sciences

Dr. John Paterson J.R. Paterson 4/19/96

Date

Approved for the College of Graduate Studies

Dr. Robert Brown R.L. Brown 5/16/96

Date

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University--Bozeman, I agree that the Library shall make it available to borrowers under rules of the Library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature Luh Bin Yang

Date April 19, 1996

ACKNOWLEDGEMENTS

I would like to thank the members of my graduate committee, Dr. Frank Munshower, Dennis Neuman, and Dr. Bill Inskeep, for their guidance in my research. The Montana Department of Natural Resources and the Montana Department of Environmental Quality Hard Rock Bureau are acknowledged for funding and assisting with the project. I would especially like to express a heartfelt gratitude to Trista Hoffman, Darcy Tickner-Gillilan, Daniel Shaw and my family for their unconditional support and encouragement.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iv

TABLE OF CONTENTS v

LIST OF TABLES viii

LIST OF FIGURES xiii

ABSTRACT xiv

INTRODUCTION 1

LITERATURE REVIEW 5
- Techniques of Cyanide Neutralization 5
  - Alkaline Chlorination 5
  - Hydrogen Peroxide 6
- Land Application of Neutralized Cyanide Solution in Montana 7
  - Background 7
  - Case Studies of Land Application 9
    - I. The Zortman Mine, 1986-87 9
    - II. Beal Mountain Mine Operating Permit, 1988. 11
    - III. The Beal Mountain Mine Pre-LAD Testing. 13
- Saline and Sodic Soils 14
- Agricultural Irrigation with Saline and Sodic Water 15
- Effects of Salinity and Sodicity on Plants 17
- The Use of Soil Columns in Soil Studies 20
  - Column Construction 20
  - Breakthrough Curve and Convection-Dispersion Equation 21
  - Experimemtns Involving Soil Columns 23

STUDY AREAS 25
- The Blue Range Mine Land Application Site 25
  - Site History 25

TABLE OF CONTENTS--Continued

Page

Site Environment and Soil Description 26
The Atlantic and Pacific Mine 28
Site History 28
Site Environment and Soil Description 29

MATERIALS AND METHODS 32
Field Soil Sampling 32
Analytical Methods 34
Soil Column Study 35
Statistical Analysis 39

RESULTS AND DISCUSSION 42
Blue Range Mine Site 42
Electrical Conductivity 42
pH 44
Sodium Adsorption Ratio 45
Chloride 45
A&P Mine Grassland Site 47
Electrical Conductivity 47
pH 48
Sodium Adsorption Ratio 50
Chloride 52
A&P Mine Forest Site 52
Electrical Conductivity 52
pH 53
Sodium Adsorption Ratio 53
Chloride 55
Conclusion of the Site Investigations 55
Column Study 59
Column AP1 59
Column AP2 62
Column BR1 65
Conclusion of the Column Study 68

SUMMARY 69

REFERENCES CITED 71

TABLE OF CONTENTS--Continued

Page

APPENDICES 77
APPENDIX A--Data Tables 78
APPENDIX B--Statistical Tables 94

LIST OF TABLES

Table **Page**

1. Soil pH, EC, and SAR at Zortman Mine LAD Area # 2 10

2. Various alkaline characteristics of the Beal Mountain Mine soil column data 12

3. Characteristics of the Shoemaker pond water at Blue Range LAD site. 27

4. Soil description of the Blue Range LAD site. 27

5. Chemical analysis of the solution disposed on Oct. 18, 1993 at A&P Mine 29

6. Soil characteristics of the grassland LAD site at A&P Mine. 30

7. Soil description of the forest land application site at A&P Mine. 31

8. Field soil sampling schedule at each study area. 33

9. Average relative percent differences (RPDs) for nine parameters based on 26 duplicate saturated paste extracts. 35

10. Physical characteristics of the soil columns. 37

11. Chemical properties of the synthetic solution used for columns 37

12. Irrigation scheme of columns AP1, AP2, and BR1. 39

13. Geometric mean levels of soil EC, pH, SAR and chloride concentration for each treatment at the Blue Range Mine LAD site. 43

14. Geometric mean levels of soil EC, pH, SAR and chloride concentration for each treatmen at the A&P Mine grassland LAD site. 48

LIST OF TABLES--Continued

Table **Page**

15. Geometric mean levels of soil EC, pH, SAR and chloride concentration for each treatment at the A&P Mine forest LAD site. 53

16. The pH, electrical conductivity, sodium adsorption ratios, and chloride concentrations in A&P Mine soil column 1 in response to solution irrigations . 60

17. The pH, electrical conductivity, sodium adsorption ratios, and chloride concentrations in A&P Mine soil column 1 in response to freshwater irrigations 61

18. The pH, electrical conductivity, sodium adsorption ratios, and chloride concentrations in A&P Mine soil column 2 in response to solution irrigations . 63

19. The pH, electrical conductivity, sodium adsorption ratios, and chloride concentrations in A&P Mine soil column 2 in response to freshwater irrigations. 64

20. The pH, electrical conductivity, sodium adsorption ratios, and chloride concentrations in Blue Range Mine soil column 1 in response to solution irrigations 66

21. The pH, electrical conductivity, sodium adsorption ratios, and chloride concentrations in Blue Range Mine soil column 1 in response to freshwater irrigations. 67

22. Soil electrical conductivity at the Blue Range Mine LAD site. 79

23. Soil pH at the Blue Range Mine LAD site. 79

24. Soil sodium adsorption ratios (SAR) at the Blue Range Mine LAD site. 80

25. Soil chloride concentrations at the Blue Range Mine LAD site. 80

26. Soil iron concentrations at the Blue Range Mine LAD site. 81

27. Soil zinc concentrations at the Blue Range Mine LAD site. 81

LIST OF TABLES--Continued

Table	Page
28. Soil sodium concentrations at the Blue Range Mine LAD site.	82
29. Soil calcium concentrations at the Blue Range Mine LAD site.	82
30. Soil magnesium concentrations at the Blue Range Mine LAD site.	83
31. Soil copper concentrations at the Blue Range Mine LAD site.	83
32. Soil electrical conductivity at the A&P Mine grassland LAD site.	84
33. Soil pH at the A&P Mine grassland LAD site.	84
34. Soil sodium adsorption ratios (SAR) at the A&P Mine grassland site.	85
35. Soil chloride concentrations at the A&P Mine grassland site.	85
36. Soil iron concentrations at the A&P Mine grassland LAD site.	86
37. Soil zinc concentrations at the A&P Mine grassland LAD site.	86
38. Soil sodium concentrations at the A&P Mine grassland LAD site.	87
39. Soil calcium concentrations at the A&P Mine grassland LAD site.	87
40. Soil magnesium concentrations at the A&P grassland LAD site.	88
41. Soil copper concentrations at the A&P Mine grassland LAD site.	88
42. Soil electrical conductivity at the A&P Mine forest LAD site.	89
43. Soil pH at the A&P Mine forest LAD site.	89
44. Soil sodium adsorption ratios (SAR) at the A&P Mine forest LAD site.	90
45. Soil chloride concentrations at the A&P Mine forest LAD site.	90
46. Soil iron concentrations at the A&P Mine forest LAD site.	91

LIST OF TABLES--Continued

Table	Page
47. Soil zinc concentrations at the A&P Mine forest LAD site.	91
48. Soil sodium concentrations at the A&P Mine forest LAD site.	92
49. Soil calcium concentrations at the A&P Mine forest LAD site.	92
50. Soil magnesium concentrations at the A&P Mine forest LAD site.	93
51. Soil copper concentrations at the A&P Mine forest LAD site.	93
52. Analysis of variance for electrical conductivity at the Blue Range LAD site.	95
53. Analysis of variance for pH at the Blue Range LAD site	96
54. Analysis of variance for sodium adsorption ratio (SAR) at the Blue Range LAD site.	97
55. Analysis of variance for chloride at the Blue Range LAD site.	98
56. Analysis of variance for electrical conductivity at the A&P Mine grassland LAD site	99
57. Analysis of variance for pH at the A&P Mine grassland LAD site.	100
58. Analysis of variance for sodium adsorption ratio (SAR) at the A&P Mine grassland LAD site.	101
59. Analysis of variance for chloride at the A&P Mine grassland LAD site.	102
60. Analysis of variance for electrical conductivity at the A&P Mine forest LAD site	103
61. Analysis of variance for pH at the A&P Mine forest LAD site.	104
62. Analysis of variance for sodium adsorption ratio (SAR) at the A&P Mine forest LAD site.	105

LIST OF TABLES--Continued

Table **Page**

63. Analysis of variance for chloride at the A&P Mine forest LAD site. 106

LIST OF FIGURES

Figure **Page**

1. Distribution of electrical conductivity at the Blue Range LAD site. 44

2. Distribution of pH at the Blue Range LAD site. 44

3. Distribution of SAR at the Blue Range LAD site. 46

4. Distribution of chloride concentrations at the Blue Range LAD site 46

5. Distribution of electrical conductivity at the A&P Mine grassland LAD site 49

6. Distribution of pH at the A&P Mine grassland LAD site. 49

7. Distribution of SAR at the A&P Mine grassland LAD site. 51

8. Distribution of chloride concentrations at the A&P Mine grassland LAD site. 51

9. Distribution of electrical conductivity at the A&P Mine forest LAD site 54

10. Distribution of pH at the A&P Mine forest LAD site. 54

11. Distribution of SAR at the A&P Mine forest LAD site. 56

12. Distribution of sodium concentrations at the A&P Mine forest LAD site 56

13. Distribution of calcium concentrations at the A&P Mine forest LAD site. 57

14. Distribution of chloride concentrations at the A&P Mine forest LAD site. 57

ABSTRACT

Heap leach operations commonly dispose of neutralized cyanide solution by means of land application. Although the reduction of cyanide is achieved by cyanide neutralization, the treated solution may contain high levels of salts, particularly sodium chloride. The purpose of this study is to examine the impact of land application on soil salinity and sodicity.

Three land application areas of different soil textures were investigated between 1992 and 1994. The soils were sandy clay loam, sandy loam, and stony loamy sand. Saturation paste extract solutions were measured for electrical conductivity, pH, sodium adsorption ratio, and chloride concentrations. The mean levels of these four parameters before, immediately after, and several months after land application were compared for each site. In addition, large soil columns were constructed to simulate land application and examine the vertical distribution patterns of the same four parameters.

Results indicate that in the sandy clay loam land application significantly raised the mean electrical conductivity, sodium adsorption ratio and chloride concentration, all of which stayed elevated one year after land application. In the sandy loam, salinity was increased by land application but returned to the control level six and a half months later. Mean sodium adsorption ratio and chloride concentration were also increased by land application, and remained elevated at this site after precipitation leaching. In the stony loamy sand, the mean electrical conductivity and chloride concentration remained elevated approximately three months after land application. A column study affirmed that leaching from precipitation events was able to greatly reduce solute concentrations but not the sodium adsorption ratios of the soils. The pH data indicated an acidifying trend after the land application sites have been inactive for a period of time.

Although one land application did not cause soil salinity and sodicity hazards, repeated discharges at the same site may result in excessive salt, exchangeable sodium and chloride levels. Soil structural damage associated with sodicity may also escalate as solutes are leached. Leaching was more rapid in sandy soil than in clayey soils. Depending on site-specific factors such as vegetation and groundwater table, sandy soil may be more suitable than clayey soils for receiving land applications.

INTRODUCTION

Land application disposal (LAD) of neutralized cyanide solution is a permitted practice in Montana for mines using the cyanide heap leaching process. It is a means by which mines dispose of excess or spent cyanide solution during heap decommissioning or in order to maintain the capacity of solution storage ponds. The Montana Department of Environmental Quality (DEQ) Hard Rock Bureau first permitted land application in the mid 1980s as an emergency measure to discharge large volumes of treated cyanide solution (Spano 1995). It is now routinely practiced in heap leach operations. Given suitable soil, hydrologic balance and properly treated cyanide solution, land application is a viable method for eliminating mining wastewaters (Haight et al. 1990).

Spent cyanide solution is a product of the heap leaching process. In an active leaching cycle, sodium cyanide solution is sprinkled onto low grade ore heaps. The percolating solution carries gold-cyanide complexes through the heaps and drains into "pregnant" solution ponds. Gold is recovered by zinc precipitation or carbon adsorption process from the pregnant solution. The resultant "barren" or spent cyanide solution is subsequently circulated to the cyanide makeup tank where it is reconstituted for further leaching (U.S. EPA 1986). The need for cyanide neutralization arises when a leached heap is ready for reclamation, or when the barren solution must be released so that the holding ponds can withstand storm events or spring runoff. In any of these cases, land application of neutralized cyanide solution may take place.

Due to the toxic nature of cyanide, regulatory agencies require that the concentration of this compound be reduced to a level acceptable for human health and environmental safety prior to disposal of cyanide-containing wastewaters (U.S. EPA 1986). Individual states vary in their specific regulatory standards (Denton et al. 1992). The Montana Water Quality Act mandates that the DEQ maintain standards of 200 *u*g total cyanide per liter of surface water to protect human health, 22 ug/l to protect aquatic life from acute danger, and 5.2 *u*g/l to prevent chronic poisoning of aquatic life (MT DEQ 1995). The DEQ also requires that rinsed heap leachate and neutralized process solution contain no more than 220 *u*g of total cyanide per liter of solution prior to disposal (Spano 1995).

Although cyanide levels are reduced, neutralized cyanide solution may contain elevated concentrations of sodium, chloride, and/or other salts. Excess sodium results from the use of sodium cyanide for ore leaching, as well as the addition of sodium hydroxide (NaOH) to maintain high solution pH (Rolfes 1989). High salinity may result from the large quantity of solutes present in the process solution. Alkaline chlorination, the most common technique employed for cyanide neutralization, is primarily responsible for increasing chloride concentration in the treated solution.

Disposal of saline and sodic water on land can create harmful conditions for plants and soils. Soils with saturation paste extract electrical conductivity (EC) greater than 4 dS/m are considered saline and may injure salt-sensitive plants by elevating soil moisture stress. Soils with exchangeable sodium percentage (ESP) greater than 15% or sodium adsorption ratio (SAR) greater than 13 are considered sodic and may inhibit plant

growth by degrading soil structure (Richards 1969). Chloride accumulation in plant tissues has been reported to injure certain species (Black 1957, Richards 1969). To date, the majority of research related to cyanide-containing wastewaters has targeted the reduction of cyanide and associated heavy metal concentrations, the degradation and movement of cyanide in ore heaps, and various cyanide neutralization techniques for the mining and electrical plating industries. Denton et al. (1992) mentioned that alkaline chlorination produces a significant quantity of sodium chloride which may prohibit the practice of land application; however, little literature is available concerning sodium and salt loading at LAD sites. Without accurate data on soil response to sodium and salt loading, it is difficult for regulatory agencies to judge the appropriateness of the rate and quantity of solution discharge proposed by mines.

The goal of this study was to evaluate soil salinity and sodicity as impacted by land application of neutralized cyanide solutions. Two land application sites of contrasting soil types were investigated. The first is a grassland soil used by the Blue Range Mining Company near Lewistown, Montana, and the second a mountain soil at the Atlantic & Pacific Mine near Pony, Montana. In order to achieve the study objective, the following tasks were performed:

- Determining the levels and distributions of pH, EC, SAR, and chloride in soils before and immediately after land application;
- Examining the movement of the above parameters following a period of leaching by precipitation;
- Monitoring the movement of salts by simulating land application and rainfall leaching in soil columns.

Ultimately, our data provide much needed information on the extent of soil salinization and sodicification by land application of neutralized cyanide solution. We hope the study will also serve as a guide to regulatory agencies and the mining industry to help them evaluate land application disposal procedures in terms of soil salinity and sodicity hazards.

LITERATURE REVIEW

Techniques of Cyanide Neutralization

Effective cyanide neutralization methodologies are well documented (Smith and Struhsacker 1988, Huiatt et al. 1983, Scott 1984, Denton et al. 1992, U.S. EPA 1986). A synthesis and comparisons of fourteen cyanide neutralization techniques are provided by Rolfes (1989). This section will focus on two common cyanide detoxification treatments, alkaline chlorination and hydrogen peroxide.

Alkaline Chlorination

Alkaline chlorination is a well known and widely utilized cyanide treatment method because of its rapid and effective cyanide destruction. The addition of chlorine to cyanide under alkaline condition facilitates the oxidation of cyanide to bicarbonate and nitrogen. Chlorine is available in the form of liquid or gaseous chlorine, sodium hypochlorite, or calcium hypochlorite (Denton et al. 1992). Sodium or calcium hydroxide is used to maintain the pH above 9. The detoxification of cyanide occurs in two stages. First, cyanide undergoes oxidation and hydrolysis at pH above 10.5 through the following two steps:

$$NaCN + Cl_2 = CNCl + NaCl$$

$$CNCl + 2NaOH = NaCNO + NaCl + H_2O$$

In the second phase, cyanate (CNO^-) is further oxidized with excess chlorine to nitrogen and bicarbonate at pH of 8.5:

$$3Cl_2 + 2NaCNO + 6NaOH = 2NaHCO_3 + N_2 + 6NaCl + 2H_2O$$

A ratio of 6.8 mg of chlorine and 6.2 mg of sodium hydroxide to 1.0 mg of cyanide is theoretically required to thoroughly oxidize cyanide (Rolfes 1989). However, chlorine consumption can greatly increase in the presence of other oxidizable substances such as thiocyanate (SCN^-) and metals in low oxidation states. A complete process of alkaline chlorination can destroy approximately 99 percent of total cyanide, leaving only stable iron cyanide complex (Scott 1984).

Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is used to treat free cyanide and weak cyanide complexes of copper, zinc, or nickel. Hydrogen peroxide can destroy cyanide more effectively by mixing with leach pad effluents than by directly rinsing the heap materials (Denton et al. 1992). At pH 7 to 9, cyanide is decomposed by oxidation and hydrolysis:

$$CN^- + H_2O_2 = CNO^- + H_2O$$

$$CNO^- + 2H_2O = CO_3^{-2} + NH_4^+$$

Ammonium and carbonate ions are the end products. Weak metal cyanide complexes are first oxidized to metal cyanates then precipitated as hydroxides. Iron cyanide complexes may be precipitated by adding copper. Whereas complete alkaline chlorination only requires approximately two hours, the hydrogen peroxide treatment may need as long as eight hours to reduce cyanide concentration to 0.5 mg/l (Stanton et al. 1986). However,

no harmful by products are formed, and residual hydrogen peroxide eventually degrades to oxygen and water. Neutralized liquid is considered environmentally safe and may be disposed of by land application (Knorre and Griffiths 1984, U.S. EPA 1986).

Land Application of Neutralized Cyanide Solution in Montana

Background

Land application disposal (LAD) of neutralized cyanide solution has been practiced in Montana since the mid 1980s. A series of critical incidences at the Golden Maple Mine in 1985, the Triad Mine in 1986, and the Zortman Mine in 1986-1987 dictated that large volumes of cyanide process solutions be discharged onto soils in order to obtain adequate "freeboard" in the solution storage ponds or to eliminate the solutions for permanent mine closure. Post-LAD studies at these sites indicated that the soil was able to effectively attenuate residual cyanide and heavy metals while inflicting minimum adverse impact on the vegetation. Therefore, with effective cyanide neutralization, suitable soils, and proper discharge rate, LAD was approved by the DEQ Hard Rock Bureau as a safe method to dispose of excess cyanide solutions. Land application was consequently adopted as a routine practice at heap leach mines in Montana (Spano 1995).

Land application serves two major functions. First, it is a means of restoring sufficient freeboard in the solution storage ponds prior to the onset of heavy precipitation events or winter shut-down. Adequate storage space in the ponds prevents spills of

untreated cyanide solution into the environment. Second, upon mine decommissioning, treated process solution can be eliminated by land application.

Several conditions unique to Montana heap leach mines also necessitate the practice of LAD. First, the majority of heap leach facilities in Montan are located in montane environment where surplus precipitation is common. This is contrary to mining in arid climate, as in Nevada and Arizona, where evaporation reduces the amount of liquid in ponds and shortage of water during cyanide makeup process is a major concern (Schafer and Hudson 1990). Second, heap leach mines are operated under the stipulation that they are to remain as "zero discharge facilities" (Grotbo and Ortman 1988; Spano 1995). As part of the Montana Water Quality Act's nondegradation policy, mine effluent cannot be discharged to surface and groundwaters unless the quantity of harmful constituents is less than that of the receiving waters. However, it is economically and technically difficult for mining operations to treat their waste solutions to a nondegradation status for direct discharge. Discharge onto soils therefore represents a feasible and enforceable alternative for the mining industry as well as the regulatory agencies, since quality of the waste solutions does not need to match that of the receiving soils as long as groundwater is not polluted (Grotbo and Ortman 1988).

Land application feasibility studies often focus on residual cyanide and metal attenuation. However, salts and sodium loading are also concerns. According to Spano (1995), hydrogen peroxide is a recommended neutralization method because the method does not produce excessive salts, sodium, and other harmful by-products. Under site-

specific conditions, if hydrogen peroxide is unable to effectively detoxify cyanide, then calcium hypochlorite is preferred over sodium hypochlorite to avoid sodicity increase.

Case Studies of Land Application

Three LAD case studies are presented below. The Zortman case illustrates an actual LAD event, and the two Beal Mountain Mine cases involved the use of soil column testing to evaluate the ability of soil to attentuate heavy metals and cyanide.

I. The Zortman Mine, 1986-87 Heavy precipitation in the fall of 1986 at the Zortman Mine, Phillips County, Montana resulted in an excess of 113.4 million liters of process solution in the storage system. Immediate disposal was necessary to prevent pond overflow, accommodate additional rainfall, and to provide adequate freeboard for the pending winter shut-down. Process solution was treated with calcium hypochlorite and 75.6 million liters were land applied, intermittently from October 1986 through June 1987 at a rate of 0.122 to 0.203 liter/min/m^2 (0.003 to 0.005 gallon/min/ft^2) over 7.1 ha (17 a). The treated solution contained 1810 to 1880 mg/l sodium, 257 to 498 mg/l chloride, and had a pH of 8.9 and an EC from 7.31 to 7.95 dS/m. Soil at the LAD site was loam or sandy loam with a surface duff layer and 50 to 80 percent rock fragments. Vegetation was mixed Douglas fir, lodgepole pine, and ponderosa pine with understory shrubs, forbs, and grasses (Haight et al. 1990).

Post-land application soil sampling indicated that the surface duff layer had effectively attenuated the majority of the heavy metals. However, soil pH and EC rose

noticeably, and SAR increased progressively down the soil profile as land application continued. Table 1 shows the soil pH, EC, and SAR at various depths at one representative LAD site of the Zortman Mine.

Table 1. Soil pH, EC, and SAR at Zortman Mine LAD Area # 2.*

Depth (cm)	Parameter	Background	Sampling Date			
			11/11/86	1/23/87	10/27/87	8/31/88
Duff	pH	4.5	--	7.5	--	7.5
	EC**	1.08	--	3.42	--	1.53
	SAR	0.27	--	5.82	--	0.98
0 to 10	pH	6.4	8	8.4	7.4	8.1
	EC**	0.72	5.27	3.21	1.78	2.06
	SAR	0.38	33.9	20.9	16.2	2.9
10 to 25	pH	6.4	8	8	7.6	8.1
	EC**	0.43	3.16	3.5	1.68	--
	SAR	0.39	10.8	25.9	14.4	26.8
25 to 50	pH	6.2	7.9	7.6	7.2	7.9
	EC**	0.56	1.39	3.19	1.35	--
	SAR	0.46	2.89	3.3	21.8	21.4

* Adopted from Haight et al. 1990.
** Measured in dS/m.

Visual inspection of site vegetation after land application reported minor burning of pine needle tips, browning of some shrub branch tips, and mortality in a stand of lodgepole pine where spills of treated solution from a ruptured pipe occurred. No substantial impact to grasses on open slopes was observed. Overall, damage to the site vegetation was considered minimal and was attributed to the elevated concentration of chloride, not cyanide or heavy metals. According to Haight et al. (1990), the increased

SAR above the threshold of 13 could inhibit site vegetation by destroying soil structure and permeability. However, the sodicity problem might be ameliorated by several site-specific factors. The soil was high in sand and low in clay and thus able to better maintain hydraulic conductivity and withstand particle dispersion. The saline water could enable the soil to flocculate and sustain permeability. Sodium on the soil exchange sites could also be replaced by calcium ions, as contributed by calcium hypochlorite, or by hydrogen ions, a product of organic matter decompsition, so that sodium may eventually disappear from the soil profile.

II. Beal Mountain Mine Operating Permit, 1988. The Beal Mountain Mine Operating Permit called for the use of land application to dispose of excess process solution under the circumstances of heavy rainfall and completion of heap leaching activity (Beal Mountain Mining Inc. 1988). Cyanide was to be detoxified by hydrogen peroxide. The resultant solution would contribute nitrogen to the soil and was thus considered beneficial.

Cyanide neutralization and the suitability of the designated LAD sites were investigated by Hydrometrics Inc. during the mine permitting process (Beal Mountain Mining Inc. 1988). Polyvinyl chloride plastic pipes, with diameter 3.8 cm and length 38 cm, were filled with site soils collected from various depth increments. Columns were irrigated with neutralized solution and pressurized with nitrogen gas equivalent to 10.6 m of hydraulic head to promote liquid flow. Effluents were analyzed for a variety of

chemical characteristics. While salinity and sodicity were not the emphasis of this study, Table 2 provides the relevant findings for the barren solution and effluents.

Table 2. Various alkaline characteristics of the Beal Mountain Mine soil column data.

Parameter	Barren Solution	Effluent from Soil # 1			Effluent from Soil # 2		
		First 1/3 PV	Second 1/3 PV	Third 1/3 PV	First 1/3 PV	Second 1/3 PV	Third 1/3 PV
pH	9.2	--	--	--	--	--	--
EC *	4.4	--	--	--	--	--	--
Sodium**	978	44	39	21	9	11	14
Calcium**	47	478	548	570	536	732	689
Magnesium**	1	66	79	83	19	26	25
Chloride**	266	--	--	--	--	--	--

* Measured in dS/m.
** Measured in mg/kg.

In addition to laboratory column testing, field test plots were also examined for the effect of land application (Beal Mountain Mining Inc. 1988). Lysimeters were installed, and the test plots were first irrigated with natural well water then with treated barren solution. Results indicated that copper, iron, and nickel were successfully adsorbed by the soils and that a deep soil profile (at least 91 cm) was necessary to remove selenium. Concentration of weak acid dissociable cyanide was also reduced by soil attenuation or degradation; however, zinc and arsenic removal was not satisfactory.

III. The Beal Mountain Mine Pre-LAD Testing. In continuation of the Beal Mountain Mine LAD testing, Schafer and Hudson (1990) conducted a laboratory study to reevaluate the consequence of land application in terms of metal and cyanide attenuation by soil. Although sodicity problems were not addressed, this study illustrates the use of soil columns and is relevant to this investigation.

Cyanide process solution was treated with 30 percent hydrogen peroxide, then applied to Tempe cells packed with soil samples collected from the potential LAD site at the Beal Mine. Soils from the 0 to 10 cm layer and the 51 to 76 cm layer were tested separately. Three hundred grams of soil were mixed with the treated solution to form a saturated paste, then pressurized with air at 0.35 bar to facilitate liquid flow and simulate the well-oxidized condition found in most soils. At the end of each extract cycle more treated solution was added to the column soil to return to the original saturated paste weight. For each column, extracts were composited to obtain approximately 0.5 pore volume; three composites were collected from each sample. A control column was run with the 0 to 10 cm layer soil using deionized water. Untreated barren solution, treated solution, and all extract composites were analyzed for pH, EC, cadmium, copper, lead, manganese, nickel, zinc, selenium, arsenic, mercury, and total cyanide concentrations.

Study results indicated that soils effectively immobilized lead, mercury, cadmium, copper, and nickel. However, concentrations of manganese, arsenic, zinc, and total cyanide in the leachates were higher than those in the treated barren solution. Schafer and Hudson (1990) postulated that the oxidizing solution released the constituents already present in the soil through ion exchange or increased solubilization, especially in the 0 to

10 cm layer. In the case of total cyanide, the formation of insoluble iron-cyanide complexes or more soluble complexes with sodium, calcium, magnesium, or potassium might have increased the measured total cyanide. With longer retention time in the soil, however, cyanide may be degraded or volatilized through natural processes.

Saline and Sodic Soils

Saline soils characteristically occur in arid regions where leaching has not been adequate to remove salts from the materials. Intense evaporation can also concentrate and move salts upward towards the soil surface. Poorly drained or low lying areas often accumulate salt deposits, and excess salts can also be introduced by agricultural irrigation (Richards 1969, Szabolcs 1989). Excessive soluble salts in soils result in poor growth of salt-sensitive species. By convention, a soil with saturated paste extract electrical conductivity greater than 4 dS/m is considered saline. Sodium, calcium, magnesium, chloride, and sulfate ions are the most common constituents of salts in such soils (Richards 1969).

When sodium becomes the dominant cation in the soil solution and soil ESP increases above 15%, a saline soil becomes a saline-alkali soil. In a nonsaline-alkali soil, sodium may hydrolyze and form sodium hydroxide, increasing the pH to between 8.5 and 10. At such high pH values, calcium and magnesium are precipitated as carbonate salts and sodium remains as the dominant cation (Szabolcs 1989).

Soils with excessive sodium in solution and on exchange sites exhibit characteristics of structural degradation. Deflocculation, or soil particle dispersion, is caused by swelling and subsequent repulsion between sodium-saturated layers of silicate clay minerals (McBride 1994). Dislodged particles as well as clay swelling can decrease mean pore diameter. Clay dispersion is often the principal process in reducing permeability in low ESP (10 to 20%) soils, and swelling dominates when ESP exceeds 25% (Frenkel et al. 1978). Other sodic soil characteristics include poor aeration, surface crusting, and clay shrinking-and-swelling under wet and dry cycles (Shainberg and Letey 1984, McBride 1994). These conditions also contribute to reduced infiltration and permeability.

Agricultural Irrigation with Saline and Sodic Water

Land application of neutralized cyanide solution mimics agricultural irrigation with water of substantial sodium and solute concentrations. This section focuses on the practice of alternating saline and sodic water irrigation with rainfall and the effects of this sequence on soil structure and permeability. Such irrigation schemes commonly occur in arid regions where soils are already alkaline. This subject has received much investigation.

Irrigation with saline and sodic water rotating with rainfall enhances degradation of soil structure. It is generally believed that sodic soils which are also saline are more resistant to sodicity-induced damage such as particle dispersion, clay swelling, and loss

of permeability. After irrigation with high-quality water, solute concentrations become diluted, and even soils with low ESP are vulnerable to structural damage (Quirk and Schofield 1955, Pupisky and Shainberg 1979, Park and O'Connor 1980, Shainberg and Letey 1984). Shainberg et al. (1981) reported that when irrigation water remained saline (greater than or equal to 3.0 meq/l), a Fallbrook loam with ESP as high as 12% did not exhibit reduced hydraulic conductivity. When water of solute concentration greater than or equal to 6 meq/l was used, hydraulic conductivity was preserved even for soil equilibrated at SAR 30. However, when soil solute concentration was diluted to 0.5 meq/l by freshwater leaching, hydraulic conductivity and clay dispersion occurred at soil ESP as low as 1 to 2%. Clay dispersion also increased positively with SAR of the soil solution. Shainberg and his associates further postulated that sodic soils with a high mineral dissolution rate are able to withstand structural deterioration during high-quality water leaching by maintaining adequate solute concentration.

Frenkel et al. (1978) investigated the effects of clay mineralogy, solution concentration, and ESP on soil dispersion and hydraulic conductivity. At a given electrolyte concentration, soils equilibrated with high ESP (20 to 30%) showed greater reduction in hydraulic conductivity than soils with low ESP (10%). Kaolinitic soils were less susceptible to hydraulic conductivity changes than montmorillonitic and vermiculitic soils. Upon irrigation with distilled water (simulating rainfall), however, nearly all soils drastically decreased their permeability due to soil dispersion. Soil surface was especially vulnerable to such impact. Frenkel et al. (1978) concluded that, for agricultural irrigation in which water of average salinity (0 to 10 meq/l) and intermediate

sodicity (SAR 10 to 30) was used, pore clogging by dispersed particles was the dominant process in restricting hydraulic conductivity. Soils enriched in expanding clay minerals, such as montmorillonite and vermiculite, and high in bulk density were also more sensitive to clay dispersion and reduced hydraulic conductivity (McNeal and Coleman 1966, Frenkel et al. 1978).

Magaritz and Nadler (1993) investigated the effect of saline water and freshwater irrigations on 20 m deep unsaturated soil profiles in Israel. Following long-term cultivation in which saline water was used for irrigation, salts (sulfate, chloride, sodium) tended to accumulate in the upper 2 to 4 m zone. Using the transport of chloride as an indicator of changes in hydraulic conductivity, Magaritz and Nadler observed decreased permeability associated with soil structural changes atop a saline water irrigated profile. Reduced hydraulic conductivity and degraded soil structure enhanced the channeling of water through partial air voids, rendering ineffective the practice of leaching salts with freshwater. In one soil profile, ten years of freshwater irrigation did not result in leaching of the salts because water moved through the profile without carrying the salt load.

Effects of Salinity and Sodicity on Plants

Salinity generally manifests two types of impacts on plant growth: osmotic potential effect and specific ion effect. Osmotic potential effect occurs when elevated salinity in soil water reduces osmotic potential at the root-soil interface and impedes root water uptake. Specific ion effect refers to the impact which a certain soil constituent has

on plant growth. Plants severely affected by salinity stress typically have stunted growth with smaller but thicker leaves, as well as a bluish green hue on leaf surface. Germination may fail completely in severely saline and sodic conditions (Bernstein 1975, Black 1957).

Hayward and Spurr (1944) studied the osmotic effect of salts on corn plant growth. They found that root water intake slowed as the soil solute concentrations increased, regardless of the types of solutes added. However, a further investigation by Wadleigh and Ayers (1945) showed that bean plant growth was negatively related to both soil moisture tension and salt concentration. They reported that the combined force of these two components, expressed as the specific free energy of the soil water in atmospheres, could more clearly account for the variation in plant production. Soil water with higher energy state yielded higher bean plant production.

The osmotic effect of salinity on plant growth can be estimated by calculating the osmotic pressure (OP) of a soil solution. Osmotic pressure, measured in atmospheres, is related to the saturation extract EC (measured in dS m^{-1}) according to the empirical equation

$$OP = 0.36^* EC$$

(Campbell et al. 1949, Richards 1969). High solute concentration increases the osmotic pressure, or lowers the specific free energy, of the water in soil solution, so that water is less readily available for plant extraction than in nonsaline condition. Plants reach permanent wilting point at approximately 15 atmospheres, but yields of many crops are restricted when EC exceeds 4 dS/m (Richards 1969). Pessarakli et al. (1991) reported 48

percent dry weight reduction in cultivated barley and 44 percent in wheat at an EC of 14.7 dS/m. However, Fowler and his coworkers (1992) demonstrated that increasing salinity (up to an EC of 33.9 dS/m) improved the forage quality of Russian thistle in terms of total nitrogen and fiber constituents.

Disproportion of certain salts in soil solution may injure plants through direct toxicity as well as ionic imbalance. Chloride salts have been demonstrated to be twice as severe as sulfate salts in suppressing osmotic potential (Eaton 1942). In sodic soils, plant growth is primarily restricted by soil structure degradation. Excessive sodium or chloride accumulation typically causes stunted growth or leaf burns in sensitive species (Bernstien 1965, Bernstein and Hayward 1958). Suhayda et al. (1992) observed stunting of commercial barley leaves and roots under high salinity when calcium concentration was controlled at a low level. Furthermore, an increase in exchangeable sodium, often accompanied by decreased calcium and magnesium, may lead to nutritional deficiency in plants (Bernstein 1975). When the sodic soil is also saline, however, the abundance of ions precludes direct sodium toxicity. Suhayda and associates (1992) attributed the high salinity resistance of wild barley to its ability to absorb and transport calcium while limiting root entry of sodium. Similarly, in tall wheatgrass and crested wheatgrass, it has been shown that salinity tolerance was partly derived from restricted transport of sodium and chloride to shoots, and withholding of potassium ions in leaves (Johnson 1991).

Chloride accumulation in sensitive species causes characteristic leaf margin burns. According to Black (1957), chloride toxicity has been associated with plant injury more than other ions in saline soils. The varied responses of fruits to chloride have been

attributed to differential chloride uptake rates, even though the phytotoxic levels in leaf-chloride were comparable among the species (Bernstein and Hayward 1958). Many woody species are sensitive to low chloride concentrations, and higher concentrations may affect more tolerant crops (Ayers and Westcot, 1985). Decreased transport of sodium and chloride to the shoots may be responsible for some tidal grass salt tolerance (Hannon and Barber 1972). In addition, sodium and chloride injury symptoms in plants have been observed to resemble drought injury, and it has been suggested that plant stomatal closure and transpiration functions are handicapped by sodium and chloride, resulting in inability to control water loss during droughts (Bernstein et al. 1972). Chloride toxicity levels range from 5 to 10 meq/l in soil saturation extract for sensitive fruit crops, to 40 meq/l for tolerant species. In terms of irrigation water quality, a chloride concentration of 4 meq/l is considered safe for sensitive plants, while concentration above 10 meq/l may cause severe problems (Ayers and Westcot 1985).

The Use of Soil Columns in Soil Studies

Column Construction

Soil columns are commonly used in laboratories for soil physical and chemical characterization and prediction. Agricultural as well as hazardous waste treatment studies employ soil columns to simulate chemical leaching, predict the ability of a specific soil to attenuate contaminants, estimate physical flow parameters, and develop predictive equations for modelling purposes. Laboratory soil columns provide the advantage of

testing a variety of soils in a controlled setting without the complications associated with field testing (Fuller and Warrick 1985).

Although specific column techniques vary with individual research objectives, the majority of column studies follow a basic construction and sampling scheme. Soil samples representative of the site of concern are passed through a two millimeter sieve and are firmly and uniformly packed into the column to minimize the formation of preferential flow paths. Preferential flow may result in inadequate contact and reaction between soil particles and the solutes of interest, thereby underestimating the soil attenuation capacity. Prior to solute input, soils are saturated and allowed to drain freely for ten to twenty days during which time the column moisture content equalizes and soil microbial population is regenerated. As solutes are fed through the column, effluents are collected at specific time intervals either manually or by an automatic fraction collector. Effluents are analyzed for solute concentrations (Fuller and Warrick 1985).

Column experiments can be conducted under saturated or unsaturated conditions. To simulate unsaturated flow conditions, excess drainage water must be removed as solute pulses are applied. Constant drainage can be maintained by inserting porous materials at the bottom of the column and applying vacuum suction to extract excess water (Fuller and Warrick 1985, van Genuchten and Wierenga 1986).

Breakthrough Curve and Convection-Dispersion Equation

A breakthrough curve is prepared to show the adsorption and transport of the solutes by soil as a function of pore volume or time. The convection-dispersion equation

(CDE) is frequently used to describe solute transport in one-dimensional flow under steady state condition (van Genuchten and Wierenga 1986, Wierenga and Van Genuchten 1989). The equation is expressed as

$$R\, dC/dt = D\, d^2C/dx^2 - v\, dC/dx$$

where R is the retardation factor, C is the solute concentration, t is time, D is the dispersion coefficient, x is depth, and v is the average pore-water velocity (defined as q/θ, where q is Darcy flux density and θ is volumetric water content). The retardation factor expresses the degree of solute sorption onto the soil matrix, and is calculated as

$$R = 1 + \rho_b * K/\theta$$

where ρ_b is soil bulk density and K is distribution or sorption coefficient equal to the ratio of adsorbed solute concentration to equilibrium solute concentration. Therefore, when inert and nonsorbing solutes are transported vertically, K is zero and R becomes 1.0. Where solutes are adsorbed by the soil matrix, R becomes greater than 1.0 and breakthrough of the solutes is delayed or "retarded". The retardation factor can be less than 1.0 when only a fraction of the liquid phase transports and interacts with the solutes. This condition is represented by anion exclusion, the electrostatic repulsion between negatively-charged soil particle surfaces and anions, or by the presence of immobile water regions which are bypassed in the convective transport process (van Genuchten and Wierenga 1986, Wierenga and van Genuchten 1989). In such cases, solutes break through the soil profile earlier than nonsorbing and adsorbing solutes.

Experiments Involving Soil Columns

Thellier et al. (1990) used soil columns to investigate the chemical effects of saline irrigation on a San Joaquin Valley soil in California. Replicate columns of 5.0 cm diameter and 58.4 cm length were irrigated with saline water or good quality water. The bottom of each column stood in 2.5 cm of saline well water to simulate a saline aquifer. Surface irrigation in combination with upward capillary flow was examined for effects on soil salinity and sodicity, as well as for the rate of equilibration between the applied water and the column soil. At the end of the experimental leaching, soil was taken out of each column and sectioned for analysis of exchangeable cations.

Oster and Schroer (1979) also used soil columns to study the relationship between infiltration rate and irrigation water quality. Undisturbed columns had diameter of 20 cm and length 53 cm. Soil was also sectioned for ESP determination. Oster and Schroer concluded that surface infiltration rate was more disrupted by the total cation concentration and SAR of the irrigation water than by the chemistry of the soil profile, and that salinity may be a more accurate index than SAR for predicting infiltration rate. In a replicated experiment involving soil columns (7.5 cm inside diameter by 50.0 cm length), Giusquiani et al. (1992) reported greater soluble metal concentrations in soils amended with composted urban wastes. They associated such increase with the water soluble organic matter fraction of the compost which complexed with and mobilized the trace metals.

Porro et al. (1993) used large soil columns, 95 cm diameter by 6 m length, to investigate solute transport through a homogeneous and a layered soil profile. The

experiment was not replicated. Suction candles and tensiometers were installed at various depths, and a neutron probe was used to monitor volumetric water content. The researchers reported preferential flow as a cause of anomalous behavior in the breakthrough curves, even though soils had been carefully packed in lifts to promote uniform, one-dimensional flow.

STUDY AREAS

Two Montana gold mines of contrasting soil type and physiography were utilized in this study. These two sites were selected because both had recent land applications. Operating permits and other documentations of mining activities for the Blue Range Mining Company and the Atlantic & Pacific Mine can be obtained from the Montana DEQ Hard Rock Bureau. The Blue Range Mining Company's land application site was not at the Blue Range Mine (which is located in the Judith Mountains northeast of Lewistown); nonetheless, the name "Blue Range Mine" is used to represent its land application site in this text.

The Blue Range Mine Land Application Site

Site History

The land application site for the Blue Range Mining Company was located near the Shoemaker mining complex, approximately 12.8 km (8 miles) southeast of Lewistown in Fergus County, Montana. The Shoemaker complex is comprised of the Heath Mine, Heath Mill, and Shoemaker Mine. Land application occurred on rolling grasslands just north of the Shoemaker complex in Township 14N, Range 19E, Section 1, southwest 1/4.

The Blue Range Mining Company refined its ore by flotation process at the Heath Mill. Tailings were deposited in the abandoned Shoemaker underground gypsum mine. On January 4, 1991, the Blue Range Mining Company was issued a Cessation Order from DEQ because cyanide was detected in one of the monitoring wells downgradient of the Shoemaker Mine. Neutralization of cyanide in the Shoemaker tailings pond was commenced, and cyanide concentration was reduced to 0.03 mg/l. Subsequently, the Blue Range Mining Company applied for a permit to dispose of the Shoemaker tailing effluent on land surface above the Heath Mill facility.

The proposed land application disposal (LAD) involved spraying approximately 17 million liters (4.5 million gallons) of the Shoemaker pond water on approximately 10 ha (25 a) of grass pasture. The main LAD area was closer to 1.2 ha (3 a). Land application commenced on July 16, 1992 and continued for approximately two months. The Blue Range Mining Company reported that the solution was neutralized with 12.5 percent sodium hypochlorite, and land application drip rate was approximately 284 liters (75 gallons) per minute. During the solution irrigation, the sprinkler system and water quality of the solution was closely monitored by the mine staff. Table 3 provides the analysis of a representative Shoemaker Pond water sample collected on July 22, 1992.

Site Environment and Soil Description

The soil of the LAD site is classified as the Hilbar loam of the Fergus Series, fine mixed Typic Argiborolls. The soil is well-drained with moderately slow permeability. The site was situated on a broad hilltop with 2 percent slope and southeast aspect.

Table 3. Characteristics of the Shoemaker pond water at Blue Range LAD site.

pH	SAR	EC dS/m	total cyanide*	WAD** cyanide*	Na*	Ca*	Mg*
7.6	14.8	5.6	0.072	0.028	933	432	102

Cl*	SO_4^{-2}*	total Cd*	total Cu*	total Fe*	total Ni*	total Pb*	total Zn*
105	3070	0.002	0.30	<0.03	<0.03	<0.01	0.05

* Measured in mg/l.

** WAD=Weak acid dissociable.

Elevation is 1432 m (4700 ft). Vegetation cover included abundant smooth brome (*Bromus inermis*), Kentucky bluegrass (*Poa pratensis*), timothy (*Phleum pratense*), and western wheatgrass (*Agropyron smithii*). According to the Soil Survey of Fergus County, mean annual soil temperature is 6.7°C (44°F), annual precipitation is 41 cm (16 in), and parent material is alluvium (USDA Soil Conservation Service 1988). Table 4 summarizes the major characteristics of each genetic horizon.

Table 4. Soil description of the Blue Range LAD site.

Horizon	Depth (cm)	Texture	Bulk density (g/cm^3)	pH	EC (dS/m)	Estimate % organic matter	Estimate % Clay
A	0-28	sandy clay loam	1.04	7.1	2.3	6	25
BA	28-43	sandy clay loam	1.10	7.9	0.14	3	30
Bt	43-76	sandy clay	1.16	8.1	0.12	1	50
Bk	76-122	sandy loam	1.31	8.3	N/A*	1	10

* Not measured.

The Atlantic and Pacific Mine

Site History

The Atlantic and Pacific Mine (A&P Mine) was a small mine operating within the Deerlodge National Forest in Township 2S, Range 3W, Section 21, southwest 1/4. The mine was situated at an elevation of 2377 m (7800 ft) on an open ridgetop in the Tobacco Root Mountains, approximately 9.7 km (6 miles) northwest of Pony in Madison County, Montana. The mine contained a processing facility, a heap leach pad, and three plastic-lined ponds holding pregnant solution and barren solution. Land applications took place adjacent to the mine.

In contrast to the Blue Range Mining Company, the A&P Mine's operation history and activities are not well documented. Records indicate that as of 1990 the mine had used alkaline chlorination for cyanide neutralization. The barren solution was mixed with calcium hypochlorite and contained chloride concentration up to 1000 mg/l. The treated solution was then sprinkled onto the leach pad. In an August, 1990 report a Deerlodge National Forest staff member observed plant discoloration in previous LAD areas, and suspected the cause to be excessive chloride in the disposed solution.

The two most recent land applications prior to the study occurred in the summer of 1993 and on October 18, 1993. Neither was well documented. According to mine company personnel, the first land application occurred sometime in 1993 in the lodgepole pine forest adjacent to the mine. A July 2, 1993 DEQ record indicated that the barren solution was neutralized with hydrogen peroxide; no other information on the LAD was

available. On October 18, 1993 the second land application took place on the open grassy slope between the mine and the lodgepole forest. Hydrogen peroxide was used to detoxify cyanide. In order to characterize the wastewater destined for disposal, a neutralized solution pond was sampled on September 14, 1993. Table 5 provides the chemical characteristics of this water. Decommissioning of the A&P Mine began in 1994.

Table 5. Chemical analysis of the solution disposed on Oct. 18, 1993 at A&P Mine.

pH	EC dS/m	Na*	Fe*	Pb	Cu*	Ni	Cd	Cl*
8.7	1.2	163	1.4	ND**	0.66	ND¶	ND¶¶	60.3

* Measured in mg/l.
** Not detected (< 318 *ug*/l).
¶ Not detected (< 269 *ug*/l).
¶¶ Not detected (< 76 *ug*/l).

Site Environment and Soil Description

The A&P Mine is outside the Madison County soil survey coverage; however, according to MAPS Atlas (Montana State University 1994a), the mean annual soil temperature is 2.2° C (36° F) and annual precipitation is 76.2 cm (30 in). Soils in the grassland portion and the forest have different classifications.

Land application in the open grassland occurred on a 16° (29 percent) slope with northwest aspect. The slope is slightly concave and the soil is loamy-skeletal, mixed Typic Cryocrepts. This soil is deeper, darker, and more clayey than the forest soil. Parent material is also granite and gneiss colluvium. The Cr horizon was dominated by

loose and abundant gravels and cobbles. Table 6 describes the profile of one pedon dug adjacent to the spray area. Vegetation on the grassy slope was dominated by bluebunch wheatgrass (*Agropyron spicatum*) and Idaho fescue (*Fescuta idahoensis*). Other common vegetation included timber oatgrass (*Danthonia intermedia*), Junegrass (*Koeleria pyramidata*), alpine timothy (*Phleum alpinum*), Hood's phlox (*Phlox hoodii*), and pussytoes (*Antennaria spp).*

Table 6. Soil characteristics of the grassland LAD site at A&P Mine.

Horizon	Depth (cm)	Texture	Bulk density (g/cm^3)	pH	EC (dS/m)	Estimate % organic matter	Estimate % Clay
A	0-10	sandy loam	N/A*	5.7	0.66	5	15
BA	10-30	sandy loam	N/A	5.9	0.32	4	15
Cr	30-91+	loamy sand	N/A	5.8	0.15	0.5	10

* Not measured.

The forest LAD site contains dense lodgepole pine, and the ground was covered with partially decomposed forest litter. The soil was classified as sandy-skeletal mixed Typic Cryocrepts, with granite and gneiss colluvium comprising the parent material. Chunks of black charcoal from past forest fires were found as deep as 80 cm in the soil profile. Table 7 provides major characteristics of each genetic horizon at the forest site.

Table 7. Soil description of the forest land application site at A&P Mine.

Horizon	Depth (cm)	Texture	Bulk density (g/cm^3)	pH	EC (dS/m)	Estimate % organic matter	Estimate % Clay
O	3-0	pine needles	0.41	4.5	0.37	99	0
A	0-4	loamy sand	0.84	5.2	0.33	10	13
Bw	4-19	cobbly loamy sand	1.38	5.0	0.12	3	11
Cr	19-91	stony loamy sand	1.51	5.9	0.10	1	10
R	91+	--	--	--	--	--	--

MATERIALS AND METHODS

Field Soil Sampling

Three sets of soil samples were collected from each study site to represent the following conditions: pre-land application (thereafter referred to as "control"), immediately after land application ("post-LAD"), and several months after land application ("post-precipitation"). For each set of soil samples, four randomly-spaced holes were dug and samples were taken from nine depth increments: 0 to 5, 5 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, 50 to 60, 60 to 76, and 76 to 91 cm (0 to 2, 2 to 4, 4 to 8, 8 to 12, 12 to 16, 16 to 20, 20 to 24, 24 to 30, 30 to 36 in). At the A&P Mine grassland and forest sites where land application occurred on a slope, holes were dug on the same contour. In each hole, a tape measure was draped over the soil profile and soil samples were scooped out with a hand trowel according to the designated depth increment. The hand trowel was decontaminated with a brush between each increment. Soils were placed in plastic-lined paper bags and stored in coolers for transportation back to the laboratory.

Several departures occurred from the general sampling regime. First, the control samples collected from the Blue Range Mine were taken down to 76 cm (30 in) only. Furthermore, because the ground was frozen after the fall 1992 land application, post-LAD samples could not be obtained until the following April. Second, for the A&P grassland control and post-LAD samples only three holes were dug. Third, at the A&P

forest site, surface duff material (pine needles, twigs, moss, humus) was collected at each hole. In order to analyze the surface chemistry, litter was allowed to come to equilibrium with deionized water of sufficient quantity to submerge the material in the suction cup; the liquid was then extracted by vacuum pressure.

At the A&P Mine, the sampling of the lodgepole forest and the open grassland soils deviated from the before-and-after-treatment schedule. The lodgepole forest was the original site planned for the fall 1993 land application and control samples had been collected on September 14, 1993. Instead, the land application took place in the grassland on October 18, 1993 and the late notice did not allow time for the collection of pre-LAD samples. As an alternative, the grassland control samples were taken upslope of the sprinkled area. In addition, information was acquired from the mine personnel that a land application had occurred earlier in 1993 in the lodgepole forest downslope from the location at which control samples had been collected. Therefore, a decision was made to collect a set of post-precipitation samples in the forest LAD area. Table 8 summarizes the field sampling dates for each site.

Table 8. Field soil sampling schedule at each study area.

Study Site	LAD Date	Sampling Date		
		Pre-LAD	Immediately after LAD	After precipitation
Blue Range	Sept. -- Oct. 1992	July 6, 1992	April 27, 1993	Sept. 11, 1993
A&P Grassland	October 18, 1993	October 26, 1993	October 27, 1993	May 20, 1994
A&P Forest	Summer, 1993	Sept. 14, 1993	Not sampled	October 26, 1993

Analytical Methods

In the laboratory, each soil sample was placed on a piece of freezer paper and air dried for several days. Saturated paste extracts were made for all samples following the American Society of Agronomy Method 10-2.3.1 (Rhoades 1982) then refrigerated until analyses for soil chemical characteristics. Electrical conductivity and pH measurements were performed first. Water soluble sodium, calcium, magnesium, iron, copper, zinc, nickel, lead, and cadmium concentrations were analyzed with Varian AA-975 Series atomic absorption spectrophotometer (AA). Chloride concentrations were measured with mercuric nitrate titration technique specified by APHA Method 4500-Cl (1989).

A quality assurance/quality control program was carried out for soil chemical analyses. To monitor the precision of analytical techniques, 26 duplicate saturated paste extracts were prepared out of a total of 320 samples. Using methods described in the U.S. EPA Contract Laboratory Program (U.S. EPA 1988), relative percent difference (RPD), defined as the difference between the sample value and the duplicate value divided by their average, was calculated for each parameter analyzed. An RPD less than 20 percent is acceptable to meet the requirements of the Contract Laboratory Program for analytical values greater than five times the detection limit. Table 9 lists the average RPDs for nine parameters. During the operation of the AA, duplicate readings were taken for each sample and relative standard deviation values were monitored. Instrument repeatability was checked against a calibration standard and a blank every ten samples. The accuracy of the AA was also monitored against EPA standards.

Table 9. Average relative percent differences (RPDs) for nine parameters based on 26 duplicate saturated paste extracts.

Analysis	pH	EC	Cl	Na	Ca	Mg	Fe	Zn	Cu
RPD %	2	8	15	12	20	13	63	52	74

The heavy metals investigated in the study generally had low concentrations and poor analytical precision. Average RPD values of iron, zinc, and copper concentrations were higher than 20 percent, indicating that their analyses were imprecise and unreliable. Selected soil samples were also analyzed for cadmium, nickel, and lead. As all of these concentrations fell below the instrument detection limits (cadmium 76 *u*g/l, nickel 269 *u*g/l, lead 318 *u*g/l), the remaining samples were not analyzed. Trace metal data are not discussed in the Results and Discussion section but are presented in Appendix A.

The determination of an elemental limit of detection was based on guidelines delineated by Keith et al. (1983). A concentration which fell below detection limit was reported as "not detected." For purpose of computation, a measurement that was below the detection limit was assigned a numerical value by multiplying the respective detection limit by 0.7 (Severson 1979).

Soil Column Study

The purpose of the soil column study was to simulate a land application of neutralized cyanide solution followed by rainfall events. The study was designed to

compliment the field phase by depicting an intense leaching scenario with a highly sodic and moderately saline solution. The objective was to closely examine the response of soil salinity and sodicity to land application, and the movement patterns of salts, sodium and chloride through the two soil profiles.

Duplicate columns were constructed for the Blue Range Mine (columns BR1, BR2) and the A&P Mine forest site (columns AP1, AP2). Tubes of PVC plastic were used, with inside diameter 19.6 cm (8 in) and length 91 cm (36 in) for the AP columns and 122 cm (48 in) long for the BR columns. The BR columns were longer because a larger quantity of site soil was available. Columns were filled in such way as to approximate the field soil horizons. The BR columns were topped with live vegetation sods collected from the site, and the AP columns with forest duff material. Ceramic cups of one-bar standard flow and 7.0 cm long by 1.3 cm I.D. (Soil Moisture Equipment Corp., Santa Barbara, CA) were installed at depths 10, 30, 60, 90 cm in the AP columns and also at 107 and 122 cm in the BR columns. Table 10 summarizes the physical characteristics of the columns.

Approximately 114 liters of neutralized cyanide solution were obtained from a gold mine for the column study. Because the solution was low in solutes (EC = 0.82 dS/m) and sodium concentration (109 mg/l), the solution was "spiked" with 3M sodium hydroxide and 3M sodium chloride solutions to approximate the pH, EC, sodium and chloride levels of the neutralized cyanide solution discharged at the Blue Range site.

Table 10. Physical characteristics of the soil columns.

Column	Horizon	Depth (cm)	Bulk density (g/cm^3)	Pore volume (liter)
AP1	AC	3-41	1.01	16.99
	C	41-91	--	
AP2	AC	3-41	1.0	16.99
	C	41-91	--	
BR1	A	0-43	1.05	22.22
	B	43-122	--	
BR2	A	0-43	1.04	22.22
	B	43-122	--	

Spiking was performed in 4-liter batches. With the pH and EC probes inserted in the solution, 3M sodium hydroxide was added until pH reached approximately 10.5, then 3M sodium chloride was added until EC reached approximately 5.5 dS/m. Assuming that the original composition of the solution in each batch was similar, all final synthetic batches should also contain comparable sodium and chloride concentrations. Based on average measurements of six batches, Table 11 lists the chemical characteristics of the spiked solution.

Table 11. Chemical properties of the synthetic solution used for columns.

pH	EC dS/m	Na mg/l	Ca mg/l	Mg mg/l	Cl mg/l
10.5	5.7	1145	13.1	0	1717

Prior to the commencement of saline irrigation, the columns were brought to saturation and allowed to drain for two days. Control samples were then extracted at various depths. All four columns were irrigated with 1050 ml of the spiked cyanide solution daily; solution was administered with a bubbler device attached to a 2 liter flask. A constant head was maintained in column AP2 because ponding often occurred. Ponding did not occur in other columns.

Soil solution was extracted by applying vacuum pressure at the end of a solute pulse, beginning at 10 cm and catching the wetting front at subsequent depths as the liquid flowed through the column. Daily attempts were made to remove all excess drainages, and to sample bottom effluents for analysis. As irrigation continued, however, some sampling ports had to be abandoned because of breakage of the ceramic cups. Infiltration rate also tended to decrease, and the daily irrigation volume was often reduced. As a result, liquids were extracted only where available and at irregular intervals.

Liquid flow through column BR2 was terminated during the experiment. There appeared to be a compacted layer between 30 cm and 60 cm so that liquid could not percolate downward. As the clog became progressively more severe, only a small amount of solution could be applied daily and extraction was available for the 10 cm and 30 cm ports only. Irrigation was finally terminated after approximately 7200 ml of solution had been applied. Therefore, the Blue Range column study was not replicated.

Column AP2 exhibited greatly reduced infiltration after the freshwater rinsing began. Soil particle dispersion induced by sodic irrigation and subsequent pore clogging

could explain the low permeability. Because of the decreased hydraulic conductivity, distilled water had to be slowly dripped onto the soil surface, thus prolonging the duration of the freshwater rinsing. Table 12 summarizes the total number of days when a solution or water pulse was actually added to the columns, and the total volume of liquids applied to columns AP1, AP2, and BR1.

Table 12. Irrigation scheme of columns AP1, AP2, and BR1.

Column	Total number of days of salt solution irrigation	Total number of days of DI water irrigation	Total volume of salt solution applied (l)	Total volume of DI water applied (l)
AP1	18	16	18.35	17.02
AP2	17	29	16.75	24.37
BR1	17	18	17.85	24.22

Statistical Analysis

MSUSTAT Version 5.2 (Montana State University 1994b) was used for the statistical analysis of the LAD site study. One-way analysis of variance (ANOVA) was used to compare the means of EC, pH, SAR and chloride concentrations with respect to the treatment type. In doing so, the measurements from all depth intervals and replicate holes were pooled, and the mean represents the level of the given parameter for the entire 91cm soil profile. Because normality plots indicated departure from normal distribution for nearly every parameter, all data involved in the statistical analysis were transformed.

Log_{10} transformation was chosen because standard deviations of the treatment factor means appeared to be proportional to the treatment factor means (Neter et al. 1990, Sachs 1982). The pH data were not converted to hydrogen ion concentrations prior to the transformation. Log_{10} transformations improved the normality of the data.

The null hypothesis was that the mean concentrations of the soil properties under investigation remained the same before and after land application and precipitation. The alternative hypothesis was that land application and subsequent precipitation events affected these soil characteristics. The analysis of variance was evaluated at the 90 percent confidence interval (alpha = 0.10). Therefore, when p-values for the F-statistic were less than or equal to 0.10, the null hypothesis was rejected. In such cases, t-test was then used to separate the differing means.

In order to examine solute movement, the vertical profiles of EC, pH, SAR and chloride concentrations as affected by the treatments were plotted and interpreted based on graphical illustrations. Geometric means were used in the plots. Because the concentration of a parameter at any given depth is dependent upon and affected by the concentration above, concentrations could not be analyzed with respect to depth. Such comparison would violate the analysis of variance model which assumes independence of error terms. Caution should be used when interpreting any depth effects, as no comparison was made within a frame of statistical control. Similarly, the soil column data were not statistically analyzed because the concentrations were depth-dependent as well as sequential in time.

Samples from the Blue Range post-precipitation Hole 2 appeared to have been collected outside the sprinkled field. Samples from the A&P Mine grassland control Hole 3 contained high sodium concentrations and electrical conductivity and appeared to have been collected within or adjacent to the sprinkled area. Such error was likely because the boundary of the spray area was not well marked at both sites. These outliers were not used for statistical analysis but are included in the data tables in Appendix A.

RESULTS AND DISCUSSION

Complete data of field soil and soil column analyses are included in Appendix A. Analysis of variance tables for EC, pH, SAR and chloride are included in Appendix B. Geometric means are used in the following discussion and figures. For brevity in the discussion, each of the soil sampling depth increments, 0 to 5, 5 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, 50 to 60, 60 to 76, and 76 to 91 cm is recorded by its midpoint depth. The corresponding midpoints are 3, 8 15, 25, 35, 45, 55, 68, and 84 cm. For the A&P Mine forest site, 0 cm designates the surface duff. Since a mean representing a parameter level of a soil profile tends to conceal the parameter's distribution pattern, interpretation of the means in Tables 13, 14 and 15 should be done in conjunction with the parameter distribution patterns illustrated in the accompanying figures.

Blue Range Mine Site

Electrical Conductivity

Land application of neutralized cyanide solution at the Blue Range LAD site significantly increased the mean EC of the entire soil profile (Table 13). After precipitation leaching, the mean EC level remained similar to the post-LAD level and both post-precipitation and post-LAD EC levels were significantly higher than the

control samples. The EC of the post-LAD profile was highest (4.1 dS/m) at 3 cm, and gradually decreased to 1.4 dS/m at 84 cm (Figure 1). However, one year later the salts had moved downward and reached the highest level (4.0 dS/m) at 55 cm. The profile also displayed an apparent accumulation of salts below 35 cm.

It appears from the data that salt leaching was in progress at the time of sampling. Assuming that rainfall leaching continues to occur at the site, salts may disappear from the soil profile over time. However, if land application occurs again before salts have leached to a desired depth or to an acceptable concentration, salinity would probably reach a hazardous level.

Table 13. Geometric mean levels of soil EC, pH, SAR and chloride concentration for each treatment at the Blue Range Mine LAD site.

Treatment	EC (dS/m)	pH	SAR	Cl (mg/l)
Control	0.21 a*	7.6 a	0.19 a	10.8 a
Post-LAD	2.5 b	7.5 a	4.5 b	30.6 b
Post-precip.	2.2 b	7.6 a	7.9 c	26.3 b

* In each column means followed by the same letter are not significantly different ($p \geq 0.1$).

pH

There were no significant differences among the overall pH values produced by the three treatments (Table 13). All pH values remained in the normal range. However, the pH distribution patterns showed that the lower soil became more acidic after land

Figure 1. Distribution of electrical conductivity at the Blue Range LAD site.

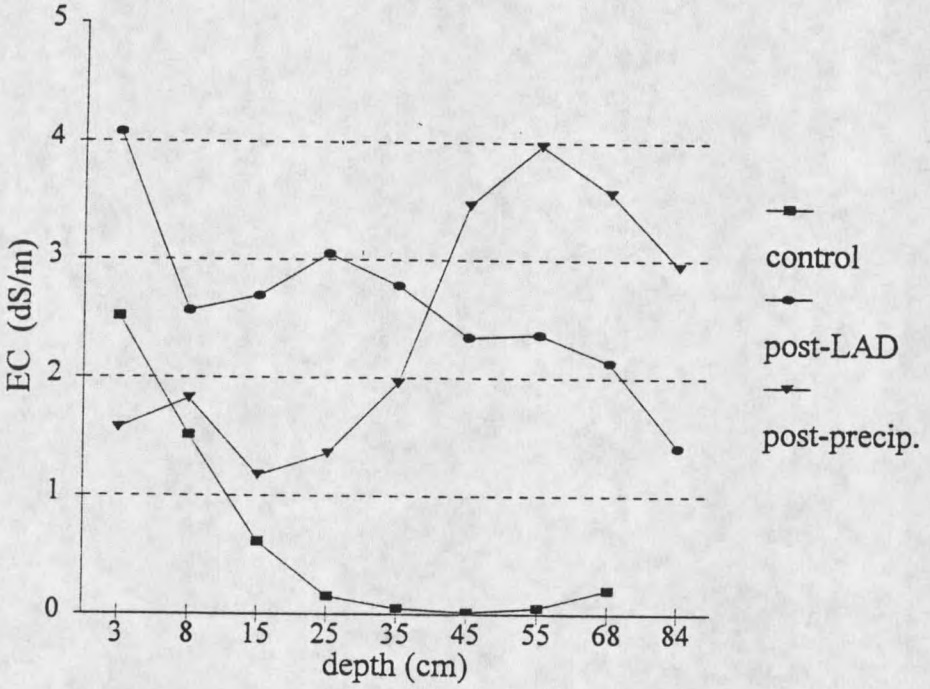
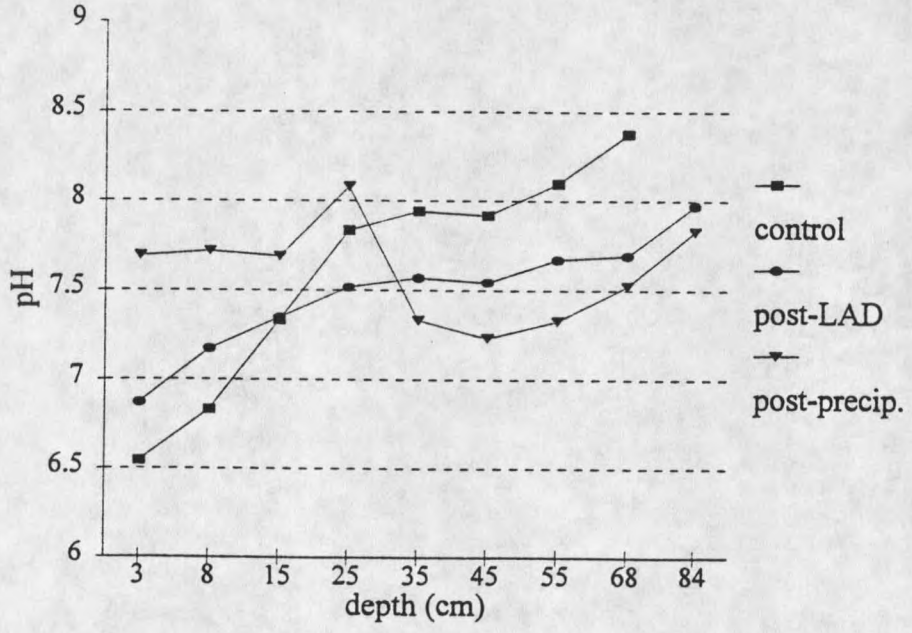


Figure 2. Distribution of pH at the Blue Range LAD site.



application (Figure 2). This condition may be explained by the displacement of hydrogen ions into soil water by exchangeable cations in the cyanide solution.

Sodium Adsorption Ratio

Sodium adsorption ratios were low throughout the native soil profile (Figure 3). The mean SAR level increased significantly after land application and remained elevated even one year later (Table 13). The mean post-precipitation SAR (7.9) was significantly greater than the post-LAD mean (4.5). Immediately after land application, SAR values were elevated above 15 cm and steadily declined below this depth. The highest SAR, 8.9, occurred at 15 cm. However, one year after the land application sodicity below 15 cm dramatically increased, reaching the highest value, 10.2, at 55 cm.

These data indicate that one year was not an adequate amount of time to diminish the concentration of the introduced sodium ions. More than one year of precipitation will be necessary to leach the salts from the soil system. Care must be exercised with land application of neutralized cyanide solution, because repeated land applications could lead to sodification of the site soil.

Chloride

The native soil profile had a mean chloride concentration of 10.8 mg/l. After land application, the overall chloride level was significantly elevated (Table 13). The mean post-precipitation chloride concentration (26.3 mg/l) remained similar to the post-LAD level (30.6 mg/l) and was significantly higher than the control level.

Figure 3. Distribution of SAR at the Blue Range LAD site.

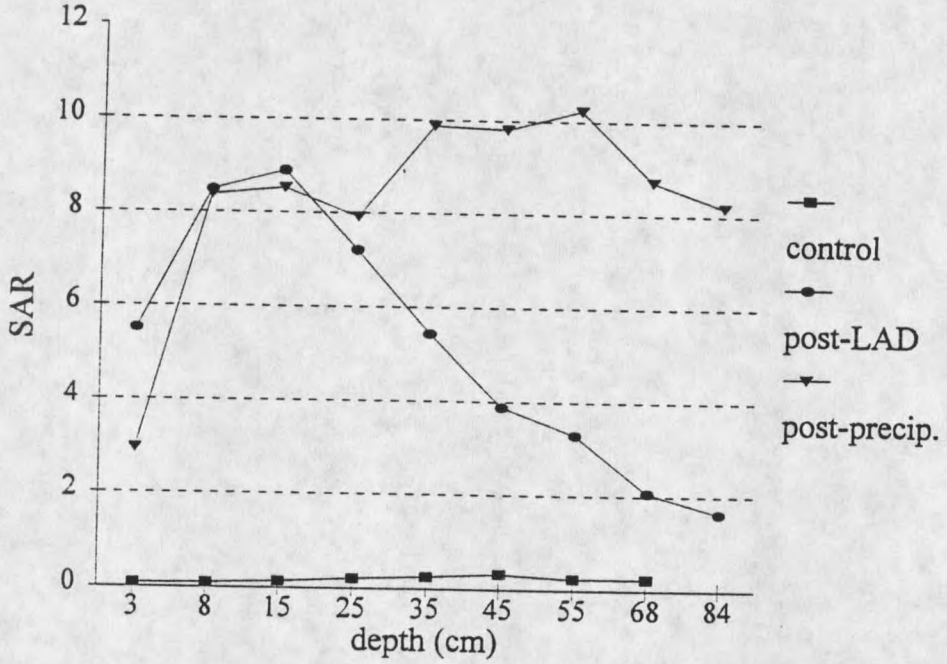
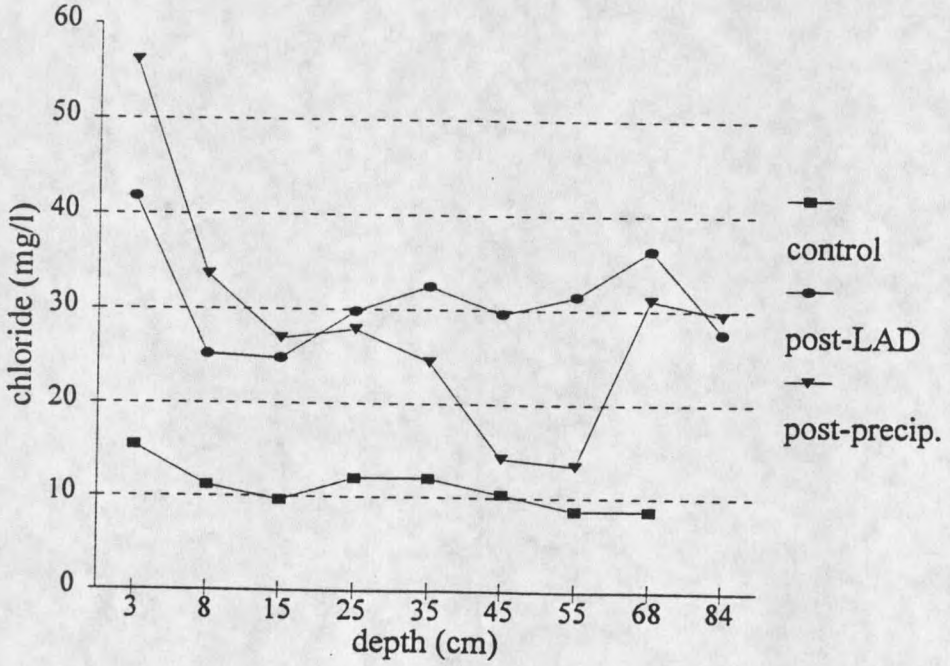


Figure 4. Distribution of chloride concentrations at the Blue Range LAD site.



Control profile chloride concentrations decreased from top (15.6 mg/l) to 68 cm (8.6 mg/l) (Figure 4). After land application, chloride levels fluctuated between 24.8 mg/l and 41.9 mg/l without any apparent trend. One year later chloride gradually declined from 3 cm (56.1 mg/l) to 55 cm (13.4 mg/l), then surged to 29.5 mg/l at 84 cm. In contrast to EC and SAR profiles, chloride reached the lowest concentration, 13.4 mg/l, at 55 cm.

Although chloride tends to be a non-sorbing anion in the soil system and is readily transported by soil water, data indicate that the accumulation of chloride in clayey soils may be a potential problem after repeated land applications.

A&P Mine Grassland Site

Electrical Conductivity

The native profile at the A&P Mine grassland site revealed low EC values (less than 1 dS/m). Land application significantly increased the soil profile's mean EC value to 1.3 dS/m (Table 14) but did not alter the vertical distribution pattern. After 6.5 months soil salinity values were similar to the control levels and ranged from 0.44 dS/m at 3 cm to 0.26 dS/m at 84 cm (Figure 5).

In contrast to the Blue Range Mine EC profile, there was no apparent accumulation of solutes at the lower depths of the A&P grassland site following land application and leaching. Data also indicated that in 6.5 months salts were transported below 91 cm in this mountain soil. Given the coarse soil texture at the A&P site, soil

probably would not accumulate excessive salts unless land applications are repeated frequently or the solution is extremely saline.

Table 14. Geometric mean levels of soil EC, pH, SAR and chloride concentration for each treatment at the A&P Mine grassland LAD site.

Treatment	EC (dS/m)	pH	SAR	Cl (mg/l)
Control	0.28 a*	5.6 a	0.72 a	13.6 a
Post-LAD	1.3 b	6.3 b	6.3 c	27.2 c
Post-precip.	0.32 a	5.4 a	3.2 b	18.0 b

* In each column means followed by the same letter are not significantly different ($p \geq 0.1$).

pH

In the control profile, pH generally increased from 3 cm (5.6) to 84 cm (6.0) (Figure 6). Land application significantly raised the mean pH of the entire soil profile from 5.6 to 6.3 (Table 14). Six and half months after land application, the mean pH returned to the pre-land application level. The post-LAD pH vertical distribution was irregular, however; the pH values fluctuated between 6.0 and 6.7. In the post-precipitation profile, even though its mean pH value was similar to that of the native system, soil steadily became more acidic with depth, with pH values decreasing from 6.5 at the surface to 5.0 at 84 cm. This condition probably resulted from the downward movement of hydrogen ions displaced by the introduced sodium and other cations.

Figure 5. Distribution of electrical conductivity at the A&P Mine grassland LAD site.

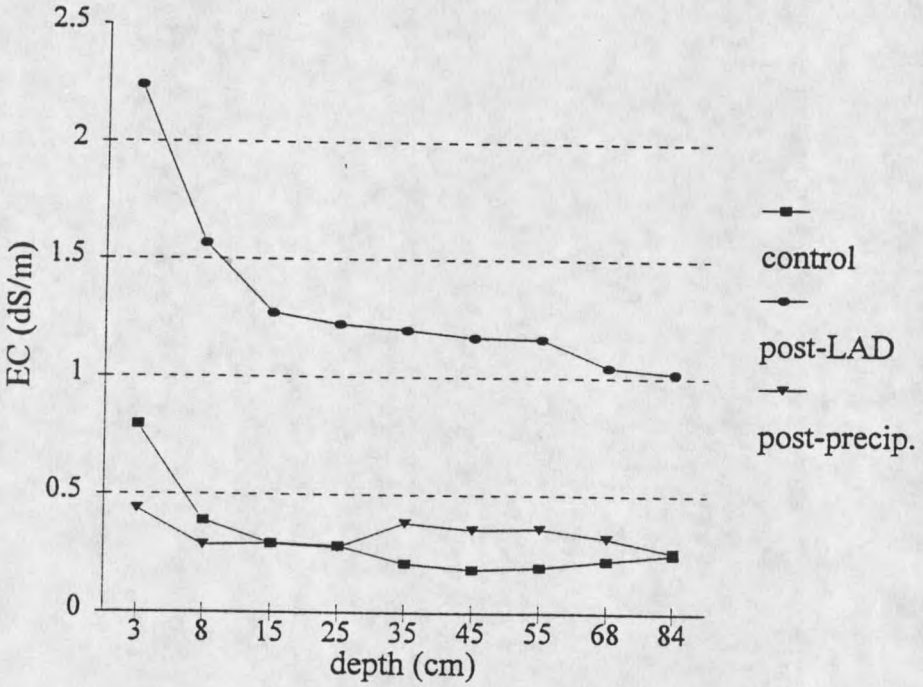
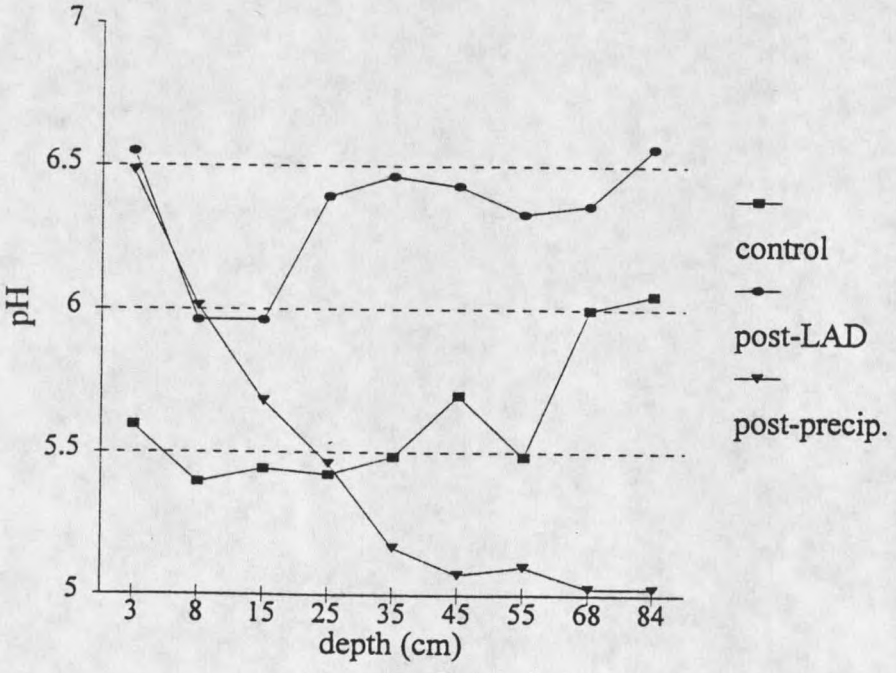


Figure 6. Distribution of pH at the A&P Mine grassland LAD site.



Sodium Adsorption Ratio

Soil became significantly more sodic after land application at the A&P grassland site (Table 14). Mean sodium adsorption ratio increased from 0.72 to 6.3 as a result of land application. Six and half months later the mean SAR had decreased to 3.2 but still remained significantly higher than the control value.

In the control soil profile, SAR values increased from the surface (0.26) to 84 cm (1.9) (Figure 7). The post-LAD distribution exhibited an increase in sodicity from control values at all depths, with values ranging between 7.0 and 5.7. Six and a half months after land application SAR was reduced at each depth; the highest value, 4.6, occurred at 15 cm. Overall, the abatement of SAR appeared to be in progress at the A&P grassland site at the time of sampling. Sodium adsorption ratio may eventually return to the pre-LAD level, unless another land application ensues within a short period of time.

There are two potential long term hazards at this site. First, data indicate that sodium was leached at a slower rate than the salts (Table 14). This raises the concern that, even though the neutralized cyanide solution contains a large quantity of solutes, once the salts are leached the residual sodium concentration may lead to soil dispersion and restricted permeability. In addition, if the soil becomes sodic, the native soil may not contain an adequate supply of divalent cations such as calcium and magnesium to displace sodium off of exchange sites, and water alone will not be an effective agent to reduce soil sodicity.

Figure 7. Distribution of SAR at the A&P Mine grassland LAD site.

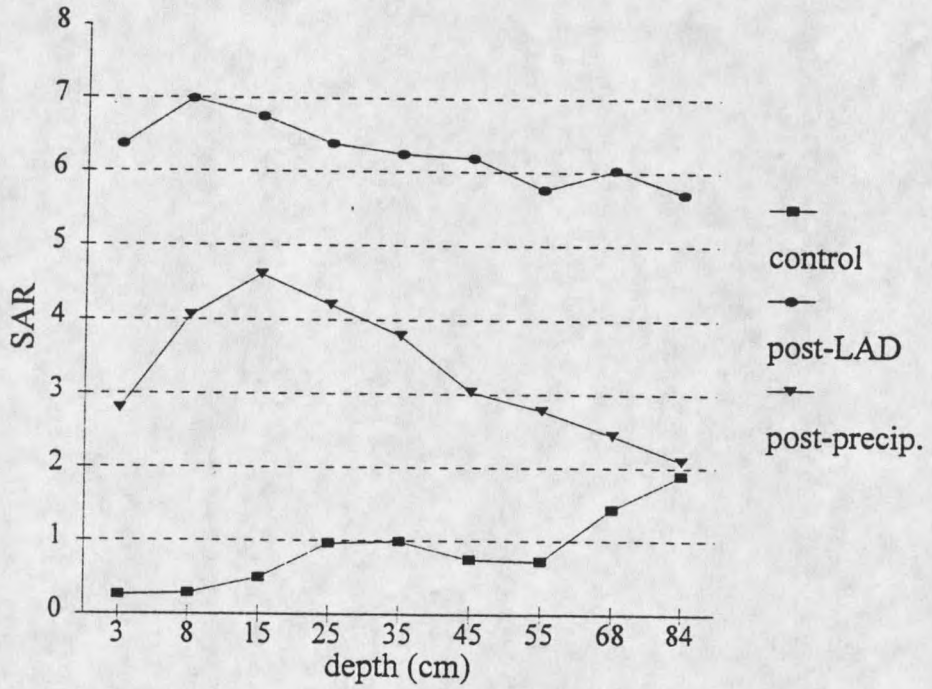
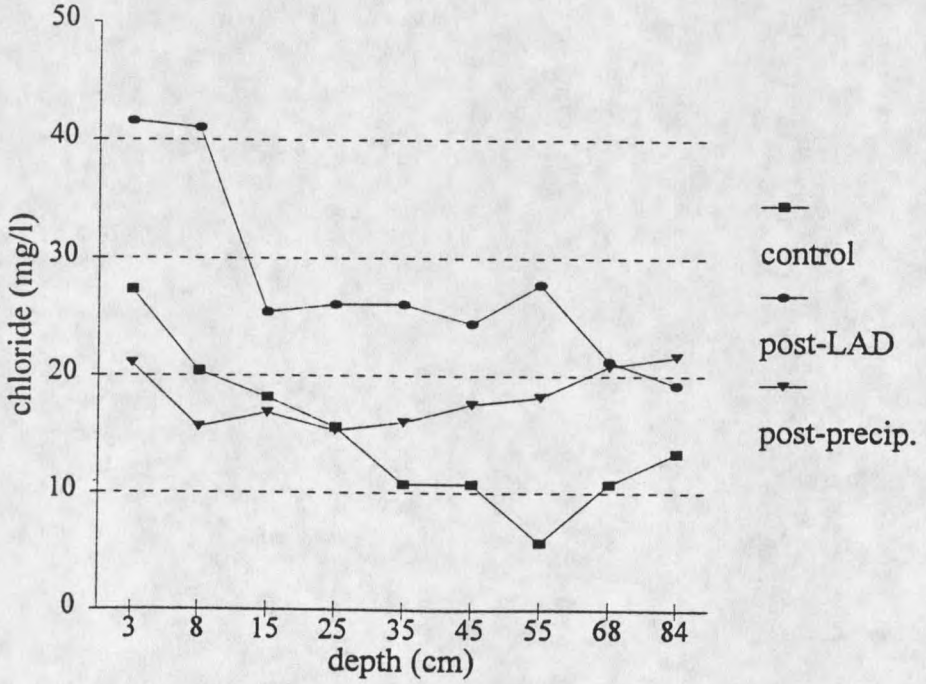


Figure 8. Distribution of chloride concentrations at the A&P Mine grassland LAD site.



Chloride

Land application significantly raised the mean chloride concentration of the soil profile (Table 14). The mean chloride concentration doubled from 13.6 mg/l to 27.2 mg/l. In the control profile the chloride levels decreased from 29.4 mg/l at 3 cm to 16.6 mg/l at 84 cm (Figure 8). After land application chloride ions retained a similar distribution pattern but had a higher concentration at each depth. The increase over the control profile is an important observation because the cyanide solution was supposedly neutralized with hydrogen peroxide. The post-precipitation mean chloride concentration was intermediate between the post-LAD and the control levels, indicating that the leaching of chloride was in progress.

A&P Mine Forest Site

Land application produced different results in the A&P forest site and the A&P grassland site. Since detailed information for the land application was not available for the forest site, and only control and post-precipitation samples were collected, interpretation is difficult.

Electrical Conductivity

In the forest control profile, EC measurements at 0, 3, and 8 cm were 0.17, 0.11, and 0.01 dS/m respectively (Figure 9). Below 8 cm, EC was less than 0.01 dS/m. In the post-precipitation profile the EC levels remained significantly elevated (Table 15),

ranging from 0.50 dS/m at 3 cm to 0.15 dS/m at 84 cm. The fact that these EC values were low and the salts did not accumulate in the lower depths indicated that rapid dilution of the salt load had occurred in this coarse soil.

Table 15. Geometric mean levels of soil EC, pH, SAR and chloride concentration for each treatment at the A&P Mine forest LAD site.

Treatment	EC ($dS\ m^{-1}$)	pH	SAR	Cl ($mg\ l^{-1}$)
Control	0.01 a*	5.6 b	0.4 1 b	16.3 a
Post-precip.	0.26 b	4.9 a	0.27 a	21.1 b

* In each column means followed by the same letter are not significantly different ($p \geq 0.1$).

pH

The control profile exhibited a gradual increase in pH from the duff layer (4.5) to bottom (6.0) (Figure 10). Approximately three months after land application, the forest soil became more acidic, with a pH value of 4.6 at the surface and 5.1 at 84 cm. The mean post-precipitation pH value of the soil (4.9) was significantly lower than that of the control soil profile (5.6) (Table 15). Soil acidification, especially in the lower depths, was observed in all three study sites some time following land application.

Sodium Adsorption Ratio

Sodicity in the forest soil was virtually negligible because none of the SAR values exceeded 0.6. Interestingly, the mean control SAR value was significantly higher than

Figure 9. Distribution of electrical conductivity at the A&P Mine forest LAD site.

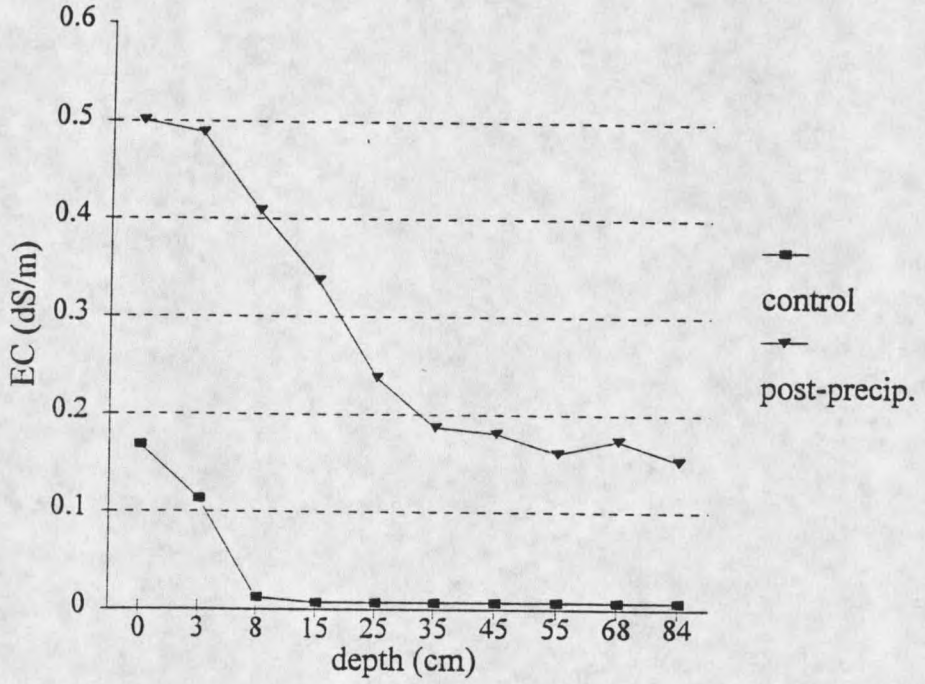
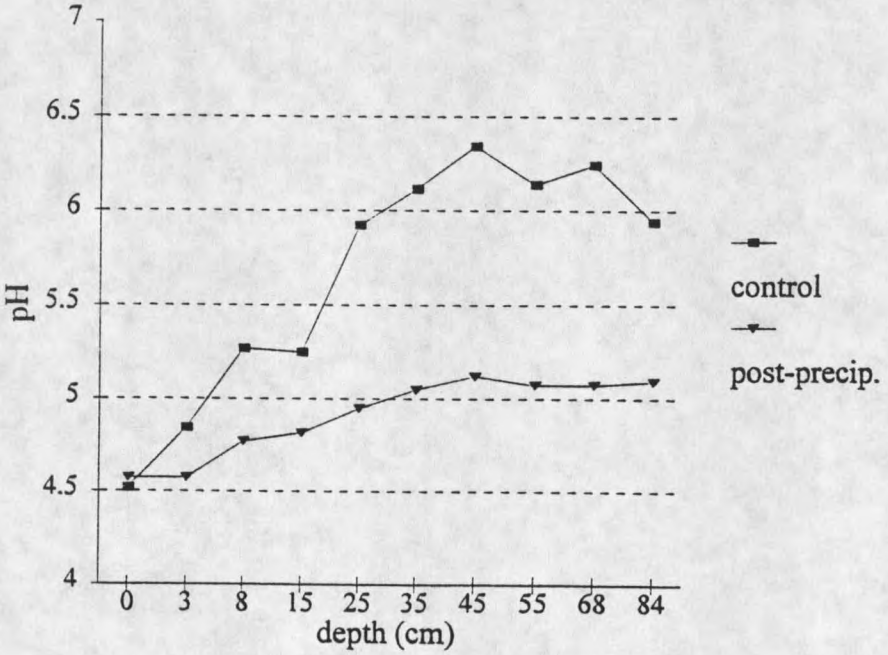


Figure 10. Distribution of pH at the A&P Mine forest LAD site.



the post-precipitation value (Table 15). In both sets of samples, SAR values increased gradually from the litter layer to 84 cm (Figure 11).

The fact that sodium concentrations declined and calcium concentrations increased following land application implies that calcium was the main component of the neutralized cyanide solution (Figures 12 and 13). Calcium hypochlorite was likely used for cyanide detoxification. These data point to the benefit of using calcium-based agents for cyanide treatment.

Chloride

The post-precipitation profile contained significantly higher chloride concentrations than the control profile (Table 15). The post-precipitation profile also showed an attenuation of chloride ions in the surface litter, which contained 59.7 mg/l in contrast to 37.8 mg/l at 3 cm (Figure 14). Chloride concentrations declined from the surface to 84 cm in both profiles.

Conclusion of the Site Investigations

Based on the three study sites and one land application event at each site, the following conclusions can be drawn regarding the effects of land application of neutralized cyanide solution on soils:

1) Salinity is not likely to become a major concern at land application sites. Salts in the site soils were either readily leached and reduced in concentration, or in a

Figure 11. Distribution of SAR at the A&P Mine forest LAD site.

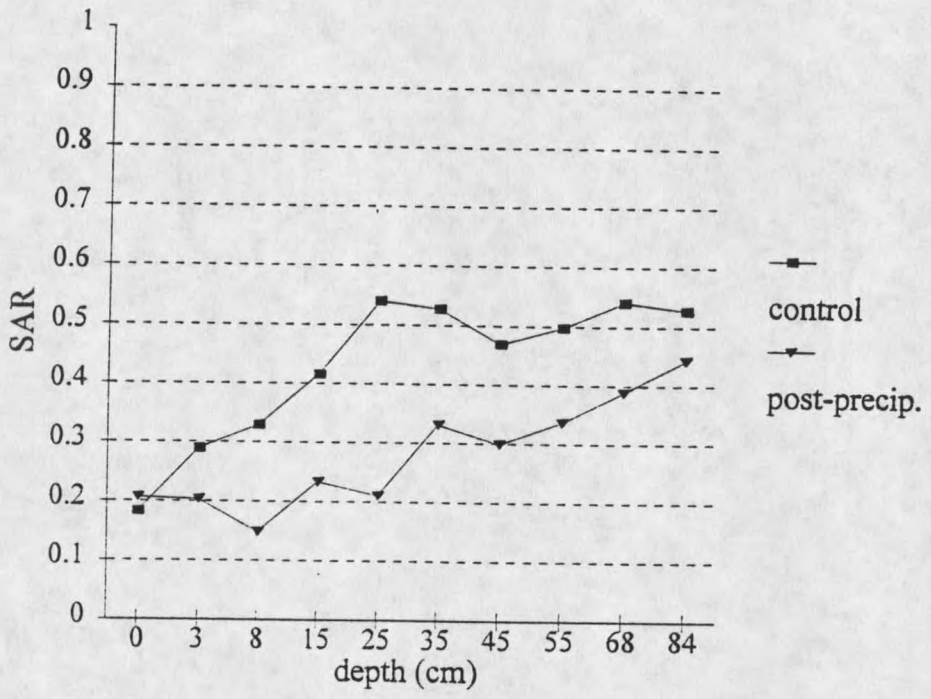


Figure 12. Distribution of sodium concentrations at the A&P Mine forest LAD site.

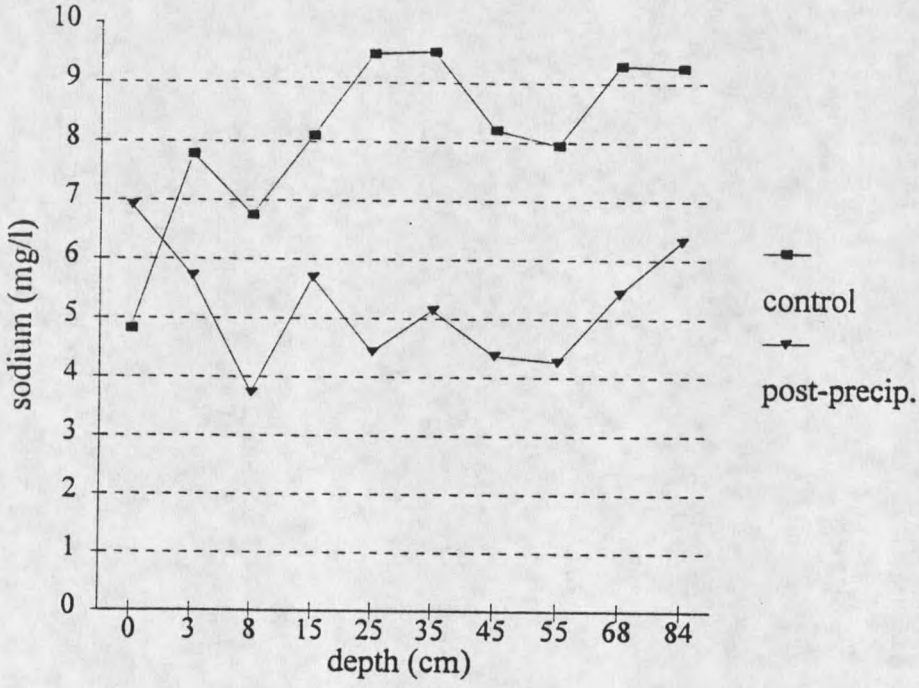


Figure 13. Distribution of calcium concentrations at the A&P Mine forest LAD area.

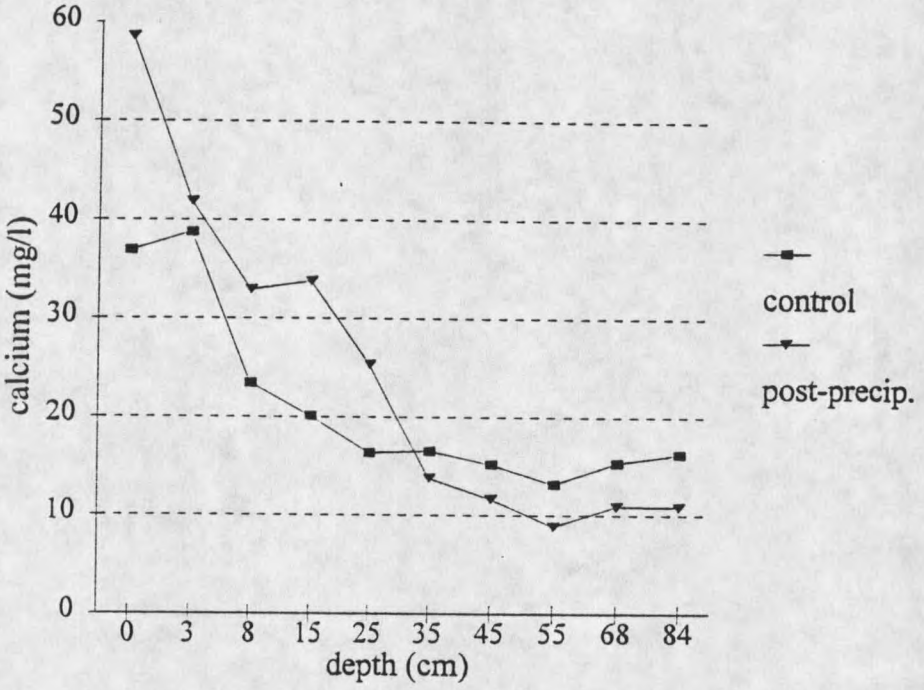
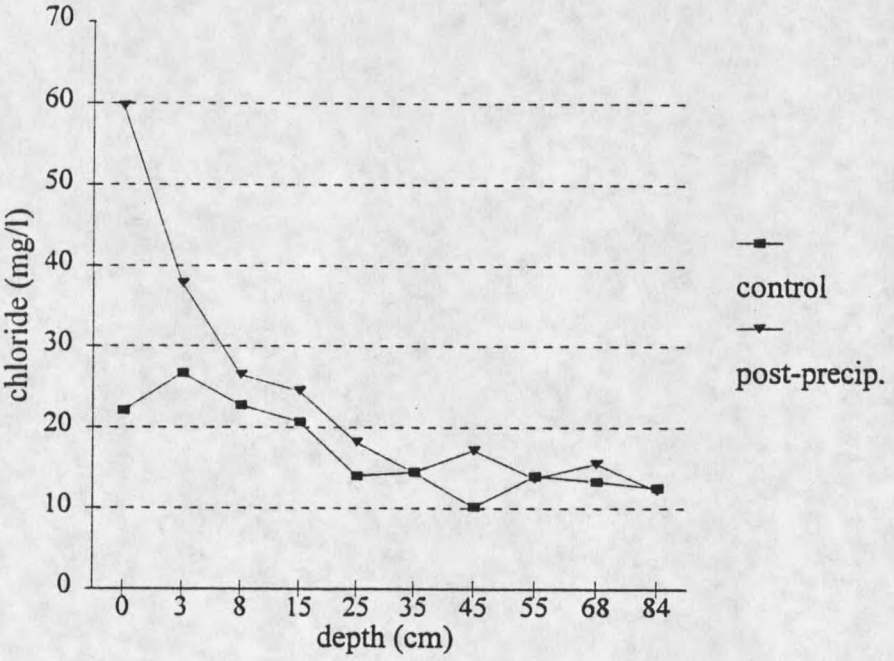


Figure 14. Distribution of chloride concentrations at the A&P Mine forest LAD area.



continuum of downward movement whereby they may eventually exit the soil profile. The clayey soil showed slower leaching, thus it is more susceptible to salinity build-up. In contrast, leaching in the coarse soils was more rapid and effective in transporting solutes. Frequent land applications should not have adverse impact on coarse soils unless repeated within short intervals or the wastewater is extremely high in salt and sodium content. If the wastewater is sodic, the presence of high solute concentrations in soil would also counteract the degradation of soil structure.

2) There are two important concerns as to how land application impacts soil sodicity. First, sodium adsorption ratios at two sites remained significantly elevated several months after land application, indicating that successive land application events could cause sodicity hazard in the soils. Data from the Blue Range and A&P grassland sites indicated that sodicity reduction occurred at a slower rate than salt reduction, and that a lapse of several months was not sufficient to return post-land application SAR values to their original levels. These observations are in agreement with the conventional belief that effective remediation of sodic soils requires displacement of exchangeable sodium by divalent cations coupled with leaching. The second issue involves the adequacy of solute concentrations in sodic soils. A sodic soil with low salinity is more likely to develop sodic characteristics such as restricted hydraulic conductivity and soil dispersion than a sodic soil with high solute concentration.

3) At all three sites chloride concentrations remained elevated several months after land applications. Clearly, in spite of its non-sorbing property, complete leaching of

the chloride ions is not a rapid process, and excessive chloride accumulation will be a threat to vegetation regardless of the site soil texture.

4) Land application had varying effects on pH at the three sites. However, all sites shared a trend in which lower depths of the soil profiles became more acidic than the same portion of the respective control profiles some time following land application. It can be concluded that the exchangeable cations in the added neutralized cyanide solution can acidify soils by displacing hydrogen, iron or aluminum ions from exchange sites. Continued monitoring will be necessary to determine the extent of the acidity increase.

Column Study

Column AP1

Column AP1 data are presented in Table 16 (solution irrigations) and Table 17 (freshwater irrigations). The pH values at all depths decreased with the solution irrigation. The pH value at 90 cm was consistently lower than those at 10, 30, and 60 cm. The levels of EC, SAR, and chloride rose progressively with each irrigation. The surface horizon showed the highest EC and SAR levels. At the end of the solution irrigations, chloride concentration reached a high of 2000 mg/l at 90 cm. Sodium adsorption ratio at 10, 30, 60, and 90 cm reached 20.0, 26.4, 15.3, and 7.8, respectively. The corresponding EC values were 4.9, 5.1, 5.0, and 5.0 dS/m, respectively. According to Frenkel et al. (1978), these EC values may be sufficiently high to prevent soil dispersion and maintain hydraulic conductivity.

Table 16: The pH, EC, SAR, and chloride concentrations in A&P Mine soil column 1 in response to solution irrigations.

Sampling days	control	day 1	day 3	day 4	day 5	day 6	day 8	day 9	day 10	day 12	day 13	day 15	day 17	day 22
Vol. added (ml)*	0	1050	1050	1050	1050	2100	1050	1050	2100	1050	2100	1050	1050	2600
Cum. P.V.**	0	0.063	0.126	0.189	0.252	0.378	0.441	0.504	0.63	0.693	0.819	0.882	0.945	1.101
	pH													
10 cm	7.0	5.9				7.2			5.5		5.5	5.8		5.9
30 cm	7.0	6.2				6.7			5.4		5.5	5.8		6.0
60 cm	6.8	6.9				6.6			5.5		5.7	6.0		6.2
90 cm	5.1	5.1	5.2	5.1	5.2	4.2	4.5	4.6	4.6	4.3	4.2	4.7	5.0	5.2
	EC (dS/m)													
10 cm	0.15	1.9				3.3			4.4		5.0	5.6		4.9
30 cm	0.09	1.2				4.8			5.3		5.6	5.8		5.1
60 cm	0.21	0.19				3.4			5.1		5.4	5.4		5.0
90 cm	0.45	0.21	0.12	0.27	0.86	2.9	3.6	3.9	4.2	4.5	4.8	5.2	5.0	5.0
	SAR													
10 cm	1.1	3.0				7.2			10.4		12.1	12.1		20.0
30 cm	1.2	4.3				11.6			15.8		19.6	20.3		26.4
60 cm	0.87	0.99				3.5			7.4		9.7	10.8		15.3
90 cm	0.66	0.63	0.75	0.79	0.90	1.4	1.9	2.2	3.1	3.6	4.4	5.4	6.8	7.8
	Cl (mg/l)													
10 cm	20.1	68.1				1142			1525		1813	1908		1813
30 cm	20.1	279				1597			1621		1813	1813		1717
60 cm	10.5	20.1				1237			1621		1813	1813		1813
90 cm	20.1	20.1	20.1	68.1	279	806	1046	1094	1333	1429	1621	1717	2100	2004

* Total volume of solution added between sampling days.

** Cumulative pore volume.

Table 17. The pH, EC, SAR, and chloride concentrations in A&P Mine soil column 1 in response to freshwater irrigations.

Sampling days	day 1	day 4	day 6	day 8	day 9	day 13	day 15	day 17	day 18	day 20	day 21
Vol. added (ml)*	2100	1050	2100	1050	1050	3370	1050	1050	1050	3150	0
Cum. P.V.**	0.126	0.189	0.315	0.378	0.441	0.643	0.706	0.769	0.832	1.021	1.021
	pH										
10 cm	5.9		6.0			6.5				6.7	
30 cm	6.2		6.3			6.9				6.9	
60 cm	6.1		6.3			6.8				6.9	
90 cm	4.4	4.7	5.0	5.0	5.5	4.9	5.7	5.4	5.6	5.9	5.8
	EC (dS/m)										
10 cm	3.8		1.9			0.28				0.01	
30 cm	2.0		1.0			0.10				0.01	
60 cm	5.6		2.7			0.38				0.10	
90 cm	6.0	5.7	5.3	4.1	3.3	1.3	0.74	0.76	0.50	0.20	0.16
	SAR										
10 cm	16.0		14.0			8.5				5.9	
30 cm	11.2		11.2			9.7				6.9	
60 cm	15.0		18.8			10.6				7.3	
90 cm	9.0	9.7	14.2	10.3	9.6	12.5	9.2	10.2	9.1	8.1	6.2
	Cl (mg/l)										
10 cm	1237		614			87.2				39.3	
30 cm	566		279			58.5				20.1	
60 cm			758			87.2				29.7	
90 cm	2004	2004	1717	1237	950	231	183	135	87.2	29.7	29.7

* Total volume of deionized water added between sampling days.

** Cumulative pore volume.

As the column was leached with deionized water, pH gradually rose toward 6.9. Salt load was reduced as indicated by extremely low EC values at the end of leaching. The majority of the chloride ions also exited the soil profil. Sodium adsorption ratio at all depths had decreased to non-sodic levels (SAR 5.9, 6.9, 7.3, and 8.1 at 10, 30, 60, and 90 cm respectively) but were still higher than the pre-irrigation levels.

Column AP2

Column AP2 was affected by reduced infiltration and possible preferential flow and behaved differently from column AP1. Preferential flow, or the selective movement of soil water through certain channels while bypassing others (Magaritz and Nadler 1993), appeared to occur after the onset of freshwater rinsing. This suggestion is based on the data that high concentrations of solutes and ions persisted in the soil profile after successive rinsing (Table 19).

The pH values fluctuated with the solution irrigations but generally were lowest at 90 cm (Table 18). Electrical conductivity also increased and began to exceed 4 dS/m after 0.38 pore volume had passed through the column. Surface soil generally revealed the highest EC values. Sodium adsorption ratio rose progressively at all depths, but exceeded 13 only at 10 and 30 cm. The highest SAR level attained was 23.5.

When leaching by deionized water, solutes moved downward at a slow rate (Table 19). After 1.45 pore volumes of water had passed through the profile, concentrations of solutes and chloride accumulated in the lower profile unlike column AP1 in which ions moved down steadily. Electrical conductivity at 60 cm and 75 cm

Table 18: The pH, EC, SAR, and chloride concentrations in A&P Mine soil column 2 in response to solution irrigations.

Sampling days	control	day 1	day 3	day 4	day 5	day 6	day 8	day 9	day 10	day 13	day 15	day 17	day 22
Vol. added (ml)*	0	1050	1050	1050	1050	2100	1050	1050	1050	2600	1050	1050	2600
Cum. P.V.**	0	0.063	0.126	0.189	0.252	0.378	0.441	0.504	0.567	0.723	0.786	0.849	1.005
	pH												
10 cm	6.6	6.1				6.5			5.7	6.0	6.1		6.3
30 cm	6.8					6.3			5.5	5.7	6.1		6.3
60 cm	6.4	7.0	4.6	6.4		6.4		5.9	5.6	6.0	6.1		6.3
75 cm		5.5	5.2	4.9	5.0	4.7	5.3	4.8	4.8			5.8	
90 cm	5.3	5.5	5.5	5.6	5.5	5.5	5.5	5.8	5.6	6.1	5.6	5.7	5.6
	EC (dS/m)												
10 cm	0.19	1.1				4.2			5.1	5.2	5.7		5.0
30 cm	0.10					2.8			4.9	5.3	5.5		4.8
60 cm	0.19	0.22	0.92	1.2				2.5	2.9	3.9	4.7		4.7
75 cm		0.35	0.79	1.6	1.7	3.4	3.5	3.6	3.6			4.7	
90 cm	0.60	0.54	0.75	1.1	1.8	2.8	2.7	3.1	3.6	3.6	3.9	4.0	4.5
	SAR												
10 cm	1.9	2.0				8.0			10.4	13.7	20.1		23.5
30 cm	0.58					3.8			6.9	12.0	12.3		15.9
60 cm	0.87	0.93	2.1	2.8				3.4	2.3	3.0	5.1		9.7
75 cm		0.76	2.0	2.9	2.7	5.2	5.2	4.7	4.5			8.3	
90 cm	0.72	0.75	1.2	1.9	3.0	4.9	4.9	4.9	4.4	4.1	5.6	6.5	8.0
	Cl (mg/l)												
10 cm	20.1	145				1717			1621	1908	1717		1813
30 cm	29.7					1190			1621	1813	1813		2100
60 cm	10.5	10.5	221	327				662	854	1429	1429		1621
75 cm		10.5	183	423	471	950	998	1046	1142			1621	
90 cm	10.5	10.5	126	231	519	758	758	806	1046	1142	950	1429	1621

* Total volume of solution added between sampling days.

** Cumulative pore volume.

Table 19. The pH, EC, SAR, and chloride concentrations in A&P Mine soil column 2 in response to freshwater irrigations.

Sampling days	day 1	day 4	day 8	day 9	day 14	day 17	day 18	day 20	day 21	day 25	day 27	day 28	day 38	day 57
Vol. added (ml)*	2100	500	950	1500	2870	250	800	350	550	1700	1050	1275	3325	7150
Cum. P.V.**	0.126	0.156	0.213	0.303	0.475	0.477	0.525	0.546	0.579	0.681	0.744	0.82	1.019	1.448
	pH													
10 cm	6.3			7.2	6.9		7.1			7.3		7.4	7.8	8.1
30 cm	6.0			6.8	6.7		6.8			7.1		7.2	7.0	7.8
60 cm	6.0	6.2		6.5	6.3		6.1		5.9	6.5		6.5	5.9	7.3
75 cm***			6.3	6.4		6.2			6.0	6.3	5.9	5.9	5.6	7.2
	EC (dS/m)													
10 cm	4.4			1.7	1.1		0.70			0.55		0.35	0.28	0.15
30 cm	5.2			3.7	2.9		2.4			1.9		1.7	1.6	1.7
60 cm	5.0	4.8		4.2	4.0		3.4		3.6	3.3		3.2	3.2	3.0
75 cm			7.1	6.3		4.3		4.0	4.0	3.8	3.8	3.7	3.5	3.4
	SAR													
10 cm	22.4			13.6	17.3		12.1			12.2		8.6	9.1	8.9
30 cm	17.8			13.6	16.4		13.3			15.4		14.7	15.2	15.4
60 cm	9.7	8.7		8.5	9.5		7.2		6.4	6.4		6.5	6.5	6.0
75 cm			10.8	11.1		7.7		7.5	7.3	8.0	6.8	7.2	7.6	7.3
	Cl (mg/l)													
10 cm	1429			471	231		183			183		87.2	87.2	68.1
30 cm	1908			1237	806		662			614		375	423	423
60 cm	1717	1621		1333	1142		1046		1046	1142		1046	950	854
75 cm			2292	2196		1237		1142	1142	1237	1142	1142	1046	902

* Total volume of deionized water added between sampling days.

** Cumulative pore volume.

*** Effluents from 90 cm were not collected due to port connector leakage.

remained near 3.0 dS/m; the column attained the highest chloride concentration, 902 mg/l, at 75 cm after leaching was completed. The SAR level remained at 15.4 at 30 cm , but had dropped below 13 at other depths. Preferential flow, in which water moved down certain paths carrying only a portion of the total salt load, would appear to be responsible for the incomplete leaching.

Column BR1

The pH level at each depth tended to increased slightly with the irrigations (Table 20). The EC level increased progressively at all depths, exceeding 4 dS/m at the conclusion of the saline irrigation, and reaching the highest value, 6.4 dS/m, at 60 cm. For SAR, the upper soil profile consistently had much greater values than at 90 and 107 cm, indicating that the introduced sodium had been attenuated by the soil. The SAR values exceeded 13 at 10 cm only. Chloride concentration exhibited a more uniform distribution with respect to depth, probably due to the non-sorbing nature of the anion. The highest chloride concentration, 2100 mg/l, occurred at 60 cm at the end of the irrigations.

The soil became more alkaline upon leaching with deionized water (Table 21). Salts moved downward and was eventually flushed from the column. Chloride concentrations also decreased uniformly at each depth, and became lower than the pre-experiment levels. The SAR distribution showed a decrease at all depths but revealed a build-up of sodicity in the lower profile. The highest SAR value was 7.1 at 60 cm.

Table 20. The pH, EC, SAR, and chloride concentrations in Blue Range Mine soil column 1 in response to solution irrigations.

Sampling days	control	day 1	day 2	day 5	day 6	day 8	day 9	day 10	day 13	day 14	day 19	day 20	day 21
Vol. added (ml)*	0	1050	1050	2100	2100	2100	1050	1050	1050	2100	1050	1050	2100
Cum. P.V.**	0	0.047	0.094	0.188	0.282	0.376	0.423	0.47	0.517	0.611	0.658	0.705	0.799
	pH												
10 cm	6.9	7.4	7.0		7.2			7.3		7.3			7.5
30 cm	7.1	7.1			6.9			7.0		7.2			7.3
60 cm	6.7	7.0	6.7		6.9			6.8		7.0			7.1
90 cm	7.2	7.3	7.1		7.6	7.1		7.4		7.4			7.6
107 cm	6.4	6.5	7.5	7.0		7.4	7.5		7.6	7.5	7.5	7.5	7.7
122 cm***	7.8	7.8											
	EC (dS/m)												
10 cm	0.01	0.65	2.2		3.9			5.1		6.2			5.4
30 cm	0.17	0.54			4.2			4.2		5.4			6.3
60 cm	0.29	0.31	0.24		3.2			4.2		5.1			6.4
90 cm	0.77	0.73	0.61		1.3	2.4		3.1		4.0			5.6
107 cm	1.6	1.3	1.1	1.0		1.6	2.6		3.3	3.4	4.0	4.2	4.5
122 cm	5.7	5.0											
	SAR												
10 cm	0.15	1.9	2.3		5.6			11.4		16.8			22.8
30 cm	0.10	0.10			1.8			4.0		6.7			10.9
60 cm	0.13	0.13	0.14		0.18			2.2		3.5			6.9
90 cm	0.11	0.11	0.10		0.07	0.11		0.10		0.19			1.8
107 cm	0.07	0.23	0.07	0.06		0.05	0.07		0.06	0.10	0.18	0.29	0.59
122 cm	0.09	0.09											
	Cl (mg/l)												
10 cm	29.7	164	566		1046			1717		1813			1908
30 cm	39.3	126			1190			1333		1621			2004
60 cm	39.3	29.7	39.3		854			1142		1429			2100
90 cm	39.3	29.7	48.9		279	566		950		1046			1813
107 cm	39.3	48.9	29.7	29.7		279	614		854	902	1045.72	1142	1429
122 cm	174	106											

* Total volume of solution added between sampling days.

** Cumulative pore volume.

*** Effluent from 122 cm was obtained on day 1 only.

Table 21. The pH, EC, SAR, and chloride concentrations in Blue Range Mine soil column 1 in response to freshwater irrigations.

Sampling days	day 1	day 2	day 5	day 8	day 10	day 13	day 15	day 18	day 19	day 21	day 22	day 25
Vol. added (ml)*	1050	1050	1050	4370	1050	4450	2950	1050	2450	1100	1050	2600
Cum. P.V.**	0.047	0.094	0.141	0.337	0.384	0.584	0.716	0.763	0.873	0.922	0.969	1.086
	pH											
10 cm		7.7		7.9		8.0	7.8		7.8			7.7
30 cm		7.2		7.6		7.7			7.8			7.8
60 cm		7.2		7.3		7.4	7.7		7.9			8.0
90 cm		7.5		7.6		7.8	7.9		8.0			
107 cm***	7.5		7.5	7.3	7.7	7.6	7.4	7.6	7.6	7.5	7.3	7.4
	EC (dS/m)											
10 cm		3.2		1.4		0.67	0.13		0.00			0.01
30 cm		6.0		2.2		0.91			0.12			0.06
60 cm		7.1		4.2		1.1	0.49		0.18			0.17
90 cm		6.0		6.5		3.4	1.1		0.74			
107 cm	5.2		6.4	6.4	6.4	4.2	2.2	1.9	1.4	1.1	1.0	0.90
	SAR											
10 cm		21.1		11.7		9.2	6.5		5.8			4.0
30 cm		12.4		7.7		9.5			7.2			6.6
60 cm		9.1		9.4		8.3	7.7		6.8			7.1
90 cm		2.5		4.5		4.4	5.8		5.5			
107 cm	0.89		1.8	3.0	2.7	3.3	2.9	2.8	2.6	2.9	2.9	2.8
	Cl (mg/l)											
10 cm		1142		279		87.2	48.9		29.7			29.7
30 cm		1813		471		135			39.3			29.7
60 cm		2196		1142		159	48.9		39.3			29.7
90 cm		2004		2100		806	183		87.2			
107 cm	1621		1908	1908	1813	1046	327	279	145	126	87.2	87.2

* Total volume of solution added between sampling days.

** Cumulative pore volume.

*** Unable to obtain sufficient quantity of effluents from 122 cm.

Conclusion of the Column Study

All columns exhibited high SAR values at the end of the neutralized cyanide solution applications, and remained higher than the pre-experiment levels after water leaching. This finding essentially agrees with that of the field study. With successive land applications sodium ions are likely to accumulate at a faster rate than their disappearance. The fact that electrical conductivity reached minimal levels at the end of water rinsing further promotes the potential for soil structure degradation.

At the end of the freshwater leaching, chloride concentrations in columns AP1 and BR1 closely matched the original levels. This observation differs from the field study data which indicated that post-precipitation chloride concentrations remained elevated. The high volume and frequency of the column rinsing explains the large reduction of chloride concentrations as well as electrical conductivity. As in the field study, soil in the columns tended to become acidic with the saline-sodic irrigations.

The slow and incomplete leaching in column AP2 was probably the result of preferential flow. Preferential flow appeared to be a consequence of large column construction, because it was difficult to uniformly compact the soil, obtain desired bulk density, and inspect apparatus defects. The columns were also not successful in predicting the rate of solute movement because flow rate could be distorted by low bulk density, preferential flow, or water seeping through the perimeter of the column tube.

SUMMARY

The effects of land application of neutralized cyanide solution on soils were investigated. Such investigation is important because the solution is often saline, sodic, or high in chloride concentration. Extensive land applications may cause soil degradation because of excess loading of salts, sodium and chloride.

Three land application sites of different soil textures were sampled before, immediately after, and several months after land application. Soils from various depths were analyzed for electrical conductivity, pH, sodium adsorption ratio, chloride and trace metal concentrations. In addition, soil columns were constructed to simulate land applications and monitor the movement of salts through the soil profiles.

The results of these studies allow us to infer that sodicity and chloride accumulation may be of major consequences at land application sites. Data indicate that a portion of the introduced sodium ions remained in soil profiles regardless of soil texture, and soil may be alkalinized over repeated land applications. Because salts were leached more rapidly than sodium ions, the lack of salts in soils may amplify undesirable soil conditions such as reduced permeability and deflocculation induced by excessive sodium concentration. Similarly, chloride concentrations were increased by land application at all sites, and remained above the control levels after several months. The slow leaching process indicates that chloride accumulation may be an important concern for land application sites. The sites also revealed a degree of acidification in the lower

depths after land application. Finally, through ongoing leaching process, land application should not raise concerns for salinity damage unless the discharge is repeated within a short period of time or the wastewater is extremely saline. In general, clayey soils exhibited slower leaching and were thus more susceptible to salinity and sodicity hazards than coarse soils.

The soil column study yielded similar results to the field studies. Soil pH declined with the solution irrigations. Sodium adsorption ratio reached an intermediate level after daily irrigation with moderately saline and highly sodic water, and failed to return to pre-irrigation level after intense leaching with deionized water. On the other hand, electrical conductivity and chloride concentrations were reduced to low levels. These observations emphasize the potential for soil sodification due to increased sodicity, reduced salt concentration, and repeated land applications.

A comprehensive analysis of the effects of land application should incorporate other site-specific factors such as vegetation, groundwater table, and land application frequency. However, based on the scope of this study, it can be concluded that sandy soil may be more suitable for land application than clayey soil, and that waste solutions should not be repeatedly applied to the same ground.

REFERENCES CITED

American Public Health Association. 1989. Chloride. pp. 4-69 to 4-70 In: Standard Methods for the Examination of Water and Wastewater, Washington, D.C.

Ayers, R.S. and D.W. Wescot. 1985. Water Quality for Agriculture, Irrigation and Drainage Paper No. 29. Food and Agriculture Organization of the United Nations. Rome, Italy. 97 p.

Beal Mountain Mining Inc. 1992. Application for a Hard Rock Operating Permit, Beal Mountain Project, Silver Bow County, MT. Submitted to Montana DEQ and Deerlodge National Forest.

Bernstein, L. 1965. Salt tolerance of fruit crops. USDA Agricultural Information Bulletin 292. Washington, D.C. 8 p.

Bernstein, L. 1975. Effects of salinity and sodicity on plant growth. Annual Review of Phytopathology 13:295-312.

Bernstein, L., L.E. Francois, and R.A. Clark. 1972. Salt tolerance of ornamental shrubs and ground covers. Journal of American Society of Horticultural Science 97:550-556.

Bernstein, L. and H.E. Hayward. 1958. Physiology of salt tolerance. Annual Review of Plant Physiology 9:25-46.

Black, C.A. 1957. Soil-Plant Relationships. John Wiley & Sons, Inc. New York, NY. 332 p.

Campbell, R.B., C.A. Bower, and L.A. Richards. 1949. Change of electrical conductivity with temperature and the relation of osmotic pressure to electrical conductivity and ion concentration for soil extracts. Soil Science Society of America Proceedings (1948) 13:66-69.

Denton, D., S. Iverson, and B. Gosling. 1992. HEAPREC--A methodology for determining cyanide heap leach reclamation performance bonds. U.S. Dept. of Interior, Bureau of Mines. Information Circular 9328. Washington, D.C. 79 p.

Eaton, F.M. 1942. Toxicity and accumulation of chloride and sulfate salts in plants. Journal of Agricultural Research 64:357-399.

Fowler, J.L., J.H. Hageman, K.J. Moore, M. Suzukida, H. Assadian, and M. Valenzuela. 1992. Salinity effects on forage quality of Russian thistle. Journal of Range Management 45(6):559-563.

Frenkel, H., J.O. Goertzen, and J.D. Rhoades. 1978. Effects of clay type and content, exchangeable sodium percentage, and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Science Society of America Journal 42(1):32-39.

Fuller, W.H. and A.W. Warrick. 1985. Soils in Waste Treatment and Utilization. Vol II, Pollutant Containment, Monitoring, and Closure. CRC Press, Inc. Boca Raton, FL.

Giusquiani, P.L., G. Gigliotti, and D. Businelli. 1992. Mobility of heavy metals in urban waste-amended soils. Journal of Environmental Quality 21(3):330-335.

Grotbo, T. and D. Ortman. 1988. Land application discharge for disposal of treated processing effluent. Presented to: Intermountain Mining and Operators Symposium, sponsored by Nevada Mining Association, Utah Mining Association, and Rocky Mountain Association of Environmental Professional. November 3-4, Elko, NV.

Haight, S., J. Frazier, and S. Spano. 1990. Emergency treatment and land application of excess cyanide solution at the Zortman Mine, Phillips County, Montana. pp. 1-16 In: Site Design Construction and Reclamation of Cyanide Heap Leach Projects, a training conference sponsored by US Forest Service, Northern Region, Missoula, MT. March 19-22, Butte, MT.

Hannon, N.J. and H.N. Barber. 1972. The mechanism of salt tolerance in naturally selected populations of grasses. Search Sydney 3:259-260.

Hayward, H.E. and W.B. Spurr. 1944. Effects of isosmotic concentrations of inorganic and organic substrates on entry of water into corn roots. Botanical Gazette 106:131-139.

Huiatt, J., J. Kerrigan, F. Olson and G. Potter (eds.). 1983. Proceedings of a workshop: Cyanide from Mineral Processing. Utah Mining and Mineral Resources Research Institute. College of Mines and Mineral Industries. Salt Lake City, UT. 122 p.

Johnson, R.C. 1991. Salinity resistance, water relations, and salt content of crested and tall wheatgrass accessions. Crop Science 31:730-734.

Keith, L.H., W. Crummett, J. Deegan, Jr., R.A. Libby, J.K. Taylor, and G.Wentler. 1983. Principles of Environmental Analysis. Analytical Chemistry 55(14): 2210-2218.

Knorre, H. and A. Griffiths. 1984. Cyanide detoxification with hydrogen peroxide using the Degussa process. pp. 519-530 In: Cyanide and the Environment. D. van Zyl (ed.). Colorado State University. Fort Collins, CO.

Magaritz, M. and A. Nadler. 1993. Agrotechnically induced salinization in the unsaturated zone of loessial soils, N.W. Negev, Israel. Ground Water 31(3):363-369.

McBride, M.B. 1994. Environmental Chemistry of Soils. Oxford University Press, Inc. New York, NY. 406 p.

McNeal, B.L. and N.T. Coleman. 1966. Effect of solution composition on soil hydraulic conductivity. Soil Science Society of America Proceedings 30(3):308-312.

Montana Department of Environmental Quality. 1995. Montana Numeric Water Quality Standards. Water Quality Division, Technical Studies and Special Projects Section. Circular WQB-7. Helena, MT. 39 p.

Montana State University--Bozeman Extension Service. 1994a. MAPS Atlas Version 5.0: A Land and Climate Information System. Montana State University--Bozeman Extension Service. Bozeman, MT.

Montana State University--Bozeman. 1994b. MSUSTAT Version 5.22. Montana State University--Bozeman. Bozeman, MT.

Neter, J., W. Wasserman, and M. Kutner. 1990. Applied Linear Statistical Model, 3rd ed. Richard D. Irwin Publishers. Homewood, IL.

Oster, J.D. and F.W. Schroer. 1979. Infiltration as influenced by irrigation water quality. Soil Science Society of America Journal 43:444-447.

Park, C.S. and G.A. O'Connor. 1980. Salinity effects on hydraulic properties of soils. Soil Science 130(3):167-174.

Pessarakli, M., T.C. Tucker, and N. Nakabayashi. 1991. Growth response of barley and wheat to salt stress. Journal of Plant Nutrition 14(4):331-340.

Porro, I., P.J. Wierenga, and R.G. Hills. 1993. Solute transport through large uniform and layered soil columns. Water Resources Research 29(4):1321-1330.

Pupisky, H. and I. Shainberg. 1979. Salt effects on the hydraulic conductivity of a sandy soil. Soil Science Society of America Journal 43(3):429-433.

Quirk, J.P. and R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. Journal of Soil Science 6(2): 163-178.

Rhoades, J.D. 1982. Saturation extract and other aqueous extracts. pp. 168-170 In: Methods of Soil Analysis, Part 2, Monograph No. 9. American Society of Agronomy, Inc., Soil Science Society of America, Inc. Madison, WI.

Richards, L.A. (ed.) 1969. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60. U.S. Department of Agriculture. Washington, D.C. 160 p.

Rolfes, H.S., Jr. 1989. Methods of Neutralizing Cyanide in Mining Wastes and Waste Waters. M.S. Thesis, Montana State University, Bozeman, MT. 63 p.

Sachs, L. 1982. Applied Statistics. Springer-Verlag. New York, NY. 706 p.

Schafer, W.M. and T. Hudson. 1990. Land application of cyanide-containing mining process solutions. pp. 60-76 In: Fifth Billings Symposium on Disturbed Land Rehabilitation Proceedings, Vol. I. Reclamation Research Unit Publication No. 9003. Bozeman, MT.

Scott, J. 1984. An overview of cyanide treatment methods for gold mill effluents. pp. 307-330 In: Cyanide and the Environment. D. van Zyl (ed.). Colorado State University. Fort Collins, CO.

Severson, R. 1979. Regional soil chemistry in the Bighorn and Wind River Basins of Wyoming and Montana. U.S. Geological Survey Professional Paper No. 1134B. U.S. Geological Survey. Denver, CO. 9 p.

Shainberg, I. and J. Letey. 1984. Response of soils to sodic and saline conditions. Hilgardia 52(2):1-57.

Shainberg, I., J.D. Rhoades, and R.J. Prather. 1980. Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil. Soil Science Society of America Journal 45(2):273-277.

Smith, A. and D. Struhsacker. 1988. Cyanide geochemistry an detoxification regulations. pp. 275-292 In: Introduction to Evaluation, Design and Operation of Precious Metal Heap Leaching Projects. D. van Zyl, I. Hutchinson and J. Kiel (eds.). Society of Mining Engineers, Inc. Littleton, CO.

Spano, S. 1995. Personal communication. Montana Department of Environmental Quality Hard Rock Bureau. Helena, MT.

Sposito, G. 1989. The Chemistry of Soils. Oxford University Press, Inc. New York, NY. 277 p.

Stanton, M., T. Colbert and R. Trenholme. 1986. Environmental Handbook for Cyanide Leaching Projects. U.S. Dept. of Interior, National Park Service, Energy, Mining, and Minerals Division. Denver, CO. 57 p.

Suhayda, C.G., R.E. Redmann, B.L. Harvey, and A.L. Cipywnyk. 1992. Comparative response of cultivated and wild barley species to salinity stress and calcium supply. Crop Science 32:154-163.

Szabolcs, I. 1989. Salt-Affected Soils. CRC Press, Inc. Boca Raton, FL. 137 p.

Thellier, C., G. Sposito, and K.M. Holtzclaw. 1990. Chemical effects of saline irrigation water on a San Joaquin Valley soil: I. Column study. Journal of Environmental Quality 19(1):50-55.

USDA Soil Conservation Service in cooperation with Montana Agricultural Experiment Station. 1988. Soil Survey of Fergus County, Montana. Washington, D.C. 622 p.

U.S. Environmental Protection Agency Water Management Division. 1986. Heap Leach Technology and Potential Effects in the Black Hills. Contract no. EPA-68-03-6289. Denver, CO. 368 p.

U.S. Environmental Protection Agency. 1988 (revised 2/89 and 6/89). USEPA Contract Laboratory Program, Statement of Work for Inorganics Analysis. SOW No. 788. Washington, D.C.

van Genuchten, M. Th. and Wierenga, P.J. 1986. Solute dispersion coefficients and retardation factors. pp. 1025-1054 In: Methods of Soil Analysis, Part 1, Monograph No. 9. American Society of Agronomy, Inc., Soil Science Society of America, Inc. Madison, WI.

Wadleigh, C.H. and A.D. Ayers. 1945. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. Plant Physiology 20:106-132.

Wierenga, P.J. and van Genuchten, M. Th. 1989. Solute transport through small and large unsaturated soil columns. Ground Water 27(1):35-42.

APPENDICES

APPENDIX A

Data Tables

Table 22. Soil electrical conductivity at the Blue Range Mine LAD site.

Depth Interval (cm)	Electrical conductivity (dS/m)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	2.9	2.4	1.9	3.1	4.7	4.6	3.4	3.8	2.2	1.1	1.1	1.6
5-10	2.7	1.5	0.94	1.4	2.1	2.0	4.6	2.2	2.2	0.13	1.4	2.0
10-20	1.3	0.62	0.27	0.69	2.0	2.6	4.4	2.4	1.9	0.21	1.0	0.84
20-30	0.24	0.25	0.07	0.15	2.3	2.9	4.4	3.0	1.6	0.24	0.69	2.3
30-40	0.06	0.19	0.03	0.02	2.0	2.6	3.9	3.0	1.4	0.18	2.6	2.1
40-50	0.01	0.14	0.01	0.01	0.98	2.5	3.7	3.4	3.0	0.16	5.3	2.6
50-60	0.01	0.52	0.10	0.02	1.1	2.8	3.4	3.0	4.5	0.35	4.3	3.2
60-76	0.14	0.47	0.12	0.25	1.1	2.8	2.8	2.4	4.1	0.35	3.2	3.5
76-91	--	--	--	--	0.30	2.7	2.6	1.9	3.2	0.25	2.8	2.9

Table 23. Soil pH at the Blue Range Mine LAD site.

Depth Interval (cm)	pH											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	6.7	6.8	6.6	6.1	6.7	6.7	7.2	6.9	8.1	7.0	7.3	7.7
5-10	6.9	7.4	7.0	6.1	7.1	7.2	7.5	6.9	7.2	6.9	8.3	7.7
10-20	7.2	8.2	7.2	6.8	7.4	7.4	7.0	7.6	7.4	7.2	8.2	7.5
20-30	7.8	8.3	8.2	7.1	7.7	8.0	7.0	7.4	7.8	7.3	8.9	7.6
30-40	7.9	8.4	8.0	7.5	7.7	7.7	7.1	7.8	7.5	7.0	7.4	7.1
40-50	7.8	8.4	7.9	7.6	7.7	7.8	7.1	7.6	7.3	7.0	7.3	7.1
50-60	8.0	8.4	8.2	7.8	7.8	7.8	7.3	7.8	7.2	7.9	7.7	7.1
60-76	8.4	8.4	8.4	8.3	8.0	8.0	7.2	7.6	7.2	7.9	8.1	7.3
76-91	--	--	--	--	8.1	7.9	8.0	7.9	7.7	8.0	8.1	7.7

-- No sample collected at this depth.

Table 24. Soil sodium adsorption ratios (SAR) at the Blue Range Mine LAD site.

Depth Interval (cm)	SAR											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	0.09	0.08	0.08	0.12	4.2	5.0	8.1	5.5	5.5	0.33	2.0	2.3
5-10	0.12	0.09	0.12	0.11	5.4	8.6	12.1	9.3	6.8	0.84	13.5	6.4
10-20	0.12	0.14	0.22	0.14	5.0	10.7	10.4	11.2	8.9	1.3	11.3	6.2
20-30	0.15	0.22	0.24	0.27	1.7	10.8	12.6	11.4	9.3	1.3	9.6	5.6
30-40	0.23	0.19	0.33	0.33	0.73	12.4	10.5	9.3	9.9	0.86	9.6	10.3
40-50	0.30	0.24	0.34	0.54	0.22	11.5	12.8	7.0	6.8	0.30	13.0	10.7
50-60	0.29	0.14	0.23	0.37	0.23	11.4	9.0	5.0	10.0	0.20	11.3	9.5
60-76	0.27	1.9	0.21	0.36	0.08	11.5	5.6	3.6	9.1	0.21	10.1	7.2
76-91	--	--	--	--	0.05	10.0	6.7	2.2	7.6	0.24	9.5	5.6

Table 25. Soil chloride concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Chloride (mg/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	13.4	18.2	13.4	18.2	50.8	42.2	27.8	51.8	66.1	37.9	51.8	51.8
5-10	8.6	8.6	13.4	15.8	23.0	23.0	42.2	18.2	32.6	20.1	42.2	27.8
10-20	8.6	8.6	13.4	8.6	27.8	13.4	75.7	13.4	20.1	23.0	42.2	23.0
20-30	8.6	13.4	13.4	13.4	32.6	18.2	99.7	13.4	20.1	13.4	47.0	23.0
30-40	13.4	8.6	13.4	13.4	37.4	18.2	90.1	18.2	27.8	13.4	23.0	23.0
40-50	8.6	8.6	18.2	8.6	27.8	18.2	66.1	23.0	8.6	8.6	18.2	18.2
50-60	8.6	8.6	8.6	8.6	27.8	18.2	51.8	37.4	13.4	8.6	13.4	13.4
60-76	8.6	8.6	8.6	8.6	32.6	27.8	51.8	37.4	13.4	8.6	80.5	27.8
76-91	--	--	--	--	18.2	18.2	47.0	37.4	20.1	13.4	94.9	13.4

-- No sample collected at this depth.

Table 26. Soil iron concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Iron (*ug*/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	ND	ND	ND	ND	194	ND	262	ND	486	758	487	400
5-10	ND	202	ND	202	ND	ND	ND	ND	378	677	1682	2047
10-20	ND	ND	ND	ND	ND	ND	225	ND	378	400	2291	2586
20-30	ND	ND	ND	ND	ND	ND	ND	ND	ND	300	1522	ND
30-40	ND	ND	283	ND	ND	ND	ND	ND	617	387	200	ND
40-50	202	ND	ND	ND	ND	ND	ND	ND	ND	200	ND	ND
50-60	ND	ND	ND	ND	ND	ND	ND	ND	ND	250	ND	ND
60-76	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
76-91	--	--	--	--	ND	ND	ND	ND	ND	ND	ND	ND

ND Not detected (detection limit = 191 *ug*/l)

Table 27. Soil zinc concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Zinc (*ug*/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	165	535	83	175	390	173	175	109	119	134	170	201
5-10	132	172	84	151	287	208	125	100	110	115	376	147
10-20	115	108	132	142	214	199	89	149	112	154	340	543
20-30	210	325	130	129	171	151	127	144	205	170	921	117
30-40	ND	106	130	100	326	467	210	195	181	92	199	192
40-50	183	103	132	129	103	188	192	133	132	92	185	140
50-60	106	ND	84	ND	149	157	127	ND	130	ND	122	131
60-76	139	108	86	103	208	256	157	ND	92	101	129	131
76-91	--	--	--	--	107	151	164	129	119	97	ND	129

ND Not detected (detection limit = 82 *ug*/l). -- No sample collected at this depth.

Table 28. Soil sodium concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Sodium (mg/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	7.7	5.6	5.2	9.7	360	409	472	413	344	18.8	97.3	144
5-10	9.7	5.2	5.6	6.0	270	323	786	362	386	23.2	361	163
10-20	6.5	5.6	6.8	5.6	265	452	732	436	371	38.4	281	169
20-30	4.4	7.3	6.0	7.3	133	503	879	527	335	37.5	188	319
30-40	5.6	6.0	7.7	7.3	54.9	489	591	482	325	25.0	468	383
40-50	6.0	6.8	7.7	10.5	11.3	461	724	472	451	8.9	942	472
50-60	6.5	5.6	6.0	8.1	13.2	495	523	362	778	7.6	782	525
60-76	7.7	72.2	5.6	10.5	4.3	474	459	257	662	8.0	582	487
76-91	--	--	--	--	1.6	457	381	140	509	8.5	481	436

Table 29. Soil calcium concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Calcium (mg/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	373	280	240	349	381	327	162	283	161	163	115	147
5-10	356	205	140	186	165	74.2	187	78.4	132	46.4	38.2	34.3
10-20	193	115	67.7	113	185	100	255	90	84.9	59.2	33.2	42.0
20-30	56.7	68.1	41.5	46.1	371	131	286	141	79.5	58.6	22.3	175
30-40	36.3	62.4	35.6	29.6	367	101	200	182	70.5	54.1	134	86.8
40-50	23.9	54.5	32.4	22.2	170	106	207	293	290	58.3	327	120
50-60	28.2	102.0	42.6	29.6	211	127	219	330	412	99.7	319	181
60-76	46.8	96.8	43.3	54.1	206	114	191	327	360	104	214	264
76-91	--	--	--	--	67.8	143	212	276	302	81.4	166	195

-- No sample collected at this depth.

Table 30. Soil magnesium concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Magnesium (mg/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	90.8	82.0	58.9	106	105	113	59.8	88.3	83.2	48.7	39.1	88.6
5-10	64.3	42.7	16.0	34.0	16.6	20.4	80.1	21.6	66.0	6.6	9.9	9.4
10-20	23.6	11.4	5.7	10.9	15.9	21.4	71.1	15.2	27.4	5.9	8.6	9.3
20-30	5.5	7.0	4.1	6.0	43.3	21.0	49.9	12.5	11.3	5.8	4.2	45.3
30-40	4.7	6.7	3.8	4.7	40.9	10.7	24.3	15.0	7.3	6.2	29.1	11.8
40-50	4.7	6.0	3.9	4.0	13.8	9.7	21.9	31.8	25.1	6.8	44.0	17.3
50-60	5.7	10.0	4.9	3.8	19.9	9.5	23.4	36.3	30.2	8.6	27.9	30.1
60-76	7.7	9.9	5.6	6.2	19.8	8.9	19.7	30.9	27.2	7.9	22.3	48.4
76-91	--	--	--	--	7.1	9.9	21.9	24.9	23.4	6.2	16.8	34.2

Table 31. Soil copper concentrations at the Blue Range Mine LAD site.

Depth Interval (cm)	Copper (*ug*/l)											
	Pre-LAD				Post-Treatment				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
0-5	ND	3619	ND	ND	224	ND	ND	ND	659	ND	ND	ND
5-10	470	ND	ND	ND	ND	ND	378	ND	ND	ND	222	ND
10-20	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
20-30	ND	ND	367	ND	ND	ND	ND	ND	1068	ND	194	ND
30-40	ND	ND	ND	ND	ND	409	ND	ND	347	ND	ND	263
40-50	ND	ND	ND	ND	ND	ND	ND	250	ND	ND	ND	194
50-60	ND	ND	ND	ND	ND	409	ND	ND	ND	ND	ND	ND
60-76	264	ND	ND	ND	ND	318	ND	ND	ND	ND	ND	ND
76-91	--	--	--	--	ND	ND	ND	367	ND	ND	ND	ND

ND Not detected (detection limit = 191ug/l). -- No sample collected at this depth.

Table 32. Soil electrical conductivity at the A&P Mine grassland LAD site.

Depth Interval (cm)	Electrical conductivity (dS/m)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	0.59	1.1	1.5	2.5	2.2	2.0	0.44	0.50	0.43	0.39
5-10	0.36	0.42	1.2	1.7	1.5	1.6	0.24	0.29	0.45	0.21
10-20	0.22	0.39	0.81	1.2	1.3	1.3	0.30	0.29	0.25	0.33
20-30	0.20	0.40	0.68	1.2	1.3	1.2	0.28	0.29	0.18	0.40
30-40	0.20	0.22	0.97	1.2	1.3	1.1	0.47	0.44	0.25	0.41
40-50	0.17	0.20	0.82	1.2	1.2	1.1	0.45	0.34	0.31	0.33
50-60	0.18	0.21	0.82	1.2	1.2	1.1	0.41	0.26	0.52	0.30
60-76	0.19	0.26	0.68	1.2	1.1	0.93	0.37	0.19	0.70	0.21
76-91	0.26	0.24	0.61	1.1	1.1	0.87	0.29	0.17	0.51	0.18

Table 33. Soil pH at the A&P Mine grassland LAD site.

Depth Interval (cm)	pH									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	5.4	5.8	7.0	7.6	7.4	5.0	6.6	6.3	7.2	5.9
5-10	5.2	5.6	6.3	5.2	6.3	5.1	6.0	5.6	7.2	5.4
10-20	5.2	5.7	6.7	6.2	6.0	5.7	5.6	5.4	6.5	5.3
20-30	4.9	6.0	6.4	6.4	6.1	6.7	5.4	5.3	6.1	5.1
30-40	5.1	5.9	6.4	6.6	6.3	6.5	5.1	5.1	5.6	4.9
40-50	5.6	5.8	6.2	6.2	6.6	6.5	5.2	5.0	5.2	4.9
50-60	5.9	5.1	6.0	6.3	6.4	6.3	5.2	5.1	5.1	5.0
60-76	5.9	6.1	6.1	6.1	6.6	6.4	5.0	5.1	5.0	5.0
76-91	6.0	6.1	6.4	6.3	6.7	6.7	5.0	4.9	5.2	5.0

Table 34. Soil sodium adsorption ratios (SAR) at the A&P Mine grassland site.

Depth Interval (cm)	SAR									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	0.22	0.32	2.2	7.6	5.4	6.2	2.6	3.5	1.8	3.7
5-10	0.25	0.32	4.3	6.9	6.8	7.2	4.6	4.5	2.7	4.9
10-20	0.50	0.49	5.4	7.6	7.2	5.7	5.0	3.8	4.8	5.0
20-30	1.1	0.90	4.9	7.7	6.5	5.2	4.0	3.4	4.4	5.2
30-40	1.4	0.73	4.9	7.7	6.3	5.0	3.5	2.7	4.4	5.0
40-50	0.84	0.67	5.2	7.0	6.3	5.3	3.4	2.4	3.5	3.0
50-60	0.94	0.55	4.8	7.6	5.7	4.4	--	1.8	3.2	3.2
60-76	1.3	1.5	3.6	8.8	5.8	4.3	--	1.7	3.1	2.6
76-91	1.4	2.5	4.2	8.2	6.2	3.7	--	1.4	2.6	2.3

Table 35. Soil chloride concentrations at the A&P Mine grassland site.

Depth Interval (cm)	Chloride (mg/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	23.0	32.6	37.4	32.6	47.0	47.0	23.0	27.8	13.4	23.0
5-10	18.2	23.0	23.0	32.6	37.4	56.5	13.4	18.2	13.4	18.2
10-20	18.2	18.2	18.2	18.2	27.8	32.6	18.2	18.2	13.4	18.2
20-30	18.2	13.4	18.2	23.0	27.8	27.8	13.4	13.4	13.4	23.0
30-40	13.4	8.6	70.9	27.8	27.8	23.0	23.0	18.2	8.6	18.2
40-50	13.4	8.6	32.6	23.0	27.8	23.0	23.0	13.4	13.4	23.0
50-60	3.8	8.6	32.6	27.8	27.8	27.8	18.2	18.2	18.2	18.2
60-76	8.6	13.4	23.0	23.0	23.0	18.2	13.4	18.2	27.8	27.8
76-91	13.4	13.4	18.2	23.0	23.0	13.4	18.2	13.4	27.8	32.6

Table 36. Soil iron concentrations at the A&P Mine grassland LAD site.

Depth Interval (cm)	Iron (mg/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	6.6	1.1	1.8	0.80	5.1	0.47	1.2	5.0	1.3	1.8
5-10	3.0	5.3	2.3	3.2	1.5	3.1	2.0	5.4	1.2	2.3
10-20	9.2	4.8	2.5	3.7	2.0	2.0	2.0	1.8	2.2	0.76
20-30	0.98	1.4	1.4	2.1	1.5	1.9	0.80	0.80	0.95	0.71
30-40	1.1	0.69	0.47	1.8	1.6	1.9	0.80	1.2	0.69	0.43
40-50	8.4	0.91	0.23	1.4	0.74	2.7	0.76	0.66	1.0	0.69
50-60	14.4	0.53	0.44	2.0	1.2	2.0	0.95	9.9	0.41	2.0
60-76	0.79	1.3	21.7	1.7	1.3	1.4	0.52	1.7	0.46	1.5
76-91	6.2	4.7	0.44	1.6	1.2	1.9	0.88	0.76	0.76	5.6

Detection limit = 0.191 mg/l.

Table 37. Soil zinc concentrations at the A&P Mine grassland LAD site.

Depth Interval (cm)	Zinc (*ug*/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	329	253	215	183	196	506	261	318	747	ND
5-10	303	830	145	310	ND	227	261	1358	357	518
10-20	462	208	455	272	253	532	2623	443	147	624
20-30	310	487	1124	221	291	424	221	631	278	3036
30-40	672	322	424	196	265	126	312	888	170	375
40-50	614	554	360	177	566	398	221	669	159	605
50-60	468	544	1194	329	310	369	106	1206	380	159
60-76	411	468	572	113	379	232	159	363	624	255
76-91	379	862	539	273	310	312	226	312	506	278

ND Not detected (detection limit = 82 *ug*/l).

Table 38. Soil sodium concentrations at the A&P Mine grassland LAD site.

Depth Interval (cm)	Sodium (mg/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	6.3	12.3	121	261	234	221	71.1	91.0	54.5	90.5
5-10	5.9	8.5	160	183	163	191	82.9	90.4	73.2	85.9
10-20	9.4	11.5	135	139	167	144	90.7	80.3	88.0	93.5
20-30	13.8	20.6	105	145	158	125	78.5	70.9	74.6	99.3
30-40	17.2	11.0	129	141	153	114	85.2	72.6	75.4	97.8
40-50	15.3	9.9	107	134	139	116	82.4	58.9	72.6	68.0
50-60	15.8	8.0	106	137	130	92.2	76.5	49.3	84.2	68.7
60-76	15.6	22.9	90.9	141	112	82.7	62.4	41.7	96.1	54.8
76-91	22.8	32.3	80.7	132	119	69.1	55.2	35.3	76.8	50.8

Table 39. Soil calcium concentrations at the A&P Mine grassland LAD site.

Depth Interval (cm)	Calcium (mg/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	46.4	81.7	216	72.3	128	76.1	45.5	41.0	58.1	38.3
5-10	29.2	36.6	94.5	41.5	35.7	40.0	19.0	22.0	49.6	17.2
10-20	17.1	28.1	40.4	19.7	30.9	37.8	18.8	24.3	18.8	19.7
20-30	8.8	26.7	27.2	22.6	33.6	32.8	22.0	23.4	15.3	19.5
30-40	8.0	11.5	39.8	19.9	33.8	28.9	32.8	35.5	16.0	20.4
40-50	14.2	11.2	22.7	21.5	27.9	25.4	30.6	30.8	23.6	25.9
50-60	10.6	10.8	25.1	18.0	29.8	23.4	27.9	32.8	37.1	23.6
60-76	7.3	11.8	27.9	14.2	21.5	19.7	21.6	30.2	53.0	23.3
76-91	11.8	7.4	18.7	13.9	21.9	19.2	22.5	31.2	47.6	24.5

Table 40. Soil magnesium concentrations at the A&P grassland LAD site.

Depth Interval (cm)	Magnesium (mg/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole 4
0-5	10.8	20.5	10.9	10.1	8.0	11.5	6.4	6.7	5.3	4.8
5-10	7.2	9.6	6.7	7.2	4.6	7.8	3.4	5.2	4.7	3.8
10-20	5.6	7.8	4.5	3.5	6.3	7.0	3.8	5.5	4.3	4.3
20-30	2.6	8.0	4.8	2.9	6.7	6.7	4.7	5.8	3.8	4.7
30-40	2.4	3.6	8.1	3.2	6.5	6.4	8.3	10.7	4.1	5.1
40-50	6.8	3.4	5.7	3.8	5.1	6.4	8.2	9.9	5.9	7.4
50-60	6.5	3.3	6.9	4.0	5.5	6.2	10.2	13.3	9.4	6.7
60-76	1.8	3.0	12.6	3.2	4.1	5.0	12.4	9.2	13.2	6.8
76-91	4.7	3.0	5.4	3.4	3.9	4.8	13.9	8.9	10.4	8.4

Table 41. Soil copper concentrations at the A&P Mine grassland LAD site.

Depth Interval (cm)	Copper (*u*g/l)									
	Pre-LAD			Post-Treatment			Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 1	Hole 2	Hole 3	Hole1	Hole 2	Hole 3	Hole 4
0-5	ND	ND	729	287	771	203	265	234	265	343
5-10	ND	ND	483	ND	ND	ND	ND	ND	ND	ND
10-20	227	ND	624	ND	ND	ND	ND	ND	ND	ND
20-30	ND	ND	272	ND	ND	ND	ND	ND	ND	ND
30-40	ND	ND	ND	ND	ND	ND	ND	ND	ND	281
40-50	225	ND	ND	ND	ND	ND	ND	ND	ND	ND
50-60	ND	ND	ND	ND	ND	ND	ND	218	ND	ND
60-76	ND	290	ND	ND	ND	ND	ND	250	ND	ND
76-91	ND	338	ND	ND	203	ND	ND	ND	ND	ND

ND Not detected (detection limit = 191 *u*g/l).

Table 42. Soil electrical conductivity at the A&P Mine forest LAD site.

Depth Interval (cm)	Electrical conductivity (dS/m)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	0.11	0.11	0.21	0.32	0.66	0.55	0.64	0.27
0-5	0.33	0.17	0.06	0.05	0.68	0.49	0.52	0.33
5-10	0.07	ND	ND	ND	0.45	0.40	0.50	0.31
10-20	ND	ND	ND	ND	0.31	0.47	0.37	0.24
20-30	ND	ND	ND	ND	0.27	0.27	0.26	0.17
30-40	ND	ND	ND	ND	0.22	0.18	0.26	0.12
40-50	ND	ND	ND	ND	0.24	0.16	0.28	0.10
50-60	ND	ND	ND	ND	0.20	0.14	0.24	0.10
60-76	ND	ND	ND	ND	0.19	0.16	0.25	0.12
76-91	ND	ND	ND	ND	0.18	0.12	0.21	0.12

ND Not detected (detection limit = 0.01 dS/m).

Table 43. Soil pH at the A&P Mine forest LAD site.

Depth Interval (cm)	pH							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	4.5	4.9	4.4	4.3	4.5	4.5	4.6	4.7
0-5	5.2	4.9	4.5	4.8	4.5	4.6	4.6	4.6
5-10	4.9	4.8	6.3	5.2	4.6	5.0	4.6	4.9
10-20	5.2	5.1	5.3	5.4	4.7	5.3	4.6	4.7
20-30	6.1	6.0	5.7	5.9	4.8	5.1	5.0	4.9
30-40	5.6	6.5	6.3	6.1	5.0	5.2	5.1	4.9
40-50	6.3	6.7	6.5	5.9	4.9	5.2	5.4	5.0
50-60	6.0	6.8	5.9	5.9	4.9	5.1	5.1	5.2
60-76	5.9	6.6	6.4	6.1	4.9	5.3	5.1	5.0
76-91	5.6	6.3	5.9	6.0	5.1	5.5	4.8	5.0

Table 44. Soil sodium adsorption ratios (SAR) at the A&P Mine forest LAD site.

Depth Interval (cm)	SAR							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	0.22	0.23	0.13	0.17	0.26	0.11	0.19	0.32
0-5	0.27	0.30	0.28	0.31	0.21	0.24	0.29	0.12
5-10	0.38	0.32	0.35	0.28	0.20	0.13	0.13	0.15
10-20	0.35	0.43	0.53	0.37	0.41	0.15	0.19	0.25
20-30	0.34	0.76	0.73	0.46	0.28	0.23	0.15	0.21
30-40	0.47	0.75	0.46	0.49	0.32	0.42	0.38	0.23
40-50	0.58	0.53	0.38	0.42	0.33	0.28	0.38	0.23
50-60	0.69	0.47	0.39	0.49	0.25	0.33	0.38	0.41
60-76	0.62	0.48	0.65	0.44	0.35	0.32	0.28	0.75
76-91	0.66	0.62	0.42	0.46	0.31	0.36	0.41	0.84

Table 45. Soil chloride concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Chloride (mg/l)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	20.6	18.2	27.8	23.0	80.5	85.3	56.5	32.6
0-5	42.2	32.6	27.8	13.4	51.8	32.6	32.6	37.4
5-10	27.8	18.2	23.0	23.0	27.8	23.0	27.8	27.8
10-20	15.8	23.0	27.8	18.2	23.0	23.0	18.2	37.4
20-30	13.4	18.2	18.2	8.6	18.2	18.2	18.2	18.2
30-40	13.4	18.2	13.4	13.4	13.4	13.4	13.4	18.2
40-50	15.8	13.4	13.4	3.8	23.0	8.6	32.6	13.4
50-60	13.4	8.6	18.2	18.2	18.2	3.8	37.4	13.4
60-76	11.0	8.6	18.2	18.2	13.4	8.6	37.4	13.4
76-91	15.8	8.6	13.4	13.4	13.4	3.8	32.6	13.4

Table 46. Soil iron concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Iron (mg/l)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	1.4	1.1	2.3	1.4	1.8	1.0	2.2	0.87
0-5	3.0	2.0	0.95	2.9	2.0	1.5	2.3	3.7
5-10	2.3	1.2	1.3	1.3	1.5	2.1	3.3	1.2
10-20	1.2	1.1	1.7	1.3	2.3	0.65	1.7	1.0
20-30	1.9	0.95	0.43	1.0	2.6	0.81	1.9	2.5
30-40	1.3	1.2	1.4	0.82	1.5	0.61	3.4	1.3
40-50	1.7	0.47	0.53	0.43	0.90	0.83	1.3	7.1
50-60	0.99	0.43	1.4	1.6	0.53	2.1	1.1	0.25
60-76	1.2	1.0	1.7	0.92	0.83	0.85	1.8	0.23
76-91	1.8	2.0	1.8	1.1	0.85	8.23	1.5	0.63

Detection limit = 0.19 mg/l.

Table 47. Soil zinc concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Zinc (*ug*/l)							
	Pre-LAD*				Post-Precipitation**			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	543	468	388	1115	2019	2960	--	851
0-5	572	890	312	890	945	580	90	592
5-10	504	685	173	130	684	383	441	367
10-20	294	369	152	406	623	266	253	462
20-30	452	246	214	214	524	1724	201	2162
30-40	310	102	235	116	162	155	214	565
40-50	504	79	159	251	227	298	567	335
50-60	438	107	157	112	207	--	921	1026
60-76	305	146	162	110	194	--	702	221
76-91	587	205	255	82	739	--	259	511

* Zinc detection limit = 32 *ug*/l for pre-LAD samples.

** Zinc detection limit = 82 *ug*/l for post-precipitation samples.

-- No analysis due to insufficient sample volume.

Table 48. Soil sodium concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Sodium (mg/l)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	4.9	5.3	3.6	5.8	9.5	4.2	8.2	7.1
0-5	8.5	7.1	8.0	7.6	6.8	6.0	8.2	3.2
5-10	8.0	6.3	7.1	5.8	4.9	3.2	3.3	3.7
10-20	7.6	8.0	9.4	7.6	7.6	5.8	4.5	5.3
20-30	8.5	10.3	11.6	8.0	5.0	4.5	4.6	3.7
30-40	8.5	17.0	8.0	7.1	5.0	5.3	7.9	3.3
40-50	9.4	12.5	6.7	5.8	5.3	3.0	6.9	3.4
50-60	9.8	9.8	7.1	5.8	3.5	3.2	6.0	5.0
60-76	9.8	11.6	9.8	6.7	4.7	3.5	4.7	11.2
76-91	13.8	9.4	8.5	6.7	5.4	4.3	6.0	11.6

Table 49. Soil calcium concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Calcium (mg/l)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	26.93	28.32	37.08	65.79	70.78	68.41	92.83	26.20
0-5	53.90	27.72	46.77	32.58	56.80	34.57	44.44	35.30
5-10	24.77	21.12	24.29	24.09	32.76	32.22	33.85	33.12
10-20	25.46	18.68	16.36	21.22	18.91	96.17	28.83	24.99
20-30	38.58	9.74	12.56	15.08	17.59	20.40	63.09	18.25
30-41	19.05	19.70	16.64	11.94	13.41	8.69	24.81	12.63
41-51	13.01	22.65	19.05	9.49	14.05	5.94	19.90	11.23
51-61	10.87	28.02	16.36	6.04	10.61	4.49	14.84	8.98
61-76	13.91	35.18	11.67	9.61	9.85	6.52	16.61	13.57
76-91	27.92	9.66	25.26	10.16	19.07	5.65	11.85	10.92

Table 50. Soil magnesium concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Magnesium (mg/l)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	7.7	7.9	10.6	12.2	19.0	20.9	27.0	6.1
0-5	11.5	9.1	10.8	7.6	16.6	8.3	11.2	8.7
5-10	5.7	5.2	4.2	5.3	8.7	9.0	11.0	7.9
10-20	5.9	4.6	4.5	6.3	4.3	12.4	8.0	4.5
20-30	5.8	2.6	4.1	4.8	4.4	5.6	4.5	3.5
30-40	3.6	11.7	4.2	2.5	2.9	2.2	4.5	2.0
40-50	4.0	11.9	3.0	3.0	3.5	1.5	3.3	3.2
50-60	2.7	3.5	5.3	2.9	2.6	1.4	2.5	1.5
60-76	3.0	5.2	3.4	4.88	2.66	1.85	3.04	1.85
76-91	3.28	4.53	3.75	3.80	2.48	3.16	2.41	2.01

Table 51. Soil copper concentrations at the A&P Mine forest LAD site.

Depth Interval (cm)	Copper (*u*g/l)							
	Pre-LAD				Post-Precipitation			
	Hole 1	Hole 2	Hole 3	Hole 4	Hole 1	Hole 2	Hole 3	Hole 4
duff	285	754	228	ND	214	ND	328	ND
0-5	ND	1587	ND	ND	ND	ND	200	ND
5-10	ND	ND	ND	ND	ND	ND	ND	ND
10-20	ND	ND	ND	ND	ND	ND	ND	ND
20-30	ND	ND	200	ND	ND	ND	ND	ND
30-40	200	ND	ND	ND	ND	ND	ND	ND
40-50	ND	ND	ND	ND	ND	ND	228	196
50-60	ND	ND	228	ND	ND	ND	257	ND
60-76	ND	ND	200	ND	ND	ND	ND	ND
76-91	ND	271	ND	ND	ND	ND	ND	ND

ND Not detected (detection limit = 191 *u*g/l).

APPENDIX B

Statistical Tables

Table 52. Analysis of variance for electrical conductivity at the Blue Range LAD site.

Model structure: Type
Variable: Electrical conductivity

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	94	46.127			
Type	2	23.269	11.634	46.83	0.0000
Residual	92	22.858	0.24846		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	-0.6693 a*				
post-precip.	0.3455 b	1.015	11.02	7.791	0.0000
post-LAD	0.4002 b	1.070	12.49	8.832	0.0000
post-precip.	0.3455 b				
post-LAD	0.4002 b	0.05474	0.6101	0.4314	0.6672

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 53. Analysis of variance for pH at the Blue Range LAD site.

Model structure: Type
Variable: pH

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	94	0.090312			
Type	2	0.0009646	0.0004823	0.50	0.6102
Residual	92	0.089347	0.0009712		

Table 54. Analysis of variance for sodium adsorption ratio (SAR) at the Blue Range LAD site.

Model structure: Type
Variable: SAR

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	94	63.582			
Type	2	47.167	23.583	132.18	0.0000
Residual	92	16.415	0.17842		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	-0.7199 a*				
post-precip.	0.8970 c	1.617	20.72	14.65	0.0000
post-LAD	0.6504 b	1.370	18.88	13.35	0.0000
post-precip.	0.8970 c				
post-LAD	0.6504 b	-0.2466	3.243	2.293	0.0241

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 55. Analysis of variance for chloride at the Blue Range LAD site.

Model structure: Type
Variable: Chloride

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	94	8.0258			
Type	2	3.8747	1.9373	42.94	0.0000
Residual	92	4.1512	0.04512		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	1.035 a*				
post-precip.	1.420 b	0.3859	9.832	6.952	0.0000
post-LAD	1.486 b	0.4518	12.38	8.755	0.0000
post-precip.	1.420 b				
post-LAD	1.486 b	0.06594	1.725	1.219	0.2258

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 56. Analysis of variance for electrical conductivity at the A&P Mine grassland LAD site.

Model structure: Type
Variable: Electrical conductivity

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	80	8.7696			
Type	2	6.9389	3.4694	147.82	0.0000
Residual	78	1.8308	0.02347		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	-0.5521 a*				
post-precip.	-0.4883 a	0.06378	2.039	1.442	0.1533
post-LAD	0.1091 b	0.6612	20.06	14.18	0.0000
post-precip.	-0.4883 a				
post-LAD	0.1091 b	0.5974	21.66	15.32	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 57. Analysis of variance for pH at the A&P Mine grassland LAD site.

Model structure: Type
Variable: pH

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	80	0.19947			
Type	2	0.07210	0.03605	22.08	0.0000
Residual	78	0.12737	0.001633		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	0.7494 a*				
post-precip.	0.7346 a	-0.01480	-1.794	-1.269	1.792
post-LAD	0.8016 b	0.05226	6.010	4.250	0.0000
post-precip.	0.7346 a				
post-LAD	0.8016 b	0.06706	9.218	6.518	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 58. Analysis of variance for sodium adsorption ratio (SAR) at the A&P Mine grassland LAD site.

Model structure: Type
Variable: SAR

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	80	12.116			
Type	2	9.6508	4.8254	152.67	0.0000
Residual	78	2.4654	0.031607		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	-0.1420 a*				
post-precip.	0.5062 b	0.6482	17.86	12.63	0.0000
post-LAD	0.7962 c	0.9382	24.52	17.34	0.0000
post-precip.	0.5062 b				
post-LAD	0.7962 c	0.2900	9.061	6.407	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 59. Analysis of variance for chloride at the A&P Mine grassland LAD site.

Model structure: Type
Variable: Chloride

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	80	2.8412			
Type	2	1.0622	0.5311	23.29	0.0000
Residual	78	1.7790	0.022808		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	1.132 a*				
post-precip.	1.255 b	0.1234	4.003	2.830	0.0059
post-LAD	1.435 c	0.3033	9.334	6.600	0.0000
post-precip.	1.255 b				
post-LAD	1.435 c	0.1799	6.618	4.680	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 60. Analysis of variance for electrical conductivity at the A&P Mine forest LAD site.

Model structure: Type
Variable: Electrical conductivity

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	79	46.646			
Type	1	32.624	32.624	181.48	0.0000
Residual	78	14.022	0.17977		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	-1.871 a*				
post-precip.	-0.5933 b	1.277	19.05	13.47	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 61. Analysis of variance for pH at the A&P Mine forest LAD site.

Model structure: Type
Variable: pH

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	79	0.2091			
Type	1	0.070598	0.070598	39.76	0.0000
Residual	78	0.1385	0.0017757		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	0.7501 b*				
post-precip.	0.6907 a	-0.05941	-8.917	-6.305	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 62. Analysis of variance for sodium adsorption ratio (SAR) at the A&P Mine forest LAD site.

Model structure: Type
Variable: SAR

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	79	3.3600			
Type	1	0.71843	0.71843	21.21	0.0000
Residual	78	2.6415	0.033866		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	-0.3859 b*				
post-precip.	-0.5754 a	-0.1895	6.514	4.606	0.0000

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

Table 63. Analysis of variance for chloride at the A&P Mine forest LAD site.

Model structure: Type
Variable: Chloride

Source	DF	Sum of Squares	Mean Square	F-value	P-value
Total	79	4.9365			
Type	1	0.24484	0.24484	4.07	0.0471
Residual	78	4.6916	0.060149		

Multiple means comparison--Treatment means with differences and t-tests for all pairs:

Type	Mean	Difference	Q-value	T-value	P-value
Control	1.213 a*				
post-precip.	1.324 b	0.1106	2.853	2.018	0.0471

* Means followed by the same letter are not significantly different ($p \geq 0.1$).

MONTANA STATE UNIVERSITY LIBRARIES
3 1762 10238476 3