RECLAMATION EFFECTIVENESS AT THREE RECLAIMED, ABANDONED MINE SITES IN JEFFERSON COUNTY, MONTANA[1]

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Abstract: Montana has an estimated 6000 abandoned mine sites, many with associated waste rock and tailings materials contributing to the release of high levels of acidity, heavy metals, and other contaminants, creating a risk to human health and the environment. Many abandoned mine sites in Montana have been reclaimed, however, little post-reclamation monitoring has been performed, and the effectiveness of reclamation has not been quantified. The goal of this project was to quantify the effectiveness of reclamation at three sites in Jefferson County, Montana based on soil suitability for sustaining plant growth. Vegetation and soil studies were executed using a stratified random sampling design. Vegetation measurements included canopy cover using Daubenmire cover classes, above ground biomass, and species richness/diversity. Co-located soil samples were excavated in increments to a depth of 60 cm, and analyzed for pH, electrical conductivity, nutrients, soluble, and total metals. Canopy cover estimates ranged from 0-120% and biomass production estimates ranged from 0-4583 kg ha^{-1}. Differences in species richness and diversity were observed between sample strata. The chemical properties of the soil varied greatly, with pH values ranging from 2.08 - 7.63, and soluble metal values ranging from <0.1-1001 mg l^{-1} for Zn, .02-20.81 mg l^{-1} for Cu, <.01-7.39 mg l^{-1} for Cd, <.05-12.26 mg l^{-1} for As, and <.1-7.6 mg l^{-1} for Pb. Sum of total metal and arsenic (As, Cu, Pb, and Zn) concentrations ranged from 133-81448 mg kg^{-1}. Associations between vegetation and soil chemistry were determined using correlation and analysis of variance (ANOVA). Significant correlations between biomass production and pH, between canopy cover and pH, and between canopy cover and total metal levels were found. Strong correlation between nutrient data and vegetation response was also found. The results of this study will be used to determine possible maintenance that needs to be done at the study sites, as well as aid in future remedial design.

Additional Key Words: abandoned mine lands, reclamation, monitoring, soil chemistry, heavy metals.

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Introduction

Historic hard-rock mining in Montana has left over 6000 abandoned or inactive mine sites, each with associated waste materials posing a threat to human health and the environment (Montana Department of State Lands/Abandoned Mine Reclamation Bureau (MDSL/AMRB), 1995). Environmental problems associated with these sites include soil and water contamination from heavy metals and other contaminants. By 1991, the Montana Department of State Lands/Abandoned Mine Reclamation Bureau (MDSL/AMRB) had concluded that imminent danger to human life had been eliminated at most mine sites in Montana; however, limited progress had been made in reducing the effects of contamination to surface and ground waters (MDSL/AMRB, 1995). In 1993 and 1994, 331 abandoned mine sites considered to have the highest hazard potential were inventoried and ranked based on severity of environmental hazards. Many of these sites had limited vegetation cover or were completely devoid of vegetation. Although reclamation of these sites began in the mid 1990's, little post-reclamation monitoring has been performed and reclamation effectiveness has not been quantified.

The purpose of this investigation was to quantify the effectiveness of riparian zone reclamation at three mine sites in Jefferson County, Montana based on soil suitability for sustaining plant growth. The primary objectives of this project were 1) to delineate whether variations in vegetation production and cover are related to soil chemistry; 2) to identify plant species that are colonizing the reclamation sites compared to the seed mix used; and 3) to identify which removal method has been most effective along High Ore Creek.

Study Area/Site Descriptions

The sites chosen for this project were the Gregory Mine, the Comet Mine, and High Ore Creek. All are located in Jefferson County, Montana, and lie within the Boulder Batholith (DEQ/MWCB, 2001). The main ore body consists of lenses, veins, and replacement bodies of chalcopyrite, pyrite, arsenopyrite, sphalerite, and galena (DEQ/MWCB, 2001). Mineralized veins were heavily mined in Montana beginning in the late 1860's, continuing through the present. The closest weather stations to all three sites are in Boulder and Basin, Montana, where average temperature ranges of 26 ^{o}C to 7 ^{o}C in July and 0 ^{o}C to -12 ^{o}C in January have been recorded. The average precipitation in these areas is approximately 30-36 cm yr^{-1}, with significantly higher rainfall levels in the surrounding mountains (DEQ/MWCB, 2001). Table 1 outlines the specific details for each site in terms of location, rank, and reclamation year. Arsenic, cadmium, copper, manganese, lead, and zinc were the contaminants of concern at these sites. Observed releases of these contaminants into surface waters occurred prior to reclamation, many exceeding Montana clean water standards for acute and chronic exposure to aquatic life (DEQ/MWCB, 1996). Removal of contaminated materials followed by replacement with non-contaminated soil was the reclamation method at the Comet and Gregory Mines. Waste materials were removed and placed into onsite repositories (one at the Comet mine, two at the Gregory Mine). Borrow materials were brought to the sites and laid as coversoil. Finally the sites were seeded using a native seed mix. Reclamation at High Ore Creek included partial, total, and no removal of wastes, depending on location and existing vegetation. Wastes were removed to the Comet repository, and an off-site Bureau of Land Management (BLM) repository. Moderate to extreme variation in vegetation cover and species ricness characterizes the post reclamation landscapes at the sites. Barren areas, evaporative salts, and iron staining characterize the exposed soil at the sites. Red top (*Agrostis alba*), and western yarrow (*Achillea millefolium*) are the dominant species at the Gregory and Comet Mines. These species are also present along High Ore Creek, but they are not the dominant species at this site.

Table 1. Elevation, location, Montana Mine Waste Clean-up Bureau priority rank, and reclamation year for the Gregory Mine, the Comet Mine, and High Ore Creek.

Mine Site	*Elevation (m amsl*)*	*Township/Range Coordinates*	*MWCB Priority Rank*	*Reclamation Year*
Gregory Mine	1661-1707	T7N, R4W, Sec. 4, 5	57	2002
Comet Mine	1860-1950	T7N, R5W, Sec. 35, 36	10	1997, 2001
High Ore Creek	1555-1920	T6N, R5W, Sec.2,7,11,14,15,22 T7N,R5W,Sec. 36	10	1999, 2000

* Meters above mean sea level.

Methodology

Soil and vegetation samples were collected during July and August of 2005 at eighteen sample areas at both the Gregory Mine and Comet Mine, and six sites along the 6 kilometer (km) stretch of High Ore Creek from the Comet Mine to the confluence with the Boulder River.

Sample Area Selection

Gregory and Comet Mines. Study areas were selected in the riparian zone of the Comet and Gregory sites. Two soil moisture regimes exist in the riparian zone; sub-irrigated (SB) (1-2yr floodplain) and overflow (OV) (10yr floodplain). Sample areas were determined in the sub-irrigated and overflow zones of the riparian zone based on vegetation cover as follows:

- Poor (0-25% cover)
- Moderate (26-75% cover)
- Good (76-100+% cover)

Using these categories, three sample areas within each vegetation class and within both moisture regimes were identified at both the Gregory Mine and Comet Mines. This created a total of eighteen sample areas at each mine site. Soil and vegetation samples were collected and field measurements were made at each sample area.

High Ore Creek. Study areas at High Ore Creek were located along the creek in the riparian zone. Sample locations were based on reclamation method used during the reconstruction of High Ore Creek:

- No removal: tailings were left in place due to historic structures, trees, or relatively good vegetative cover;

- Partial/Total Removal: All or some of the waste materials were removed, and cover soil from a borrow area was placed on the surface.

Three sample locations for each reclamation method were selected along High Ore Creek. Exploratory soil pits were dug to identify the removal type at each location. Soil and vegetation samples were collected and field measurements were made at each sample area.

Soil Sample Collection and Analyses

Soils were collected in three randomly located pits within each sample area. Pits were excavated using a sharpshooter and standard shovel. Soil pits were excavated to 60cm in overflow sample areas, and to 46cm in sub-irrigated areas. Groundwater was typically encountered at 30 cm in soil pits located in sub-irrigated areas. Samples were collected as a function of visual or textural changes within the soil profile. Samples were collected using stainless steel shovels and placed into labeled plastic bags. Wet decontamination of sampling equipment was performed and a clean shovel was used for each sample. Equipment decontamination included the following steps: 1) dry decontamination using a wire brush to remove excess soil from the shovels, 2) soapy wash consisting of 1 tablespoon of Alconox soap mixed with one gallon of deionized water 3) deionized water rinse, and 4) deionized water spray. Field quality control was performed at a rate of 5% (1 set of field QC samples for each 20 natural field samples), and included sample duplicates, cross contamination blanks, and pure silica blanks.

Following field collection, soils were air dried, de-aggregated with a mortar and pestle, and passed through a 2mm sieve. Rock fragments larger than 2mm were discarded. Composite samples were formed from soils within sample areas, based on similarities in physical properties and field description. Following preparation, soils were taken to the Montana State University Soils Testing lab for analysis. Soil analytical procedures and methods are outlined in Table 2.

Vegetation Collection and Analyses

Canopy cover measurements were taken by species using Daubenmire (1959) cover classes (Table 3). Ten 20x50cm frames (.1 m^2) were randomly located within each sample area, and cover was estimated and recorded. Live cover by species, litter, rock, and bare ground cover classes were recorded on specialized field forms. Mean cover by species, mean total live cover, and standard deviation were calculated for each sample area.

Above ground biomass frames were co-located with cover frames, and vegetation was clipped by life form. Life forms included: perennial grass, annual grass, forbs, and shrubs. Ten 25x25 cm (.0625 m^2) frames were clipped within each sample area. Clipped vegetation was placed in labeled paper bags to allow moisture to escape. After oven drying at 75^{o}C for 48 hours, vegetation samples were weighed to the nearest .01 gram and total above ground biomass production and standard deviation were calculated. A species list was also compiled for each site. Taxonomic names are adapted from Hitchcock et al (1973).

Statistical analysis

One-way analysis of variance (ANOVA) and independent sample t-tests (R version 2.0.1, Sigma Stat version 3.0) were used to determine statistical differences within and between sample strata in terms of soil and vegetation data. A conservative version of the F-max test for equal variances (Largest SD/smallest SD<2) was used to determine equal variances in data sets. Data transformations were used to pass the normality and equal variances test, where needed. Several data sets were unable to pass these tests and ANOVA was completed using Kruskal-Wallis one-way analysis of variance based on ranks.

Correlation (R version 2.0.1, Sigma Plot version 9.0) was used to determine significant associations among vegetation and soil chemistry data. Production and cover were the response (dependant) variable and soil chemistry was the explanatory variable.

Table 2. Soil analytical procedures and methods.

	Constituents	*Method*
Electrical Conductivity	Saturated Paste Extract	USDA Handbook 60, Method 3a, 4b (U.S. Salinity Lab Staff, 1969)
pH	Saturated Paste Extract	USDA Handbook 60,Method 3a, 21c (U.S. Salinity Lab Staff, 1969)
Total Recoverable As and metals	As, Cu, Pb, Zn in solution following nitric acid digestion	EPA method 3050, Standard EPA-CLP methods (SOW 787, U. S. EPA)
Soluble As and Metals	As, Cd, Cu, Pb, Zn in saturated paste extract solutions	Standard EPA-CLP methods (SOW 787, U. S. EPA)

Table 3. Daubenmire cover classes and midpoints (Daubenmire, 1959).

Class	*Coverage Range*	*Midpoint*
1	0-5%	2.5%
2	6-25%	15%
3	26-50%	37.5%
4	51-75%	62.5%
5	76-95%	85%
6	96-100%	97.5%

Results and Discussion

Vegetation

The vegetation was highly variable at all three mine waste sites. The Gregory Mine had the greatest average canopy cover and biomass production, as well as the greatest species richness (Table 4). High Ore Creek had the highest species diversity, probably due to older plant communities residing in no removal areas. The plant communities at the Comet and Gregory Mines are less than six years old and have had less time to establish a diverse community (Table 1).

Table 4. Vegetation summary for all sites.

Site	*Mean Cover** (%)*	*Mean Production** ($kg\ ha^{-1}$)*	*Species Richness* Entire Site	Sample Areas	*Species*** Diversity (D)*
Gregory	70.9	1652.9	60	37	4.70
Comet	38.1	873.6	39	12	2.38
High Ore Creek	66.6	1447.1	50	28	7.55

* Cover and production are given as mean values for each site.

** Species diversity calculated using the inverse Simpson's index ($D=1/\Sigma p_i^2$, where *p* is the proportion of individuals in the ith species)for species located within sample areas.

Soil Chemistry

Soil chemistry was highly variable at all sites, and may be attributed to the characteristics of the original waste materials and the applied reclamation method. Tailings and waste rock materials that were present below the borrow soil will be discussed in the following sections. Soil pH, soluble metal levels, total metal levels, and soil nutrients play a role in soil productivity and vegetation re-establishment. Electrical conductivity may also affect plant re-establishment at elevated levels (EC>5mS); however, electrical conductivity values were within suitable levels in all samples collected at the Gregory Mine, the Comet Mine, and High ore Creek, and will not be discussed further. Several soil samples revealed concentrations of total As, Cu, Pb, and Zn that are likely phytotoxic (Table 5), which contribute to the high variability in vegetation cover and production (Table 6). The effects of metals residing in the root zone restrict root development in plants, therefore inhibiting plant establishment (Tordoff, 2000). Low soil pH resulting from the weathering and oxidation of sulfide minerals is the most common toxicity problem in mine soils (Bradshaw, 1997). The most common sulfide mineral responsible for acid production in mine spoils is pyrite (FeS_2) (Caruccio et al, 1988).

Table 5. Summary of soil trace elements evaluated for this study.

Trace Element	*Regional Background Level*** ($mg\ kg^{-1}$)	*Phytotoxicity** ($mg\ kg^{-1}$)	*Plant Nutritional Requirement** (Y/N)
Arsenic	9.3	15-315	N
Cadmium	0.9	3-100	N
Copper	22.4	100-1636	Y
Lead	35.7	100-1000	N
Zinc	66.1	100-500	Y

* Data summarized from: Adriano, 2001; CDM Federal, 1997, CH2M Hill, 1987a,b; Kabata-Pendias and Pendias, 1992;

** Data summarized from PTI, 1997.

Table 6. Summary of soil pH and metals in topsoils from the Gregory Mine, the Comet Mine and High Ore Creek.

Site	*Mean Soil pH top†*	*Mean Soil pH bottom†*	*Sum of Metals* (mg kg^{-1})*	*Soluble Metals** (mg L^{-1}) As*	*Cd*	*Cu*	*Pb*	*Zn*
Gregory	3.92	3.05	1817±1395	1.2±2.7	1.1±3.1	0.4±1.2	0.6±1.4	62.4±176
Comet***	6.41	6.28	16998±21837	0.2±0.2	1.1±1.9	0.3±0.4	0.3±0.4	163 ±190
High Ore Creek	6.17	6.24	6447±7614	0.3±0.4	0.1±0.2	.08±.04	0.3±0.1	75.5±195

* Sum of total As, Cu, Pb, and Zn, given as means and standard deviations.

** Values given as means and standard deviations of soluble metals for all samples throughout the 0-60cm soil profile.

*** Soluble metal levels from subset of 10 samples.

† Top increment was typically 0-30cm and bottom increment was 30-60cm, though, there was some variation in these increments, and sample collection was delineated as a function of soil layers, not distinct numerical increments.

Gregory Mine

Vegetation. The vegetation at the Gregory Mine was characterized by high variability in canopy cover and biomass production (Table 7). Canopy cover estimates ranged from 2-171%. Sample areas initially categorized as Good typically had over 100% vegetation cover. Poor areas had limited vegetation cover, typically in small patches, while Moderate and Good areas had relatively uniform vegetation throughout the sample area. Sample areas above ground biomass ranged from 10-4583 kg ha^{-1}. Thirty-seven species were found within sample areas (Table 8), and the site species list contained 60 species. *Agrostis alba*, *Festuca idahoensis*, and *Achillea millefolium* were the dominant species at this site, contributing approximately 78% of the total cover in sample areas (Table 8). Two seed mixes containing 17 species were used during revegetation of the Gregory Mine. *Poa secunda*, *Stipa viridula*, *Agropyron spicatum*, *Linum lewisii*, and *Lupinus sericeus* were seeded species that did not occur in sample areas. *F. idahoensis*, *Phleum pratense*, *A. millefolium*, and *Medicago sativa* were the only seeded species to contribute greater than 0.5% of the overall cover. *A. alba* was not seeded, but contributed 33% of the total cover. This may be attributed to metal tolerance in *Agrostis* species (Bleeker et al, 2002; Farago, 1981), and aggressive colonization in disturbed areas (Munshower,1998).

Table 7. Gregory Mine vegetation summary.

Vegetation Criteria	*Mean Cover* (%)*	*Mean Production* (kg ha^{-1})*	*Species Richness in Sample Areas*
Good	127±26a	4202±1519a	35
Moderate	73±16b	1498±491b	24
Poor	13±11c	473±377c	9

* Cover and production values are given as means and standard deviations.

a,b,c Means followed by the same letter are not significantly different at P<0.05.

Table 8. Summary** of species from sample areas at the Gregory Mine.

Common Name	*Species Name*	*Major Species* (Y/N)*	*Seeded (Y/N)*	*Native (Y/N)*	*Relative Cover (%)*
Red Top	*Agrostis alba*	Y	N	Y	33
Western Yarrow	*Achillea millefolium*	Y	Y	Y	23
Idaho Fescue	*Festuca idahoensis*	Y	Y	Y	22
Alfalfa	*Medicago sativa*	Y	Y	N	3.0
Sedge	*Carex sp.*	Y	N		2.0
Timothy	*Phleum pratense*	Y	N	N	1.8
Red Clover	*Trifolium pratense*	Y	N	N	1.4
White Clover	*Trifolium repens*	Y	N	N	1.0
Kentucky Bluegrass	*Poa Pratensis*	Y	N	N	0.9
Baltic Rush	*Juncus balticus*	Y	N	Y	0.8
Smooth-Scouringrush	*Equisetum laevigatum*	Y	N	Y	0.8
Dwarf Fireweed	*Epilobium latifolium*	Y	N	Y	0.7
Moss		Y			0.7
Slender Wheatgrass	*Agropyron trachycaulum*	Y	N	Y	0.6
Rocky Mountain Iris	*Iris missouriensis*	Y	N	Y	0.6
Tufted Hairgrass	*Deschampsia caespitosa*	Y	Y	Y	0.5
Sulfur Cinquefoil	*Potentilla recta*	Y	N	Y	0.5
Thickspike-Wheatgrass	*Agropyron dasystachyum*	N	Y	Y	0.4
Nebraska Sedge	*Carex nebrascensis*	N	Y	Y	0.3
Fowl Mannegrass	*Glyceria striata*	N	Y	Y	0.3
Goldenrod	*Solidago missouriensis*	N	N	Y	0.1
Tar Weed	*Madia sativa*	N	N	Y	0.1
Strawberry	*Fragaria vesca*	N	N	Y	<0.1
Toad rush	*Juncus bufonius*	N	N	Y	<0.1
Ryegrass	*Lolium multiflorum*	N	Y	Y	<0.1
Purple Aster	*Machaeranthera canescens*	N	N	Y	<0.1
Woods Rose	*Rosa woodsii*	N	N	Y	<0.1
Tall Buttercup	*Ranunculus acris*	N	N	N	<0.1
Quaking Aspen	*Populus tremuloides*	N	N	Y	<0.1
Cudweed Sagewort	*Artimsia ludoviciana*	N	N	Y	<0.1
Switch Grass	*Panicum virgatum*	N	N	Y	<0.1
Broadleaf Plantain	*Plantago major*	N	N	N	<0.1
Rough Fescue	*Festuca scabrella*	N	N	Y	<0.1
Pussytoes	*Antennaria spp.*	N	N	Y	<0.1
Bull thistle	*Cirsium vulgare*	N	N	N	<0.1
Forb #1-4		N			<0.1

* Major species contribute >0.5% of the total cover within sample areas.

** Species data adapted Hitchcock et al (1973).

<u>Soil Soluble Metals and Arsenic.</u> Soil pH levels were determined for all soil samples collected at the Gregory Mine. The pH range for topsoils was 3.84-6.91, and for subsoils pH values ranged from 2.08-7.05. Average pH values for sample areas are displayed in Table 9. Water soluble soil metal and arsenic concentrations were determined in topsoils from all sample areas and average values are also presented in Table 9. Soil pH is a significant determining factor in the bioavailability of metals (Kabata-Pendias and Pendias, 1992). There was an overall increase of soluble metal concentrations as soil pH decreased from Good to Poor sample areas. Soluble Pb

levels were reported as below detection limits for Good and Moderate sample areas, most likely due to limited solubility of lead in relation to other metals (Kabata-Pendias, 2001 and Adriano 2001). Soluble metal concentrations were greatest in Poor sample areas due to lower soil pH values.

Table 9. Summary of soil pH (standard units) and soluble metals and arsenic (mg L^{-1}) levels in topsoil samples from the Gregory Mine.

Vegetation Criteria	*Soil pH surface***	*Soil pH lower***	*Metal**				
			As	*Cd*	*Cu*	*Pb*	*Zn*
Good	5.28	3.71	.13±.11	.01±.004	.045±.037	<.1	4.2±3.1
Moderate	4.88	3.07	.21±.21	.02±.01	.056±.037	<.1	4.8±6.2
Poor	3.49	2.85	1.63±2.05	1.5±2.6	1.5±1.6	1.63±2.65	217.9±355.1

* Metals data are presented as means and standard deviations.

** Top increment was typically 0-30cm and bottom increment was 30-60cm, though, there was some variation in these increments, and sample collection was delineated as a function of soil layers, not distinct numerical increments.

Soil Total Arsenic and Metal Levels. Total metal and arsenic levels were determined in topsoil samples in all sample areas. Mean concentrations and standard deviations are displayed in Table 10. Relationships between vegetation response, soil pH, and sum of total metal levels have been postulated by EPA (1999). Mine wastes typically contain a mixture of metals, and it is difficult to identify the effects of individual metal levels in terms of a phytotoxic response (Kaputska et al, 1995). One approach at these sites is to identify the level of association that vegetation attributes have with sum of total metal levels and soil pH (PTI, 1994; Neuman et al, 2002; and Kaputska, 2002). One-way analysis of variance showed no significant difference (P<0.05) among sums of total metal levels between Good, Moderate, and Poor areas. This is due to the large variation in metal levels at the site and large standard deviations among sample areas.

Table 10. Summary of total metals* and arsenic (mg kg^{-1}) in topsoil samples from the Gregory Mine.

Vegetation Criteria	*As*	*Cu***	*Pb*	*Zn*	*Sum of Metals****
Good	172±179†	80±46	259±226	540±323†	1224±716a
Moderate	1123±1240†	100±98†	701±653	394±214†	1867±2285a
Poor	813±519†	115±40†	1274±1094†	636±629†	2361±1068a

* Total metals displayed as means and standard deviations in topsoil samples from sample areas.

** Copper data from the overflow zone only.

***Sum of As, Cu, Pb, and Zn from overflow zone only.

a Means followed by the same letter are not significantly different at P<0.05.

† Indicates possible phytotoxicity.

Discussion Correlation was used to determine the level of association between vegetation, soil pH (Fig. 1, A), and soil metal levels. Significant negative correlation (cover decreased with increased metal levels) (r =-0.65, P=0.004) was determined between percent canopy cover and soil pH (H-ion concentration). Significant negative correlation (r =-0.41, P<0.1) was not found between the sum of total metals and the percent canopy cover. As expected, significant association was not found for soil pH and sum of total metals. Phytotoxic levels of As, Cu, Pb, and Zn were observed in topsoil samples (Table 10). Zinc and As levels lie within the phytotoxic range in all vegetation groups, however, significant correlation does not exist between either metal level and percent canopy cover. Significant negative correlation was found between total Pb and percent canopy cover (r =-.55, P=0.02) (Fig. 1, B). The species richness at this site was moderately high, with 37 species located within sample areas. Species richness decreased as total metal concentrations increased from Good to Moderate to Poor areas. This was the expected result based on an EPA study on the Clark Fork River in 1999. The study concluded that species richness and sum of total metal levels were inversely correlated (as metal levels increased, species richness decreased) (EPA, 1999).

Comet Mine

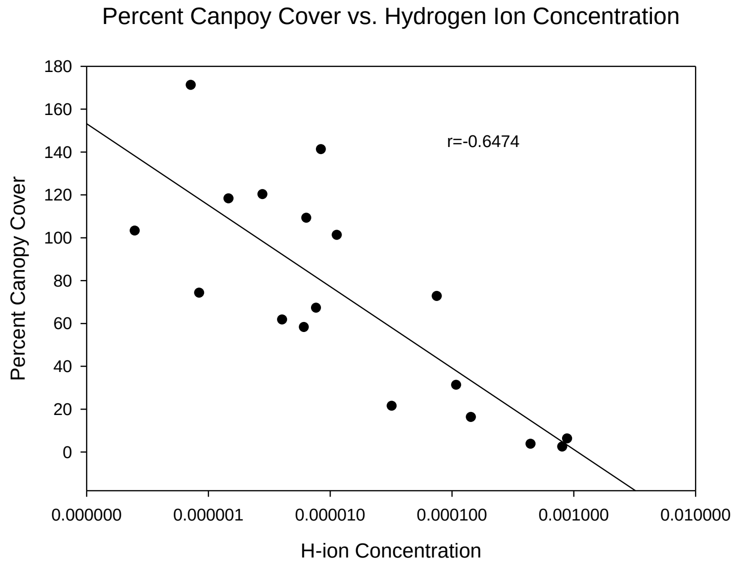
Vegetation. Vegetation at the Comet Mine was highly variable. Canopy cover estimates rangedfrom 0-88% and biomass production ranged from 0-3598 kg ha^{-1} (Table 11). Barren areas were scattered throughout the site, and species richness and diversity were extremely low (12 and 2.83 respectively). Good sample areas had thick vegetation, mostly comprised of one or two species. Moderate areas had uniform cover and slightly higher species evenness and richness. The poor areas typically had very sparse to no vegetation, and cover was limited to one or two species. Twelve species were present in sample areas and 39 species are present at the site, including upland areas (Table 12). *A. alba* and *Agropyron trachycaulum* were the dominant species at this site, comprising of approximately 83% of the total cover in sample areas. Two seed mixes comprising of 13 species were used at the Comet Mine during revegetation. *Agropyron smithii*, *A. thachycaulum*, *F. idahoensis*, and *A. millefolium* were the seeded species located in sample areas, and the only seeded species to comprise of 0.5% cover or higher. *A. alba* was not a seeded species, and made up 60% of the total cover. This may be due to *Agrostis* species being colonizers of mine sites, and displaying metal tolerance (Bleeker et al 2002; Farago, 1981).

Table 11. Comet Mine vegetation summary.

Vegetation Criteria	*Mean Cover* (%)*	*Mean Production* (kg ha^{-1})*	*Species Richness in Sample Areas*
Good	74±9a	2025±926a	7
Moderate	37±4b	562±198b	8
Poor	3±3c	22±24c	3

* Cover and production values are given as means and standard deviations.
a,b,c Means followed by the same letter are not significantly different at P<0.05.

(A)



(B)

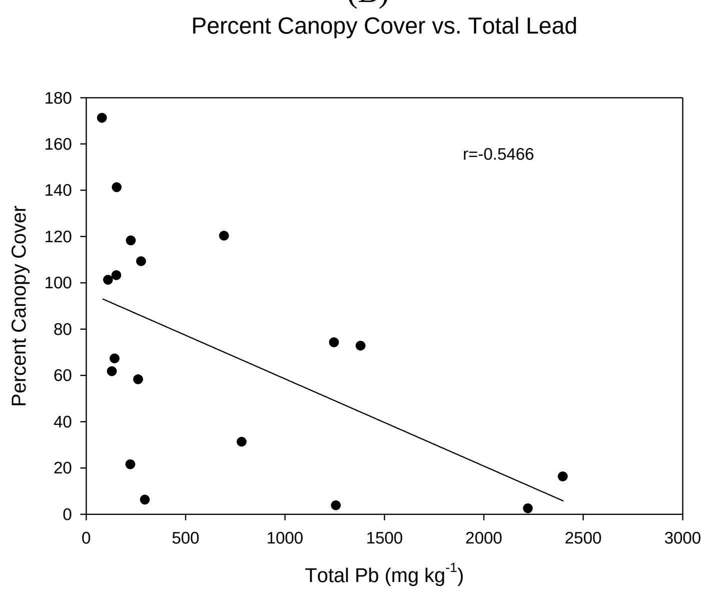


Figure 1. Correlation analysis for percent canopy cover and soil pH (A), and total Pb at the Gregory Mine (B).

Table 12. Summary** of species from sample areas at the Comet Mine.

Common Name	*Species Name*	*Major Species* (Y/N)*	*Seeded (Y/N)*	*Native (Y/N)*	*Mean Cover (%)*
Red top	*Agrostis alba*	Y	N	Y	60.0
Slender wheatgrass	*Agropyron trachycaulum*	Y	Y	Y	23.0
Western wheatgrass	*Agropyon smithii*	Y	Y	Y	5.5
Western yarrow	*Achillea millefolium*	Y	Y	Y	5.2
Dwarf fireweed	*Epilobium latifolium*	Y	N	Y	2.0
White clover	*Trifolium repens*	Y	N	N	1.6
Field Horsetail	*Equisetum arvense*	Y	N	Y	1.3
Idaho fescue	*Festuca idahoensis*	N	Y	Y	0.4
Tufted hairgrass	*Deschampsia caespitosa*	N	N	Y	0.3
Cudweed sagewort	*Artemisia ludoviciana*	N	N	Y	0.1
Willow	*Salix spp.*	N	Y	Y	<0.1
Grass #1		N			0.1

* Major species contribute >0.5% of the total cover within sample areas.
** Species data adapted Hitchcock et al, 1973.

Soluble Metals. Soil pH levels for all topsoil samples were analyzed, and ranged from 5.90-7.21. A subset of 10 samples was analyzed for soluble metal levels. Thirty percent of the samples had high (200-800 mg L^{-1}) soluble zinc at pH≈6, which was not expected because zinc bioavailability is significantly reduced at pH>5.0 (Adriano, 2001). Natural soils with pH values near neutral typically have low soluble metal levels. Contaminated soils and mine wastes however, may exhibit high levels of bioavailable metals at neutral pH due to extremely high levels of total metals.

Total Metals. Total metal and As levels were determined for all topsoil samples collected at the Comet Mine. Table 13 displays mean concentrations and sum of total metal concentrations. Metal levels in all sample areas were within or above phytotoxic levels for plant growth. Lead and zinc concentrations were particularly elevated in all vegetation areas. There was no significant difference in the sum of total metal levels between Good and Moderate areas, and both are significantly lower than total metal levels in Poor areas.

Table 13. Summary of total metal and As levels (mg kg^{-1})in topsoil samples from the Comet Mine.

Vegetation	*Metal**				*Sum of all Metals*
Criteria	*As*	*Cu*	*Pb*	*Zn*	
Good	1004±603†	348±205†	1766±1214†	3219±2004†	7580±3535a
Moderate	749±764†	250±147†	1420±1014†	3170±2822†	6060±3030a
Poor	3916±3444†	1220±900†	10988±12453†	17462±13856†	37356±29187b

* Total metal levels displayed as means and standard deviations in topsoil samples within sample areas.
a,b Means followed by the same letter are not significantly different at P<0.05.
† Indicates possible phytotoxicity.

Discussion. Correlation was used to determine associations between vegetation cover and soil metal levels (Fig. 2, A-E). Significant negative correlation was found between percent canopy cover and total As (r=-0.5, P=0.03), total Zn (r=-0.58, P=0.01), total Cu (r=-0.57, P=0.01), total Pb (r=-0.50, 0.03), and the sum of total metals (r=-0.58, p=0.01). No significant relationship was found between percent canopy cover and soil pH (H-ion concentration). This was the expected result due to the narrow range of circum neutral soil pH values. Metal levels in Poor sample areas were representative of mine waste materials, not borrow soil. There are three possible explanations for this; 1) waste materials left in place during reclamation were exposed after the borrow soil was eroded away, 2) borrow soil was placed as a thin veneer, or never placed on these areas, or 3) upward migration of metals has contaminated the clean borrow soil. Metal and As levels in all topsoils indicate possible upward migration. This is most likely due to waste materials located within 30 cm from the surface, and a positive water balance (groundwater within 1 meter). The species richness was very low, with only 12 species found in sample areas. Species diversity was negatively correlated with high total metal levels (species diversity decreased with increasing metal levels) along the Clark Fork River, MT (EPA, 1999). Species richness was similar in the Good and Moderate areas, as expected, but was reduced in the Poor areas, where metals levels were two to three orders of magnitude higher.

High Ore Creek

Vegetation. Vegetation at High Ore Creek was moderately variable, with the highest variation being in No Removal areas. Canopy cover estimates ranged from 30-89%, and biomass production ranged from 468-2288 kg ha^{-1} (Table 14).

Table 14. High Ore Creek vegetation summary.

Removal Type	*Mean Cover* (%)*	*Mean Production* (kg ha^{-1})*	*Species Richness in Sample Areas*
Partial	70±17a	1446±328a	12
No removal	63±29a	1448±918a	21

* Cover and production values are given means and standard deviations.

a Means followed by the same letter are not significantly different at P<0.05.

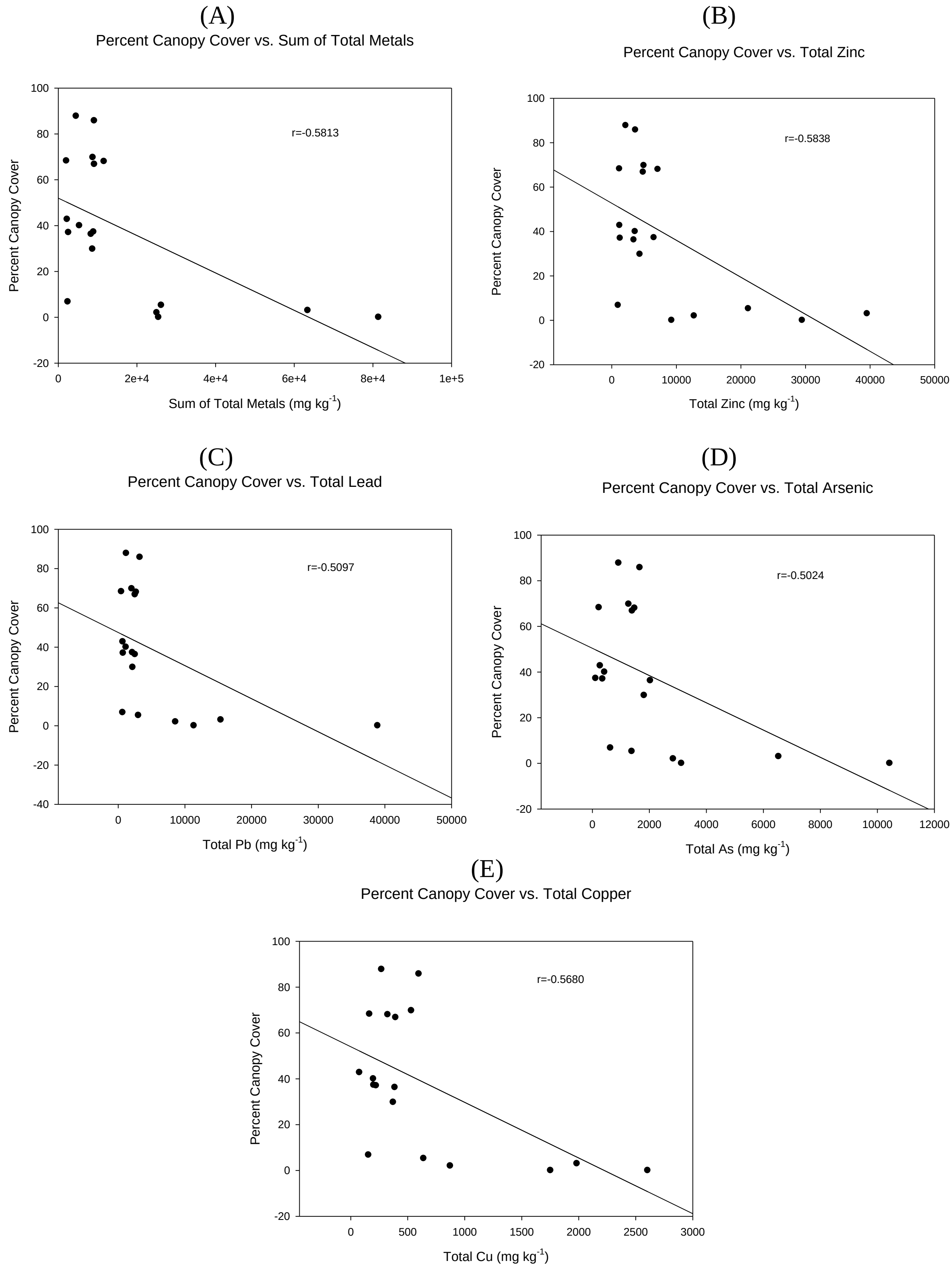


Figure 2. Percent canopy cover as a function of the sum of total metal levels (A), total Zn levels (B), total Pb levels (C), total As levels (D), and total Cu levels (E) at the Comet Mine.

Mean cover and production were not significantly different between No Removal and Partial Removal areas. Cover in all areas was relatively uniform, and there were no barren areas within the study area. Study areas contained 28 species, and the entire site had 50 species (Table 15). Two seed mixes comprised of 12 species were applied in the revegetation phase of reclamation. *Agropyron spicatum*, *F. idahoensis*, *Koeleria cristata*, *A. trachycaulum*, and *A. millefolium* were seeded species that made up >0.5% of the total cover in sample areas.

A. alba, *Juncus balticus*, *Equisetum arvense*, and *Melilotus officinalis* were not seeded species, and comprised of 44% of the total cover in sample areas. *A. alba* and *A.millefolium* were the only species to be present in both No and Partial Removal areas.

Table 15. Summary** of species from sample areas at High Ore Creek.

Common Name	*Species Name*	*Major Species** (Y/N)*	*Seeded (Y/N)*	*Native (Y/N)*	*Mean Cover (%)*
Western Yarrow	*Achillea millefolium*	Y	Y	Y	25.0
Red top	*Agrostis alba*	Y	N	Y	15.0
Baltic rush	*Juncus balticus*	Y	N	Y	12.6
Idaho fescue	*Festuca idahoensis*	Y	Y	Y	12.0
Yellow sweetclover	*Melilotus officinalis*	Y	N	N	9.3
Field Horsetail	*Equisetum arvense*	Y	N	Y	7.4
Bluebunch-wheatgrass	*Agropyron spicatum*	Y	Y	Y	3.3
Red clover	*Trifolium pratense*	Y	N	N	2.7
Prarie Junegrass	*Koeleria cristata*	Y	Y	Y	1.9
Slender wheatgrass	*Agropyron trachycaulum*	Y	Y	Y	1.4
Intermediate-wheatgrass	*Agropyron intermedium*	Y	N	N	1.3
Willow	*Salix spp.*	Y	Y	Y	1.0
Bull thistle	*Cirsium vulgare*	Y	N	N	0.9
Quaking aspen	*Populus tremuloides*	Y	N	Y	0.9
Western wheatgrass	*Agropyon smithii*	Y	N	Y	0.8
Nebraska sedge	*Carex nebrascensis*	Y	N	Y	0.7
Tufted hairgrass	*Deschampsia caespitosa*	N	Y	Y	0.4
Cudweed sagewort	*Artemisia ludoviciana*	N	N	Y	0.4
Dandelion	*Taraxacum officinale*	N	N	N	0.3
Canada bluegrass	*Poa compressa*	N	N	N	0.2
Dwarf fireweed	*Epilobium latifolium*	N	N	Y	0.1
Columbia-needlegrass	*Achnatherum nelsonii*	N	Y	Y	<0.1
Ragwort	*Senecio spp.*	N	N	Y	<0.1
Forb #1-2, 6-8		N			1.0

* Major species contribute >0.5% of the total cover within sample areas.
** Species data adapted from Hitchcock et al, 1973.

<u>Soluble Metals</u>. Soil pH levels were analyzed for all samples, and ranged from 5.48-7.63. Soil pH and soluble metal levels are displayed in Table 16. As expected, soluble metal levels were very low, due to relatively high pH values. Soluble Zn and Cd levels were significantly higher in

No Removal areas than Partial Removal areas. Soluble As, Cu and Pb concentrations were not significantly different between No and Partial Removal areas.

Total Metals. Total metal and arsenic levels were determined for topsoil samples collected at High ore Creek. Table 17 displays mean total metal concentrations and sum of total metals. Metals levels in No Removal areas were significantly higher than in Partial Removal areas. This

was the expected result, as tailings were left in place in No Removal areas. The total metal concentrations in No Removal areas are well above the phytotoxic range for all metals. Total metal levels in Partial Removal areas lie within the phytotoxic range for all metals, indicating species richness or biomass production may be reduced in these areas.

Table 16. Summary of soil pH and soluble metal and arsenic levels (mg L^{-1}) in topsoil samples from High Ore Creek.

Vegetation Criteria	*Soil pH Top***	*Soil pH Bottom***	*Metal**				
			As	*Cd*	*Cu*	*Pb*	*Zn*
Partial	7.23	7.39	.40±.29a	.01±.005a	.088±.035a	<.1a	0.19±0.07a
No	5.99	5.90	.17±.09a	.23±.22b	.077±.034a	.17±.13a	58.9±77.4b

* Metals data are presented as means and standard deviations.

** Top increment was typically 0-30cm and bottom increment was 30-60cm, though, there was some variation in these increments, and sample collection was delineated as a function of soil layers, not distinct numerical increments.

a,b Means followed by the same letter are not significantly different at P<0.05.

Table 17. Summary of total metal and arsenic levels (mg kg^{-1}) in topsoil samples from High Ore Creek.

Removal Type	*Metal**				*Sum of all Metals*
	As	*Cu*	*Pb*	*Zn*	
Partial	120±118†	72±33	323±336†	353±292†	769±925a
No	3993±1244†	498±221†	2735±1541†	4806±2872†	12126±6880b

* Total metal levels displayed as means and standard deviations in topsoil samples within sample areas.

a,b Means followed by the same letter are not significantly different at P<0.05.

† Indicates possible phytotoxicity.

Discussion. Correlation was used to determine associations among vegetation and soil chemistry. Significant correlations were not determined between vegetation cover and biomass, soil metals, and soil pH. This was the expected result because biomass production and percent canopy cover did not differ between No and Partial Removal areas. Although the cover and production were not significantly different between No and Partial Removal areas, the species composition was very different. No Removal areas had much higher species richness than Partial Removal areas (21 and 12 respectively). This was not expected due to the high levels of total metals present in No Removal areas. The plant community in No Removal Areas was dominated by *A. alba*, *J. balticus*, and *E. arvense*, which made up approximately 70% of the total cover. Partial removal areas were dominated by *F. idahoensis* and A. *millefolium*, which comprised of 64% of the total cover. *A. alba* and *A. millefolium* are the only species that occurred in both removal types. Differences in species richness may be a function of the age of the plant community. Plant communities in No Removal areas have had several decades to establish, while Partial Removal areas were seeded 5 years ago. The difference in species composition may also be a result of the soil metal levels. The dominant species in No removal areas may have metal tolerant genotypes that have adapted the metal enriched soils over time. The dominant species in Partial Removal areas are seeded species that are reproducing successfully and are adapted to the borrow soil properties.

<u>Conclusions</u>

Significant negative correlation between vegetation attributes (cover, biomass, species richness) and soil chemistry (pH, As and metal levels) was found at both the Gregory Mine and the Comet Mine. Percent canopy cover and biomass production had significant negative correlation to total arsenic and metal levels at both sites. As metal levels increased, production and cover decreased. Significant negative correlation was also found between species richness and soil metal levels. Soil pH at the Gregory Mine was strongly correlated to percent canopy cover and biomass production. This may be problematic in the future if upward migration of acidic water into the soil cap occurs. Soil pH values could continue to decrease, affecting the overall plant production, cover, and species richness. Only the most tolerant plant species may be able to persist. Total metal levels and pH had no correlation with biomass production and plant cover along High Ore Creek. Species composition may be influenced by total metal levels, which may be driving the differences in species composition at this site. Metal tolerant species dominated No Removal areas where soil metal levels are elevated.

A. alba was not seeded at any of the study sites, but was the dominant grass species in most areas. This species colonized all reclaimed sites, likely due to high metal tolerance in this species (Farago, 1981; Bleeker, et al 2002; Munshower, 1998). Several of the native seeded species were rare or had not established at these sites. In particular, *Festuca scabrella*, *Stipa viridula*, *Agropyron spicatum*, *Poa compressa*, *Calamagrostis spp*., and *Linum lewisii* were not successful at these sites. *A. millefolium* and *F. idahoensis* established successfully on all sites. There is some question as to whether the *Festuca spp*. is a mix of *F. idahoensis* and *Festuca ovina*. *Festuca ovina* is a known metal tolerant grass species (Farago, 1981) and is physically very similar to *F. idahoensis*. Monitoring the species richness and diversity over time will be the most effective way to determine what species are successfully establishing at mine reclamation sites. It is concluded that the seed mix needs to be adjusted and unsuccessful species should be eliminated in order to increase cost effectiveness and allow faster establishment of successful species.

Reclamation along High Ore Creek has been effective. The average percent cover was over 70% and the species diversity is relatively high. The results of this study were inconclusive as to which removal type was the most effective. Metal levels were elevated in No Removal areas, but the percent cover and biomass production were not significantly different compared to Partial Removal areas. No Removal areas had higher species richness, but were dominated by metal tolerant species. Partial Removal areas had lower species richness, but had less variation in cover and production, and higher occurrence of grass species.

It is concluded that reclamation was moderately effective at all three sites. All three sites had soil metal levels considerably higher than regional background metal levels (Figures 5 and 6). Aesthetically, the sites are greatly improved, however, there is mine waste residing under the soil cap, which may affect the long-term sustainability of these sites. There are indications of upward movement of both low pH solutions and metals from underlying contaminants into the soil cap. The presence of a shallow water table at all three sites is a major concern for the mobility of contaminants into the clean soil cap. Long term monitoring should be implemented to determine the effectiveness of reclamation at the Gregory Mine, the Comet Mine, and High Ore Creek.

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