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MOLYBDENUM UPTAKE BY 33 GRASS, FORB, AND SHRUB SPECIES GROWN IN MOLYBDENUM TAILINGS AND SOIL

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ABSTRACT

A concern resulting from the revegetation of molybdenum mill tailings is the possible occurrence of elevated molybdenum concentrations (Mo) and molybdenum/copper concentration ratios (Mo/Cu) in aboveground plant biomass; molybdenosis might be induced in animals grazing or browsing plants growing on these reclaimed areas. A controlled uptake experiment was conducted to determine Mo levels and Mo/Cu ratios in the shoots of 33 plant species grown in soil-covered tailings and in soil alone. The species tested represent a range of plant growth forms including cool- and warm-season grasses, herbaceous legumes, forbs and half-shrubs, and woody shrubs.

The results of our study show 3 species with less than 10 μg/g Mo when grown in tailings: summer cypress (*Kochia scoparia*), rubber rabbitbrush (*Chrysothamnus nauseosus*), and mountain mahogany (*Cercocarpus montanus*). Three shrubs and two forbs had shoot Mo/Cu ratios less than 2.5 when grown in tailings: rubber rabbitbrush, mountain mahogany, one ecotype of four-wing saltbush (*Atriplex canescens*), summer cypress, and purple aster (*Machaeranthera bigelovii*). Significant differences in shoot Mo concentration and Mo/Cu ratio exist between ecotypes within individual species. As an example, Mo/Cu ratios for two ecotypes of little bluestem (*Schizachyrium scoparium*) were 7.2 and 3.3. The presence of these differences illustrates that germplasm selection might allow the production of releases which discriminate against Mo uptake and translocation.

INTRODUCTION

A common concern resulting from the reclamation of mineral waste dumps is the potential for plant uptake of toxic constituents present in the waste material. Specific concerns related to the revegetation of molybdenum mill tailings and mine spoils include the molybdenum (Mo) concentration in aboveground plant biomass and the concomitant molybdenum/copper (Mo/Cu) concentration ratio; high levels of these parameters are indicators of potential toxicity to animals grazing or browsing plants on reclaimed areas. Studies to determine Mo concentrations of plants growing on waste dumps are often complicated by the presence of varying amounts of surficial particulates (i.e. soil, tailings, or waste rock) and their accompanying contaminants. The constituents in these particulates can mask the actual uptake and translocation of Mo from the plant roots to the aboveground plant tissues. Other complicating variables influencing uptake include a) spatial variability in total and available Mo within the substrate (i.e. tailings or spoils), b) soil cover thickness, c) heterogeneity of soil physical and chemical characteristics, d) depth and spread of root systems of sampled plants, and e) time of year the plants are sampled.

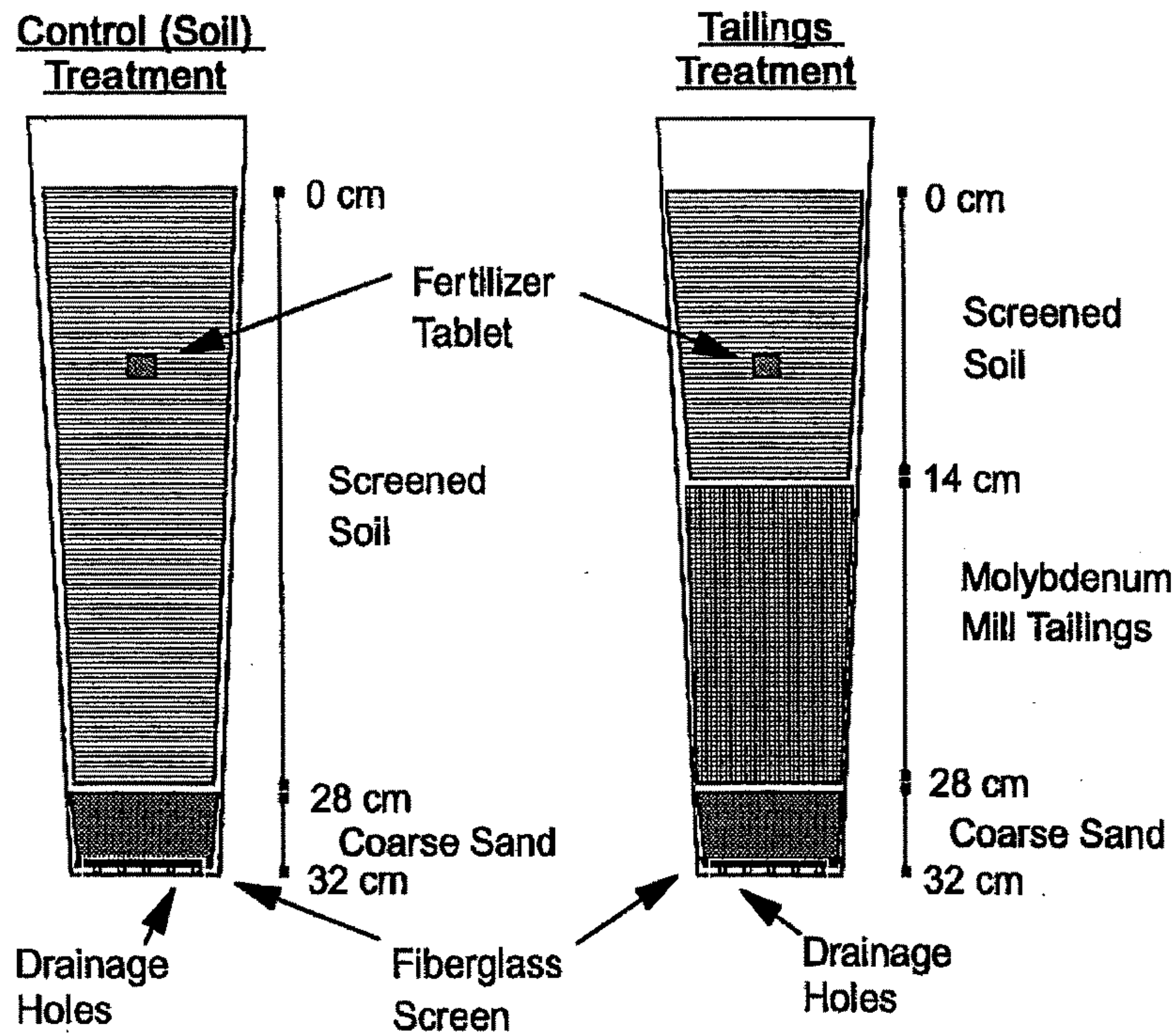
The Los Lunas Plant Materials Center has conducted a preliminary assessment to determine which plant species are least likely to take up and translocate toxic quantities of Mo from soil-covered molybdenum tailings disposal areas. The difficulties outlined above regarding measurement of Mo shoot concentrations and Mo/Cu ratios in samples collected in situ prompted us to perform a controlled uptake experiment. The objective was to reduce the influence of surficial contaminants and substrate variability while allowing a statistically valid examination of differences in Mo and Cu uptake as affected by plant growth form, species, and ecotype (i.e., source identified germplasm, release, cultivar).

METHODS

Molybdenum mill tailings and subsoils were collected from an active mine/mill operation in the southern Rocky Mountains. The silty sand tailings were obtained from the top 0.5 m of an inactive tailings disposal area and the clayey silt soil from a stockpile used in reclaiming decommissioned tailings disposal areas. The testing unit was a 35 cm deep tree pot with dimensions of 10 x 10 cm (top) and 7 x 7 cm (bottom). The control soil treatment consisted of 3 components (top to bottom): a screened (<6 mm) soil layer from 0 to 28 cm deep, a coarse sand layer from 28 to 32 cm deep, and a fiberglass screen covering the bottom drainage holes (Figure 1). A slow-release fertilizer tablet containing 4.2 g N, 0.9 g P and 0.8 g K as well as minor nutrients was placed at an 8 cm depth in the control and tailings testing units. The tailings treatment consisted of 4 components (top to bottom): a screened soil layer from 0 to 14 cm deep, a tailings layer from 14 to 25 cm deep, a coarse sand layer from 28 to 32 cm deep, and the fiberglass screen. When sufficient plant numbers were available, 4 plug seedlings (root ball dimensions of 2.5 x 2.8 x 9 cm {l x w x h}) were planted in each pot. For a few species, one to three plugs were planted but the control and tailings units always received equal plant numbers for each species.

For statistical analysis, the species were grouped into classes based on plant growth forms (grasses, forbs, and woody shrubs), plant families (grasses - *Poaceae*, legumes - *Fabaceae*), and plant physiology (cool-season grasses, warm-season grasses). Half-shrub species with woody bases were lumped with forbs. The resulting 5 "plant growth form" groups were as follows:

Figure 1. Configuration of the control (soil) and tailings testing units.



a) ten cool season grass species including 3 releases of western wheatgrass, *Pascopyrum smithii* (PASM-1 through -3, Table 1);
b) six warm-season grass species including 3 ecotypes of little bluestem, *Schizachyrium scoparium* (SCSC-1 through -3, Table 2);
c) five legume species, see Table 3;
d) four forb species and 2 half-shrub species, see Table 4;
e) six woody shrub species including 3 ecotypes of four-wing saltbush, *Atriplex canescens* (ATCA2-1 through -3, Table 5).

For most species, three replicate control and three replicate tailings testing units were planted with plug seedlings during late May to early June. Testing units with barley, oats, and winter wheat were seeded eight weeks later. The control and tailings units were arranged randomly in four large outdoor tanks which allowed periodic subirrigation of all testing units; one tank contained xeric species and the other mesic species. Plants grew for 17 weeks (9 weeks for grains) under outdoor conditions before harvesting in early October. All aboveground tissue 2.5 cm above the soil surface was harvested. The biomass was air dried for two months before weighing and grinding for analysis. Elemental contents of Mo, Cu and nine other elements were determined by inductively coupled plasma emission spectrometry of solutions prepared by acid digestion of plant dry matter.

The experiment was analyzed as a complete random design. Plant growth form group means were compared by a Fisher's F-protected least significant difference (LSD) test. Within plant growth form groups, species and ecotypes (cultivars, releases) were compared by the least square means procedure. The effect of substrate (soil versus tailings) on elemental concentrations in shoots was determined with a F test for each element.

RESULTS

Plant Growth Form Groups

Mean molybdenum (Mo) concentrations for all the groups (Table 6) in the control treatment were less than 5 μg/g (dry matter basis). In tailings, four groups had Mo concentrations which were not statistically different; the forb and half-shrub group had a significantly higher mean of 67 μg/g as shown in Table 6. All the molybdenum to copper ratio (Mo/Cu) group means were less than 1.4 in soil. In tailings, the group means of Mo/Cu ratios were generally in the range of 6.0 to 9.3 except for the forbs and half-shrubs with a mean ratio of 18.5 (see Table 6). For all groups, greater shoot Mo concentrations and Mo/Cu ratios were found in the tailings treatment than in the soil treatment.

Table 1. Cool-season grass species and ecotypes used in molybdenum uptake experiment.

Common Name	Traditional Scientific Name	Release, Variety, or 'Collection Location'	Current Scientific Name	Symbol
Crested Wheatgrass	*Agropyron cristatum*	Ephraim	*Agropyron cristatum*	AGCR
Hybrid Crested Wheatgrass	*Agropyron cristatum x desertorum*	Hycrest	*Agropyron cristatum x desertorum*	AGDE2
Oats	*Avena sativa*	unknown	*Avena sativa*	AVSA
Bottlebrush Squirreltail	*Sitanion hystrix*	'Grand Canyon AZ'	*Elymus elymoides*	ELEL5
Arizona Fescue	*Festuca arizonica*	Redondo	*Festuca arizonica*	FEAR2
Barley	*Hordeum vulgare*	unknown	*Hordeum vulgare*	HOVU
Mammoth Wildrye	*Leymus racemosus*	Volga	*Leymus racemosus*	LERA5
Indian Ricegrass	*Oryzopsis hymenoides*	Paloma	*Oryzopsis hymenoides*	ORHY
Western Wheatgrass	*Pascopyrum smithii*	Arriba	*Pascopyrum smithii*	PASM-1
Western Wheatgrass	*Pascopyrum smithii*	Rosana	*Pascopyrum smithii*	PASM-2
Western Wheatgrass	*Pascopyrum smithii*	Barton	*Pascopyrum smithii*	PASM-3
Winter Wheat	*Triticum aestivum*	Scout	*Triticum aestivum*	TRAE

Table 2. Warm-season grass species and ecotypes used in molybdenum uptake experiment.

Common Name	Traditional Scientific Name	Release, Variety, or 'Collection Location'	Current Scientific Name	Symbol
Sideoats Grama	*Bouteloua curtipendula*	Niner	*Bouteloua curtipendula*	BOCU
Blue Grama	*Bouteloua gracilis*	Hachita	*Bouteloua gracilis*	BOGR2
Galleta Grass	*Hilaria jamesii*	Viva	*Hilaria jamesii*	HIJA
Sprangletop	*Leptochloa dubia*	unknown	*Leptochloa dubia*	LEDU
Spike Muhly	*Muhlenbergia wrightii*	El Vado	*Muhlenbergia wrightii*	MUWR
Little Bluestem	*Schizachyrium scoparium*	'Tucumcari, NM'	*Schizachyrium scoparium*	SCSC-1
Little Bluestem	*Schizachyrium scoparium*	Pastura	*Schizachyrium scoparium*	SCSC-2
Little Bluestem	*Schizachyrium scoparium*	'Panhandle, TX'	*Schizachyrium scoparium*	SCSC-3

Table 3. Legume species used in molybdenum uptake experiment.

Common Name	Traditional Scientific Name	Release, Variety, or 'Collection Location'	Current Scientific Name	Symbol
Cicer Milkvetch	*Astragalus cicer*	Lutana	*Astragalus cicer*	ASCI4
Birdsfoot Trefoil	*Lotus corniculatus*	unknown	*Lotus corniculatus*	LOCO6
Black Medic	*Medicago lupulina*	unknown	*Medicago lupulina*	MELU
Alfalfa	*Medicago sativa*	unknown	*Medicago sativa*	MESA
Yellow Sweetclover	*Melilotus officinalis*	unknown	*Melilotus officinalis*	MEOF

Table 4. Forb and half-shrub species used in molybdenum uptake experiment.

Common Name	Traditional Scientific Name	Release, Variety, or 'Collection Location'	Current Scientific Name	Symbol
Fringed Sagebrush	*Artemisia frigida*	unknown	*Artemisia frigida*	ARFR4
Blanketflower	*Gaillardia aristata*	unknown	*Gaillardia aristata*	GAAR
Prostrate Kochia	*Kochia prostrata*	Immigrant	*Kochia prostrata*	KOPR80
Summer Cypress	*Kochia scoparia*	'Los Lunas, NM'	*Kochia scoparia*	KOSC
Purple Aster	*Aster bigelovii*	unknown	*Machaeranthera bigelovii var. bigelovii*	MABIB
Scarlet Globemallow	*Sphaeralcea coccinea*	unknown	*Sphaeralcea coccinea*	SPCO

Table 5. Shrub species and ecotypes used in molybdenum uptake experiment.

Common Name	Traditional Scientific Name	Release, Variety, or 'Collection Location'	Current Scientific Name	Symbol
Big Sagebrush	*Artemisia tridentata*	unknown	*Artemisia tridentata*	ARTR2
Fourwing Saltbush	*Atriplex canescens*	Rincon	*Atriplex canescens*	ATCA2-1
Fourwing Saltbush	*Atriplex canescens*	NM 155	*Atriplex canescens*	ATCA2-2
Fourwing Saltbush	*Atriplex canescens*	NM 812	*Atriplex canescens*	ATCA2-3
Shadscale	*Atriplex confertifolia*	'Northwest, NM'	*Atriplex confertifolia*	ATCO
Mountain Mahogany	*Cercocarpus montanus*	unknown	*Cercocarpus montanus*	CEMO2
Rubber Rabbitbrush	*Chrysothamnus nauseosus*	'San Juan County, NM'	*Chrysothamnus nauseosus*	CHNA2
New Mexico Olive	*Forestiera neomexicana*	Jemez	*Forestiera pubescens var. pubescens*	FOPUP

The warm-season grass group and forb and half-shrub group had the greatest shoot mass in soil (Table 7). The legumes and cool-season grasses yielded the least shoot mass in both soil and tailings treatments. The shoot mass did not differ between tailings and soil treatments for any group. The shoot Mo content was consistently greater in the tailings treatment for all groups.

Cool-Season Grasses

Two annual grains in the tailings treatment, oats (*Avena sativa*) and barley (*Hordeum vulgare*), showed significantly higher levels of Mo in shoots (Table 8) compared with winter wheat (*Triticum aestivum*). Among the native perennial cool-season grasses, Arizona fescue (*Festuca arizonica*) and bottlebrush squirreltail (*Elymus elymoides*) showed significantly higher Mo concentrations (54 to 56 μg/g) in tailings than 2 western wheatgrass releases (PASM-1 and -3) and mammoth wildrye (*Leymus racemosus*) which had Mo concentrations ranging from 18.0 to 28.3 μg/g. Two annual grains (oats and barley) exhibited higher Mo shoot concentrations than all the perennial cool-season grasses in the soil control.

High Mo/Cu ratios (12.8 to 16.5) in the tailings treatment were found for oats and bottlebrush squirreltail, and one release of western wheatgrass (PASM-3). In contrast, winter wheat and crested wheatgrass (*Agropyron cristatum*) exhibited low Mo/Cu ratios (3.4 to 4.8), as shown in Table 8. The three western wheatgrass releases exhibited similar Mo shoot concentrations (i.e., 23.7 to 32.3 μg/g) and Mo/Cu ratios (i.e., 8.8 to 12.0).

Warm-Season Grasses

The highest Mo concentrations and Mo/Cu ratios in the tailings treatments (Table 9) were found for galleta grass (*Hilaria jamesii*). The molybdenum level in little bluestem ecotype SCSC-1 was significantly greater than ecotype SCSC-3 (31.3 versus 13.5 μg/g). In the control treatment, spike muhly (*Muhlenbergia wrightii*) had significantly greater shoot Mo levels (4.3 μg/g) than the other warm-season grasses (1.9 to 2.3 μg/g). The little bluestem ecotype SCSC-1 in tailings had a greater Mo/Cu ratio (7.2) than ecotypes SCSC-2 and SCSC-3 (ratios of 3.3 and 3.9, respectively).

Legumes

As shown in Table 10, black medic (*Medicago lupilina*) had a significantly greater Mo level (51.7 μg/g) and Mo/Cu ratio (12.0) in the tailings treatment than alfalfa (*Medicago sativa* - Mo concentration of 21.7 μg/g and a Mo/Cu ratio of 5.0). In the control treatment, birdsfoot trefoil (*Lotus corniculatus*) exhibited a greater Mo

Table 6. Group means (across species) for shoot Mo concentration and shoot Mo/Cu concentration ratios for plants grown in molybdenum tailings and soil.

Plant Growth Form Group		Shoot Mo Conc. in Tailings Treatment (μg/g)	Shoot Mo Conc. in Soil Treatment (μg/g)		Shoot Mo/Cu Conc. Ratio in Tailings Treatment	Shoot Mo/Cu Conc. Ratio in Soil Treatment
Cool-Season Grasses		40.3 bA*	3.1 bB		9.3 bA	0.8 bB
Warm Season Grasses		25.1 bA	2.3 bB		6.1 bA	0.6 bB
Legumes		35.8 bA	4.7 aB		8.1 bA	1.3 aB
Forbs and Half-Shrubs		66.6 aA	2.4 bB		18.5 aA	0.5 bB
Shrubs		23.3 bA	2.6 bB		6.0 bA	0.7 bB

* Means within columns having the same lower case letter are not significantly different ($P < 0.05$) by Fisher's F-protected LSD. Tailings and soil treatment means within rows (for one characteristic) having the same upper case letter are not significantly different ($P < 0.05$) by least square means testing.

Table 7. Group means (across species) for shoot mass and shoot Mo content for plants grown in molybdenum tailings and soil.

Plant Growth Form Group		Shoot Mass in Tailings Treatment (g/plant)	Shoot Mass in Soil Treatment (g/plant)		Shoot Mo Content in Tailings Treatment (μg/plant)	Shoot Mo Content in Soil Treatment (μg/plant)
Cool-Season Grasses		3.1 bA*	3.8 bA		102.0 aA	9.9 aB
Warm-Season Grasses		5.5 aA	5.8 aA		116.0 aA	13.2 aB
Legumes		2.9 bA	3.5 bA		88.2 aA	12.8 aB
Forbs and Half-Shrubs		4.5 abA	5.6 aA		144.0 aA	13.8 aB
Shrubs		4.1 abA	5.2 abA		78.7 aA	13.7 aB

* Means within columns having the same lower case letter are not significantly different ($P < 0.05$) by Fisher's F-protected LSD. Tailings and soil treatment means within rows (for one characteristic) having the same upper case letter are not significantly different ($P < 0.05$) by least square means testing.

Table 8. Mean shoot molybdenum concentrations and mean molybdenum/copper ratios for cool-season grass species and releases grown in molybdenum tailings and soil.

Common Name	Current Scientific Name	Mean Mo Conc. for Tailings Treatment (µg/g)	Mean Mo Conc. for Soil Treatment (µg/g)	Mean Mo/Cu Ratio for Tailings Treatment	Mean Mo/Cu Ratio for Soil Treatment
Oats	*Avena sativa*	89.5 a*	6.0 a	16.5 a	1.37 ab
Barley	*Hordeum vulgare*	61.5 ab	6.0 a	6.8 cde	1.41 a
Arizona Fescue	*Festuca arizonica*	55.7 bc	3.0 bc	10.5 abcd	0.50 cd
Bottlebrush Squirreltail	*Elymus elymoides*	54.0 bcd	2.4 bc	13.9 ab	0.81 abcd
Hybrid Crested Wheatgrass	*Agropyron cristatum x desertorum*	41.3 bcde	3.0 bc	7.2 cde	0.58 cd
Indian Ricegrass	*Oryzopsis hymenoides*	35.3 bcde	3.0 bc	8.2 bcde	0.80 abcd
Crested Wheatgrass	*Agropyron cristatum*	33.8 cde	1.9 c	4.8 de	0.34 d
Western Wheatgrass	*Pascopyrum smithii* PASM-2	32.3 cde	3.3 bc	10.8 abcd	1.07 abc
Winter Wheat	*Triticum aestivum*	30.5 cde	4.0 ab	3.4 e	0.61 bcd
Western Wheatgrass	*Pascopyrum smithii* PASM-3	28.3 e	1.9 c	12.0 abc	0.74 bcd
Western Wheatgrass	*Pascopyrum smithii* PASM-1	23.7 e	1.9 c	8.8 bcde	0.85 abcd
Mammoth Wildrye	*Leymus racemosus*	18.0 e	1.9 c	7.7 cde	0.83 abcd

* Means within columns having the same letter are not significantly different ($P<0.05$) by Fisher's F-protected LSD.

Table 9. Mean shoot molybdenum concentrations and mean molybdenum/copper ratios for warm-season grass species and ecotypes grown in molybdenum tailings and soil.

Common Name	Current Scientific Name	Mean Mo Conc. for Tailings Treatment (µg/g)	Mean Mo Conc. for Soil Treatment (µg/g)	Mean Mo/Cu Ratio for Tailings Treatment	Mean Mo/Cu Ratio for Soil Treatment
Galleta Grass	*Hilaria jamesii*	58.0 a*	1.9 b	15.7 a	0.63 bc
Little Bluestem	*Schizachyrium scoparium* SCSC-1	31.3 b	2.0 b	7.2 b	0.46 bcd
Sprangletop	*Leptochloa dubia*	26.0 bc	2.3 b	4.5 bc	0.45 cd
Little Bluestem	*Schizachyrium scoparium* SCSC-2	22.0 bc	1.9 b	3.3 c	0.41 cd
Spike Muhly	*Muhlenbergia wrightii*	17.3 c	4.3 a	5.3 bc	1.06 a
Blue Grama	*Bouteloua gracilis*	13.7 c	1.9 b	5.3 bc	0.95 a
Little Bluestem	*Schizachyrium scoparium* SCSC-3	13.5 c	1.9 b	3.9 c	0.69 b
Sideoats Grama	*Bouteloua curtipendula*	11.7 c	1.9 b	3.2 c	0.37 d

* Means within columns having the same letter are not significantly different ($P<0.05$) by Fisher's F-protected LSD.

Table 10. Mean shoot molybdenum concentrations and mean molybdenum/copper ratios for legume species grown in molybdenum tailings and soil.

Common Name	Current Scientific Name	Mean Mo Conc. for Tailings Treatment (µg/g)	Mean Mo Conc. for Soil Treatment (µg/g)	Mean Mo/Cu Ratio for Tailings Treatment	Mean Mo/Cu Ratio for Soil Treatment
Black Medic	*Medicago lupulina*	51.7 a*	4.0 b	12.0 a	0.97 b
Cicer Milkvetch	*Astragalus cicer*	41.0 ab	1.9 b	9.4 ab	0.59 b
Birdsfoot Trefoil	*Lotus corniculatus*	39.0 ab	12.3 a	8.2 ab	3.65 a
Yellow Sweetclover	*Melilotus officinalis*	26.7 ab	2.1 b	5.9 b	0.62 b
Alfalfa	*Medicago sativa*	21.7 b	3.1 b	5.0 b	0.84 b

* Means within columns having the same letter are not significantly different ($P<0.05$) by Fisher's F-protected LSD.

shoot concentration than the other legumes (12.3 versus 1.9 to 4.0 µg/g) and a greater Mo/Cu ratios (3.7 versus 0.6 to 1.0) than the other legumes.

Forbs and Half-Shrubs

In the tailings treatment, the forbs, purple aster (*Machaeranthera bigelovii*) and summer cypress (*Kochia scoparia*), had significantly lower Mo shoot concentrations (18.7 and 9.0 µg/g) and Mo/Cu ratios (2.3 and 2.5) than the other species in the group (see Table 11). Fringed sage (*Artemisia frigida*), scarlet globemallow (*Sphaeralcea coccinea*), and blanketflower (*Gaillardia aristata*) had the highest shoot Mo levels of any species tested in the tailings treatment (100 to 110 µg/g). Two of these species, scarlet globemallow and blanketflower, had the highest Mo/Cu ratio of any species tested in the tailings treatment (51.8 and 22.7, respectively). These extreme values in tailings for scarlet globemallow and blanketflower were not reflected in the soil treatment which had shoot Mo levels similar to other species within the forb and half-shrub group and species in other groups. Prostrate kochia (*Kochia prostrata*) and summer cypress had significantly greater Mo/Cu ratios (0.75 and 0.87) than the other forbs and half-shrubs (0.31 to 0.45) grown in soil.

Shrubs

Big sagebrush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*) in tailings had significantly greater shoot Mo concentrations (57 µg/g) than the other shrubs (see Table 12). Mountain mahogany (*Cercocarpus montanus*) and rubber rabbitbrush (*Chrysothamnus nauseous*) had extremely low levels of Mo in shoots (8.6 and 8.0 µg/g, respectively); these concentrations were the lowest of all the tested species grown in tailings. New Mexico olive (*Forestiera pubescens*) in tailings had a significantly greater Mo/Cu ratio (16.1) in tailings than the other shrubs. Mountain mahogany, rubber rabbitbrush, and one ecotype of four-wing saltbush ATCA2-3 had among the lowest Mo/Cu ratios (1.8 to 2.4) of all tested species. Mountain mahogany was the only species tested which had almost equivalent Mo/Cu ratios in the tailings and soil treatments (2.2 and 1.9, respectively).

Major, Minor, and Trace Element Shoot Concentrations

The elemental analysis of shoot tissue revealed patterns of uptake and translocation among the plant growth form groups (see Table 13). The grass groups (warm-season and cool-season) had the lowest concentrations of Ca, Mg, Al, and B. The warm-season grasses had the lowest S. The two grass groups differed in concentrations of S, P, Fe, and Zn. The legumes had the lowest Mn concentration. The forb group had the greatest concentrations of S and Mn. The shrub group and forb

Table 11. Mean shoot molybdenum concentrations and mean molybdenum/copper ratios for forb and half-shrub species grown in molybdenum tailings and soil.

Common Name	Current Scientific Name	Mean Mo Conc. for Tailings Treatment (µg/g)	Mean Mo Conc. for Soil Treatment (µg/g)	Mean Mo/Cu Ratio for Tailings Treatment	Mean Mo/Cu Ratio for Soil Treatment
Fringed Sagebrush	*Artemisia frigida*	110 a*	2.3 ab	16.7 a	0.31 b
Scarlet Globemallow	*Sphaeralcea coccinea*	110 a	1.9 b	51.8 a	0.45 b
Blanketflower	*Gaillardia aristata*	100 a	2.6 ab	22.7 a	0.40 b
Prostrate Kochia	*Kochia prostrata*	51.3 a	3.3 a	15.4 a	0.75 a
Purple Aster	*Machaeranthera bigelovii var. bigelovii*	18.7 b	1.9 b	2.3 b	0.32 b
Summer Cypress	*Kochia scoparia*	9.0 b	2.6 ab	2.5 b	0.87 a

* Means within columns having the same letter are not significantly different ($P<0.05$) by Fisher's F-protected LSD.

Table 12. Mean shoot molybdenum concentrations and mean molybdenum/copper ratios for shrub species and ecotypes grown in molybdenum tailings and soil.

Common Name	Current Scientific Name	Mean Mo Conc. for Tailings Treatment (µg/g)	Mean Mo Conc. for Soil Treatment (µg/g)	Mean Mo/Cu Ratio for Tailings Treatment	Mean Mo/Cu Ratio for Soil Treatment
Big Sagebrush	*Artemisia tridentata*	57.3 a*	1.9 a	11.6 b	0.23 b
Shadscale	*Atriplex confertifolia*	56.7 a	1.9 a	4.9 c	0.22 b
New Mexico Olive	*Forestiera pubescens var. pubescens*	23.7	2.3 a	16.1 a	0.53 b
Fourwing Saltbush	*Atriplex canescens* ATCA2-2	22.0 bc	2.3 a	4.8 c	0.61 ab
Fourwing Saltbush	*Atriplex canescens* ATCA2-1	13.0 bc	4.0 a	4.3 c	1.32 ab
Fourwing Saltbush	*Atriplex canescens* ATCA2-3	11.7 bc	1.9 a	1.8 c	0.39 b
Mountain Mahogany	*Cercocarpus montanus*	8.6 c	4.5 a	2.2 c	1.91 a
Rubber Rabbitbrush	*Chrysothamnus nauseosus*	8.0 c	2.6 a	2.4 c	0.63 ab

* Means within columns having the same letter are not significantly different ($P < 0.05$) by Fisher's F-protected LSD.

Table 13. Elemental concentrations averaged across substrates for each plant growth form group.

Element (conc. units)	Cool-Season Grasses	Warm-Season Grasses	Legumes	Forbs and Half-Shrubs	Shrubs
Ca (mg/g)	6.5 c*	4.9 c	12.7 b	15.5 a	13.9 ab
S (mg/g)	3.3 b	1.7 c	3.4 b	4.9 a	3.9 b
Mg (mg/g)	2.6 c	2.1 d	3.8 b	4.5 a	4.5 a
P (mg/g)	1.7 a	1.1 b	1.6 a	1.6 a	1.9 a
Al (µg/g)	100 c	79 c	133 b	183 a	189 a
Mn (µg/g)	96 b	92 bc	75 c	124 a	99 b
Fe (µg/g)	91 a	62 b	83 ab	111 a	98 a
Zn (µg/g)	33 c	57 a	51 ab	40 bc	41 bc
B (µg/g)	22 d	15 d	71 a	56 b	40 c
Cu (µg/g)	4.5 a	4.6 a	4.1 a	5.1 a	5.2 a

* Means within rows (for each element) having the same letter are not significantly different ($P<0.05$) by least square means testing.

Table 14. Comparison of element concentrations between tailings and soil treatments. Mean concentration from data pooled across all groups and all species.

Element (conc. units)	Shoot Concentration in Soil Treatment	Shoot Concentration in Tailings Treatment
Ca (mg/g)	9.7 a*	10.2 a
S (mg/g)	3.3 a	3.4 a
Mg (mg/g)	3.3 a	3.3 a
P (mg/g)	1.6 a	1.5 a
Al (µg/g)	125 a	139 a
Mn (µg/g)	96 a	99 a
Fe (µg/g)	85 a	92 a
Zn (µg/g)	41 a	46 a
Mo (µg/g)	2.9 b	37.4 a
B (µg/g)	36.6 a	35.6 a
Cu (µg/g)	4.5 a	4.9 a

* Means within rows (for each element) having the same letter are not significantly different ($P<0.05$) by least square means testing.

group had the highest Mg and Al levels. The legumes had the greatest B concentration. When elemental concentration data for all groups was pooled, the only element which was significantly different between the soil and tailings treatments was molybdenum (see Table 14).

CONCLUSIONS

Past research by others has shown that pastures containing plants with Mo at 10 to 20 μg/g (dry weight basis) pose risks of molybdenosis to domestic ruminants and Mo levels between 20 and 100 μg/g have been linked to teart disease (Eisler, 1989). The results of our study show 3 species with less than 10 μg/g when grown in tailings (summer cypress, rubber rabbitbrush, and mountain mahogany). Ten species showed less than 20 μg/g; these include the 3 species above and mammoth wildrye, purple aster, 2 ecotypes of four-wing saltbush ATCA2-1 and ATCA2-3, sideoats grama , blue grama, one ecotype of little bluestem SCSC-3, and spike muhly.

Molybdenosis is probable in cattle if their forage contains Mo and Cu at a ratio (Mo/Cu) of greater than 2.5 (Eisler, 1989). Three shrubs and two forbs grown in tailings have shoot Mo/Cu ratios less than 2.5: rubber rabbitbrush, mountain mahogany, one ecotype of four-wing saltbush ATCA2-3, summer cypress, and purple aster. The only species grown in the soil control with a Mo/Cu ratio greater than 2.5 and Mo concentration greater than 10 μg/g was birdsfoot trefoil.

Mule deer are at least 10 times more resistant to the adverse effects of Mo than domestic ruminants (Eisler, 1989). If this assumption is translated into criteria for forage Mo levels, Mo concentrations of 100 μg/g and Mo/Cu ratios greater than 25 in forage may pose a risk to mule deer. Fringed sage, scarlet globemallow, and blanketflower when grown in tailings had Mo concentrations greater than 100 μg/g and only scarlet globemallow had a Mo/Cu ratio of greater than 25.

A list of species for revegetation of molybdenum tailings areas in pinon-juniper and ponderosa pine ecosystems can be developed based on low Mo shoot concentrations (less than 30 μg/g) or low Mo/Cu ratios (less than 6) found in the tailings treatment.

Plant Growth Form Group	Criteria Mo ≤ 30 μg/g	Criteria Mo/Cu ≤ 6
Cool-Season Grasses	Western Wheatgrass Mammoth Wildrye* Winter Wheat (annual)*	Crested Wheatgrass* Winter Wheat (annual)*
Warm-Season Grasses	Little Bluestem Blue Grama Sideoats Grama Spike Muhly Spangletop**	Little Bluestem Blue Grama Sideoats Grama Spike Muhly Spangletop**
Legumes	Yellow Sweet Clover* Alfalfa*	Yellow Sweet Clover* Alfalfa*
Forbs and Half-Shrubs	Purple Aster (biennial) Summer Cypress (annual noxious weed)*	Purple Aster (biennial) Summer Cypress (annual noxious weed)*
Shrubs	Rubber Rabbitbrush Mountain Mahogany Four-wing Saltbush New Mexico Olive	Rubber Rabbitbrush Mountain Mahogany Four-wing Saltbush Shadscale

*Introduced species
**Questionable hardiness at high elevations

Significant differences in Mo shoot concentrations exist among ecotypes. As an example, Mo/Cu ratios for little bluestem SCSC-1 and SCSC-2 were 7.2 and 3.3. The presence of these differences illustrates that germplasm selection might allow the production of cultivars which discriminate against Mo uptake and translocation. Plant breeding might provide means of further reducing the Mo/Cu ratios below that achieved through selection.

LITERATURE CITED

Eisler, R. 1989. Molybdenum hazards to fish, wildlife, and invertebrates: a synoptic overview. Contaminant Hazard Review Report No. 19. Biological Report 85(1.19), August 1989. Fish and Wildlife Service. U.S. Department of Interior. 61 p.