# THRESHOLDS FOR POTENTIAL EFFECTS OF MINING-RELATED TRACE ELEMENTS ON RIPARIAN PLANT COMMUNITIES

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**Abstract:** Plant biomass and other indicators were measured in relation to soil chemistry in trace elements-enriched riparian habitats of the Upper Clark Fork River Basin. Distinct zonation of plant species was commonly observed from almost bare areas of mining-related waste to relatively unaffected communities. Multiple linear regression (MLR) was used to relate plant biomass or species richness to trace element concentrations (As, Cd, Cu, Pb, and Zn), pH, and other soil variables. The resulting MLR models were used to estimate the plant community effect levels (PCELs), based on a specified decrease in plant biomass or species richness. These PCELs were generally higher than other available toxicity thresholds based on ecological endpoints. For example, at a pH of 7.0, the MLR-based PCELs for plant biomass was approximately an order of magnitude greater than literature-derived values.

**Additional Key Words:** trace elements, plants, toxicity thresholds, mining.

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## Introduction

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The Clark Fork River Superfund site is located within the Upper Clark Fork River Basin (UCFRB) in western Montana (Fig. 1). Many of the operable units at this site contain surface waters, wetlands, and associated riparian habitats that have received mine tailings and other wastes related to past mining practices throughout the region. As part of the Superfund process, the U.S. Environmental Protection Agency (EPA) and ARCO are conducting ecological risk assessments at selected operable units to assess the potential adverse ecological effects of chemical enrichment related to mining (e.g., ARCO 1992d; 1994; Pascoe and Blanchet 1993). Issues being addressed in these risk assessments include the potential for phytotoxic effects of five trace elements (As, Cd, Cu, Pb, and Zn) in riparian meadow communities and the transfer of these trace elements through food chains to important wildlife species.

The present study focuses on the derivation of plant community effect levels (PCELs) expressed as concentrations of selected trace elements (As, Cd, Cu, Pb, and Zn) and hydrogen ions in soil, above which total plant biomass or species richness is reduced relative to reference area conditions. PCEL values may be used to identify areas for evaluation of contaminant sources and potential remedial actions. However, these PCELs were not developed for direct use as cleanup levels, which must be established taking into consideration, among other factors, a technical and economic evaluation of risk management options (ARCO 1992d). Finally, these PCELs are not intended for application in upland areas or other habitats. Because physical-chemical conditions and biological communities differ greatly among habitat types, it is inappropriate to extrapolate the results for riparian habitats to other areas.

## Methods

### Study Area

Plant biomass and other indicators were measured in relation to soil chemistry in riparian habitats in each of three subregions of the Clark Fork River Superfund site: Silver Bow Creek, Warm Springs Creek, and the Upper Clark Fork River (Fig. 1). Tailings and other mining wastes originating from numerous mining, milling, and smelting operations in Butte have been deposited along and within Silver Bow Creek and subsequently have eroded and redeposited along the length of Silver Bow Creek and the Upper Clark Fork River. The Warm Springs Creek subregion received fluvial deposition of tailings as well as aerial deposition of emissions from the smelter at Anaconda, Montana.

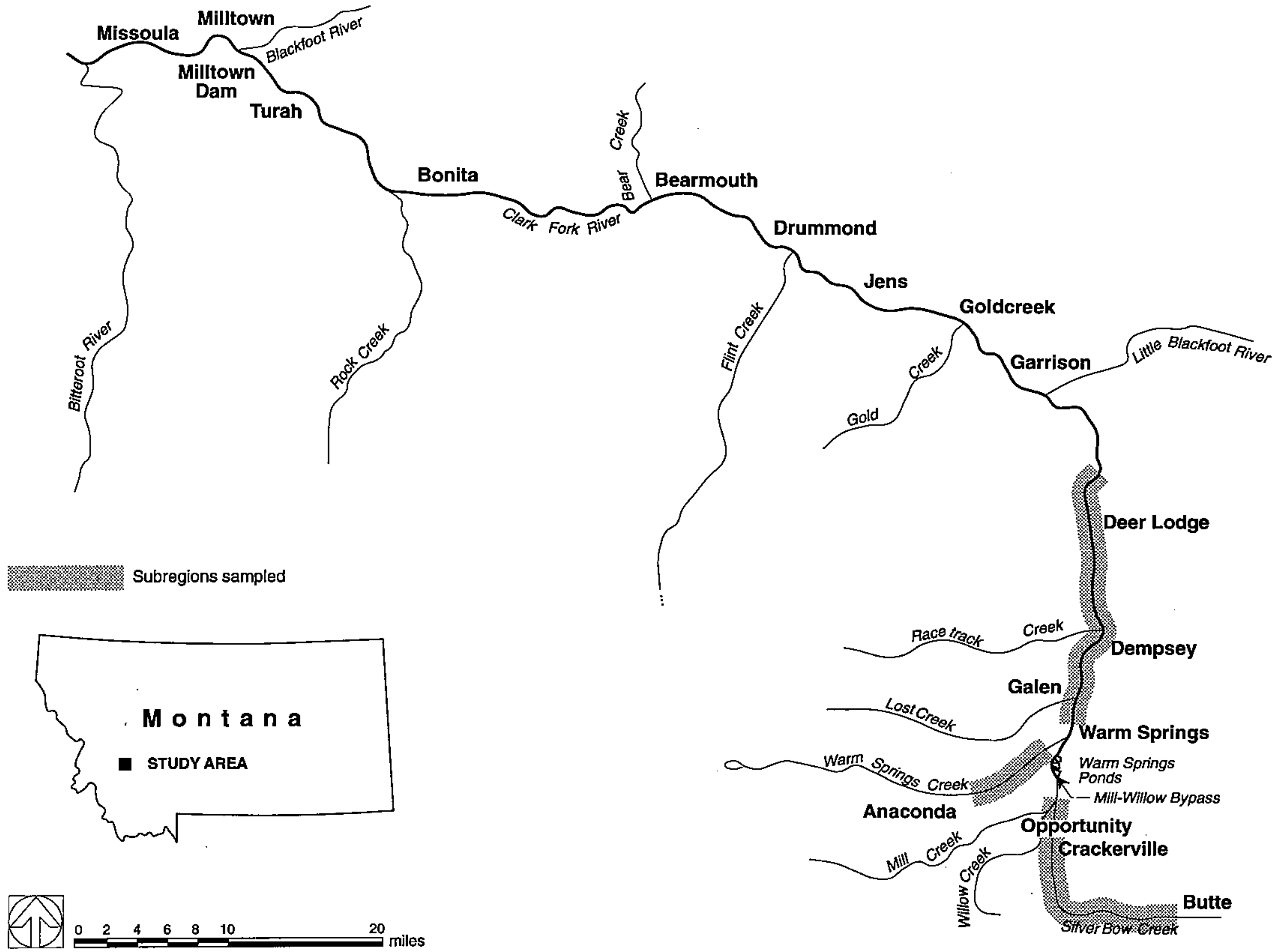



**Figure 1. Upper Clark Fork River Basin subregions.**

Sampling Stations

Sampling stations are described in detail in ARCO (1994). Plant community observations and samples for analysis of soil chemistry were taken from the same stations. Sixteen site stations and two reference stations were positioned within each subregion primarily on the basis of characteristics of the vegetation community.

Sampling and Analysis

PTI (1993, 1994) describes sampling and analysis methods and quality assurance procedures (ARCO 1992a) in detail. EPA-approved or EPA-recommended methods were used for target analytes.

A single composite sample for analyses of soil chemistry and ancillary variables was collected from each of the 54 stations where vegetation characteristics were measured (Fig. 2). Each sampling station was a 10- by 10-m plot with 10 subsample sites corresponding to the vegetation sampling quadrats. These quadrats were located randomly within the plot. Equal amounts of soil from the 0- to 12-in. depth interval were collected from the 10 quadrats with hand tools, composited, and homogenized thoroughly with stainless-steel sampling tools. Single composite samples also were collected from each of seven small mammal trapping stations where existing data were not available. Soil samples were analyzed for the trace elements of concern and ancillary variables listed in Table 1.

Plant community characteristics (Table 1) were evaluated at each of 54 stations. Ten replicate quadrats were located randomly within a 10- by 10-m plot, and aboveground plant parts were clipped for determination of biomass (after drying for approximately 24 hours at 85–100°C). An adjacent 10- by 10-m plot was used for collecting data on vegetation cover and species composition. Plot size and shape were sometimes modified to fit localized habitat conditions.

Data Analysis

***Multiple Linear Regression***—Multiple linear regression (MLR) was used to develop linear models to predict vegetative biomass and species richness in relation to soil trace elements, pH, moisture content, and other variables. The "Decker" moisture index is an estimate of percent water in soil at the wilting point and is calculated as

$$\text{Decker moisture index} = \frac{\text{TOC}}{2} + \frac{\text{Clay}}{3} + 2$$

where:

TOC = percent total organic carbon

Clay = percent clay (Decker 1972).

Soil variables that were excluded from the final models because they did not contribute significantly included sulfate, cation exchange capacity, total organic carbon, total Kjeldahl nitrogen, soluble phosphorus, total chloride, percent gravel, percent sand, percent silt, and percent clay.

The final models were based on the simple sum of concentrations of individual trace elements because the other weighting schemes investigated did not provide models with better predictive capacity. Moreover, selection of the sum of trace elements as a driving variable is justified by the high correlations among trace elements (ARCO 1994). The final models were selected for their ability to account for variability in the response endpoint.

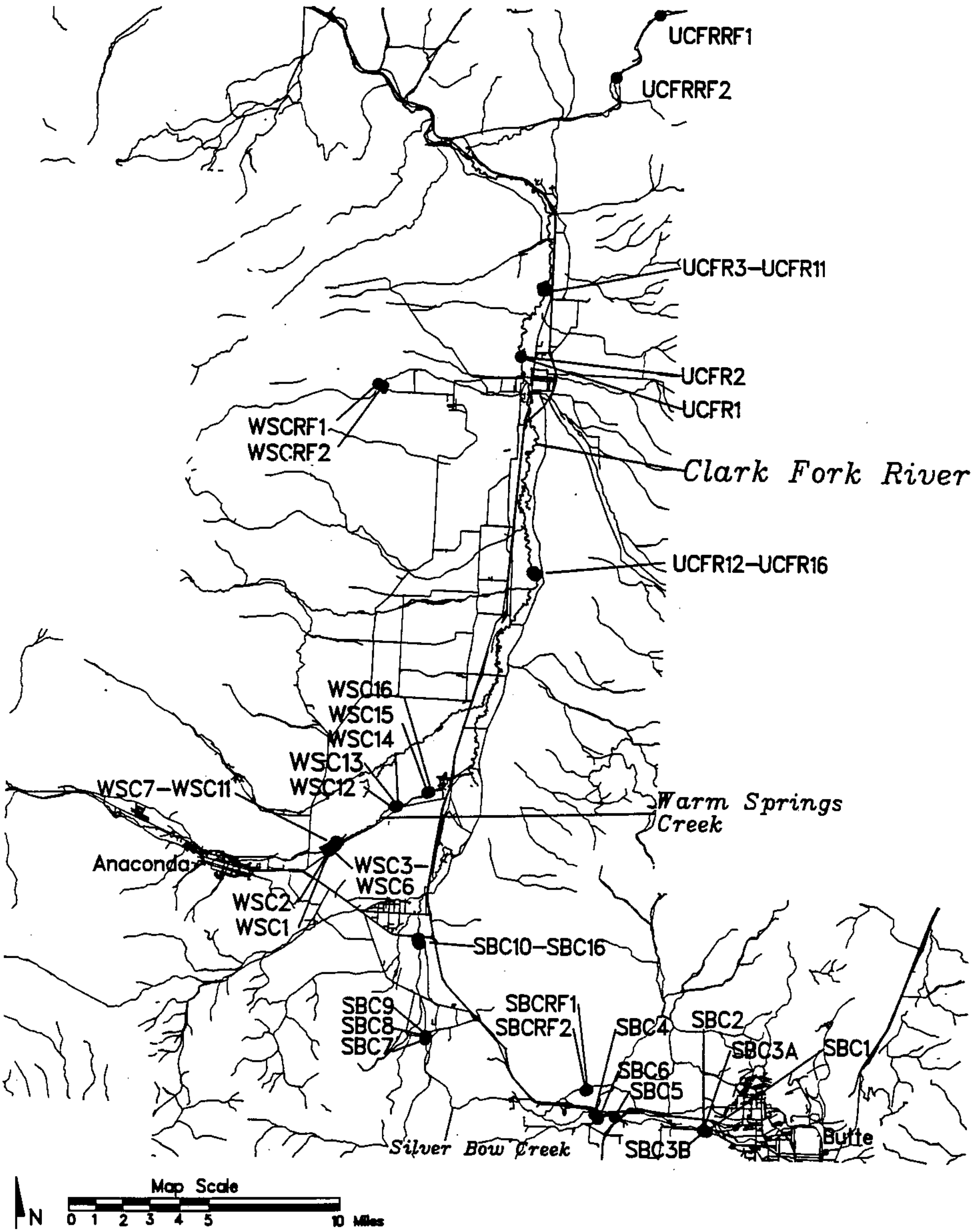



**Figure 2. Riparian plant community and soil sampling stations.**

Table 1. Endpoints for the regional ecorisk field investigation

| Study Component | Area of Investigation | Number of Species | Chemical Endpoint | Biological Endpoint |
|---|---|---|---|---|
| Soil Chemistry[a] | SBC, WSC, UCFR, 3 reference areas | NA | Total As, Cd, Cu, Pb, Zn; ancillary variables: moisture, percent solids, chloride, grain size, cation exchange capacity, total organic carbon, sulfate, pH, soluble phosphorus, total Kjeldahl nitrogen | NA |
| Plant Community | SBC, WSC, UCFR, 3 reference areas | >1 | NA | Cover, species diversity, biomass production |
| Plant Bioaccumulation | SBC, WSC, UCFR, 1 reference area | 3[b] | Total As, Cd, Cu, Pb, Zn; arsenic speciation (WSC subregion only); percent solids | NA |
| Crop Bioaccumulation | SBC, WSC, UCFR, 1 reference area | 1 | Total As, Cd, Cu, Pb, Zn; percent solids | NA |
| Invertebrate Bioaccumulation | SBC, WSC, 1 reference area | 3[c] | Total As, Cd, Cu, Pb, Zn; percent solids | NA |
| Small Mammal Bioaccumulation | SBC, WSC, UCFR, 1 reference area | 1 | Total As, Cd, Cu, Pb, Zn; percent solids | NA |
| Small Mammal Reproductive Effects | SBC, WSC, UCFR, 1 reference area | 1 | NA | Bands on uteri, implantation sites, embryos; field measures include age class, sex, weight, testicular status, vaginal status, lactation status |

**Note:** NA - not applicable
SBC - Silver Bow Creek
UCFR - Upper Clark Fork River
WSC - Warm Springs Creek

[a] During the reconnaissance trip, other soil parameters were measured in the field to ensure comparability of sites.

[b] In each subregion, three species were selected for analysis of trace elements in above-ground plant tissues. At some stations, more than one species was sampled.

[c] Three species/species groups were selected at each station. Efforts were made to select the same species across stations.

For a given vegetative endpoint and set of predictor variables, observations were excluded from analysis on the basis of standard regression diagnostics (Belsley et al. 1980). When a predictor variable was strongly lognormal, and its scale and variance had a deleterious effect on the regression model, it was log-transformed and the regression model was rerun. Independent variables were dropped when their contribution to the adjusted $R^2$ (as defined by Draper and Smith 1981) was negligible and not statistically significant ($P \gg 0.05$) after diagnostic treatment of the model.

***Plant Community Effect Levels***—PCELs for the sum of trace element concentrations in soil at specified pH were estimated for total biomass and total number of plant species per station. The MLR model was used to estimate soil conditions (i.e., combinations of trace element concentrations and pH) that corresponded to a tolerance limit equal to the minimum plant community biomass (or number of species) that could reasonably be expected from a reference area. At a given station, an average biomass or number of species less than its respective tolerance limit indicates that the plant community is different from typical reference conditions possibly due to phytotoxic soil. Tolerance limits were calculated from the pooled data for all reference stations. The resulting limits estimate values below which only 5 percent (on average) of individual observations from a reference population would fall. Using these tolerance limits, the MLR models were solved to find PCELs for soil trace elements and pH.

## Results and Discussion

### Soil Properties

#### Trace Elements

For all five trace elements (i.e., As, Cd, Cu, Pb, and Zn), concentrations in soils from the three subregions were higher than in reference area soils (Fig. 3). Trace element concentrations in study area soils ranged from 63 to 1,980 mg/kg for As, 0.61 to 20.5 mg/kg for Cd, 184 to 5,690 mg/kg for Cu, 38 to 5,070 mg/kg for Pb, and 118 to 9,930 mg/kg for Zn. Although the lowest concentration of each trace element was always found at a Warm Springs Creek station and the highest concentration was always found at a Silver Bow Creek station, each subregion captured a wide range of concentrations for all trace elements. Reference area concentrations of trace elements ranged from 14.6 to 45.8 mg/kg for As, 0.32 *U* (*U* = undetected) to 0.64 mg/kg for Cd, 11.2 *U* to 59.3 mg/kg for Cu, 7.4 to 45.2 mg/kg for Pb, and 45.9 to 96 mg/kg for Zn (Fig. 3). These results are consistent with previous results for regional background soils in the region (CH2M Hill 1987a,b, 1991; ARCO 1994).

#### Ancillary Soil Variables

Soils of all three subregions and the reference areas ranged in texture from silt loam to loam to sandy loam, with the exception of Stations UCFR1 and SBC9, which were loamy sands, and Stations UCFR9 and UCFR11, which were silty clay loams. With the exception of Stations UCFR9 and UCFR11, all soils contained less than 25 percent clay in the less than 2-mm fraction. Soil pH varied from 3.7 to 8.3 (Fig. 4). Concentrations of trace elements at the Silver Bow Creek stations with the lowest pH values were generally higher than at stations with higher pH. Both extractable sulfate and available phosphorus (Fig. 4) were lower in the reference area soils than in soils from the three subregions. Sulfate is a constituent of native soils as well as mine waste materials; thus, total sulfate concentrations in soil would be expected to be higher in a mineralized basin generally and in areas where waste deposition occurred. Soluble phosphorus generally increased as total sulfate increased for the soils analyzed in this investigation. Total organic carbon, total Kjeldahl nitrogen, and cation exchange capacity were generally higher and total chloride was generally lower in soils from the Warm Springs Creek subregion than in soils from the other two subregions or from the reference areas (Fig. 4).

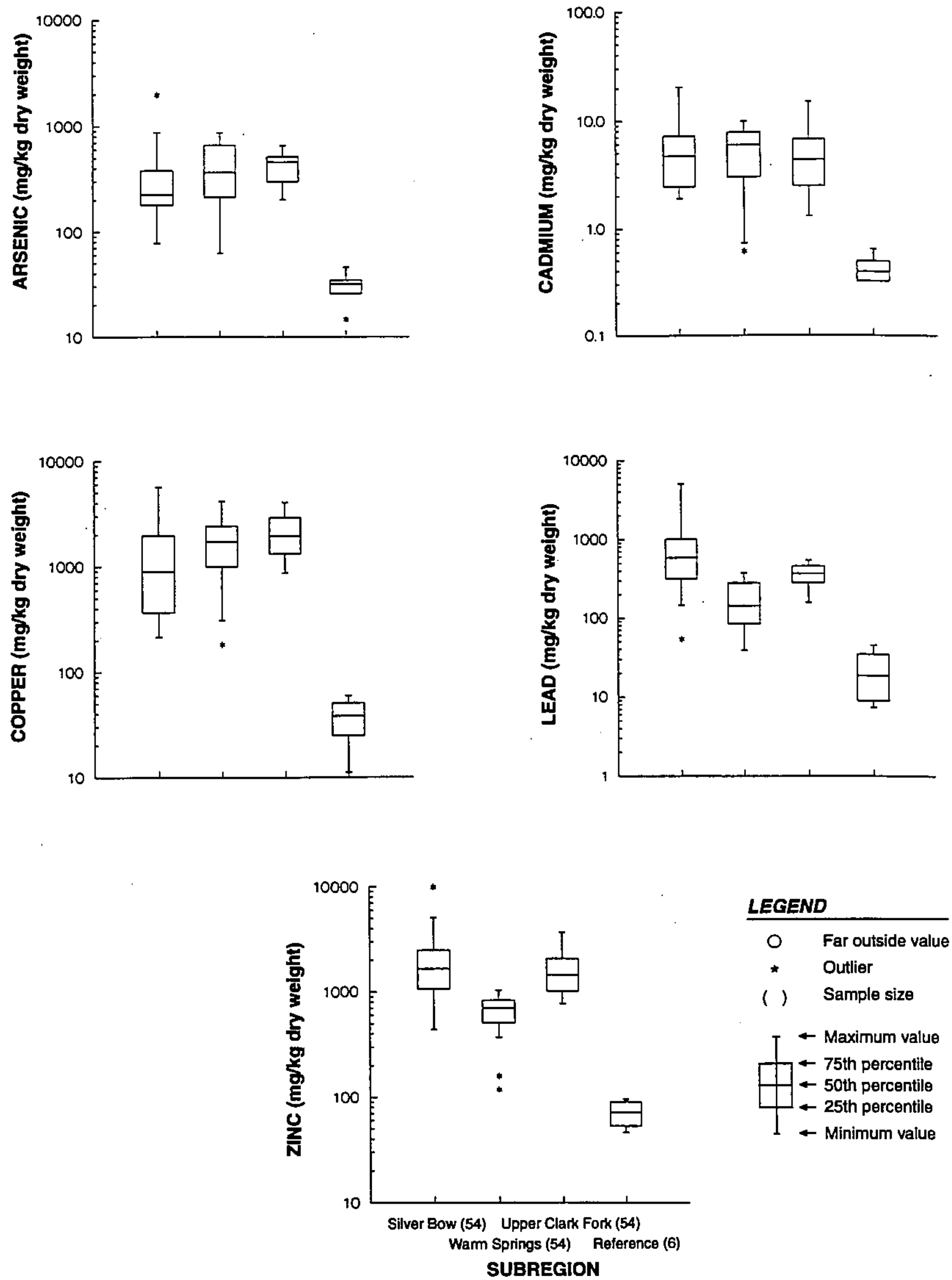



**Figure 3. Trace element concentrations in soil for riparian plant community stations by subregion.**

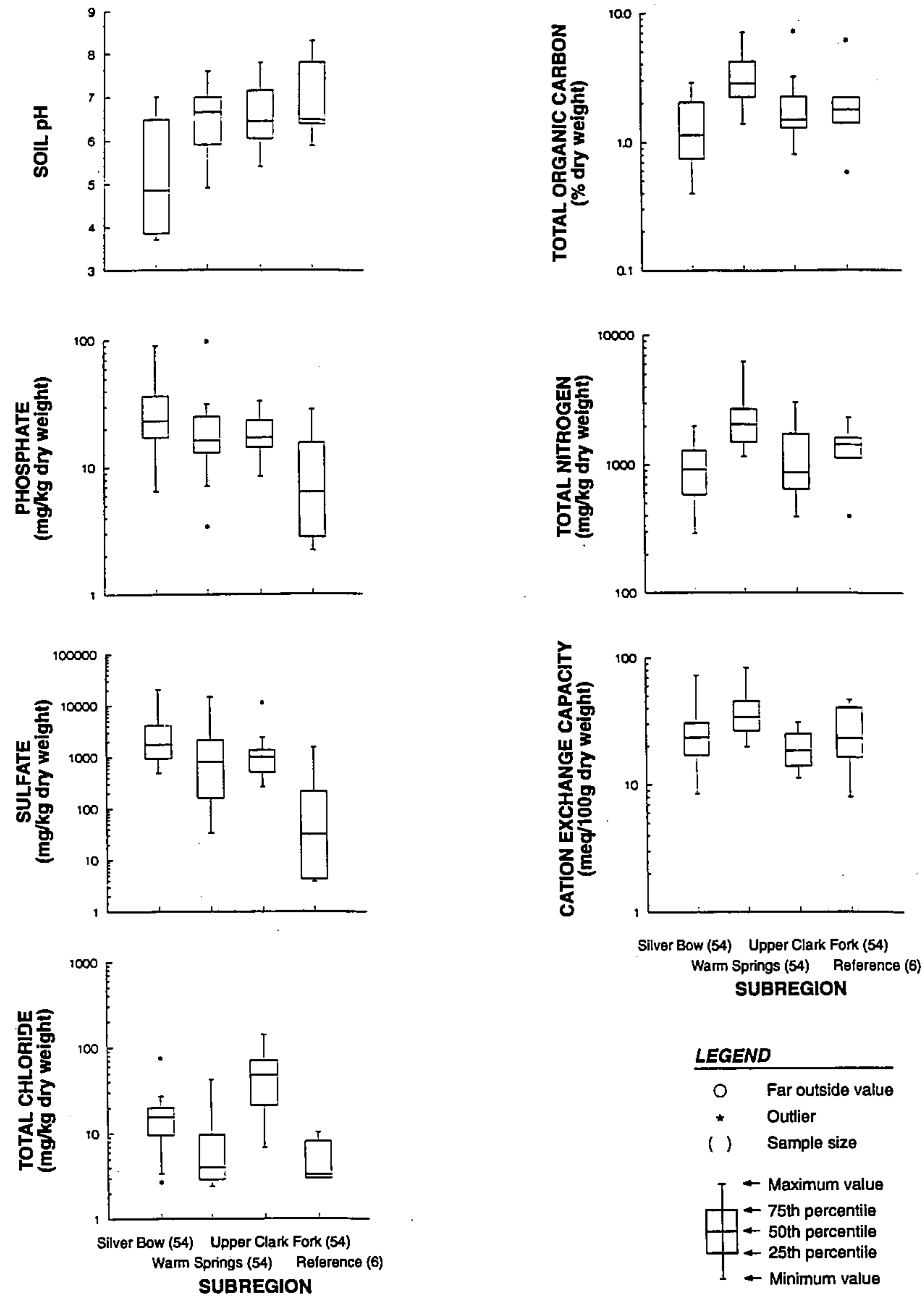



**Figure 4. Conventional soil characteristics for riparian plant community stations by subregion.**

## Riparian Plant Communities

The species composition, biomass, and richness of the riparian meadow communities sampled are characterized in the following sections (see Keammerer and Kuenstling [1993] for details). Total biomass and species richness are related to soil conditions, including pH and trace element concentrations, and the resulting models are used to develop PCELs.

### General Characteristics of Plant Communities

During field sampling, distinct zonation of plant species and biomass was commonly observed from bare areas of tailings to relatively unaffected soils. The plant communities sampled during this study included the following:

- Low biomass monocultures of tufted hairgrass (*Deschampsia caespitosa*) in areas with the highest tailings content in soil;
- Moderate to high biomass stands of mixed tufted hairgrass, redtop (*Agrostis alba*), and sometimes other species in areas of low or moderate tailings content in soil; and
- High biomass stands of a variety of species, typically in areas without the influence of tailings.

The meadow communities sampled were characterized mainly by cool season perennial grasses, such as tufted hairgrass; introduced perennial grasses, such as redtop, bromegrass (*Bromus inermis*), and Kentucky bluegrass (*Poa pratensis*); perennial forbs, such as asters (e.g., *Aster adscendens, Aster campestris*), Tweedy's plantain (*Plantango tweedyi*), and clovers (*Trifolium hybridum* and *Trifolium repens*); annual and biennial forbs, such as knapweed (*Centaurea maculosa*); and occasional rushes (*Juncus balticus*), sedges (*Carex* sp.), willows (*Salix* spp.), wood rose (*Rosa woodsii*), quaking aspen (*Populus tremuloides*), and river birch (*Betula occidentalis*).

Reference stations sampled for characterization of vegetation and associated soil conditions included two areas along each of three streams: Browns Gulch Creek, Tin Cup Joe Creek, and the Little Blackfoot River. The two reference stations along Browns Gulch Creek were similar to each other, with Kentucky bluegrass, clover, and slender wheatgrass as the dominant species. The two reference stations along Tin Cup Joe Creek were somewhat drier than the other reference sites and had vegetation characteristic of transitional and upland areas, including Kentucky bluegrass (the dominant species), needlegrass (*Stipa richardsonii*), and dandelion (*Taraxacum officinale*). Redtop was the dominant species at the reference stations along the Little Blackfoot River. Other common species at these stations included Kentucky bluegrass and slender wheatgrass. A variety of perennial grasses and forbs was also found at each of the six reference stations.

### Total Biomass and Species Richness Prediction Models

The MLR models (Fig. 5–7) to predict plant biomass and number of species from the sum of trace element concentration and ancillary soil variables are specified below:

MODEL 1: $\text{Biomass} = -0.0186 \times \text{Sum (As, Cd, Cu, Pb, Zn)} + 78.2 \times \text{pH} - 208$
(Adjusted $R^2 = 0.52$)

MODEL 2: $\text{Number of Species} = -0.0012 \times \text{Sum (As, Cd, Cu, Pb, Zn)} + 5.61 \times \text{pH} - 18.0$
(Adjusted $R^2 = 0.77$)

MODEL 3: $\text{Biomass} = -0.0217 \times \text{Sum (As, Cd, Cu, Pb, Zn)} + 68.0 \times \text{pH} + 66.3 \ln(\text{Decker}) - 249$
(Adjusted $R^2 = 0.49$)

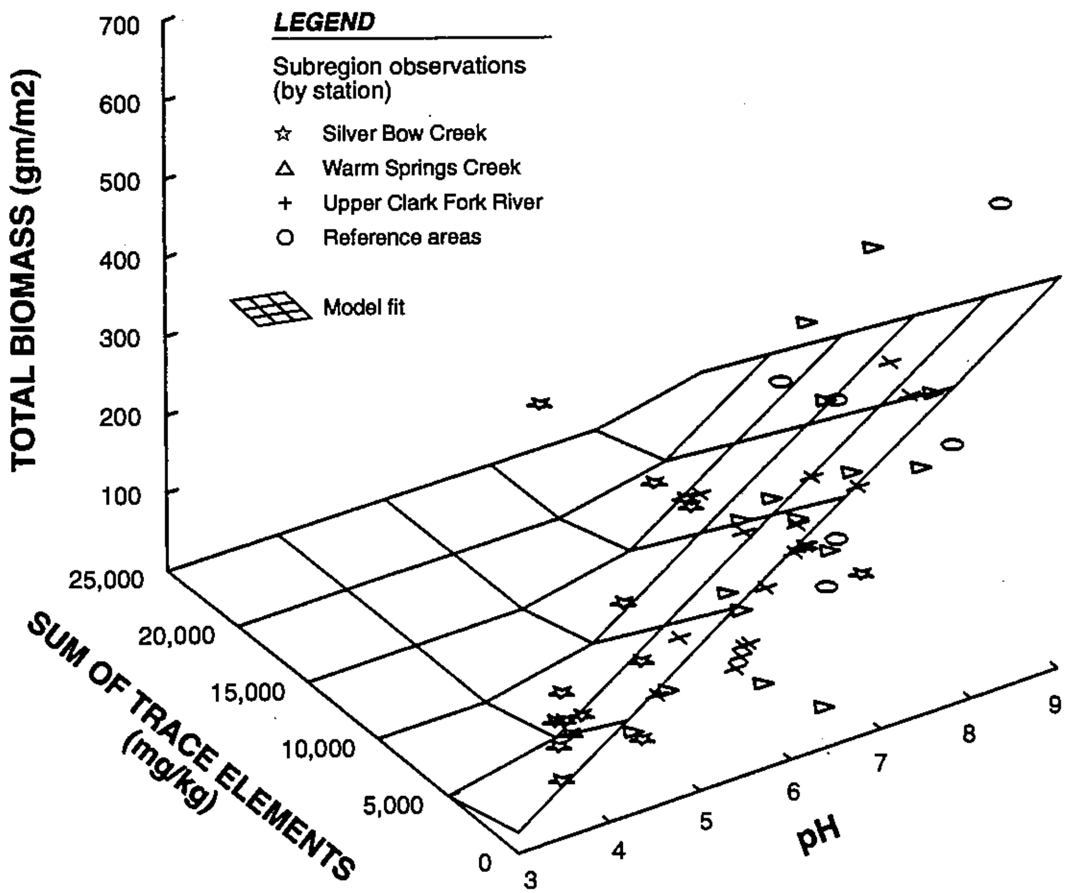



**Figure 5. Model for prediction of vegetation total biomass from soil trace element concentrations and pH.**

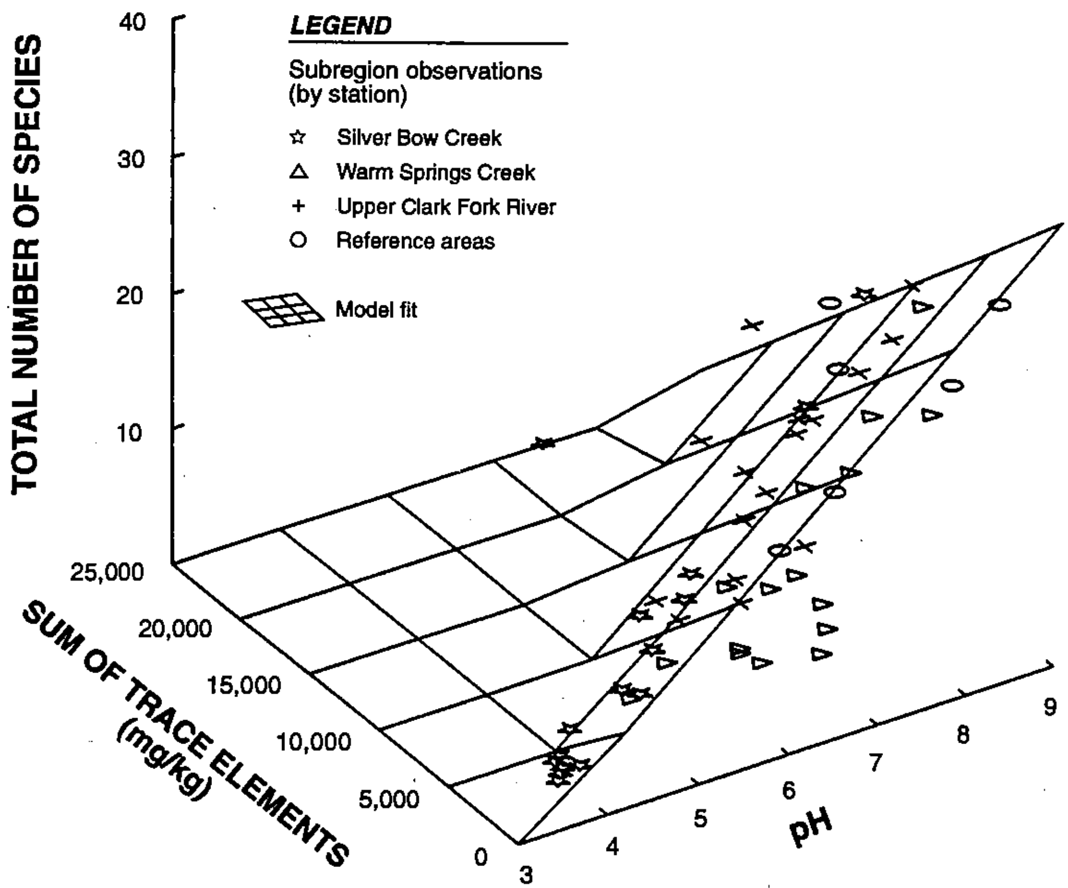



**Figure 6. Model for prediction of vegetation species richness from soil trace element concentrations and pH.**

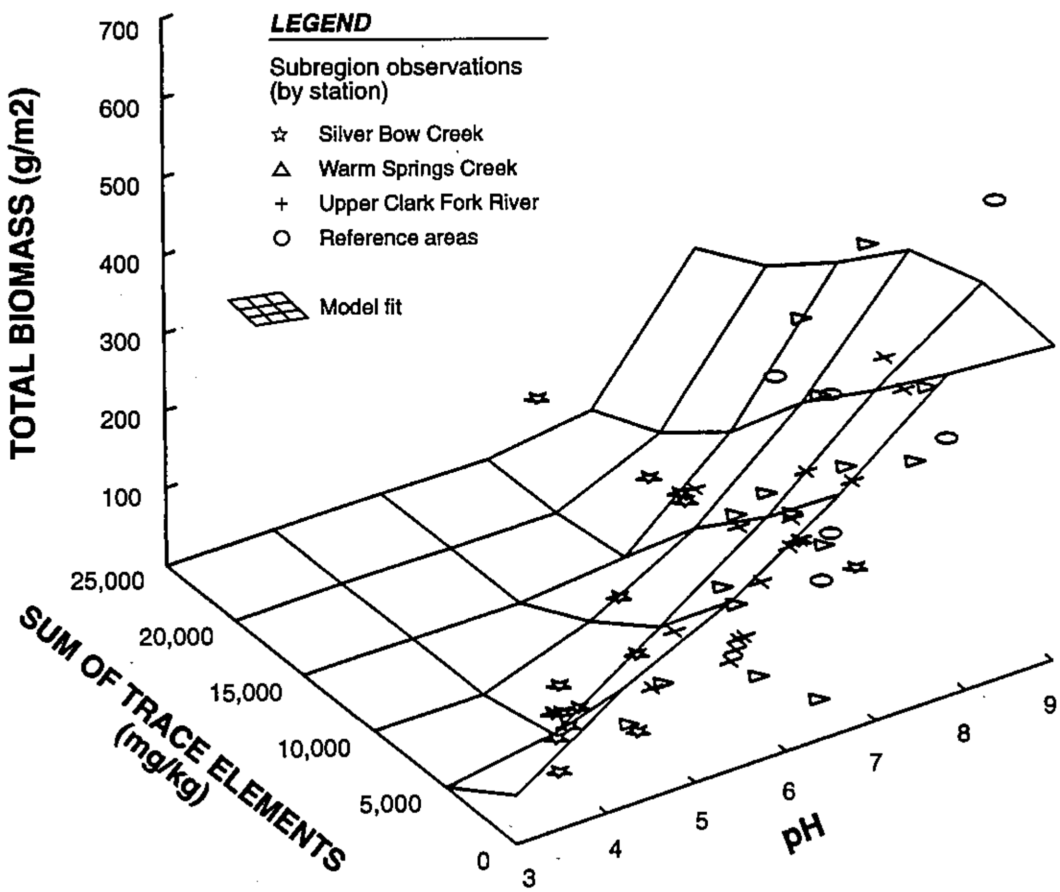



**Figure 7. Model for prediction of vegetation total biomass from soil trace element concentrations, pH, and water holding capacity.**

The trace elements variable and pH were the primary factors that contributed to prediction of plant community endpoints. The natural logarithm of the Decker value, which is an estimate of soil water-holding capacity, was not significant ($P$=~0.5) for the model to predict the number of plant species. The natural logarithm of the Decker value was nearly significant ($P$=0.08) for the model to predict the plant biomass, but the adjusted $R^2$ of the model did not increase because the number of predictor variables increased. Only Models 1 and 2 above (Fig. 5 and 6, respectively) were used to develop PCELs.

Plant Community Effect Levels (PCELs)

Model 1 was used to estimate the total concentration of five trace elements (i.e., As, Cd, Cu, Pb, and Zn) at each pH level that would be expected to result in a total plant biomass value less than the defined acceptable level; that is, fifth percentile of the population represented by all reference area values (Fig. 8). Second, soil PCELs for each pH level were developed with Model 2 and the fifth percentile of the reference area values for number of species (Fig. 8). Figure 9 shows station data classified by the model-based PCELs.

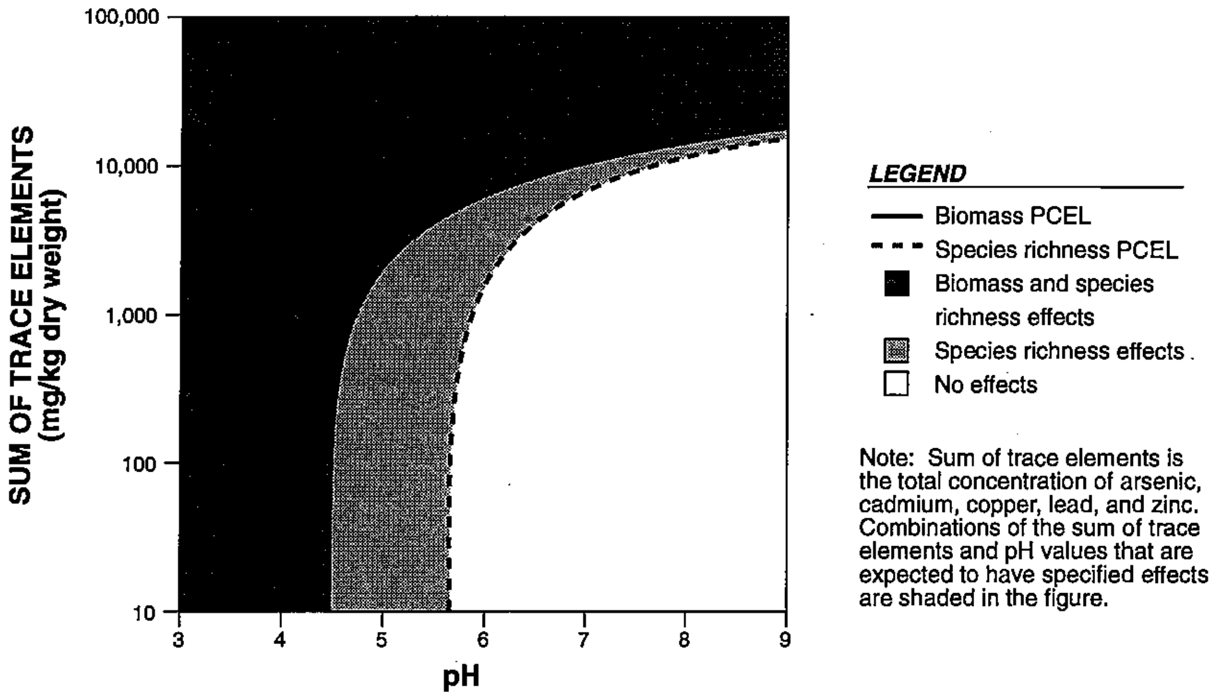
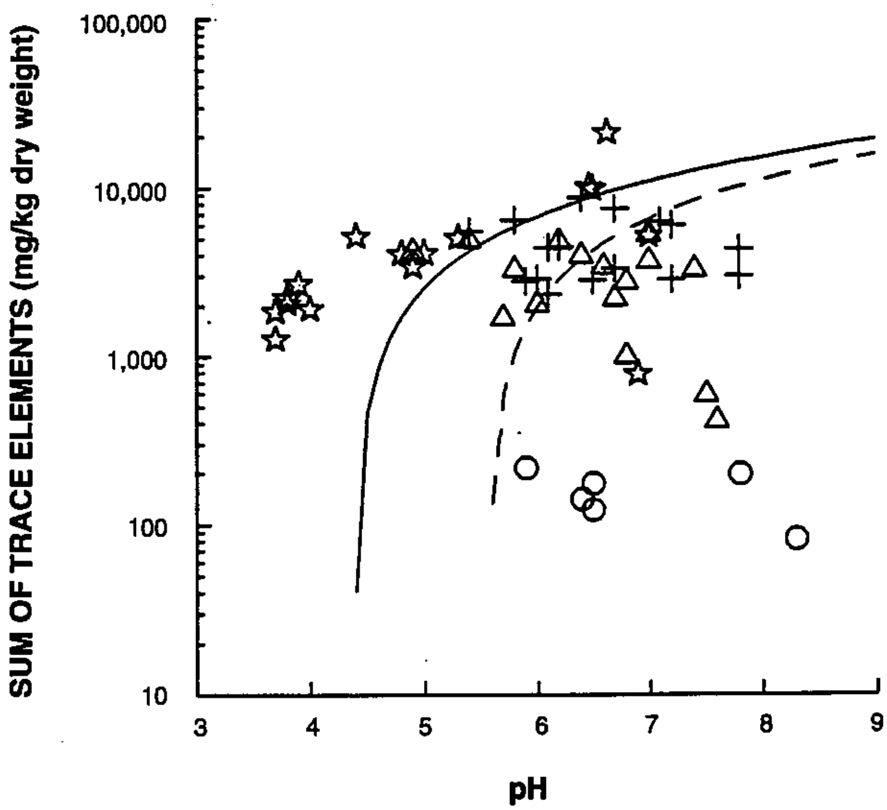



**Figure 8. Plant community effect levels (PCELs) based on empirical models.**

PCELs are intended for use as screening tools in baseline ecological risk assessments to evaluate the potential for effects of soil pH and trace elements in soils on total biomass and total number of riparian plant species. Available data on soil chemistry can be evaluated relative to PCELs to focus on areas where ecological risk investigations may be warranted. In cases where trace element concentrations in soil are less than PCELs at given pH values, it is appropriate to conclude that risks to riparian plant communities are *de minimis* and no further investigation is needed. In cases where trace elements or hydrogen ion concentrations in soil exceed PCELs, the information can be used to identify areas of potential concern that may need to be evaluated further. The MLR models and PCELs were not developed for the purpose of deriving cleanup levels, which must be established in the context of a technical and economic evaluation of risk management options (ARCO 1992d). Also, the PCELs are intended for use in evaluating baseline risks or other preremedial activities. These PCELs may not relate directly to the responses of vegetation used in remedial activities because species used for remediation may be more or less tolerant of trace elements compared with the riparian plant species used to derive the PCELs. Thus, the PCELs derived in this study should not be




Note: Station observation falling above a given curve for plant community effect levels indicates where plant community is expected to be significantly affected by tailings in soil.

*LEGEND*

| Vegetation effect thresholds | Subregion observations (by station) |
|---|---|
| —— Total biomass (g/m²) | ☆ Silver Bow Creek |
| — — Number of species | △ Warm Springs Creek |
| | + Upper Clark Fork River |
| | O Reference areas |

**Figure 9. Classification of stations in relations to model-based plant community effect levels (PCELs).**

viewed as cleanup levels or as criteria to evaluate the potential risks associated with soils already subjected to remedial actions. Finally, these PCELs were not intended for application in upland areas.

## Conclusions

- Soil trace element concentrations and pH are the main factors controlling total plant biomass and species richness in the meadow areas sampled. At pH values less than approximately 4.5, riparian meadow communities had significantly lower total biomass than communities in reference areas. An apparent threshold for significant reduction in the number of plant species relative to reference values was observed at a pH value of approximately 5.5. Water-holding capacity of soil was not an important factor controlling vegetation characteristics.
- Waste-affected sites in riparian habitats typically are dominated by tufted hairgrass and redtop. Tufted hairgrass appears to be more tolerant of low pH and mining-related waste than does redtop.
- Willows and a variety of grasses and forbs are more sensitive to mining-related waste than tufted hairgrass and redtop. Along a gradient of increasing trace element concentrations and decreasing pH in soil, there is a sharp threshold for the transition from a meadow dominated by one or both of the tolerant species to a more diverse community that includes many of the apparently more sensitive species.

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