PROBLEMS ASSOCIATED WITH SELENIUM
LEACHING FROM WASTE SHALE

by

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Abstract: Leachates from overburden waste rock originating from phosphorus mining activities containing selenium-bearing shale contributed to the dispersion of selenium (Se) in downstream environments. Surface waters and sediments impacted by waste rock leachates contained significantly elevated levels of Se that are above the background levels of local non-contaminated streams and soils. Transects placed across a stream flowing through pastures were sampled to examine Se concentrations in upland (e.g., native), midslope, and low-lying areas that were impacted by the contaminated waters. Soils in upland and midslope sites that were unaffected by the waste shale leachates had bioavailable (i.e., phosphate extractable) Se concentrations that were approximately 0.1 mg/kg soil, where as low-lying sites had levels ranging from 0.5 to 2.6 mg/kg soil. Se levels in stream sediments (e.g., muck samples) were extremely high at concentrations between 6.0 and 7.2 mg/kg. Additional sampling indicated that plant Se contents within the contaminated sites were also high: ranges included 20 to 170 mg Se/kg for grasses and 40 to 210 mg Se/kg for forbs. Additional soils were also examined, with one stream-side location having soil Se levels as high as 14 mg/kg. Contaminated soils and associated vegetation Se levels are well above the concentrations recommended as suitable, e.g., 0.4 mg Se /kg for soils and 5 mg Se/kg for plants. Horses grazing in the Se-enriched pastures were susceptible to selenosis, a form of Se poisoning. Many of the horses that were poisoned from drinking the Se-contaminated waters and foraging on the vegetation with excessive Se had to be euthanized. Results are presented on the conditions that caused this unfortunate situation.

Additional Key Words: Bioavailable Selenium, Phosphorus, Stream Waters, Sediments, Soils, Grasses, Forbs, Horses, Euthanasia.

Introduction

Selenium (Se) is known to adversely impact disturbed lands such as agricultural, mining and military environments that are located in arid climates because of potential Se toxicity (Vance

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and Schuman 1996, Frankenberger and Engberg 1998). Prolonged dietary intake of vegetation containing approximately 3-15 mg Se/kg can be toxic to certain grazing animals (National Academy of Science 1976, 1983, Mayland 1994, Oldfield, 1998). Aquatic ecosystems are also susceptible to Se problems when erosion, migration, and/or leaching increases Se bioavailability to wetland organisms. Selenium, however, is also essential for animal and human nutrition (Frankenberger and Engberg 1998).

Disturbance activities in areas containing seleniferous geological materials have recently become a concern due to the potential for in-

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creasing Se bioavailability in both the disturbed environment and surrounding areas impacted by eroded Se sediments and Se-containing waters (Vance and Schuman 1996, Frankenberger and Engberg 1998). Materials previously in reducing environments that are exposed by disturbance events are subjected to oxidative conditions (Frankenberger and Benson 1994). The consequence of this may be increased Se availability to plants which might result in greater plant uptake of Se and the possibility of Se toxicity to animals (Palmer 1998). At present, we do not know what overall effects disturbance activities will ultimately have on wildlife and livestock (O'Toole and Raisbeck 1998), and aquatic organisms. Thus, without appropriate Se research to ascertain the relationship between native and disturbed soil characteristics to plant Se uptake, these questions cannot be reliably answered.

Plant Se concentrations vary with plant species, soil properties (e.g., pH, clay content, soil mineralogy, and competing ions), climatic conditions (temperature and rainfall), and Se species present (Mikklesen et al. 1989, Mayland 1994, Gissel-Nielsen 1998). In undisturbed native landscapes in the western United States, grasses tend to contain low Se concentrations (<1 mg/kg), shrubs generally containing slightly higher Se levels (<5 mg/kg), and forb Se concentrations are extremely variable (depending on specific forb analyzed) (Inhat 1989, Harms 1995, personal observations of the author). In low soil-Se environments (<1.0 mg/kg total Se for the western United States: Presser et al. 1994, Harms 1995), plant uptake and accumulation is site, plant species, and hydrologic-condition specific (Berrow and Ure 1989, Mayland 1994). Irrigation or addition of water (i.e., leaching, flooding, dewatering operations, etc.) can create conditions that greatly enhance Se bioavailability to plants, microorganisms and especially aquatic life if Se-containing leachates drain into surface water environments (Zhang and Moore, 1998). These conditions are extremely different from native arid and semi-arid environments that receive low rainfall (Erdman

et al. 1989, Mayland et al. 1989).

Surface waters with Se concentrations >50 ug/L (EPA 1998 website) are considered unsuitable as a drinking water source for cattle, sheep, horse and other domestic animals. These waters can also exacerbates Se toxicity problems due to Se bioaccumulation by the surrounding vegetation used as forage (Zhang and Moore 1998). Concerns involving Se bioavailability are also due to food chain transfer and concentration of Se by evaporative processes in arid and semi-arid environments (Mayland 1994, Seiler 1998).

In aquatic ecosystems, the Se species present can influence the degree of Se bioconcentration. For example, selenomethionine (Se-containing amino acid) can be bioconcentrated by factors of 50,000 to 350,000 for algae and daphnids, respectively (Presser et al. 1994). Water quality standards for freshwater aquatic life are 5 ug Se/L (chronic - four day average) or 20 ug Se/L (acute - one hour average); however, some studies suggest a lower water quality standard (2.3 ug Se/L) is required (Presser et al. 1994). Bottom sediments in surface water ecosystems are considered problematic at levels >0.5 mg Se/kg (see Presser et al. 1994). Again, the form of Se present (e.g., inorganic versus organic) is important, as are aquatic conditions such as pH, competing ions, and affected aquatic life (Cutter 1989, Zhang and Moore 1998).

The objective of this study was to evaluate a site where Se poisoning of horses has occurred. Overburden waste rock from a phosphorus mine was deposited in an adjacent valley that drained a forested area. Surface water leaving the valley was the source of water entering nearby pasturelands. After examining the surrounding environment, a study was conducted that included the sampling of soils and vegetation across pastures to evaluate Se levels in the collected materials based on landscape position. Additional sediment and muck samples were also collected within streams crossing the pastures.

Materials and Methods

Study Site and History

The study site is located in southeastern Idaho in an area impacted by a phosphorus mining operation that disposed of its waste rock in an adjacent canyon. Waste from the phosphorus mining activity contained shale materials that were relatively high in Se (>0.5 mg/kg extractable Se). Waste from the mining activities accumulated over a seven year period during the late 1970s to early 1980s and resulted in a waste rock dump of about 22 million m^3 that covers approximately 50 ha. An intermittent stream flows out of the canyon's 10 km^2 watershed. During average rainfall years there is minimal or no flow during the summer months until late summer (i.e., September or October). Several wet years in the mid and late 1990s have resulted in constant stream flows.

Construction of a road and railroad line perpendicular to the canyon opening in early 1990s caused a realignment of the natural stream flow pattern. Instead of normal creek diversion of water from the canyon, which included leachate from the waste rock pile, low lying areas in pasture lands adjacent to the canyon were receiving the stream waters originating from the canyon watershed including that which was derived from the waste pile leachates.

In the mid 1990s, horses grazing in the pastures were diagnosed with selenosis, which is often related to elevated Se levels of forage and drinking water sources. An investigation of the area suggested there may be a problem with the stream waters draining the canyon where waste rock from the phosphorus mining activities were dumped. Leachates from the waste rock pile were sampled and determined to contain high soluble Se concentrations. Stream water samples collected below the waste pile had Se levels as high as 1.5 mg/L, which is extremely high. The present study was then initiated to evaluate materials influenced by stream waters as well as native areas within the immediate surroundings.

Soils and Sediments

Transects were delineated that crossed the streams and native areas. Sediments were collected from the streams and soils sampled using a Dutch auger along the transect at depths of 0-25, 25-50, 50-75, and 75-100 cm and placed in plastic bags for transport to the University of Wyoming Soil and Environmental Chemistry laboratory for analysis. A sufficient volume of the soil and sediment was collected and the samples stored in closed containers to eliminate contact with atmospheric oxygen. Additional grab samples were collected at various locations to evaluate suspected Se source materials and uncontaminated sites.

Soil and sediment samples were air-dried at room temperature (~22C). Clods were crushed using a ceramic mortar and pestle, then passed through a 2-mm sieve to remove rocks, pebbles and larger pieces of plant material. The sieved soils and sediments were transferred to plastic soil collection bags for storage.

Vegetation

Vegetation samples were also collected at each site with a minimum sample of 5 grams from each form of vegetation (i.e., grass and forb), as well as selective individual plant species. All plant life forms sampled for a specific site were placed in zip-lock plastic bags, then immediately chilled on ice and frozen within 8 hours of collection. Plants were clipped at ground level and/or selective parts were sampled; current year's growth was sampled. Excess soil material that had collected on vegetative parts, primarily from rain splash or wind erosion, was removed before drying the samples.

Plants were removed from the freezer, cut into 2 to 3 cm lengths, and dried in glass beakers at 50C for 24 to 48 hours or until no change in sample weight is detected, which was an indication that the plants are dried. Each sample was then ground in a Wiley Mill to pass through a 40-mm mesh screen.

Miscellaneous Samples

In addition to soil, sediment, and vegetation sampling, earthworms and caddisfly (*Hesterpophylax spp.*) larvae and pupae were collected from sites below the waste rock pile. Earthworms were carefully removed from soils that were influenced by the leachate waters, whereas the caddisfly samples were collected from the stream. All miscellaneous samples were dried and ground as described for plant tissue preparation.

Laboratory Se Analysis

Soils and sediments were analyzed for Se using the phosphate extraction method described in the "Standard Operating Procedures for the Sampling and Analysis of Se in Soil and Overburden/Spoil Material" (Spackman et al. 1994). The extracting solution used was KH_2PO_4, which has been shown to be capable of determining bioavailable soil Se concentrations (Orso et al. 1993).

Air-dried soil samples weighing 5.0 grams were placed into 50-ml centrifuge tubes to which 25-ml 1.0 M di-basic phosphate extracting solution was added. Tubes were placed on a reciprocating shaker for 2 hours at a rate of 120 oscillations per minute to keep the samples suspended, then centrifuged at 2000-rpm for 15 minutes. Supernatant solutions were filtered into clean plastic centrifuge tubes through Whatman® 40 filter paper.

For each filtered sample, a 3-ml aliquot was placed into a 50-ml test tube, to which 12-ml deionized-distilled water and 1-ml 30% H_2O_2 was added. Tubes were placed into a hot water bath and heated for 20 minutes at 85° to 90°C, followed by the addition of 10-ml HCl to each sample and a second 20 minute heating in a hot water bath at 85° to 90°C. After cooling for a minimum of 12 hours, each sample was then analyzed for Se concentration using hydride generation with atomic adsorption spectrophotometry (HGAAS) (Spackman et al. 1994).

Preparation of the plant and miscellaneous samples for Se analysis followed the guidelines listed in "Standard Operating Procedures for Sampling Se in Vegetation prepared by the Wyoming State Subcommittee on Se in Soils, Vegetation, Overburden, and Wildlife" (Steward et al. 1994). Each 0.500-gram biological sample was digested in 10-ml concentrated nitric acid (HNO_3) and 2-ml concentrated perchloric acid ($HClO_4$). Samples were digested for 2 hours at 100 C on an aluminum block digester, then heated and brought to a final volume of 35-ml with deionized-distilled water.

Similar to that for Se analysis of soil and sediment samples, a 3-ml aliquot of the biological digests was placed into a 50-ml glass test tube, to which 12-ml deionized-distilled water and 1-ml 30% hydrogen peroxide (H_2O_2) was added. Tubes were placed into a hot water bath and heated for 20 minutes at 85° to 90°C, removed to cool for 12 hours, and brought to a final volume of 35 ml with deionized distilled water. Samples were analyzed for Se concentration using HGAAS (Steward et al. 1994).

Results and Discussion

Preliminary Studies

A preliminary study was conducted on the pasture where horses with selenosis were diagnosed. The study was designed to evaluate native sites and areas affected by the stream waters draining out of the waste rock canyon. For transect number 1, six sites were identified that ranged from upland areas that were assumed to be out of the influence of stream waters, areas midslope between the upland points and the stream, and areas adjacent to the stream (Figure 1). In addition to the two sites sampled next to the stream, a stream sediment and muck were also collected.

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Figure 1 illustrates the relationship among the sampling sites, stream water course, and a nearby road. A representative layout of the transect and the sampling sites are noted with the four depth increments that the soils were sampled. It is clear that samples taken from the upland (sites 1 and 6) and midslope (sites 2 and 5) areas contained relatively low extractable Se concentrations that ranged from 0.02 to 0.09 mg Se/kg. A general characteristic of these uncontaminated sites would suggest that bioavailable Se, as defined by the phosphate extraction method, in background soils of the area is less than 0.1 mg Se/kg.

TRANSECT #1

Selenium (mg/kg)
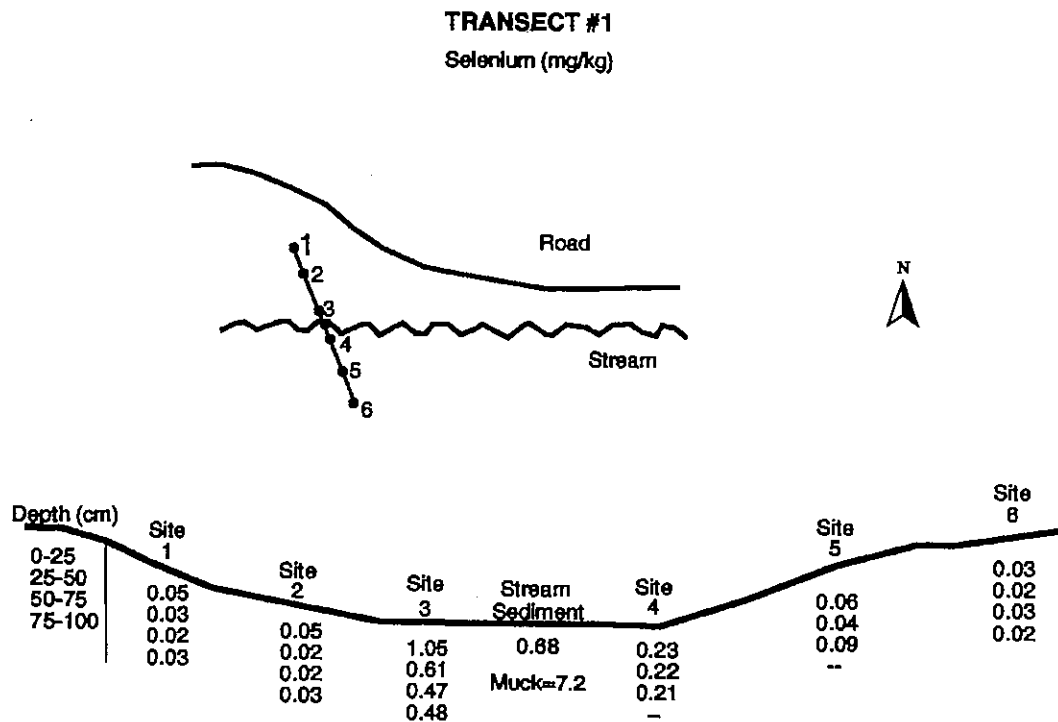
Figure 1. Location of sites within transect #1 that were sampled from upland areas (sites 1 and 6), midslope positions (sites 2 and 5), and in the stream water impacted area (sites 3 and 4). In addition to soils sampled at depths of 0-25, 25-50, 50-75, and 75-100 cm, stream sediment and muck samples were also collected. Sample depths are noted in the figure. Diagram not to scale.

Soils sampled in the low lying area (sites 3 and 4) that were impacted by stream waters containing elevated Se concentrations were observed to have extractable Se that ranged from 0.21 to 1.05 mg/kg. This would suggest that Se has accumulated in these soils, which was undoubtably due to the high sorption capacities that most soils have for both selenate and selenite Se species. Speciation analysis of stream waters collected at four locations below the waste rock pile indicated Se was primarily present as selenate (SeO_4^{2-}, 68 to 95%), followed by organic Se (2 to 28%) and then selenite (SeO_3^{2-}, 1% or less). Selenate is strongly adsorbed by soils and geological substrata (Vance 1990, Blaylock et al. 1995, Vance et al. 1998).

Two samples collected from the stream (e.g., sediment and muck) also contained significant extractable Se concentrations. The stream sediment had an extractable Se level (0.68 mg Se/kg) that was intermediate between the two 0-

25 cm depth samples of the nearby soils. As for the muck sample, the extractable Se of 7.2 mg/kg is one of the highest Se concentrations that the author has measured. When extractable Se concentrations exceed 0.5 mg/kg there is a definite potential that bioavailable Se is present in the environment. This should also be evident in vegetation Se levels within the affected area.

A second transect was also sampled during the preliminary pasture studies. There were only three areas sampled at this location - an upland site, an old stream channel site, and a site impacted by the Se-containing stream waters (Figure 2). This transect was located closer to the canyon and was assumed to have potentially higher Se levels in the affected soils and sediments. Analysis of the upland soils indicated there was again low extractable Se (0.02 to 0.02 mg Se/kg) in these materials. An old stream channel that was a remnant of a past flow pattern that conveyed waters out of the surrounding canyons was determined to contain low extractable Se concentrations (0.05 to 0.08 mg Se/kg). This is possible evidence to suggest that the high Se concentrations identified in samples affected by the current stream waters in transect 1 were caused by the waste rock pile leachates.

TRANSECT #2

Selenium (mg/kg)
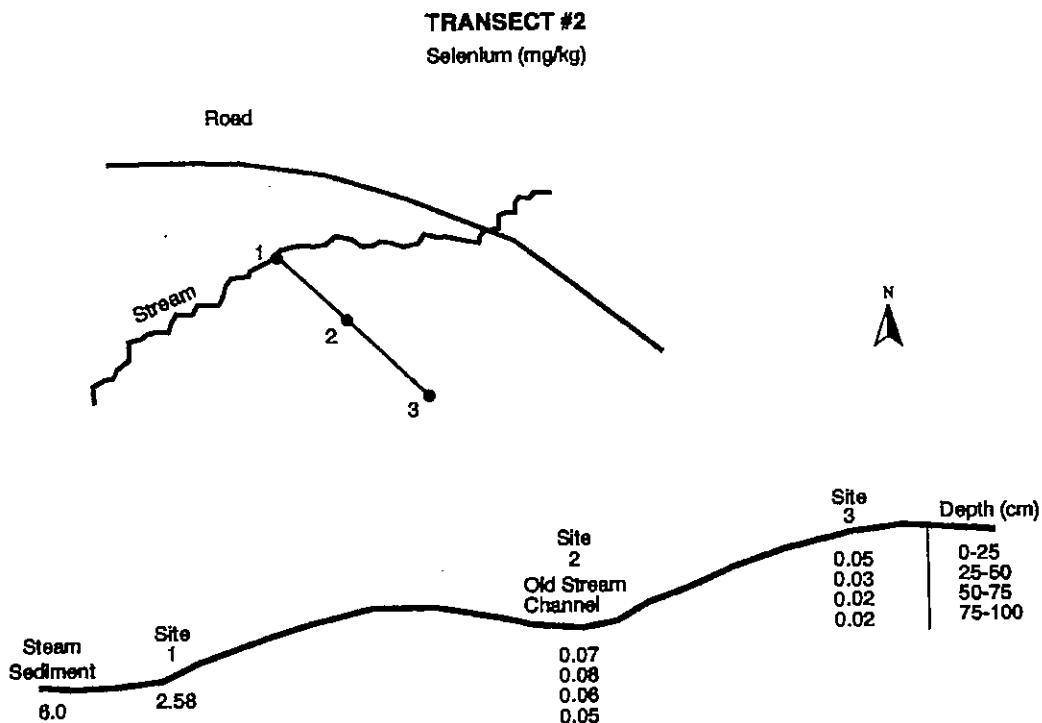
Figure 2. Location of sites within transect #2 that were sampled in the stream water impacted area (site 1), an old stream channel (site 2), and an upland area (site 3). In addition to soils sampled at depths of 0-25, 25-50, 50-75, and 75-100 cm, a stream sediment sample was also collected from the stream. Sample depths are noted in the figure. Diagram not to scale.

Two samples collected in the area where the Se-containing waters flowed had significant extractable Se concentrations. A surface soil sample and a sediment material contained 2.58 and 6.0 mg/kg extractable Se, respectively. Both of these samples have extremely high Se concentrations and, as noted with the muck sample analyzed in transect 1, there is a high potential for Se bioavailability to be a problem at this location.

Soil and Vegetation Studies

Additional sampling was conducted to confirm the hypothesis that areas with soils and stream waters high in Se would have increased Se bioavailability that would be manifested through plant uptake and accumulation. Four transects were sampled that represented a greater degree of variability in the landscape positions within the areas impacted by the Se-containing stream waters. Although these transect followed the same sampling design as described for transect 1, there was evidently some sites that were also in contact with the contaminated stream waters as will be noted in the discussion below.

Based on the assumption that all sites numbered 1 and 6 should be upland areas that have not been in contact with the stream waters containing leachate Se from the waste rock pile, it was expected that these sites would have extractable Se concentrations at less than or equal to 0.1 mg/kg. Of the eight sites sampled, one did not follow the premise that these were uncontaminated sites (Table 1). In transect 6 site 1 the extractable Se concentration in the soil ranged from 0.4-0.8 mg/kg. Selenium in grass (4 mg/kg) and forb (43 mg/kg) vegetation sampled at this location was the highest of vegetation samples analyzed in the upland sites. This suggests that site 1 of transect 6 was probably affected by the Se-containing stream waters, although at the time of sampling this was not evident.

Sites 2 and 5 along the transects were also located closer to the stream channels then were sites in the preliminary study. Many of these sites were found to contain elevated extractable soil Se. Only three of the eight midslope sites contained Se concentrations ≤ 1.0 mg/kg. Vegetation Se contents at the midslope sites followed a pattern that suggests when extractable soil Se is high, plant Se will also be high relative to sites with low extractable soil Se.

In transect 3, sites 2 and 5 were far enough outside the influence of the Se-containing waters as indicated by the extractable Se concentrations of up to 1.0 mg/kg. Vegetation Se was generally low; however, a forb sample at site 5, which had an extractable soil Se of 1.0 mg/kg in the surface horizon, contained 13 mg Se/kg. This is not unexpected as forbs tend to be quite variable with respect to their ability to accumulated Se.

Transect 4, sites 2 and 5 were both high in extractable soil Se at 0.05-0.5 and 0.04-0.4 mg Se/kg, respectively. There was a distinct increase in grass and forb Se contents when compared to sites 1 and 6 in the same transect. A level of vegetation Se that has commonly been used as a suitability limit is 5 mg Se/kg. Based on this value, the grass in site 5 and the forbs in both sites 2 and 5 are potentially problematic if consumed over extended periods of time.

Transect 5, site 2 was low in extractable soil Se (0.05-0.06 mg/kg), but site 5 had high Se concentrations (0.09-0.6 mg Se/kg). It is evident from the vegetation Se data that a trend is also apparent better these two sites. For example, site 2 had grass and forb Se levels below the 5 mg Se/kg suitability limit, whereas grass (11 mg/kg) and forb (25 mg/kg) Se levels were in excess of those considered safe.

Transect 6, sites 2 and 5 were also high in extractable soil Se ranging from 0.9-5.5 mg/kg at site 2 to 0.4-4.3 mg/kg at site 5. These levels of Se are definitely high and are a cause for concern. Another reason these site can be labeled problematic is due to the extremely high vegetation Se contents. Grasses contain significant levels of Se at 17 and 44 mg/kg, and forb Se is also excessive at 140 and 146 mg/kg.

All of sites 3 and 4 were expected to contain high levels of extractable soil Se. This was the case for each of the stream water influenced locations. Extractable soil Se levels at these sites

Table 1. Selenium (Se) concentrations in soil extracts and plant digests of samples collected from four transects across pastures impacted stream waters contaminated by Se leachates from a waste rock pile.

Transect #	Site #	Extractable Soil Se (mg/kg)	Grass Se (mg/kg)	Forb Se (mg/kg)	Additional Plant Se (mg/kg)
3	1	0.02-0.04	2	3	
	2	0.04-0.05	1	1	
	3	2.2-4.3	65	84	
	4	0.3-2.0	32		
	5	0.05-0.1	3	13	
	6	0.02-0.04	2	3	
4	1	0.02-0.08	1	4	
	2	0.05-0.5	3	11	
	3	0.6-1.1	20	41	54, 94, 141
	4	0.7-1.8	35	127	
	5	0.04-0.4	6	14	
	6	0.02-0.05	1	4	
5	1	0.02-0.04	1	2	
	2	0.05-0.06	4	3	
	3	0.8-2.0	164	103	40
	4	0.2-1.1	62	209	
	5	0.09-0.6	11	25	
	6	0.01-0.04	1	2	
6	1	0.4-0.8	4	43	
	2	0.9-5.5	44	146	
	3	0.9-12	75	143	45, 65
	4	1.9-14	42	67	
	5	0.4-4.3	17	140	
	6	0.02-0.06	1	3	

ranged from a low of 0.2 mg Se/kg at site 4 of transect 5 to a high of 14 mg Se/kg at site 4 of transect 6. It should be noted that the high extractable Se content of soils in sites 3 and 4 of transect 6 are the highest the author has ever measured. As expected, all of the vegetation samples contained Se at levels that were far in excess of the suitability (e.g., toxicity) limit.

Analysis of Miscellaneous Samples

Both the earthworm and caddisfly samples contained significant Se concentrations. The earthworm samples had an overall total Se content of 140 mg/kg. Caddisfly larvae and pupae materials were combined and the Se content of the bulk sample was 150 mg/kg.

General Comments

As stated earlier, due to disturbance events, geological materials can be brought into contact with atmospheric conditions where they may be oxidized; Se species that are produced through the oxidation of reduced forms are generally more soluble, and consequently more toxic (Trelease and Beath, 1949; Milne 1998). The oxidation process may be either abiotic or biotic with microorganisms being the primary biological component (Bainbridge et al., 1988, Martens and Saurez 1998). The major Se compounds that result from this oxidation are selenate (SeO_4^{2-}) and selenite (SeO_3^{2-}).

Selenium uptake by plants and the subsequent ingestion by animals and humans has been a subject of considerable concern for the past 100 years (Jacobs 1989, Frankenberg and Benson 1994, Frankenberg and Engberg 1998). Selenium is known to be both an essential and toxic element. While Se deficiencies have been associated with low Se contents of forage and food products resulting from insufficient soil Se concentrations (Chen et al. 1980, Kishchak, 1998, Maas 1998), Se toxicity problem have also been noted. For example, in the western United States, Se toxicity has been identified in wildlife (Ohlendorf 1989), aquatic biota (Stephens and Waddell 1998) and livestock (James et al. 1989) and was due to acute and chronic Se toxicosis. Chronic intoxication can result in alkali disease and blind staggers (Rosenfeld and Beath 1964, O'Toole and Raisbeck 1998, Wu 1998). Selenium poisoning and mortality can be directly related to either long-term consumption of highly seleniferous forage or bioaccumulation and biomagnification in food chains (Ohlendorf 1989, James et al. 1989, Presser and Piper 1998, Skorupa 1998, Wu 1998).

Different extraction methods provide diagnostic information concerning soil Se (Williams and Thornton, 1973, Pasch and Vance, 1995). The water soluble fraction is a good estimate of a true soil solution, whereas KH_2PO_4 extraction better defines the Se concentration associated with plant uptake and mobility (Orso et al. 1993, Pasch and Vance 1995). Selenium determined by KH_2PO_4 may approximate the amount of Se that will become accessible over time and which may be solubilized readily by plant root interactions. Results of the extraction analysis should provide information needed to better understand the extent of seleniferous soils and plants, and potential soil-plant relationships for developing guidelines that can be used to characterize disturbed lands. In this study, KH_2PO_4 analytical procedures were used to provide information on the bioavailability Se (Spackman et al. 1994, Pasch and Vance 1995).

Conclusion

In the present study, examination of soil and plant samples in transects from native areas through sites impacted by stream waters flowing from the canyon provided evidence that Se had accumulated in the pastures. Some of the levels for extractable soil Se levels in the contaminated sites extremely high (as high as 14 mg Se/kg) and at concentrations the author had never encountered before. Vegetation samples collected in the Se-contaminated areas also contained significant Se concentrations that were above the suitability limit for forage material. Combining the Se-laden stream waters with the high Se vegetation makes for extremely hazardous conditions for foraging animals, as was the case for the horses that had to be euthanized Results of these studies indicate Se in the stream waters was derived from the waste rock pile that was constructed due to the result of the nearby phosphorus mining activity.

Several remediation approaches must be developed in order to prevent Se leaching from the waste rock pile, and to reduce the bioavailability of Se currently associated with streams in the canyon, and reclamation of pasture soils and vegetation. Covering the waste rock pile with an

impermeable material would be costly and impractical. If uncontaminated materials could be located in the nearby areas, it may be possible to cover the strategic sites on the waste rock pile and vegetate these areas. This would reduce the amount of rainfed leachate that would occur and possibly encourage anaerobic conditions in the waste pile that could minimize oxidation of the Se-bearing shale.

Waters draining from the waste rock pile would required treatment to reduce Se bioavailability (Owens 1998). Alternating aerobic and anaerobic wetlands may be used to assist the microbial transformation of Se to volatile compounds and/or to produce reduced forms of Se that have a greater chance of precipitating from solution.

Areas impacted by the contaminated stream waters would also require reclamation efforts. First, streams would have to be diverted into alternative routes that avoid the pastures. Second, areas with identified Se levels above an extractable phosphate level of 0.2 mg/kg should be delineated. Soils in areas unaffected by the stream waters such as in upland sites, could be used as cover for the contaminated locations. A soil cover of approximately 60 cm or more would be needed so that revegetation plants species do not contact the contaminated material. An alternative plan would be to remove the contaminated soil and bury it.

All these remediation alternatives are expensive. However, due to the hazardous conditions that exist at the waste rock pile and the downstream environments, it is important to act responsible so that future problems are avoided.

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