REVEGETATION OF STREAMBANK TAILINGS ALONG SILVER BOW CREEK, MONTANA[1]

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Abstract: This study was an assessment of in-place chemical immobilization of metal contaminants in mine wastes followed by revegetation as a potential remedial alternative for clean-up of a Superfund site. This six year treatability study evaluated the use of different amendments, various incorporation techniques, and selected plant species in both laboratory/greenhouse tests and at five waste/contaminated soil locations along Silver Bow Creek between Butte and Opportunity, Montana.

Amendments (mainly calcium hydroxide and calcium carbonate) found in the laboratory to be most effective in controlling pH and metal solubility of these acid producing metalliferous wastes were mixed with the wastes/soils in replicated greenhouse trials. Amendments and selected plant species were combined into replicated field trials using different incorporation techniques. Vegetation response, components of the soil chemistry, and soil hydrology were measured and differences among treatments were assessed.

Data support coversoil as the most effective treatment, but coversoils are not available in quantities adequate for the rehabilitation of all the disturbances along silver bow Creek. Pressure injection of lime slurry into the wastes did not provide an adequate rootzone for long-term plant growth. Agricultural tilling of amendments provided only 15 cm of adequate rootzone materials. A plow capable of mixing waste to a depth of 122 cm provided an ameliorated rootzone that varied from 30 to 60 cm deep. Plant cover and production were greater on deep-plowed plots than on plots prepared by the two other incorporation techniques. Deeper root penetration was also found in the deep-plowed plots than in plots treated by agricultural tillage or the injection technique. Surface runoff was markedly reduced and surface water quality improved by all treatments.

Additional Key Words: revegetation, tailings, metals immobilization.

Introduction

Superfund cleanup requires that various alternatives for amelioration of the problem be evaluated. The accumulations of wastes from mining and mineral processing along Silver Bow Creek near Butte and Anaconda, Montana have been declared a series of Superfund Sites. One of the potential remedial activities proposed for the Silver Bow ecosystem is the insitu neutralization and stabilization of these wastes. The Reclamation Research Unit evaluated the use of soil amendments, incorporation techniques, and selected species of plants as potential remedial strategies to correct this pollution problem. Over 35 amendments were evaluated for their ability to correct waste pH and reduce metal solubility. These amendments ranged from industrial wastes to locally mined limestone. The most effective amendments ($CaCO_3$ and $Ca(0H)_2$) were utilized in greenhouse trials of the performance of different grasses and forbs in neutralized wastes. The amendments and plant species were combined into a field trial of different amendment incorporation techniques.

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Remediation of flood deposited wastes along the Silver Bow Creek channel and floodplain with innovative, low cost, insitu techniques was the goal of this study. The approach was a treatability study involving the chemical neutralization and fixation of contaminants by mixing amendments into the wastes and revegetation with acid, metal, and drought tolerant species of vegetation. The soil amendments would neutralize the acidity of the waste, reduce mobility of metals, and reduce the toxicity of the materials. The vegetation would reduce transient dust, water erosion, and surface water runoff. It would also harvest water in the soil profile.

Study Description

This treatability study consisted of three phases. Phase One was composed of laboratory and greenhouse investigations. Phase Two was the field implementation of the information gained in Phase One. Phase Three consisted of the monitoring phase.

Phase One - Laboratory and Glasshouse Investigations

Existing data and contaminated soils along Silver Bow Creek were reviewed by the investigators. From this mass of data and actual visits to the area 35 unique contaminated sites were identified. They were believed to represent the range of contaminated wastes and soils in the ecosystem. A 150 to 200 kg waste or soil sample was collected from each of these sites. These samples were prepared and analyzed for chemical and physical characteristics. Statistical analysis separated the 35 sites into six groups of similar materials. Six sites were selected as representative of all of the types of wastes/contaminated soils in the study area.

Candidate amendments were selected from both traditional and innovative materials. The amendments were evaluated on their ability to raise waste pH, reduce the solubility of metals, availability of the amendment, and cost. Materials evaluated included calcium carbonate (agricultural lime), cement kiln dust, calcium chloride, calcium hydroxide, calcium oxide, power plant flyash, sugarbeet waste, gypsum, zeolite, triple superphosphate, fluoro-phospho silicate, phosphogypsum, ferric sulfate, phosphate ore, and several organic amendments. After chemical and physical characterization the amendments were mixed with the wastes. Waste/amendment reactions were measured in specially designed reaction flasks.

Soluble metals and pH were measured in the effluents from these modified reaction flasks (Tempe Cells). The leached and amended wastes were also analyzed. Combinations of calcium carbonate, calcium hydroxide, phosphogypsum, iron sulfate, calcium chloride, and triple superphosphate performed best and were studied in the glasshouse segment of Phase I.

An equation for the quantity of calcium compound required for each material was developed:

$$\text{t CaCO}_3/1000 \text{ t Soil} = 1.25\,(A + B)$$

where t = tons
A = Potential Acidity
B = Active Acidity
Potential Acidity = 31.25 (% HNO_3 S + Residual S) + 23.44 (% HCl S)

where S = sulfur content extracted from or remaining in the sample
Active Acidity = SMP Buffer Test

The use of calcium carbonate alone did not raise the pH fast or high enough to permit seeding within a reasonable amount of time. It was found that portioning the liming rate into 60% calcium carbonate and 40% calcium oxide rapidly raised the pH and reduced metal toxicity. All amendments used in the glasshouse experiments were composed of these two calcium sources.

Plant species used in the greenhouse trials were selected on the basis of their ability to tolerate acidic soil conditions, nutrient deficiencies and the climatic conditions at the Silver Bow Creek site (Reclamation Research Unit et al. 1989). In addition, some species were selected for site specific characteristics such as elevated salinity or textural extremes. Finally, all species were screened for commercial availability. Seventeen species and two cultivars of two species were grown in amended tailings in the greenhouse.

At the termination of the greenhouse growth period, the plants were evaluated for vigor, height, color, root growth, and production (Reclamation Research Unit et al. 1989). Plant tissues were also analyzed for metal levels. Livestock and wildlife toxicities from elevated metal levels were thought to present a concern if the area is revegetated. In the plant tissues analyzed, concentrations of boron, calcium, and lead were comparable to tissue levels in nonpolluted areas of Montana. Cadmium, copper, manganese, and zinc were elevated compared to background levels in Montana but these concentrations would not be toxic to any grazers and they were not phytotoxic. Aluminum and arsenic levels were higher than most background values in the literature, but they would not be toxic to animals. The higher aluminum values were high enough to indicate some plant growth inhibition. Metal loading in and on plants grown in the field were much higher. These data are discussed later in this paper.

Phase II: Field Implementation

Although six unique groups of contaminated materials were identified in Phase I of this investigation, only five sites were included in Phase II (Table 1). One of the original waste types was contaminated agricultural lands. This group of waste materials was not included in the Phase II study. Sites selected for Phase II study were:

a. Site 2: in place tailings, fine textured, saline, and extremely acid.

b. Site 33: fluvially deposited mixture of tailings, waste, and soil; streamside deposit of extremely acid and very saline waste.

c. Site 7: fluvially deposited, streamside, sandy, very acid waste.

d. Site 21: a large expanse of fluvially deposited, streamside, finer textured, very acid wastes.

e. Site 27: flood affected pasture, acid soil.

To mix the amendments selected during Phase I studies with the contaminated materials, four or five different incorporation techniques were evaluated at each Phase II study site. Treatment 1 involved use of a standard moldboard plow. This instrument tilled the land to a depth of 15 to 20 cm. Treatment 2 involved deep (1.2 m) mechanical plowing of amendments into tailings with a plow pulled by a D8-H Caterpillar tractor. An aqueous slurry of lime was pressure injected 1.2 m into the waste as Treatment 3. Treatment 4 was a topsoil wedge (0 to 45 cm). A control plot was also maintained at each site. Fertilizer was applied prior to seeding and was rototilled into the rooting media as part of the seed bed preparation program.

Seeding recommendations were based on the greenhouse evaluations. Two seed mixtures were developed for each site. All of the sites were mulched after seeding.

Phase III: Monitoring and Evaluation

The purpose of the Phase III monitoring program was to measure the effectiveness of the treatments to abate contaminant movement and reduce the phytotoxicity of the tailings. This was accomplished by 1) measuring soil chemical, physical, and hydrologic properties, and evaluating plant performance at each site; and then 2) comparing data collected at each treatment to determine relative differences in measured parameters. Treatment effectiveness may be inferred from these data. Specific data collection needs were:

Table 1. Type and characteristics of streambank wastes, effective amendments, and successful vegetation found in Phase I.

Tailings/Waste Type	General Characteristics (Range or Mean)	Effective Laboratory Amendments and Rates (tons/1000 tons waste)	Successful Greenhouse Vegetation	Representative Field Site
In-Place Tailings (Man-made ponds)	pH 2.7 - 4.2 EC 4.9 - 6.7 mS/m As 1000 mg/kg Cu 4500 mg/kg Zn 10000 mg/kg	$Ca(OH)_2$ 13.2 $CaCO_3$ 50.5 $Fe_2(SO_4)_3 \cdot 7 H_2O$ 2.0	Altai wildrye (*Elymus angustus* Prairieland) Pubescent wheatgrass (*Agropyron trichophorum)* Tall wheatgrass (*Agropyron elongatum* Orbit)	Site 2, Manganese Stockpile
Class 1 (Fluvially deposited)	pH 3.0 - 4.0 EC 2.0 - 5.0 mS/m Coarse 50 - 85% Silt 10 - 30% As 250 mg/kg Cu 1200 mg/kg Zn 1200 mg/kg	$CaCO_3$ 56.1 Phosphogypsum 5.0	Western wheatgrass (*Agropyron smithii* Rosana) Basin wildrye (*Elymus cinereus* Magnar) Pubescent wheatgrass (*Agropyron trichophorum* Luna) Altai wildrye (*Elymus angustus* Prairieland)	Site 33, Opportunity
Class 2 (Fluvially deposited)	pH 3.5 - 4.5 EC 0.5 - 2.5 mS/m Coarse > 85% Silt < 10% As 80 mg/kg Cu 250 mg/kg Zn 1200 mg/kg	$CaCO_3$ 39.9 Phosphogypsum 5.0	Canadian bluegrass (*Poa compressa* Common) Mammoth wildrye (*Elymus giganteus* Volga) Tufted hairgrass (*Deschampsia caespitosa)*	Site 7, Rocker
Class 3 (Fluvially deposited)	pH 3.5 - 5.5 EC 4.0 - 12.0 mS/m Coarse < 50% Silt > 30% As 1000 mg/kg Cu 2500 mg/kg Zn 4000 mg/kg	$Ca(OH)_2$ 17.7 $CaCO_3$ 35.7 $Fe_2(SO_4)_3 \cdot 7 H_2O$ 2.0	Tall wheatgrass (*Agropyron elongatum* Orbit) Saltgrass (*Distichlis spicata)* Basin wildrye (*Elymus cinereus* Magnar) Western wheatgrass (*Agropyron smithii* Rosana)	Site 21, Ramsay Flats
Flood Affected Lands	pH 4.4 - 5.3 EC 0.3 - 5.0 mS/m As 250 mg/kg Cu 200 mg/kg Zn 20 mg/kg	$Ca(OH)_2$ 3.3 $CaCO_3$ 16.6 TSP 1.1	Basin wildrye (*Elymus cinereus* Magnar) Crested wheatgrass (*Agropyron cristatum* Ephraim)	Site 27, Fairmont

a. soil chemical properties, contaminant solubility and bioavailability,
b. erosion (soil loss),
c. dissolved and total metal concentrations in surface runoff,
d. metal cation and anion concentrations in soil pore water,
e. metal loadings in forage plants, and
f. performance of seeded vegetation.

Soil Chemical Monitoring

Wastes were collected from various depths within the profile three growing seasons after amendment. Soil pH, EC, and concentrations of soluble metals were measured in the aqueous extract of a saturated paste prepared from amended tailings/soils. Levels of bio-available metals were determined in extracts of ammonium acetate (pH 7.0), bio-available arsenic was measured in Bray P-1 extracts of the wastes. Samples were collected within a plot and adjacent to the plots. The offsite plot samples represent the pre-treatment condition and no action alternative. Total metal levels were determined in all samples. The degree of soil-amendment mixing was evaluated during the last year of the study by spraying a pH indicator dye on the face of excavations made to a depth of 2.1 m in several plots. Results of these and other monitoring activities not reported in this text may be found in the final report on this activity (Schafer and Associates and Reclamation Research Unit 1993).

Figure 1 exhibits pH response to the treatments at Site 2 (Manganese Stockpile) and Site 7 (Rocker). At Site 2, Manganese Stockpile (Figure 1, top), the pH values of the materials in the treated plots were much higher than the control plot wastes, especially for the upper depth increments. At a tailings depth of approximately 40 cm, wastes treated by agricultural tillage revealed a similar mean pH to the untreated materials. In contrast, wastes amended with lime using the two deep incorporation techniques exhibited elevated mean pH levels throughout the profile.

At Site 7 mean pH levels of the upper amended wastes (0 to 15 and 15 to 30 cm) were elevated compared to the mean value of the control plots. Low pH levels were encountered below the zone of incorporation for the agricultural tillage treatment. At the deepest profile depths, the pH of the control, deep plow and injected treatment plots were all similar. These depths were below the amendment incorporation zone and the relatively high pH values most probably indicate these materials were natural soils - not effected by the overlaying mine waste materials. Similar patterns of pH, depth of treatment, and depth to natural soils were exhibited at the other three sites.

Mean water soluble metal levels in the upper 15 cm of the wastes/soils are shown for four of the sites in Figure 2. In general, concentrations of water soluble Cd, Cu and Zn were reduced by orders of magnitude compared to the control plot levels. Concentrations of Pb were slightly reduced, but levels of As were enhanced, especially at Sites 21 and 27. This increased As mobility is clearly exhibited in Figure 3 (top). Only slight (nonsignificant) increases in As levels were found in the lower profile depths. In contrast to the increased As availability, the decreased concentration of soluble Cu is displayed in Figure 3 (bottom).

Vegetation Monitoring

Plant performance on the plots was inferred from measurements of species areal cover, production, rooting depth, and metal levels. Areal cover permitted the researchers to make generalizations about the effectiveness of the vegetation to reduce leaching, surface runoff, and fugitive dust. Plant production data enabled the research team to draw some inferences about the ability of the seeded communities to support grazing animals. Depth of root penetration provided evidence of long term plant survival in these amended

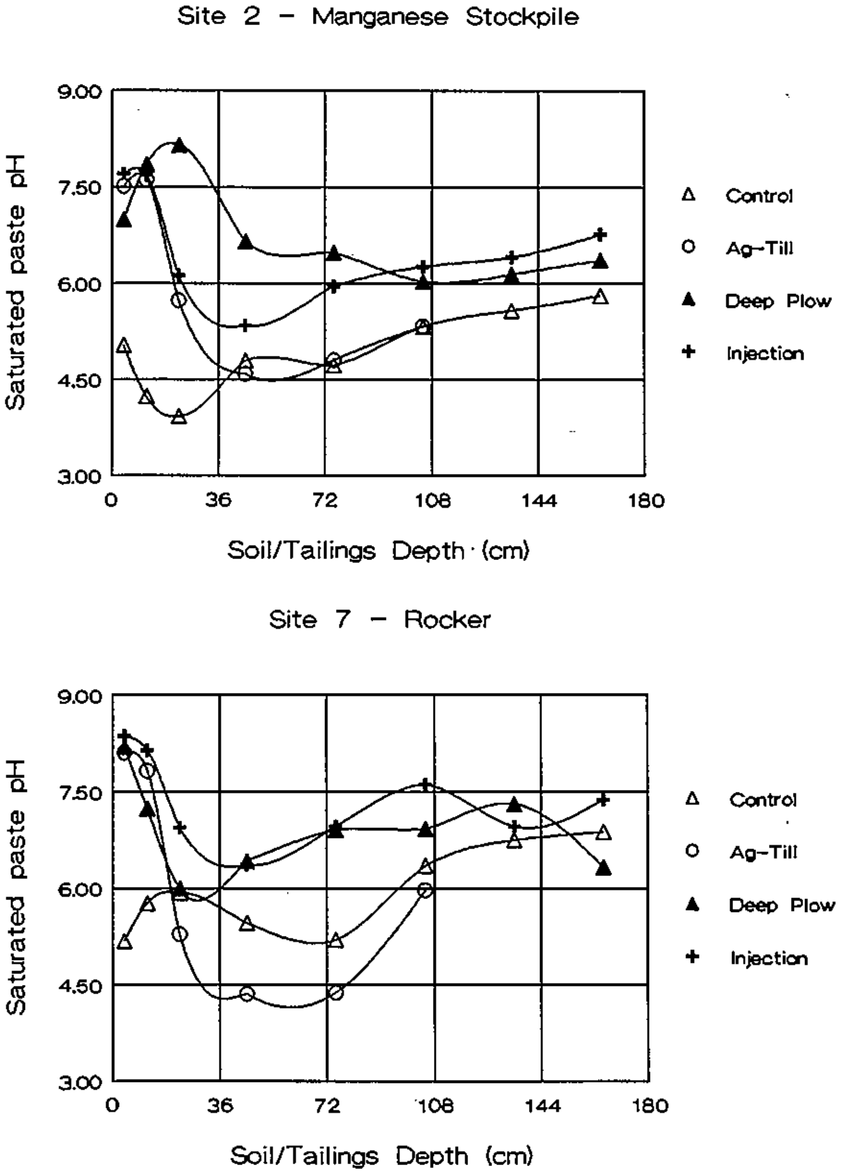
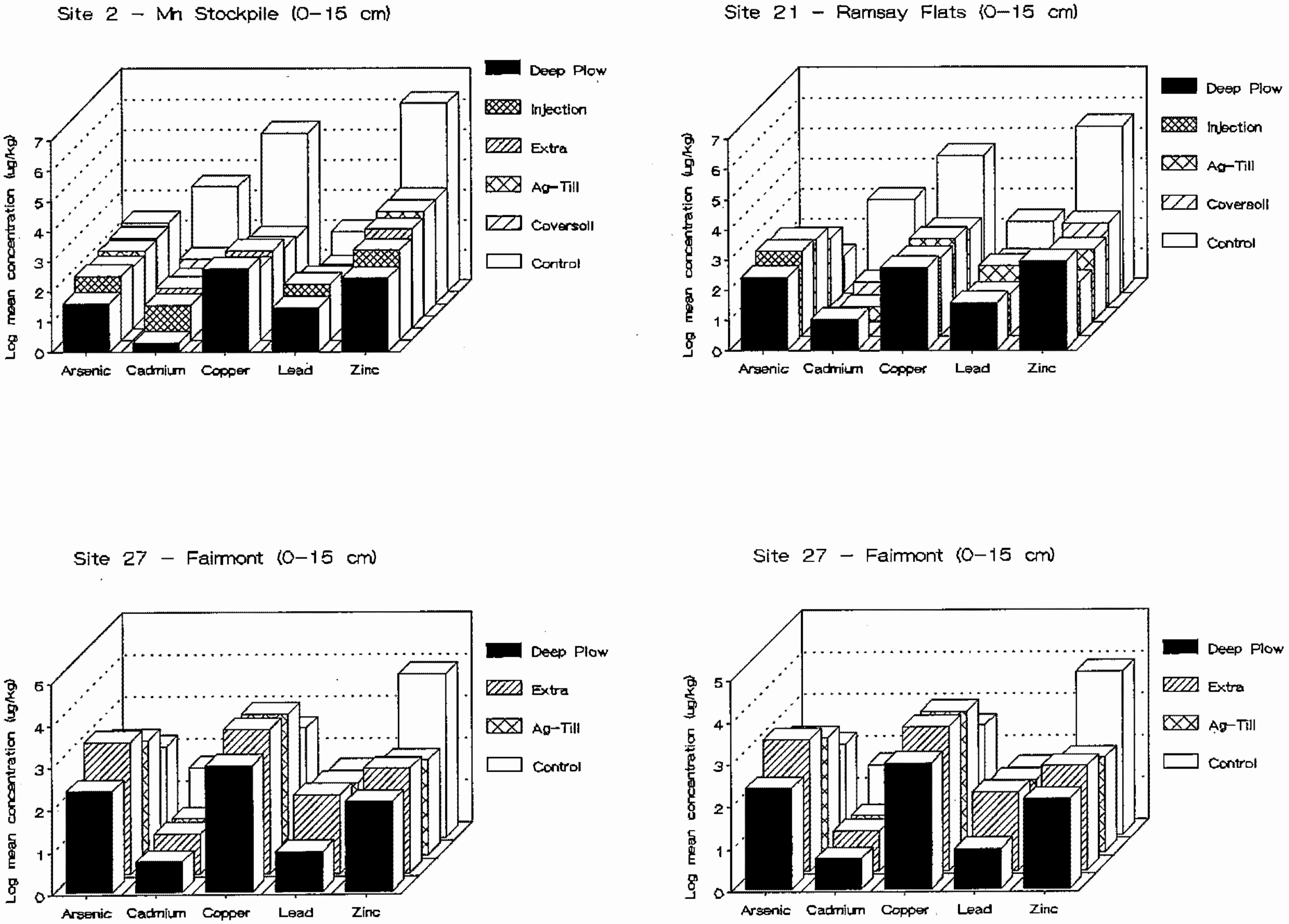


Figure 1. Saturated paste pH levels and tailings/soils depth for Sites 2 (top) and 7 (bottom).

materials. When compared to soil metal levels, plant metal levels indicate whether plants are accumulating metals, possibly passing them into food chains, or simply excluding them from plant tissues.

At Site 2 all plants seeded directly into the amended wastes died by the third growing season. This site was considered the most difficult of the revegetation study sites. Pre-treatment metal levels in the waste material were very high (Table 1), salinity was elevated, and the site exhibited poor drainage. In terms of the remedial activities investigated in this study, insitu neutralization and revegetation will not be possible in these materials. Some other type of amendment may be attempted or the wastes must be removed from the site.

Response, in terms of vegetation performance at the other four sites, was variable but generally indicated that the toxic properties of the soils had been ameliorated sufficiently to permit plant growth and soil stabilization. The following discussion pertains only to the other four sites examined in this study.



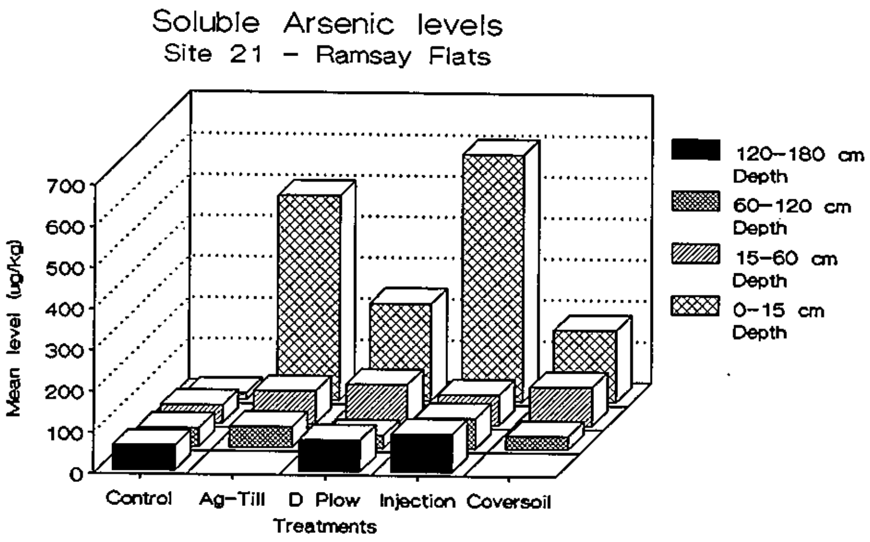
Site 2 – Mn Stockpile (0–15 cm)

Site 21 – Ramsay Flats (0–15 cm)

Site 27 – Fairmont (0–15 cm)

Site 27 – Fairmont (0–15 cm)

Figure 2. Mean water soluble soil (0-15 cm) metal and As levels for Sites 2, 21, 27 and 33.



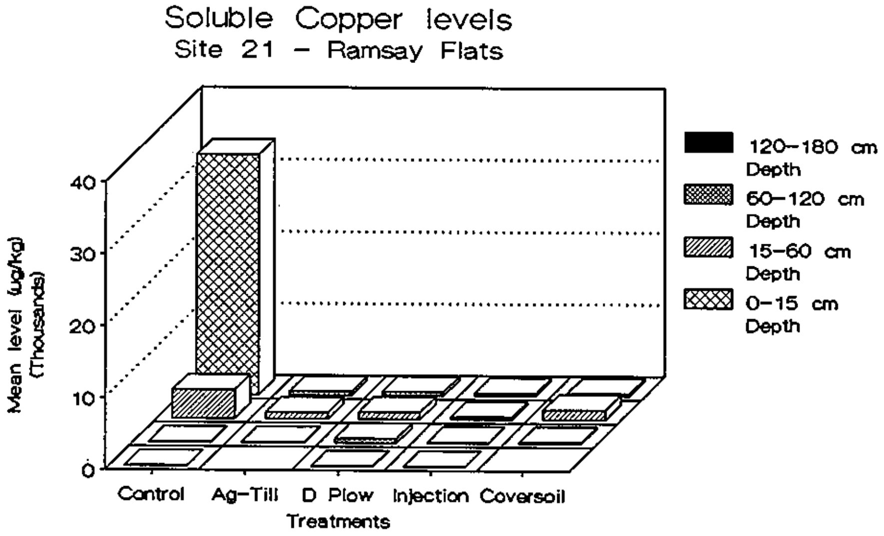


Figure 3. Mean water soluble soil As (top) and Cu (bottom) levels at Site 21 arranged by profile depth and treatment.

At every site, vegetation production and cover on the Control plots was significantly lower than the same parameters on the amended plots. When these two parameters were measured on the Coversoil Wedge they were usually comparable to these same parameters on the Deep Plowed treatment.

To designate the plant species that performed well on each waste type, Importance Values (IV) were generated. They were calculated (relative % cover + relative % production) for the most common seeded species on each plot (Table 2). This number provides an objective, data based measurement of the importance of each species based on cover and production. Long-term survival of these species cannot be determined from these data, however, only short term survival data are available at this time.

Metal levels in or on nonwashed plant tissues were very high at Site 21 (Table 3). It may be inferred that these metal levels are on rather than in the plant tissues since plant performance was very good on this site. Metal levels in and on plants at Sites 7, 27, and 33 were generally within ranges recommended for livestock consumption. Cadmium was the notable exception. This element is absorbed rather readily by plants and concentrations often exceeded recommended tolerances for livestock consumption.

Table 2. Species exhibiting highest Importance Values.

Site	Species	Overall Rating[1]
7	Mammoth wildrye	109.2
	Altai wildrye	103.2
	Thickspike wheatgrass	36.4
21	Tall wheatgrass	184.9
	Intermediate wheatgrass	125.3
	Russian wildrye	59.5
27	Desert wheatgrass	144.9
	Crested wheatgrass	101.3
	Russian wildrye	72.8
33	Altai wildrye	103.7
	Basin wildrye	51.8

[1] Grand mean of Importance Values.

Table 3. Comparison of mean elemental levels (mg/kg) in dominant vegetation collected (July 1991) from Site 21.

	Treatment				SE Montana
Element	Agricultural Tillage	Deep Plow	Slurry Injection	Topsoil	Western Wheatgrass[2] (*Agropyron Smithii*)
	Tall wheatgrass (Agropyron elongatum)				
Aluminum	316.0 AB[1]	384.0 B	302.0 AB	74.0 A	5 to 50
Arsenic	26.1 AB	33.2 B	21.9 AB	4.3 A	<1 to 2
Cadmium	2.0 B	1.7 AB	1.5 AB	0.61 A	0.01 to 0.1
Copper	278.0 B	247.0 AB	216.0 AB	63.9 A	2.5 to 4.5
Lead	30.5 AB	60.6 B	25.1 AB	5.4 A	1.0 to 2.0
Manganese	917.0 B	672.0 AB	512.0 A	320.0 A	25 to 65
Zinc	750.0 B	541.0 AB	393.0 A	249.0 A	12 to 21
	Intermediate wheatgrass (*Agropyron intermedium*)				
Aluminum	311.0 B	266.0 B	286.0 B	48.4 A	
Arsenic	21.7 B	22.3 B	26.6 B	3.1 A	
Cadmium	1.9 B	1.6 AB	2.1 B	0.57 A	
Copper	228.0 B	196.0 AB	268.0 B	59.5 A	
Lead	28.3 B	38.2 B	29.7 B	3.5 A	
Manganese	790.0 B	622.0 B	677.0 B	243.0 A	
Zinc	589.0 B	491.0 AB	575.0 B	195.0 A	

[1] Multiple mean comparison based on LSD at significance level of 0.05. Means followed by same letter in *rows* are not different.

[2] Al and As estimated from the literature; Cd, Cu, Pb, Mn, and Zn from Munshower et al. 1987).

Plant root penetration into the waste varied by treatment and site. Table 4 summarizes the plots opened to measure this plant parameter. The deep plowed plots supported the deepest roots and the agricultural treatment contained the most shallowly rooted plants. Roots at the interface of the amended material and the non-amended waste were growing laterally in many of the agricultural treatments and had ceased downward penetration of the wastes. This was not evident in the deep plowed treatments. Roots generally were found deeper in these soils and were still growing downward.

Soil Hydrology Monitoring

Because of the expense of hydrologic monitoring only one plot in each replicated block on each waste type was instrumented. This reduced statistical validity of the sampling but permitted the researchers to gain some understanding of the impact of treatments on ground water quality. Hydrologic monitoring equipment installed at the sites included one neutron access tube, a piezometer, and up to three nested pore water samplers. In addition a climate station was installed at Site 21 and precipitation gauges at the other sites. A complete discussion of this program is not possible within the confines of this paper but this information is available in the final report for this study (Schafer and Associates and Reclamation Research Unit 1989).

It has been assumed that amendment of the wastes and vegetation growth will increase infiltration, water harvest, and reduce erosion of surface materials. During the third growing season simulated rainfall was applied to several plots to evaluate this phenomenon. Precipitation rates were 5 cm/hr for two hours. Runoff at three sites was collected, measured, and elemental levels in the runoff water determined.

After amendment and plant growth the coarse textured material at Site 7 had relatively little runoff. Both of the treatments, deep plow and agricultural plow, yielded insufficient runoff for chemical analyses. Runoff at Site 21 (Table 5) was adequate from all treatments for the analytical determination of the elemental

Table 4. Depth of root penetration in study site soils.

Site	Treatment	Depth of Root Penetration (cm)	Comments
33	Agricultural plow	20	Lateral growth at amended soil/waste interface
	Slurry injection	20	
		35	Rhizomes of Distichlis spicata
	Deep plow	38, 38	Vertical growth still evident (two pits)
7	Deep plow	25, 25	Vertical growth still evident.
21	Agricultural plow	17, 15	Lateral growth at amended soil/waste interface.
	Slurry injection	20, 17.5, 27.5	
	Deep plow	38	Vertical growth still evident.
27	Agricultural plow	17.5	
	Deep plow	30	Vertical growth still evident.
	Agricultural plow w/ supplemental PO_4 amendment	15, 20	

Table 5. Contaminants in runoff water from simulated rainfall[1] tests, Site 21 (Ramsay Flats).

	Treatment and Total Runoff Volume				
Analyte Mass (mg)	Ag-Till (2.84 l)	Control (20.15 l)	Deep Plow (7.00 l)	Injection (16.10 l)	Coversoil (0 l)[2]
Arsenic					
Dissolved	0.11	1.08	0.33	1.48	0
Copper					
Total	34.1	676	11.6	73.2	0
Dissolved	0.41	579	2.8	0.78	0
Iron					
Total	119	1200	38.2	222	0
Dissolved	0.17	4.32	0.13	0.50	0
Manganese					
Total	37.6	2120	56.7	73.5	0
Dissolved	14.2	2050	52.1	6.87	0
Zinc					
Total	46.5	1680	30.5	83.9	0
Dissolved	1.46	1590	20.47	0.41	0

[1] Simulated rainfall rate was 5 cm/hour for a period of 2 hours.

[2] No runoff was obtained from coversoil treatment plot.

levels. Results of the analyses support the hypothesis that amendment application will reduce contaminant concentrations entering surface waters.

Conclusions

This study demonstrated that flood deposited mine and mill wastes in the Silver Bow watershed may be rehabilitated by the addition of amendments and seeding appropriate vegetation. The chief problem continues to be the question, how to incorporate the amendments to a depth sufficient to maintain a healthy plant community. In this investigation the deep plow provided the deepest mixing of amendments into the rootzone and better stands of vegetation compared to other treatments.

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