RELATIONSHIPS AMONG SOIL DEPOSITION PATTERNS, SOIL PHYSICAL AND CHEMICAL PROPERTIES, AND PLANT METAL UPTAKE ON AN ABANDONED ZINC-LEAD TAILINGS POND[1]

by

Jeanne C. Chambers, Roy C. Sidle, and C. Val Grant[2]

Abstract. A 50 year-old abandoned tailings pond from a zinc-lead mill near Pecos, New Mexico, was sampled to determine relationships among soil deposition patterns, physical and chemical properties of the tailings and surface deposited soils, plant community development, and Cu, Zn, Pb, and Cd concentrations in plant tissue. Percentage silt and clay and concentrations of Cu, Zn, Pb, and Cd in surface soils were highest at the lower end of the pond indicating accumulation of both water-transported fine materials and heavy metals. The degree of vegetation development was greatest at the lower end of the pond, was positively related to soil organic matter, and may have contributed to metal accumulation. Plant tissue concentrations of Cu, Zn, Pb, and Cd were highly correlated to soil concentrations. and were at potentially toxic food-chain levels for some of the metals. Potential food-chain movement and bioaccumulation of the metals and methods of reclaiming the site are discussed.

Additional Key Words: food-chains, mine tailings, Cu, Cd

Introduction

Successful reclamation of tailings ponds that contain toxic elements depends on a thorough knowledge of the environmental and edaphic conditions that exist on the site at the time reclamation is initiated. Equally important but more difficult to acquire is information about the processes that occur on the site after it has been reclaimed, such as soil deposition or erosion, soil development, plant and animal succession, movement of potentially toxic elements, and incorportation or accumulation of potentially toxic elements in food-chains. Information on these processes can provide valuable insights into the development of the best reclamation methods. It can help to determine the optimal shape of the site, the depth and type of surface materials, species selection and planting or seeding methods, postreclamation land uses, and

---

[1] Paper presented at the conference Reclamation, A Global Perspective, held in Calgary, Alberta, Canada, August 28-31, 1989.

[2] Jeanne C. Chambers is Plant Ecologist and Roy C. Sidle is Hydrologist, Intermountain Research Station, U. S. Department of Agriculture, Logan, Ut 84321 and C. Val Grant is a Wildlife Biologist, Bio-Resources, Inc., Logan, UT 84321.

Proceedings America Society of Mining and Reclamation, 1989 pp 403-414

DOI: 10.21000/JASMR8900403

https://doi.org/10.21000/JASMR89010403

monitoring methods.

The upper tailings pond within the State of New Mexico's Burt Clancy Fish and Wildlife Management Area presented a unique opportunity to study relationships among soil deposition patterns, soil and vegetation development, and heavy metal concentrations in soils and plants 50 years after abandonment. The tailings within the pond were from a zinc-lead mill and were high in elements such as Pb, Zn, Cd, and Cu (Grant 1988). They also contained high concentrations of sulfuric compounds and, consequently, were characterized by low pH, i.e., 3-4. An ephemeral stream ran through the tailings pond and had resulted in extensive flooding and deposition of sediment on top of the original tailings. Distinct vegetation communities had developed on the site in the 50 years since abandonment.

This study examined the natural developmental processes that had occurred on the pond. We addressed several questions: (1) What were the patterns of soil deposition on the tailings pond and how were they related to topography? (2) What were the physical and chemical characteristics of the tailings and of the soils that were deposited over the tailings? (3) What was the relationship between soil characteristics, plant community development, and plant metal concentrations ? (4) What was the potential for food-chain movement and bioaccumulation of metals? Study results were the basis for recommendations for reclamation.

Methods

The 14-ha tailings pond was in Alamitos Canyon (T16N, R12E, S30) at an elevation of 2,182 m near Pecos, New Mexico. The vegetation surrounding the pond ranged from Colorado pinyon (Pinus edulis)/one-seed juniper (Juniperus monosperma) to ponderosa pine (Pinus ponderosa)/ gambel oak (Quercus gambelii) woodland (Gass 1983). Average annual precipitation was 40 cm, over one-half of which arrived from June through September. The geology of the ore that was processed in the zinc-lead mill was described by Stott (1931) and the milling process was detailed by Bemis (1932).

A grid system with nodes spaced 25 m apart was superimposed over the entire pond to facilitate sampling. Relative elevational differences at each of the 180 nodes on the pond's surface were determined using an engineer's level. The pond's area was determined by digitizing its boundary from an aerial photo.

Patterns of soil deposition and associated vegetation were determined from an initial survey of the soil and vegetation at each node within the grid. Soils were sampled with a 10-cm diameter auger to determine the depth to tailings, soil or tailings texture, and soil or tailings color. Vegetation was sampled adjacent to each node. Each species was assigned a cover code value that reflected percentage of aerial cover of a 0.25 m^2 rectangular quadrat: cover code percent 1 = < 1, 2 = 1-5, 3 = 6-15, 4 = 16-25, 5 = 26-35, 6 = 36-45, 7 = 46-55, 8 = 56-65, 9 = 66-75, 10 = 76-85, 11 = 85-95, and 12 = 95-100. The soil and vegetation survey was used to provide an initial characterization of the soil/ vegetation types on the pond. Six types were classified: (1) tailings (loamy sand/no vegetation); (2) sands or xeric meadow (loamy sands/blue grama [Bouteloua gracilis] - sand dropseed [Sporobolus cryptandrus]); (3) mesic meadow transition (sandy loam/ vegetation typical of both sands and mesic meadow); (4) mesic meadow (loam/ creeping bentgrass

[Agrostis stolonifera]); (5) wet meadow transition (loam - clay loam/ vegetation typical of both mesic and wet meadow); and (6) wet meadow (clay loam/Baltic rush [Juncus balticus] - Kentucky bluegrass [Poa pratensis]). Each sample node was assigned a soil/vegetation type and a subset of nodes within each type was selected for collection of plant tissue and soil samples (N = 60).

Soil samples for physical and chemical analyses were collected at all 60 nodes. The depths sampled were dependent upon the depth of the soils deposited over the tailings. In general, these were 0-5, 15-25, 35-45, and the 10 cm increment above the tailings transition. Also, samples of surface tailings and tailings beneath each soil/vegetation type were collected. For the purposes of this paper, only the results from the tailings and the 0-5 cm samples of the soil/vegetation types will be discussed. Knowledge of the mining and milling process and a previous study of elemental concentrations on the pond (Grant 1988) indicated that Cu, Zn, Pb, and Cd posed the greatest environmental hazard and, thus, they were the main focus of this study. The initial study indicated low levels of available (DPTA-extractable) Cd; total concentrations of both Cd and Pb were determined for this study. All samples were analyzed for texture (Day 1973), organic matter (OM) (Schulte 1980), available P (Knudson 1980), exchangeable K and Mg (Carson 1980), pH (McLean 1980), cation exchange capacity (CEC) (Carson 1980), SO_4-S (Eik 1980), DTPA-extractable Mn, Fe, B, Cu, and Zn (Whitney 1980), and total Pb and Cd (EPA 1986). Soil analyses were performed by A and L Labs[3], Omaha, Nebraska.

Plant tissue samples (leaves and flowering stalks) were collected from three grass species for chemical analyses. Alkali muhly (Muhlenbergia asperifolia) occurred on all soil/ vegetation types and was collected at each of the 60 nodes. Blue grama was sampled from sands and mesic meadow transition (N = 30), while creeping bentgrass was collected from mesic meadow, wet meadow transition, and wet meadow (N = 30). Elemental concentrations of two deep-rooted woody species, coyote willow (Salix exigua) and narrowleaf cottonwood (Populus angustifolia), were evaluated by collecting and analyzing leaf samples from six nodes at which they both occurred. Tissue analyses were performed by A and L Labs to determine concentrations of Cu, Zn, Cd, and Pb (AOAC 1984).

Before analyzing the data, the initial soil/vegetation types were refined based upon the results of the physical and chemical soil analyses and the plant species cover data. Differences in soil physical and chemical properties among soil/ vegetation and differences in plant tissue concentrations of the various elements among soil/vegetation types and between species were determined from one- or two-way ANOVA.

Results and Discussion

Soil deposition patterns and, consequently, vegetation development were greatly influenced by the elevation gradient within the tailings pond and the effects of the ephemeral stream. The elevational change over the 900 m length of the pond was about 7 m with the steepest

---

[3] The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

gradient in the upper portion of the pond (Figure 1). It appeared that the main stream channel had undergone periods of both aggradation and degradation but that it was currently downcutting, ranging from 1 to 2 m deep in the upper portion of the pond. Overland flow from adjacent hillsides onto the pond and sedimentation adjacent to the stream resulted in a patterned depositional surface at the upper end of the pond. The sand soil/vegetation type was primarily in this well-drained area (Figure 2). The lower end of the pond was characterized by significant deposition from both the stream and adjacent hillsopes. The wet meadow type occurred in the lowest area within the pond and experienced standing water during part of the year. The mesic meadow and meadow transitions were found at intermediate elevations or along the stream channel.

The tailings materials were characterized by uniformly low pH and high concentrations of total Pb and Cd and available Cu and Zn (table 1). Despite inherently high variability in tailings chemical and physical properties, tailings beneath the wet meadow type had significantly higher percentages of silt and clay and higher concentrations of Pb than tailings on the surface or beneath the sands type. Also, tailings beneath the wet meadow tended to have nonsignficantly higher concentrations of Zn, Cd, and Cu than other sites. Differences in the elemental concentrations may have resulted from differences in the tailings at the time of deposition. However, it is more likely that the lower end of the pond experienced an accumulation of both water-transported fine materials and associated heavy metals through time.

Physical and chemical soil properties (0-5 cm) of the different soil/vegetation types also indicated that there had been an accumulation of water-transported fine materials and of most elements, including the heavy metals, in the surface deposited materials at the lower end of the pond (table 2). Although pH approached neutral and was relatively constant across the pond, percentages of both silt and clay increased significantly toward the lower end of the pond. Percentage OM was significantly higher in the meadow types than in the sands or mesic meadow transition, but a similar trend did not exist for CEC. Concentrations of K, Mg, and B were significantly higher in the mesic meadow, wet meadow transition, and wet meadow than in the sands or mesic meadow transition, while the opposite was true for available P. In general, metal concentrations were lowest in the sands and mesic meadow transition, highest in the wet meadow transition and wet meadow, and intermediate in the mesic meadow.

Levels of metals in the surface deposited soils were influenced not only by transport and depositional processes, but also by properties of the metals, tailings, and soils. Concentrations of Cd, Zn, Cu, and Pb in the different surface soils relative to those in the tailings materials were predictable based upon their solubilities, that is Cd~Zn>Cu>>Pb. The proportion of metals in surface soils relative to tailings was higher for metals with higher solubilities (Cd and Zn) than for metals with lower solubilities (Cu and, especially Pb) (tables 1 and 2), although the exact nature of this relationship may have differed if the comparisons were based only on available instead of both available and total concentrations. Retention of metals was highly dependent on the pH, texture, and OM of the soils. In

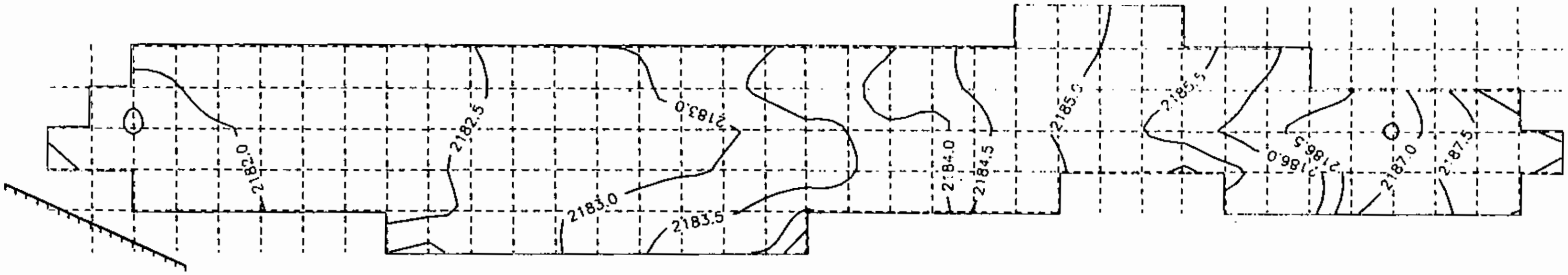
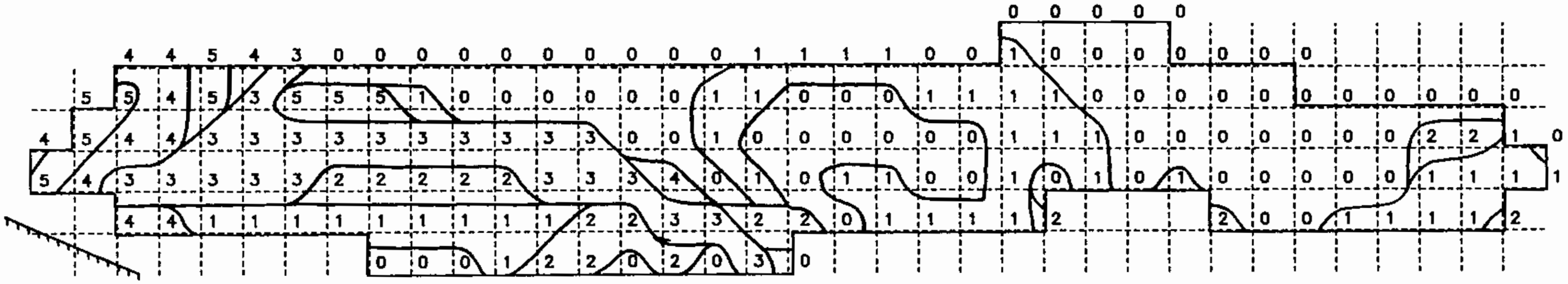


Fig. 1. Elevational change over the length of the tailings pond. Node distance is 25 m. Contour interval distance is 0.5 m.



																							0	0	0	0	0									
		4	4	5	4	3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	0	0						
	5	5	4	5	3	5	5	5	1	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	
4	5	4	4	3	3	3	3	3	3	3	3	3	3	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	2	2	1	0
5	4	3	3	3	3	3	2	2	2	2	2	3	3	3	4	0	1	0	1	1	0	0	1	0	1	0	1	0	0	0	0	0	1	1	1	1
		4	4	1	1	1	1	1	1	1	1	1	2	2	3	3	2	2	0	1	1	1	1	2				2	0	0	1	1	1	1	2	
								0	0	0	1	2	2	0	2	0	3	0																		

Fig. 2. Soil/vegetation types on the tailings pond. Numbers specify types: 0 = tailings, 1 = sands, 2 = mesic meadow transition, 3 = mesic meadow, 4 = wet meadow transition, 5 = wet meadow. Node distance is 25 m.

Table 1. Characteristics of tailings material at the surface and beneath the sands and wet meadow soil/vegetation types of an abandoned tailings pond.

Property	Surface tailings (n = 10)	Sands (n = 5)	Wet meadow (n = 3)
pH	3.1 ± 0.2[1]	3.3 ± 0.2	3.5 ± 0.5
CEC (meq/100 g)	42.6 ± 8.8	35.3 ± 14.8	29.4 ± 6.4
% Sand	66.4 ± 5.3 b[2]	69.2 ± 3.3 b	19.3 ± 7.7 a
% Silt	24.5 ± 5.2 a	20.4 ± 4.1 a	60.3 ± 5.2 b
% Clay	9.1 ± 1.2 a	0.4 ± 2.0 a	20.3 ± 5.5 b
Total Pb (mg/kg)	3626.1 ± 678.4 a	5123.6 ± 693.6 a	9393.7 ± 870.0 b
Total Cd (mg/kg)	0.8 ± 0.4	1.3 ± 0.6	8.9 ± 8.5
OPTA Zn (mg/kg)	45.7 ± 30.0	35.9 ± 22.3	241.9 ± 237.6
DPTA Mn (mg/kg)	6.9 ± 2.8	4.4 ± 3.4	2.0 ± 0.6
OPTA Fe (mg/kg)	372.0 ± 197.3	645.0 ± 538.9	93.0 ± 75.6
DPTA Cu (mg/kg)	42.6 ± 25.6	24.8 ± 10.1	103.8 ± 98.6
So_4-S (mg/kg)	95.6 ± 0.4	95.8 ± 0.9	96.0 ± 0.6

[1] Values are means ± 1 S.E.

[2] Different letters indicate significant differences among soil/vegetation types where shown (Fisher's Protected LSD; p < .05).

Table 2. Physical and chemical properties of the 0-5 cm soil samples from 5 soil/vegetation types on an abandoned tailings pond.

Property	Sands (n = 18)	Mesic meadow transition (n = 8)	Mesic meadow (n = 11)	Wet meadow transition (n = 9)	Wet meadow (n = 5)
OM (%)	[1]1.3 ± 0.1 a[2]	1.2 ± 0.1 a	3.0 ± 0.3 b	3.4 ± 0.3 b	3.6 ± 0.4 b
CEC (meq/100g)	12.1 ± 1.5 a	18.5 ± 3.7 bc	23.1 ± 2.5 c	16.9 ± 1.3 abc	15.3 ± 1.1 ab
pH	7.1 ± 0.3 a	6.8 ± 0.5 a	6.8 ± 0.1 a	6.5 ± 0.4 a	6.8 ± 0.3 a
% Sand	73.9 ± 2.7 c	72.3 ± 2.3 c	31.6 ± 4.0 b	18.7 ± 1.6 a	21.6 ± 2.2 ab
% Silt	16.8 ± 2.4 a	17.3 ± 1.6 a	49.6 ± 3.4 b	43.0 ± 2.1 b	41.0 ± 1.8 b
% Clay	9.2 ± 0.5 a	10.0 ± 0.8 a	18.7 ± 2.3 b	38.2 ± 2.2 c	37.4 ± 3.3 c
P (mg/kg)	4.9 ± 1.3 b	4.0 ± 0.4 b	1.5 ± 0.2 a	1.4 ± 0.2 a	1.4 ± 0.4 a
K (mg/kg)	80.0 ± 7.6 a	78.0 ± 13.1 a	151.4 ± 9.7 b	166.4 ± 12.6 b	175.0 ± 23.5 b
Mg (mg/kg)	46.9 ± 4.0 a	90.3 ± 17.2 a	241.8 ± 30.2 b	213.3 ± 18.3 b	213.3 ± 14.8 b
So_4-S (mg/kg)	84.8 ± 5.4 a	96.3 ± 0.4 a	96.1 ± 0.4 a	92.8 ± 3.4 a	96.0 ± 0.5 a
B (mg/kg)	0.8 ± 0.0 a	0.9 ± 0.1 a	1.1 ± 0.1 b	1.1 ± 0.0 b	1.2 ± 0.1 b
Total Pb (mg/kg)	530.8 ± 67.6 a	515.3 ± 67.1 a	2644.2 ± 290.7 b	5199.2 ± 381.2 d	3899.4 ± 765.5 c
Total Cd (mg/kg)	1.5 ± 0.2 a	1.3 ± 0.5 a	4.7 ± 0.4 b	6.7 ± 0.8 bc	9.3 ± 2.9 c
OPTA Zn (mg/kg)	36.5 ± 5.7 a	49.3 ± 13.5 a	165.1 ± 14.9 b	190.7 ± 12.7 bc	231.8 ± 41.3 c
DPTA Cu (mg/kg)	13.0 ± 1.8 a	15.1 ± 2.4 a	84.4 ± 6.1 b	122.9 ± 7.2 c	114.0 ± 4.9 c
DPTA Mn (mg/kg)	5.2 ± 0.3 a	6.0 ± 2.2 ab	7.9 ± 0.8 b	7.9 ± 0.8 b	8.6 ± 2.0 b
DPTA Fe (mg/kg)	29.2 ± 8.8 a	53.3 ± 32.9 ab	81.5 ± 6.5 b	92.0 ± 13.4 b	76.0 ± 20.3 ab

[1] Values are means ± 1 S.E.

[2] Different letters indicate significant differences among soil/vegetation types (Fisher's Protected LSD; p < .05).

general, availability of Cd, Zn, Pb, and Cu decreases with increases in pH and percentage clay and OM. At higher pH levels metals are precipitated as insoluble compounds. The near neutral pH of the soils in this study resulted in lower availability of the metals but higher retention than would be expected in lower pH soils. Metals can be adsorbed onto clay surfaces depending on the exchangeable cation present on the clay surface and the metal species. They can also form stable complexes with OM, although the stability of these complexes may be greater for Cu and Pb than for Cd or Zn (Safaya et al. 1987). The higher percentages of OM and clays at the lower elevations of the pond in the mesic meadow, wet meadow transition, and wet meadow indicated a greater capacity for retention of the heavy metals.

The amount and type of vegetation development can affect OM and elemental accumulation in surface soils. Aerial vegetation cover on the pond was 14, 32, 44, 62, and 61 percent for the sands, mesic meadow transition, mesic meadow, wet meadow transition, and wet meadow soil/vegetation types, respectively. Higher vegetation production results in larger amounts of above- and below-ground litter and may, ultimately, result in greater turnover of elements and in higher levels of OM (Antonovics et al. 1971). Many plant species take up certain mineral nutrients in excess of nutritional needs and will also take up nonessential elements, often in large amounts. When the plants die and their litter is decomposed, the elements are released back into the soil and are usually concentrated near the surface. Over time, these processes can contribute to the redistribution or accumulation of elements in soils.

Plant tissue concentrations of Pb, Cd, Zn, and Cu for alkali muhly were highly correlated with soil concentrations of those elements in the different soil/vegetation types. Linear and nonlinear regression resulted in r^2 values of 0.99, 0.97, 0.90, and 0.99 for total Pb and Cd and available Zn and Cu, respectively. The relationships between soil and plant tissue correlations were reflected in the analyses of just the plant tissue concentrations (table 3). Concentrations of Pb in alkali muhly on the sand type did not differ from those on the mesic meadow transition but were significantly lower than those on the other types. Also, concentrations of Cd in alkali muhly on the wet meadow were similar to those on the wet meadow transition but were significantly higher than those on other types. Plant tissue concentrations were often highly variable within soil/vegetation types. Despite apparent trends, there were no significant differences among the types in blue grama or creeping bentgrass for any of the metals or in alkali muhly for Zn or Cu. Also, there were no significant differences between species.

Concentrations of Zn and Cd in the two deep-rooted species, coyote willow and narrowleaf cottonwood, were extremely high when compared to the three grasses (table 4). In

Table 4. Elemental concentrations (mg/kg) in *Salix exigua* and *Populus angustifolia* on an abandoned tailings pond.

Element	*Salix exigua* (n = 7)	*Populus angustifolia* (n = 6)
Pb	15.32 ± 7.08[1]	11.99 ± 8.42
Zn	1041.00 ± 140.68	1092.83 ± 147.23
Cd	8.66 ± 1.38	21.95 ± 8.30
Cu	11.86 ± 2.02	8.33 ± 1.20

[1] Values are means ± 1 S.E.

Table 3. Elemental concentrations (mg/kg) of 3 grasses on 5 different soil/vegetation types on an abandoned tailings pond.

	M. asperifolia	*B. gracilis*	*A. stolinifera*	*M. asperifolia*	*B. gracilis*	*A. stolinifera*
	Pb			Zn		
Sands	24.7 ± 19.0 (17)a	16.7 ± 12.7 (16)a		103.1 ± 59.5 (18)a	118.1 ± 55.7 (16)a	
Mesic meadow transition	36.8 ± 38.8 (8)ab	18.6 ± 9.3 (6)a		110.9 ± 73.4 (8)a	113.7 ± 39.7 (6)a	
Mesic Meadow	57.9 ± 26.1 (11)b		62.3 ± 41.8 (11)a	148.0 ± 51.7 (11)a		136.6 ± 59.6 (11)a
Wet Meadow transition	69.0 ± 64.2 (5)b		37.6 ± 28.6 (9)a	127.6 ± 45.8 (9)a		154.0 ± 60.0 (9)a
Wet Meadow	68.6 ± 26.7 (9)b		38.9 ± 21.9 (5)a	159.4 ± 80.9 (5)a		154.0 ± 46.8 (5)a
	Cd			Cu		
Sands	0.4 ± 0.2 (17)a	0.2 ± 0.2 (16)a		11.2 ± 4.7 (18)a	9.4 ± 2.4 (16)a	
Mesic meadow transition	0.4 ± 0.5 (8)a	0.4 ± 0.4 (6)a		12.2 ± 8.4 (8)a	8.7 ± 3.1 (6)a	
Mesic meadow	0.7 ± 0.6 (11)a		0.6 ± 0.4 (11)a	14.1 ± 5.0 (11)a		11.4 ± 4.1 (11)a
Wet meadow transition	0.9 ± 0.6 (9)ab		1.0 ± 0.6 (90)a	14.8 ± 10.9 (9)a		10.5 ± 3.0 (9)a
Wet meadow	1.5 ± 1.5 (5)b		1.2 ± 0.7 (5)a	13.4 ± 3.4 (5)a		10.6 ± 1.7 (5)a

[1] Values are means ± 1 S.E., n is in parenthesis.

[2] Different letters indicate significant differences among soil/vegetation types within species (Fisher's Protected LSD; $p < .05$).

contrast, concentrations of Pb were generally lower than those of the grass species, and concentrations of Cu were similar to those of the grasses. The higher Pb concentrations in the grasses may have resulted, in part, from surface contamination of Pb from the soil.

Lead, Zn, Cd, and Cu are toxic to both plants and animals at high concentrations. Although Zn and Cu are essential nutrients for plants and animals, Pb and Cd have no known function in living organisms. Determining the concentrations at which these metals become toxic is difficult for several reasons: (1) different sampling and extraction methods have been used to obtain reported values; (2) natural variability of these elements in soils is high; and (3) concentrations at which these elements become toxic varies greatly among individual species of both plants and animals. However, to evaluate potential toxicity it is necessary to establish tolerance limits. Table 5 attempts to present reasonable values for the ranges of concentrations common in plant leaves and for suggested maximum concentrations in plant tissue for plants and for livestock forages. Elevated plant tissue concentrations for Pb and Cd existed in the three grass species. Tissue concentrations of Cu were within normal ranges, while those for Zn were at the upper end of the range for both alkali muhly and creeping bentgrass and were greatly elevated for coyote willow and narrowleaf cottonwood. Plant tissue concentrations of Pb exceeded or were at the upper range of maximum suggested values for all species in all soil/vegetation types but were within the upper limits for the other metals for the grasses. Levels of Zn and Cd were much higher than suggested maximums for the two woody species.

There were no visible signs of plant toxicity within any of the soil/vegetation types. However, the high concentrations of metals may have had negative effects on plant metabolic processes that were not visually apparant. Although plant leaf concentrations of Zn and Cd are usually linearly related to soil concentrations, leaf concentrations of Cu and Pb may not reflect soil levels, and root concentrations may be better indicators of toxicity. Certain plant species are capable of rapidly adapting to high concentrations of metals, and tolerant species may accumulate high levels of metals in the roots without subsequent translocation to the shoots. Excess Cu, Cd, Zn, or Pb can decrease root and shoot growth in both tolerant

Table 5. The range in elemental concentrations (mg/kg) of Pb, Zn, Cd, and Cu common in plant leaves and suggested maximum concentrations for plants and for livestock forages.

Element	Plant leaves	Max plants	Max forages
Pb	0.1 - 5.0[c]	10 - 20[bc]	30[e]
Zn	15 - 150[bc]	400[d]	300[e]
Cd	0.2 - 0.8[a]	3[a]	0.5[e]
Cu	5 - 15[b]	16 - 20[b]	25[e]

[a] Allaway (1968). [c] Mehlstad (1973). [e] NRC (1980).
[b] NEC-28 (1985). [d] Marschner (1986).

and nontolerant species by interfering with metabolic processes such as respiration and photosynthesis (Bingham et al. 1975). The high metal concentrations may have resulted in total exclusion of sensitive species, especially in the mesic meadow, wet meadow transition, and wet meadow.

Because the pond is within a state wildlife management area, potential food-chain movement and bioaccumulation of metals in wildlife are of concern. While most animals can tolerate high amounts of Zn, mammals have low tolerance for both Cd and Cu, and Pb and Cd act as cumulative toxins. High variation in trace metal accumulation by different animals is to be expected from their different and highly specialized diets, and seasonal influences on food availability and dietary metal concentrations (Hunter et al. 1987). Because of the tendency for metals to concentrate in higher food-chain levels, metal concentrations in plant tissue should be used as risk indicators only for strictly herbivorous species. The maximum suggested values in forages in table 5 are for the lowest given for livestock (NRC 1980) and are presented here only to provide general guidelines. The three grasses were well within suggested limits for Zn and Cu in livestock forages, while the woody species greatly exceeded the levels given for Zn. Cd was within suggested limits for all but the two woody species. Excessive Pb levels were present in alkali muhly and creeping bentgrass in the mesic meadow transition, mesic meadow, wet meadow transition, and wet meadow. Although surface contamination may have increased plant Pb and Cd values, these levels accurately reflect the amounts ingested by animals.

The results of this study have strong implications for the reclamation of the tailings pond. The depositional processes on the site result in an accumulation of water-transported sediments and heavy metals and organic matter that exacerbate the accumulation of those metals in the meadow areas at the lower end of the pond. To prevent these processes from occurring, it will be necessary to reroute the stream so that it no longer flows over the tailings pond in an uncontained manner. This will result in more xeric site conditions and will necessitate revegetation of the meadow types with species adapted to xeric conditions. High concentrations of Pb were found in the mesic meadow, wet meadow transition, and the wet meadow that were reflected in plant tissue concentrations of alkali muhly and creeping bentgrass. Elevated levels of Cd and Cu were present in the wet meadow transition and the wet meadow, but these levels were not reflected by plant tissue concentrations in the grass species. The deep-rooted species, coyote willow and narrowleaf cottonwood, had high levels of Cd and Zn. This indicates the need to topsoil the mesic meadow, wet meadow transition, and the wet meadow in addition to the tailings materials prior to revegetation of the site with noncontaminated materials from offsite. Currently available topsoil materials are similar to the soils of the sand soil/vegetation type, and revegetation species can be selected from those that occur on the sand type. Deep-rooted woody species should not be seeded and should be removed from the site if they colonize naturally.

Literature cited

Allaway, W. H. 1968. Agronomic controls over the environmental cycling of trace elements. Adv. Agron. 20: 235-274.
http://dx.doi.org/10.1016/S0065-2113(08)60858-5

Antonovics, J., A. D. Bradshaw, and R. G. Turner. 1971. Heavy metal tolerance in plants. Adv. Ecol. Res. 7: 1-85.
http://dx.doi.org/10.1016/S0065-2504(08)60202-0

AOAC. 1984. Official methods of analysis. 14th ed. Association of Official Analytical Chemists, Washington, D.C.

Bemis, H. D. 1932. Milling methods and costs at the Pecos concentrator of the American Metal Co., Tererro, N. Mex. U.S. Bur. Mines Info. Circ. 6605. 23 p.

Bingham, F. T., A. L. Page, R. J. Mahler, and T. J. Ganje. 1975. Growth and cadmium accumulation of plants grown on a soil treated with a cadmium-enriched sewage sludge. J. Env. Qual. 4: 207-211.
http://dx.doi.org/10.2134/jeq1975.00472425000400020015x

Carson, P. L. 1980. Recommended potassium test. p. 12-13. in: W. C. Dahnke (ed). Recommended chemical soil test procedures for the North Central Region. North Dakota Agricultural Experiment Station, North Dakota State University.

Day, P. 1973. Particle fractionation and particle size analysis. p.545-546. in: C. A. Black (ed). Methods of soil analysis. Part 1. Physical and mineralogical properties including statistics and measurements of sampling. Amer. Soc. Agron.

Eik, K. 1980. Recommended sulfate-sulfur test. p. 25-28. in: W. C. Dahnke (ed). Recommended chemical soil test procedures for the North Central Region. North Dakota Agricultural Experiment Station, North Dakota University.

EPA 1986. Test methods for evaluating solid waste. United States Environmental Protection Agency. SW-846.

Gass, J. M. 1983. Soil and vegetation changes along a climatic gradient in the Southern Sangre de Cristo Mountains. p. 82-84. in: Proceedings of the workshop on Southwestern habitat types, April 8-10, 1983, Albuquerque, New Mexico. USDA Forest Service, Southwestern Region.

Grant, C. V. 1988. Report to Amax Mineral Resources Co., Inc.: Wildlife enhancement of tailings ponds in Bert Clancy Fish and Wildlife Management Area, Alamitos Canyon, Pecos, New Mexico. Bio-Resources, Inc., Logan, Ut. 27 p.

Hunter, B. A., M. S. Johnson, and D. J. Thompson. 1987. Ecotoxicology of copper and cadmium in a contaminated grassland ecosystem. I. Soil and vegetation contamination. J. Appl. Ecol. 24: 573-586.
http://dx.doi.org/10.2307/2403894

Knudson, D. 1980. Recommended phosphorus tests. p. 14-16. in: W. C. Dahnke (ed). Recommended chemical soil test procedures for the North Central Region. North Dakota Agricultural Experiment Staion, North Dakota State University.

Marschner, H. 1986. Mineral nutrition of higher plants. Academic Press. New York, N.Y. 674 p.

McLean, E. O. 1980. Recommended pH and lime requirement tests. p. 58. in: W. C. Dahnke (ed). Recommended chemical soil test procedures for the North Central Region. North Dakota Agricultural Exper- iment Station, North Dakota State University.

Mehlstad, S. W. 1973. Soil-plant relationships (some practical considerations in waste management). p. 121-128. in: Proc. Recycling Municipal Sludges and Effluents on Land. Champaign, Il.

NEC-28. 1985. Criteria and recommendations for land applications of sludges in the Northeast. Northeastern Regional Research Coordinating Project for Soil Research. Bulletin 851. Pennsylvania Agricultural Experiment Station, Pennsylvania State University.

NRC. 1980. Mineral tolerance of domestic animals. Nat. Research Council, Nat. Acad. Sci., Washington, DC. 577 p.

Safaya, N. M., J. E. McLean, and G. A. Halvorson. 1987. Cadmium and zinc. p. 283-312. in: R. D. Williams and G. E. Schuman (eds). Reclaiming mine soils and overburden in the western United States. Soil Cons. Soc. Amer.

Schulte, E. E. 1980. Recommended soil organic matter tests. p. 28-31. in: W. C. Dahnke (ed). Recommended chemical soil test procedures for the North Central Region. North Dakota Agricultural Experiment Station, North Dakota State University.

Stott, C. E. 1931. Geology of the Pecos Mine. Engin. Min. J. 131: 270-275.

Whitney, D. A. 1980. Micronutrient soil tests - zinc, iron, manganese and copper. p. 18-21. in: W. C. Dahnke (ed). Recommended chemical soil test procedures for the North Central Region. North Dakota Agricultural Experiment Station. North Dakota State University.