The Potential Use of Vegetation for Selenium Management at Kesterson Reservoir: Final Report 10/26-1988

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Table of Contents

Part I. The use of vegetation for selenium management at Kesterson Reservoir—overview

1. Introduction

Areas where agricultural drainage water from soils with elevated levels of selenium is stored and evaporates can develop levels of selenium harmful to aquatic life, waterfowl, and perhaps other components of the ecosystem. This problem was first identified at Kesterson Reservoir (Saiki, 1985; Ohlendorf, 1985) and much of the research on methods for treating selenium contaminated lands has focused on this site.

Subsequent studies have shown that this is not the only problem area in the San Joaquin Valley (U.S. Fish and Wildlife Service, 1988). Other evaporation ponds are also affected and more are likely to become problems after they have been utilized for several years. There are now 24 pond systems covering a total of approximately 7,000 acres and many more are planned. The Central Valley Regional Water Quality Control Board has received applications for ponds covering about 10,500 additional acres, and the Board has projected that acreage requested for ponds could double in the next 5 to 10 years (SJVDP, 1987).

The substantial land requirement (approximately 10-20 acres of pond for each 100 acres of drained land) and the ultimate problem of disposal of accumulated selenium and salts are serious flaws associated with the expanded use of evaporation ponds. Other potential problems from increasing use of evaporation ponds are ground-water degradation from pond leakage and potentially adverse effects of contaminants on wildlife, especially fish and aquatic birds.

A number of technical solutions to the problem of selenium contamination have been explored. These range from disposal on-site in a sealed dump to treatment in chemical process systems that remove selenium from the water (Bainbridge et al., 1988). These solutions are very expensive and are unlikely to be implemented without millions of dollars of Federal and State support. This money may not be readily available, and as recent field studies at Kesterson Reservoir have shown (LBL, 1988) the amount of selenium deeper in the soil may make even a very costly program of moving contminated soil into sealed dumps only a partial solution. The solution to the enormous problem of agricultural drainage water must be found in techniques that can be used on-farm by farmers and produce an economic return rather than being a continual economic drain.

2. Options

Treatments based on vegetation management have not been explored in depth but offer the potential of reduced cost and the possibility of saleable products and economic returns from the treatment program. These treatments are generally simple, relatively inexpensive, and adaptable to on-farm operation. Biological methods have proven effective in managing wastewater (Williams and Sutherland, 1979) but technical engineering solutions are still usually the first option explored. The full potential of vegetation managment of selenium problems will not be known until ongoing and future studies are completed.

Two basic strategies for biological management with vegetation are being explored and appear promising. These are the augmentation or replacement of evaporation ponds with tree plantations (Cervinka, 1987; Cervinka et al., 1987; Watson, 1987; Bainbridge and Jarrell, 1987; Bainbridge, 1987; Bainbridge et al., 1988) to minimize future problems and the use of vegetation to treat areas that have already been contaminated. This latter topic is discussed here.

3. Use of Vegetation to Manage Selenium

Three basic strategies of using vegetation to deal with the selenium problems exist. These are: A. the use higher plants to accumulate and concentrate selenium from the deeper soil for subsequent removal and treatment, B. the use higher plants to volatilize selenium, and C. the development of a vegetation plan that will stabilize the site and minimize impacts on wildlife.

A. Selenium harvesting with vegetation

The first step in the treatment program may be volatilization of selenium by soil fungi (Frankenberger et al., 1987). Initial lab and field studies have been promising and the results of field volatilization studies will be available soon. This technique may be able to remove much of the selenium from the surface layer and will also increase the soil organic matter and promote leaching of salts.

It should then be possible to concentrate and collect selenium from the deeper soil with plants. Although some trials will have to be done to determine which plants are best adapted to high boron and salinity it appears likely that several types of selenium accumulating plants can be grown on the contaminated soils. The seleniferous plant material can then be used as fuel for a power plant (with selenium scrubbers), processed as a high selenium feed for animals in selenium deficient areas, or prepared for use as a soil amendment for selenium deficient soils.

The viability of biofuel power production has been confirmed by studies conducted by the California Energy Commission (Eden et al., 1988). The flyash from the biofuel power plant might also prove useful as a soil selenium amendment. Use as either feed or soil supplement appear feasible because selenium deficient soils and animals are common east of the San Joaquin River.

The selection of the best species for a selenium management project will depend on the intended end use, soil characteristics, and water availability. In general the best species for selenium managment should have the following characteristics:

Effective uptake of selenium
High productivity (biomass)
Hardy and easy to grow and harvest
Salinity and boron tolerance
Drought tolerance (no need for irrigation and possible drainage problems)
Deep roots
High water use
Tolerate waterlogged soils
Economic products

The end use will determine whether the goal should be maximum uptake, maiximum volatilization, maximum palatability (but controlled access) or minimal palatability. The selenium accumulators typically take up less arsenic than non-accumulators (Cowgill, 1981) and may therefore be suitable for feed supplements if other trace element levels are satisfactory. Mechanical harvesting and processing appears most promising. The technology and equipment for wetland harvesting lags behind that available for dry lands. However, the biomass production of wetlands can be very high and may be worth futher development.

The pilot and lab studies that have been completed suggest that this type of treatment is feasible. The plants that are used may either be known selenium accumulators such as *Astragalus*, that may concentrate selenium as much as a thousand times over the soil selenium level, or plants that reach concentrations of only several hundred times as much as the soil levels. Uptake of non-accumulators can be increased by growing them in conjunction with or after selenium accumulators (Trelease and Greenfield, 1944; Trelease and di Somma, 1944).

Table 1 illustrates the range of selenium concentrations found in a variety of plants growing on seleniferous soils or with added selenium.

Table 1. Selenium content of plants grown in seleniferous soils or in experiments with added selenium

Species	Se conc. µg/g (dry wt.)	Reference
Crops		
Cauliflower	0.425	(Burau et al., 1987)
Cotton	0.425	(Burau et al., 1987)
Broccoli	0.480	(Burau et al., 1987)
Alfalfa	1-2	(Page and Bingham, 1987)
Alfalfa	100-900	(Page and Bingham, 1987) Se added
Wheat grain	39	(Fleming 1962)
Agropyron spp.	99	(Beath et al., 1941)
Pascopyrum (Agropyron) smithii[a]	84	(Trelease and Beath., 1949)
White clover	153	(Fleming 1962)
Turnip leaves	204-457	(Fleming 1962; Yang et al., 1983)
Cress leaves	212	(Fleming 1962)
Cabbage leaves	409	(Fleming 1962)
Dry land		
Aster commutatus var crassulus Blake	334	(Beath et al., 1941)
Astragalus beathii	1,034	(Beath et al., 1941)
Astragalus bisulcatus	10,000	(Beath, 1959)
Astragalus bisulcatus	5,530	(Rosenfeld and Beath, 1964)
Astragalus bisulcatus	4,040	(Beath et al., 1941)
Astragalus (confertiflorus) flavus[c]	1,361	(Beath et al., 1941)
Astragalus crotalariae	800-2,000	(Virginia and Kramer, 1988)
Astragalus (limatus) crotalariae[b]	2,175	(Beath et al., 1941)
Astragalus crotalariae	6,000	(Virginia and Kramer, 1988) Se added
Astragalus (bisculcatus var.) haydenianus[c]	2,377 ad	(Beath et al., 1941)
Astragalus (pattersonii) var praelongus[c]	4,835	(Beath et al., 1941)
Astragalus racemosus	6,801	(Beath et al., 1941)
Astragalus racemosus	15,000	(Beath et al., 1937)
Astragalus sabulosus	2,210	(Beath et al., 1941)
Atriplex canescens (Pursh.)	450	(Beath et al., 1941)
Atriplex (nuttallii) canescens[c]	536	(Beath et al., 1941)
Atriplex (nuttallii) canescens[c]	300	(Rosenfeld and Beath, 1964; Cooper et al., 1974)

continued

Species	Se conc. µg/g (dry wt.)	Reference
Eucalyptus camaldulensis	41-780	(Rice. 1988)
Machaeranthera ramosa	500	(Beath et al., 1941)
Prosopis glandulosa		
whole pod	106	(Bainbridge and Mikkelson. unp)
Stanleya pinnata		
(var. integrifolia)[c]	904	(Beath et al., 1941)
Stanleya pinnata	1,456	(Beath et al., 1941)
Stanleya pinnata	200	(Norman., 1987)
Stanleya pinnata	1.190	(Rosenfeld and Beath. 1964)
Wetlands		
Juncus mexicanus	16.24	(Wu et al., 1987)
Distichilis spp.	5	(U.S.D.I., 1986)
Distichilis spicata	12.55	(Wu et al.. 1987)
Typha latifolia	15.25	(Wu et al., 1987)
Typha latifolia	2.2	(Presser and Barns. 1985)
Cattails and bullrush	8	(Kesterson EIS. 1986)
Bullrush tuber	2.4	(Presser and Barns, 1985)
Scirpus robustus	4.9	(Presser and Barns, 1985)

[a]Asay and Knowles, 1985.

[b]Munz and Keck, 1985.

[c]Soil Conservation Service, 1982.

The distribution of selenium within plants is not well understood. Some studies have suggested selenium is concentrated in growing points, seeds, and roots (Arvy et al., 1974; Ehlig et al., 1968), but other studies have shown higher leaf and stem levels and reduced content in seeds (Wu et al., 1987; Hamilton and Beath, 1963a). Hamilton and Beath (1963a,b) found that the straw selenium concentration was typically much higher than the seed, buckwheat--grain 18 µg/g, straw 56 µg/g, rye--grain 18 µg/g, straw 41 µg/g, wheat --grain 81 µg/g, straw 112 µg/g. The root concentrations of selenium are in general much higher than the tops. Root levels were 2-23 times as high as leaves in a variety of crops in ^{75}Se studies (Johnson et al., 1967). In Astragali the opposite seems to be the case. *Astragalus crotalariae* tops had 44 times higher selenium concentration than the roots (Rosenfeld and Beath, 1964).

i. Dryland harvest

The following section examines some of the candidate plants for selenium harvesting on land.

a. Plants

Astragalus (Leguminosae)

Many species of *Astragalus* have been tested by Davis (1972a, 1986). Species of *Astragalus* varied in their uptake of selenium with that in young rapidly growing plants ranging from 0 to 61 µg/g. These accessions were tested by growing them in clay pots with selenate which may not accurately reflect what happens in the field. Only three of 110 sp accumulated more than100 µg/g, 45 showed none, and 3 contained less than 5 µg/g. Several species represented by multiple accessions showed some irregularity between presence or abscence of selenium. Selenium toxicity was observed in three species. *A. bisulcatus* accumulated considerable selenium (47 µg/g). Simialr differences were also noted by Trelease and Trelease (1939).

A. bisulcatus is mentioned by Beath et al. (1939, 1941) as a strong accumulator and indicator species. The highest recorded content for *Astragalus* is 15,000 µg/g for *Astraglus racemosa* (Beath et al, 1937). *A. crotalariae* is a promising native plant for selenium harvest. Field measurements of over 2,000 µg/g have been reported in California (Beath et al., 1941; Virginia and Kramer, 1988) and concentrations of 6,000 µg/g have been observed in the lab with no apparent signs of toxicity (Virginia and Kramer, 1988).

Beath (1959) calculated the potential selenium harvest from *Astragalus bisulcatus* at 6.8 kg/(ha yr) with a good recovery process. Assuming concentrations of 2,000-6,000 µg/g and a yield of 3 t/ha then 6-18 kg/(ha yr) might be harvested.

Wheatgrass (Gramineae)

About 60 species of wheatgrass are known in the temperate regions and 15 are found in California (Munz and Keck, 1968). The taxonomy is now undergoing considerable debate, with revisions that would both increase and decrease the number of species and group them differently (Asay and and Knowles, 1985; Sanders, 1988). They include a variety of dry-lands-adapted species which range from weeds to useful fodder plants. The wheatgrasses showed relatively good uptake of selenium compared to other grasses (Ehlig et al., 1960; Hamilton and Beath, 1963a,b; Beath et al., 1941). Olson et al. (1942) found western wheat grass.

Pascopyrum (Agropyron) smithii to be the most efficient absorber of selenium. *Agropyron desertorum*, was found to accumulate 250 µg/g from a 1 µg/g selenium solution. (Wu and Burau, 1986). With a dry land yield of 784 kg/ha (Vallentine, 1980) the harvest could yield 200 g/(ha.yr). A considerably larger harvest should be possible with irrigation.

Elytrigia (Agropyron) elongatum, tall wheatgrass, is salt tolerant and able to grow in waterlogged soil. It is probably the best wheatgrass for this work because of its ability to produce forage in areas that are too salty or alkaline for other productive crops (Asay and Knowles, 1985). It is perennial, has a big stalk and could be harvested annually or grazed. Wheatgrass has been found to have good flavor and milling characteristics and have excellent potential for use in perennial grain cropping systems (Wagoner, 1986).

Oryzopsis hymenoides Indian ricegrass (Gramineae)

Indian ricegrass accumulated by far the highest amount of selenium of the grasses with values of 526 and 546 µg/g when grown on soil containing 10 µg/g inorganic selenium (Hamilton and Beath, 1963a). Little is known about commercial production of Indian ricegrass but seed is available from Southwest Seed Inc., Dolores, Colorado and they have some experience combining it.

Helianthus spp. Sunflowers (Compositae)

Hamilton and Beath (1963b) looked at selenium uptake and conversion by several crop plants. Sunflowers reached the highest selenium concentration, with 426 µg/g from a 20 µg/g selenate solution. A number of wild and domestic sunflowers should be evaluated, including the Jerusalem artichoke (*H. tuberosus*).

The Asters (Compositae)

Tansy aster was the most efficient absorber of selenium in a trial conducted by Hamilton,and Beath (1963a) and most of the selenium occurred as water-soluble inorganic selenium. This confirms the observation by Beath et al. (1941) that the selenium in Asters is water soluble. The Western aster *Aster occidentalis* reached 1,413 µg/g from soil with 20 µg/g selenate and Tansy aster *Machaeranthera grindelioides* reached 3,900 µg/g from a soil with 10 µg/g selenate (Hamilton and Beath, 1963a).

Crucifers (Cruciferae)

Crucifers have been found to contain higher amounts of selenium on a range of soils compared with other plants (Hamilton and Beath 1964). Bisberg and Gissel-Nielsen (1969) found the following decreasing plant selenium concentrations on low-selenium soils: crucifers > rye grass > legumes > cereals. This trend was unchanged by variations in soil-selenium concentrations and selenium oxidation states.

Turnip greens (*Brassica rapa)* have been found to contain up to 457 µg/g dry weight in China (Yang et al., 1983) and might be a good candidate for harvest. If a yield of 5,000 kg/ha is achieved then the harvest might be 2.5 kg/(ha yr).

Cabbage (*Brassica oleracea*) has also been found to be have elevated selenium levels in some areas, with up to 409 µg/g reported by Fleming (1962). This is a possible winter crop which might be combined in a rotation with a summer accumulator. Yield is up to 50 t/ha fresh weight (Walters and Fenzau, 1979). If a yield of 5 tons ha dry wt and a selenium concentration of 400 µg/g are possible then the harvest could be 2 kg/(ha yr).

A field survey of the selenium uptake of a wide range of cultivated and wild Gramineae, Compositae, and Cruciferae is in order. Other plants that may be worth evaluating include Bur medics and strawberry clover.

b. Shrubs

Perennial plants offer some advantages for selenium harvesting. Deeper more extensive roots can be developed for better uptake of selenium deeper in the soil profile. Nitrogen fixing plants would offer the additional benefit of requiring little or no fertilizer.

Atriplex (Chenopodiaceae)

A preliminary survey of possible *Atriplex* species for use in a selenium biofilter has been undertaken and continuing work is underway (Watson, 1987). The highest selenium content in these at the first evaluation was about 1 µg/g for *A. canescens* var. 824, and *A. barclayana*. Previous field studies have found sondierable higher levels of selenium in *Atriplex nuttallii* (Wats), from 300 to536 µg/g (Beath et al., 1941; Rosenfeld and Beath, 1964; Cooper et al., 1974).

Atriplex has been evaluated as a forage candidate in saline soils. Yields in Israel have been 3-13 mt/dwt/ha with seawater or freshwater irrigation (Forti, 1986). Higher Yields of up to 15 t/(ha yr) have been reported (Le Houerou, 1986). Yields of 7.5 t/ha have been reported at Murrietta Farms in the San Joaquin Valley (Cervinka et al.. 1987). If these plants contained 500 µg/g then the harvest of selenium could be about 4 kg/(ha yr).

c. trees

Prosopis spp. (Leguminosae)

Mesquite is one of the most promising candidates for selenium harvesting in the San Joaquin Valley. At one time there were more than 20.000 ha of mesquite in the San Joaquin Valley (Holland, 1987) and mesquite can be very productive in arid and semi-arid areas. Uptake is not well known but whole tree selenium content was 450 µg/g in the glasshouse trial and whole pod selenium content of 100 µg/g in *Prosopis glandulosa* from Harpers Well, CA (Mikkelsen and Bainbridge, unpub).

Many mesquite species are salt tolerant (Felker et al., 1981) and they produce a variety of useful products (Meyer, 1985; Felker, 1981). Mesquite is also a nitrogen fixer with N production of 30-40 kg/ha/yr with 30% canopy cover (Rundel et al.. 1982). Mesquite may produce an edible pod, useful fodder (particularly for sheep), galactomannan gum, edible wood with treatment (Parker, 1982), useful hardwood, and has excellent biofuel potential.

Productivity in t/(ha yr) has been studied in trial plantings and yields ranged from *Prosopis chilensis* 13.4 t, Riverside; *P. chilensis, P. alba,* 14.5 t, Imperial Valley; *P. articulata*, 16.6 t, Riverside (Felker et al., 1983). Harvest potentially would include wood, leaves and pods. Pod yields of 6 t/(ha yr) have been reported for *Prosopis* (Lima, 1986). With a wood yield of 10 t and 200 µg/g the selenium harvest would be about 2 kg/(ha yr). The pod selenium yield might be about 1 kg/(ha yr).

Eucalyptus (Myrtaceae)

Eucalypts are also potential candidates for selenium harvesting. Several of the more than 450 species are salt tolerant and have done well in existing agroforestry trials in the San Joaquin Valley (Cervinka et al., 1987). Plantations in California have produced up to 30 mt/(ha yr) although 15 mt/(ha yr) is more common (Standiford et al., 1987) and production in salt affected areas is more likely to be 5 t/(ha yr). The biofuel potential of Eucalypts is well known and the trees have also been used extensively for fiber and paper production (Mariani et al., 1978). Concentrations of selenium in *Eucalyptus camaldulensis* leaves in test plantings in areas irrigated with drainage water have reached 700 µg/g (Rice, 1988). If these values are comparable to wood concentrations then with a production 5 tons of wood ha this could remove up to 3.5 kg Se/(ha yr). At 300 µg/g (which was more common) the removal might still exceed 1 kg/(ha yr). If wood concentrations are lower than leaves, the harvest would be less, perhaps 1 kg/(ha yr).

Acacia spp. (Leguminosae)

A. nilotica appears to good potential for selenium harvesting (see part 1). *A. nilotica* reached the highest selenium concentrations in the trials, at 1,500 µg/g. *A. nilotica* is very drought resistant, adaptable to a wide range of soil conditions and may produce 20-30 t/(ha yr) with a fuel value of 4,800-4,950 kcal/kg (BOSTID, 1983).

Acacai greggi also tolerated the selenium test well and reached more than 400 µg/g selenium.

Acacia saligna tolerates salt well and produces both useful fodder, 5.5 t wwt, and firewood, 18 t wwt/(ha yr) (El Hamrouni, 1986) but this species did not do well in preliminary screening for selenium tolerance (see Part 1).

Leucaena leucocephala (Leguminosae)

Leucaena exhibited excellent tolerance of sodium selenate (see part 1). Leucaena is an evergreen plant but can be drought or frost deciduous. *Leucaena* has a substantial taproot when young. It is best planted from seed and responds well to mowing or coppicing (Board on Science and Technology for International Development and the Nitrogen Fixing Tree Association BOSTID, 1984). Plantations have been planted with 10,000 trees per ha. These dense plantings remain clear underneath. Establishment may require careful fencing as young seedlings are preferred by many herbivores.

Leucaena grows best with 1-3 m of water per year but survives and is the dominant vegetation in some areas at 250 mm/yr (BOSTID, 1984). Good growth is maintained throughout the year in tropical and subtropical areas when groundwater is within reach. Standing water inhibits growth although good yields have been obtained in waterlogged soils in Thailand. Salt tolerance is considerable and *L. leucocephala* often survives in exposed coastal areas. *Leucaena* prefers alkaline soil, pH 7.7, and available Ca, P, S, K, and Mg are important.

Heavy frost may kill trees of *L. leucocephala* but moderate frost will kill tops only and it will resprout. One tree (K-8) is doing very well near March Air Force Base and has survived temperatures in the low 20^{o}s F (Clark, 1988). *Leucaena* may fix 100-200 kg N /(ha yr) (BOSTID, 1984).

Wood production is often 40-50 $m^3/(ha\ yr)$ with a wood density higher than many other fast growing trees. The specific gravity of the wood is 0.54 for 6-8 yr old Giant type trees. With suitable soils *L. leucocephala* may reach 18 m in 4-8 years with dbh of 21-37 cm after 8 years. The fuel value, from 2-4 yr old Giants wood is 4,640 kcal/kg and the charcoal fuel value is 7,000 kcal/kg (BOSTID, 1984).

The forage value of *Leucaena* is good for ruminants and it is being increasingly used for dairy cattle, cattle, and goats (BOSTID, 1984). It is browsed, harvested by hand, or by machine (alfalfa type equipment). In Northern Australia the milk yield from cattle fed with *L. leucocephala* has been 5-6,000 L/ha. On *L. leucocephala* and grass (1:1) pastures cattle have gained 300-800 kg/ha/yr. The high mimosine content of some species causes hair to fall out of sheep (which has been explored as an alternative to shearing) and ruminants in some areas are affected if their rumen microflora lacks the appropriate microbes. This deficiency has been successfully remedied by introducing the appropriate bacteria to herds. Pod yields of 7.3 t/ha/yr have been reported for *Leuceana* (Lima, 1986). Leucaena pods are used as human food in several areas of the world, most notably in Indonesia where the seeds are fermented like soybeans to make tempe type products (Wirjodarmodjo and Wiroatmodjo, 1983).

The *L. leucocephala* K-8, named by James Brewbaker, used in the glasshouse experiment.is a high yielding variety originating from the inland forests of Central America and Mexico. *L. pulverulenta* is drought tolearant and frost resistant, has harder wood, lower mimosine content. A hybrid *L. leucocephala x L. pulverulenta* has been developed which produces few pods or seeds.

With a wood yield of 10 t/ha and selenium concentration of 100 µg/g this represents a potential harvest of 1 kg/(ha yr). Pod selenium harvest could be 700 g/(ha yr).

Albizia spp. (Leguminosae)

The mimosa trees, *Albizia* spp., may also be good candidates for selenium harvest. They are closely related to *Prosopis* and are well adapted to the San Joaquin Valley. They are regarded as one of the better multipurpose trees and are used for fuelwood in many areas of the world (Burley, 1985)

ii. Wetland harvest

Not a great deal is known about selenium uptake of aquatic and wetland plants. Some data has been gathered in the recent surveys of the San Joaquin Valley and this suggests that wetland harvesting might be feasible. Wetlands are very productive with freshwater swamp mean primary productivity of 2,000 g/m^2/yr, or 20 mt/ha (Lieth and Whittaker, 1975). The use of wetlands would also remove pressure on more valuable drier areas. Recent interest in wetland ecology and restoration has led to much better understanding of the ecology, management, and establishment of wetland plants (Chan et al., 1982; Garbisch, 1986; Godfrey et al., 1985). Harvested material could be fed to livestock (Bagnall, 1979), used to make a selenium rich fertilizer, or burned in a power plant (Pratt and Andrews, 1981). However, concern over risk to waterfowl might make screening necessary.

Algae

This method has application for the wet ponds. The Lawrence Berkeley Laboratory at the University of California at Berkeley has reported that growth of the large algae, *Nitella*, can be used to isolate selenium in the sediment as the algae die and settle to the bottom and anerobic sludge layers develop (LBL, 1985). The use of blue green algae has also been evaluated (Packer et al., 1986).

Distichilis

Salt grass, *Distichilis spicata* a salt and alkalai tolerant low perennial was found to contain 12.55 µg/g selenium (Wu et al., 1987). *Distichilis* has been found to respond well to nitrogen fertilizer (Valiela et al., 1985). The recomended propagules for *Distichilis* include: seeds, sprigs, and peat pots (Garbisch, 1986).

Juncus

The rushes are a common and productive member of wetlands communities. Productivity of *Juncus* has been studied in several areas, primarily in the SE U.S. Above ground productivity estimates range from 792 to 3,295 g/m^2 (Mitsch and Gosselink, 1986). Wu et al. (1987) found *Juncus mexicana* contained 16.24 µg/g selenium. If a harvest of 3 t/ha could be achieved it would be possible to collect 50 g/(ha yr).

Phragamites

Reeds have a photosynthetic conversion efficiency of 4-7%, similar to corn and sugar cane, with a root–shoot biomass ratio of 0.9-2. *Phragamites communis* grows up to 7 meters tall with productivity of 1,000 to 6,000 g/m^2/yr, or 10-60 t/ha (Kvet and Husak,1978; Good et al., 1978). Reeds are often considered a weed in wetland restoration due to their fast spread and vigourous growth. The potential harvest should be similar to *Juncus*.

Typha

Wu et al. (1987) found selenium content of *Typha latifolia* of15.25 µg/g. Cattail. *Typha latifolia*, productivity has been measured from 3,450 g/m^2/yr to 4,640 g/m^2 (Mitsch and Gosselink.1986; Wetzel, 1975). *Typha* is a C_3 plant but has a very high efficiency, perhaps from close control over photorespiratory pathway (McNaughton and Fullem, 1970; McNaughton, 1973). Considerable work on *Typha* has been done in the Midwest because its high productivity makes it a candidate for biofuel use.

Cattails also have edible pollen, flower, young stems, and rhizomes (Harrington, 1967) and might be used as a selenium enriched feed for livestock. Cattails are less tolerant of salinity than Alkalai bulrush *(Scirpus robustus)*. Therecommended propagules are rhizomes (Garbisch, 1986). With a yield of 35-46 t/ha the potential harvest would be about a half kilogram/(ha yr).

Scirpus robustus

Alkalai bulrush, *Scirpus robustus* has a high tolerance for salinity, up to 50 mmhos/cm (Wilson and Tchonbanoglos, 1984). Productivity of a related species, *Scirpus subterminalis* was estimated at 1.55 g/m^2 in Michigan (Wetzel, 1975). Productivity in California should be much higher. The recomended propagules for *S. robustus*. are seeds, sprigs, or peat pots (Garbisch, 1986).

Water hyacinth

Water hyacinth has been used in water treatment plant systems. When harvested to maintain a low density population the production in nutrient-rich water has reached 154 t/ha in 7 months (Godfrey et al., 1985).

B. Volatilization with vegetation

Selenium is volatilized by plants as well as by fungi. This process has not been studied sufficiently to say what volatilization rates can be achieved and maintained in the field. Selenium gasses are released metabolically and as plants dry out after cutting or reaching maturity (Allaway and Hodgson, 1964; Rosenfeld and Beath, 1964; Lewis et al., 1966). Beath et al. (1937) reported volatilization of up to 60% of the selenium from *Astragalus*.. *A. bisulcatus* regularly yields less selenium if analyzed after drying and the form of selenium in this species appears to volatilize readily during drying (Beath et al., 1941).

With selenium concentrations of 2,000 µg/g selenium common in this plant and a biomass of 5,000 kg/ha this may amount to volatilzation of 5 kg/(ha yr). *Astragalus crotalariae*, with the bulk of the selenium partioned to the top, 44 times as much as in the roots (Rosenfeld and Beath, 1964) is a particularly promising plant for volatilization.

The amount of selenium released on drying was found to be a function of the total selenium in the plant (Johnson et al., 1967). Lower rates of volatilization for *Astragalus* were observed than Beath et al. (1937), with volatilization of only 4.8% of the tops and 7.6% of the root selenium. These were however, much lower concentrations of selenium. Alfalfa and subterranean clover lost 1/2-1% in 24-48 hours at 70^{o}C. Ryegrass, Harding grass, barley, wheat tomato, spinach, mustard, and onion also released higher amounts of selenium.

Tracer studies by Lewis et al. (1966) showed that volatile losses were not confined to plants with high selenium concentrations. The volatilization rate from intact alfalfa reached a high in the early afternoon. Most of the release was from the tops—since their removal reduced the amount lost by the whole system to very low levels. Both tops and roots were subsequently shown to release volatile compounds.

One of the questions that must be answered is rate of absorption of these selenium gasses by vegetation and soils versus transfer out of the area. As Burton (1980) discovered some selenium gasses are readily taken up by some plants. If the transfer rate is low it could be increased by developing solar-thermal chimneys to increase vertical mixing and long range transport.

C. Site stabilization with vegetation

It is also possible that seleniferous sites could be stabilized with vegetation to minimize the release of selenium and the impacts of selenium on wildlife and aquatic systems. This would require leveling of the site (now underway) and development of a planting program to establish ground cover and trees that will grow under the adverse site conditions and not be attractive to wildlife or uptake significant amounts of selenium. This vegetation should be chosen so that it will find moisture in the phreatic zone after establishment and help maintain or increase the depth to water table. This vegetation (which might be mowed regularly to limit cover for wildlife) would also reduce the soil temperature, and increase soil organic matter (reducing selenium mobility). A crop with acid leaf litter (pines for example) could reduce soil pH and further reduce selenium mobility and availability (Gissel-Nielsen, 1971).

D. Kesterson: An example

The estimated amount of selenium at Kesterson Reservoir is around 7,900 kg (USDI, 1986), primarily concentrated in the top 30 cm with another 2,400 kg in the San Luis Drain sediments. If this selenium were uniformly distributed there would be 16 kg/ha. The 7,900 kg of selenium at Kesterson was deposited between January 1981 and September 1985 from the drainage of 17,000 ha. This is a release of almost 500 g of selenium/ha over 5 years, or about 100 g/ha/yr.

If the selenium were uniformly distributed and is removed with vegetation alone it would take from 2 to 10 years to remove the bulk of the selenium by harvesting and/or volatilization with plants. As the amout of selenium in the soil decreases the rate of uptake would be expected to decline. Trees or other long-lived plants would probably be grown on a five or ten year rotation. If 30 % of the selenium is removed by volatilization with soil fungi in 2-3 years the remaining amount could be largely collected and removed within 2 to 5 years if the in field performance comes close to past experience and lab studies.

4. Summary

The use of vegetation to manage selenium problems in California is very promising and appears to be worth comprehensive evaluation at the field scale. On-site studies are needed to confirm experimental findings and to verify estimates based on ecological analogs. If the fairly conservative estimates of volatilization rate, biomass yield and selenium concentration can be matched then it should be possible to remove several kilograms of selenium per hectare each year with vegetation and to clean up the site within a few years while producing an salable product. Vegetation management appears to be a very economical method for the cleanup of Kesterson Reservoir and similar sites.

The first stage in treatment may be volatilzation with fungi to remove selenium in the surface soil. This might then be followed with volatilization by plants such as *Astragalus crotalariae* which may volatilize up to several kg Se/(ha yr). A perennial tree crop with good accumulation rates could be started at the the same time and grown as a short-rotation fuelwood coppice. Grasses such as *Agropyron elongatum* could be grown for two or three years between the rows of trees. *Acacia nilotica* or *Eucalyptus camaldulensis*, averaging 5 t/(ha yr) and 500 µg/g could remove 12.5 kg/ha (the bulk of the selenium remaining in the soil) in a 5 year period while providing a salable crop of firewood or biofuel.

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Part II. Selenium accumulation trial, leguminous trees

1. Introduction

One possible solution to the problem of selenium buildup in areas used for disposal of agricultural wastewater is growing plant species that can accumulate selenium. These plants, which may accumulate large amounts of selenium (10^2 to 10^4 µg/g Se/dry wt.), include species such as *Astragalus* (Leguminosae) and *Stanleya* (Cruciferae).

Many of these plants are deep-rooted and will take up selenium in the deep soil and move it to the surface where it can be harvested and removed. Perennial plants, which should not require irrigation after establishment in areas such as Kesterson Reservoir with relatively shallow depth to groundwater, are of particular interest. Nitrogen fixing plants, may help prevent the remobilization of soil selenium in groundwater which may occur as a result of the addition of nitrate from the use of nitrogen fertilizers.

A preliminary trial of potentially useful leguminous trees was undertaken in the glasshouse at UCR. The initial evaluation was a simple screen for selenium tolerance and uptake.

2. Materials and methods:

Seeds for a number of candidate species were collected and scarified mechanically or with acid and germinated in wet paper towels. After sprouting the plants were transferred to conetainers with the bottom holes blocked with crumpled paper towels and filled with 16 grit silica sand. After growing for from one to two weeks these were transferred to a conetainer rack placed in a rectangular plastic tank filled with sufficient 0.25mM sodium selenate in deionized water to reach approximately 1/4 of the way up the conetainer.

The plants were watered with solution taken from the tank twice a day for the first two weeks. At that time those plants that had not already died from the exposure to the selenate solution were able to draw moisture from the solution in the tank. Each plant was given 5 ml of 50% Hoagland's after one and two weeks in the tank.

The conetainers were left in the tank for 6 weeks. At the end of six weeks the plants were taken from the conetainers and the root and shoot development was observed and the survival was recorded. Plant tissues (both roots and tops) were collected, dried at 70-80^{o}C for two and a half days, ground in a mill, and then analyzed for selenium.

Acacia saligna

Only 1 of 10 had a living shoot. All roots were white and appeared alive but were poorly developed.

Cercidium floridum Cal Trans (215 µg/g)

One of 10 tops was in good condition, 1 fair, 1 poor (green stem but no leaves) and 7 were dead. Roots were well developed but brown.

Acacia radiatta-all died
Acacia tortillis-all died

Growth was probably limited by lack of nutrients as well as the effect of the selenium.

We intially planned to compare uptake of these trees with *Astragalus*, Indian Ricegrass, *Orzyopsis hymendoides*, and Tall Wheatgrass, *Agropyron elongatum* but had difficulty obtaining seed and establishing these species in the limited time available. Dr. R.A. Virginia and Nancy Kramer at SDSU provided information on the accumulation of selenium in *Astragalus crotalariae* from sodium selenate solutions that included the same range. Plant selenium concentration in *A. crotalariae* appeared to plateau at about 6,000 µg/g under a range of conditions.

4. Conclusions

Several of the leguminous trees appear to have considerable potential for selenium harvesting. Production of several metric tons of wood per hectare per annum should be possible even under the adverse site conditions. With tissue concentrations of 500 µg/g and a yield of 3 tons per hectare per year this would allow the harvest and removal of 1.5 kg/(ha yr). It is also conceivable that much better results could be realized with growth of 10 tons per hectare and concentrations of 1,000 µg/g. This would remove as much as 10 kg/(ha yr). Field trials are suggested as a logical next step.

3. Results

The survival and performance of the species was as follows, ranked from best to worst including tolerance of 0.25mM selenate under the experimental conditions and accumulation of selenium.

Acacia greggii (426 µg/g)

The roots were well developed and white except at the tips which were red (reduction of Se?). Four of five were in good condition and the fifth was in fair condition. Growth was limited.

Acacia nilotica (1,500µg/g)

All seedlings had well developed white roots. Tops on 3 of 5 were alive and appeared healthy. Growth was limited.

Prosopis glandulosa Harper's Well (450 µg/g)

All of the mequite seedlings had fairly well developed roots that were white except at the tips. 4 of 10 tops were in good condition, and 4 of 10 were alive but in poor condition at the conclusion of the experiment. Growth was limited.

Leuceana leucocephala K-8 (139 µg/g))

The Leuceana seedlings exibited the least apparent effect from the selenium. Leaf development was good and the roots were white and well developed. All roots (10 of 10) appeared healthy. The tops on 5 appeared dead but the other 5 were in very good condition.

Albizia julibrissin CATI (194µg/g)

The Albizia looked strong initially but gradually died back until only 2 of 10 tops were in fair condition. Roots were well developed, white, with many fine roots even on those with apparently dead tops. Growth was limited.

Acacia albida

Roots were poorly developed with few root hairs. Only 1 of 5 had a living (just barely) top.

Part III. Selenium accumulation, plant collection

Two trips were taken to collect plant material from seleniferous areas. Timing (late summer) was not good for the collection or identification of plant material but several samples were collected in the Panoche Fan, Kesterson, and west of the Salton Sea.

The following selenium levels were determined for these samples:

West of the Salton Sea

Astragalus crotalariae	
tops	1,335 µg/g
tops	1,113.76 µg/g
Mesquite *Prosopis glandulosa*	
leaf	2.39 µg/g
wood	8.22 µg/g
pod without seeds	30.51 µg/g
Atriplex (*polycarpa*?)	below detection limit
Tamarisk (*Tamarix aphylla*)	below detection limit

Previous studies in the area.

Mesquite, whole pod Bainbridge, D.A. and Mikkelsen, R. unpub.	106 µg/g
Astragalus crotalariae Virginia, R.A. unpub.	800-2,000 µg/g
Astragalus crotalariae	2,175 µg/g
Soil	2.4 µg/g

Beath, O.A., Gilbert, C.S., and Eppson, H.F. 1941. The use of indicator plants in locating seleniferous areas in Western United States. IV. Progress Report. Am J Bot 28:887-900.

Panoche Fan

Fremont Cottonwood (*Populus fremontii*) Silver Creek	1.44 µg/g
Atriplex spp. Panoche Rd	0.89 µg/g

Kesterson

Willow (*Salix spp.*) North Kesterson	0.71 µg/g
Sunflower (*Helianthus spp.*) Gun Club Rd.	1.00 µg/g