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Selenium Uptake by Some Agricultural Crops from Central California Soils

H. F. WAN, R. L. MIKKELSEN,* AND A. L. PAGE

ABSTRACT

Greenhouse experiments were conducted to study Se uptake and partitioning by crops grown in five California soils of differing physical and chemical properties. Alfalfa (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), beet (*Beta vulgaris* L.), and tomato (*Lycopersicon esculentum* Mill.) were grown in soil to which 0, 0.5, and 1.5 mg Se(VI) kg^{-1} was added. Alfalfa was also grown in four additional soils to which 0, 0.5, 1.5, and 3.0 mg Se(VI) kg^{-1} had been added. Plants were grown to maturity, separated into plant parts, and analyzed for yield and tissue Se. For the barley, beet, and tomato, the edible portion of the plant contained much less total Se than the generally inedible plant parts. The presence of soluble SO_4^{2-} in the soil was the major soil factor in determining Se accumulation by plants. Alfalfa grown in low-SO_4^{2-} soil accumulated Se to a concentration 10 to 20 times greater (>1000 mg Se kg^{-1}) than plants growing in high-SO_4^{2-} soil (<100 mg Se kg^{-1}). When exposed to Se(VI) in the root zone, all plants tested were capable of accumulating Se to concentrations potentially harmful to animals.

Additional Index Words: Selenate, Se toxicity, Se partitioning, *Medicago sativa* L., *Hordeum vulgare* L., *Beta vulgaris* L., *Lycopersicon esculentum* Mill.

High Se concentrations have recently been found in irrigation and drainage water in parts of central California (Presser and Barnes, 1985; Oster, 1987). Since this discovery, concern has been expressed over possible accumulation of excessive Se in plants grown in this region, especially those entering the human and animal food chain. When Se concentrations in food and forage become elevated, these food sources may be hazardous to humans, animals, and wildlife consuming this material. High Se concentrations in plants have recently been implicated in human health problems in China (Yang et al., 1983) as well as wildlife problems in California (Mikkelsen et al., 1986). Although Se is an essential element for animals, the range between deficiency and toxicity is narrow (Underwood, 1977). Selenium deficiencies may occur in grazing animals when the Se concentration in feed is <0.05 mg Se kg^{-1}, while the toxicity threshold for livestock is 4 to 5 mg Se kg^{-1} (NRC, 1983).

Selenium uptake by plants is influenced by many factors including the form and concentration of Se in the soil, soil properties such as pH and clay content, and the presence of other ions (Mikkelsen et al., 1988). In the southern portion of the Central Valley of California, the dominant form of Se in soils is selenate [Se(VI)] (Presser and Barnes, 1985), which is generally quite soluble, mobile, and readily available for plant uptake (Adriano, 1986).

Selenium uptake is also related to the plant species involved. There are plants, known as Se accumulators, capable of accumulating extremely high concentrations of Se (several thousand mg Se kg^{-1}) when grown in seleniferous soils. These plants include species from genera such as *Astragalus, Oonopsis, Stanleyea,* and *Xylorhiza*. Typical agricultural crops, however, have a much lower tolerance for Se (<50 mg Se kg^{-1}) (Mikkelsen et al., 1988).

The objective of this experiment was to examine Se uptake and partitioning by some common agricultural crops grown in various California soils with elevated concentrations of Se(VI).

MATERIALS AND METHODS

Five soils were collected from the Panoche Fan area of the San Joaquin Valley of California. The Panoche Fan is believed to be a major source of Se entering irrigation and drainage waters in the region (Mikkelsen et al., 1986). These soils were Ciervo sandy loam (Vertic Xerochrepts). Lethent sandy clay loam (Typic Natrargids), Lost Hills clay loam (Typic Haplargids), Panhill clay loam (Typic Haplargids), and Panoche loam (Typic Torriorthents). Some important chemical and physical properties of these soils are shown in Table 1. The high concentration of SO_4^{2-} present in the Panoche soil was not detected until soil analysis at the conclusion of the experiment.

Panoche loam soil was air-dried, sieved, and thoroughly mixed with Na_2SeO_4 to obtain a concentration of 0, 0.5, or 1.5 mg of added Se kg^{-1}. Nitrogen and P were added to the soil at a concentration of 100 mg kg^{-1} as NH_4NO_3 and KH_2PO_4. Pots lined with polyethylene bags were filled with 6 or 10 kg of treated soil.

Alfalfa (*Medicago sativa* L., Germain WL 512), barley (*Hordeum vulgare* Briggs), and beet (*Beta vulgaris* L., Detroit dark red) were planted in the pots containing 6 kg of soil. After emergence, the pots were thinned to 10 alfalfa plants per pot, five barley plants per pot, and one beet plant per pot. One tomato plant (*Lycopersicon esculentum* Mill., Early Girl) was transplanted into each pot containing 10 kg soil. Each crop was grown at three concentrations of Se with four replications in a completely randomized block design. The plants were irrigated with deionized water as needed.

Alfalfa was harvested four times at 0.25 bloom stage, barley was harvested at maturity and separated into grain and shoots,

Table 1. Selected physical and chemical characteristics of soils used.

Soil series	pH†	Clay	Organic C	Soluble SO_4^{2-}	EC	Total Se‡
		%	g kg^{-1}	mg L^{-1}	dS m^{-1}	mg kg^{-1}
Ciervo	8.7	17	6.4	167	0.5	1.29
Lethent	8.3	23	5.3	2285	3.7	1.04
Lost Hill	5.6	25	7.4	106	0.7	1.83
Panhill	6.9	37	6.4	268	0.6	0.93
Panoche	7.2	27	4.9	3088	5.3	0.65

† pH, soluble SO_4^{2-} and electrical conductivity (EC) measured in saturated paste extract.
‡ Measured in soil digested in nitric and perchloric acids.

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9465

and beet plants were harvested 67 d after planting and separated into root and shoot portions. Ripe tomato fruit was harvested for 2 weeks before the plant was harvested and divided into leaves and stems.

All plant samples (except tomato fruit) were dried at 50°C and weighed prior to grinding and digestion with nitric and perchloric acids (Ganje and Page, 1974). The fresh tomato fruit was weighed and homogenized in a laboratory blender, then an aliquot taken for drying and subsequent digestion and analysis.

Selenium was determined using an atomic absorption spectrophotometer with hydride generation.

In a subsequent study, Ciervo, Lethent, Lost Hill, and Panhill soils were treated in a similar manner as the Panoche soil, except Se was added at a rate of 0, 0.5, 1.5, and 3.0 mg Se kg^{-1} as Na_2SeO_4. Alfalfa was planted in these soils in four replications of a complete randomized block design and maintained and analyzed in the same manner as described previously. Three alfalfa harvests were made.

A logarithmic transformation of the alfalfa Se concentrations was performed before mean separation by Duncan's multiple range test.

RESULTS AND DISCUSSION

There were no significant differences in yield or dry matter production of the four crop species due to added Se in the Panoche soil (data not shown). Selenium accumulation by alfalfa, barley, beet, and tomato was proportional to the Se(VI) added to the soil (Table 2). Although all the crops were capable of accumulating Se to concentrations that could be potentially harmful to humans or animals when Se(VI) was added to the soil, significant differences were observed between the plant species and among parts within a given plant.

It is apparent that for the crops normally consumed by humans (beet, barley, and tomato) the edible portion of the plant contained lower Se concentrations than the generally inedible portion of the plant. At the highest levels of Se addition [1.5 mg Se(VI) kg^{-1}], the barley grain Se concentration was about 65% that of the remaining shoot, beet root Se concentrations were 50% less than the tops, and tomato fruit Se concentrations were less than 20% that of the leaves. These results support earlier research by Hamilton and Beath (1963, 1964) showing similar trends with a variety of crops [illegible] ferent conditions. In experiments with [illegible] Ylaranta (1983) and Gissel-Nielsen (1973) [illegible] Se accumulated to equal or greater conce[illegible] straw compared to the grain. It should [illegible] that the vegetative portion of beets is oc[illegible] and contains higher Se concentrations than [illegible] results of the alfalfa will be discussed la[illegible]

All crops tested readily accumulated Se(VI) [illegible] is actively absorbed by plants (Shrift and U[illegible] Ulrich and Shrift, 1968) along the same tra[illegible] as SO_4^{2-} (Epstein, 1955). Once within the p[illegible] moves unchanged in the xylem stream until it re[illegible] leaves (Asher et al., 1977). Selenate is reduced to [illegible] in the leaf and then incorporated into various [illegible] seleno-compounds (Brown and Shrift, 1982). Since the site of Se(VI) reduction and subsequent incorp[illegible] into organic compounds is in the leaf, this may [illegible] why the vegetative portion of the plants tested had higher Se concentrations than the other plant parts. S[illegible] translocation of organic seleno-compounds [illegible] phloem may be low and perhaps accounts [illegible] Se concentrations found in the tomato fruit [illegible] grain. A specific fractionation of Se comp[illegible] the plant was not performed in this experi[illegible]

Results from the second experiment with [illegible] soils demonstrate the influence of soil prope[illegible] soluble salts can exert on Se accumulation b[illegible] observed in the first study, Se was accumulated [illegible] in proportion to the amount of Se(VI) added [illegible] However, there was a great difference in [illegible] alfalfa among the five soils tested (Table [illegible] grown in the Ciervo, Lost Hills, and Panhill [illegible] 3 mg Se kg^{-1} treatment level accumulated Se [illegible] ly high concentrations (>900 mg Se kg^{-1}) [illegible] grown in the Lethent soil had much lower co[illegible] of total Se (<100 mg Se kg^{-1}).

Alfalfa dry matter production of both roo[illegible] was influenced by Se accumulation and [illegible] negative effect of Se on plant growth (Ta[illegible] vegetative portion of the alfalfa consistently acc[illegible] Se to higher concentrations than the roots and [illegible] respondingly greater reduction in yield. S[illegible] toxicity, although not generally observed [illegible] (NRC, 1976), is probably caused by the substitution [illegible] Se for S in essential organic compounds. T[illegible] ment can lead to a disruption of normal bioc[illegible] tions and enzyme function (Anderson and S[illegible]

A large accumulation of Se and an acc[illegible] growth reduction was not observed for the L[illegible] Panoche soils (Tables 3 and 4). This response [illegible] likely due to the high levels of soluble S in the [illegible] tion (Table 1). Epstein (1955) reported that Se(VI) [illegible] SO_4^{2-} compete for uptake by the plant. Thus, the presence of abundant SO_4^{2-} in the soil solution preve[illegible] cumulation of Se by the alfalfa (Fig. 1). The [illegible] high level of soluble SO_4^{2-} in the Panoche soil may [illegible] have reduced the Se concentration in the barley, beet, [illegible] tomato compared to what the plant Se co[illegible]

Table 2. Effect of added Se(VI) on Se accumulation by barley, beet, and tomato.

Crop	Se(VI) added (mg kg^{-1}) 0	0.5	1.5	LSD (0.05)
	mg Se kg^{-1}			
Barley				
Leaves	0.2	8.3	35.6	7.9
Grain	0.2	7.0	22.0	2.6
LSD (0.05)	0.1	1.8	10.9	
Beet				
Leaves	0.09	7.7	34.8	8.6
Root	0.05	4.4	16.8	6.6
LSD (0.05)	0.08	1.9	12.3	
Tomato				
Leaves	0.9	27.8	76.8	8.7
Stems	0.5	6.0	13.8	1.3
Fruit	0.1	4.0	12.3	0.5
LSD (0.05)	0.5	3.8	7.9	

Table 3. Alfalfa shoot and root Se concentrations in five soils with added Se(VI).

Se(VI) added (mg Se kg⁻¹)	0				0.5				1.5				3.0			
	Harvest, mg Se kg⁻¹															
Soil series	1	2	3	Root	1	2	3	Root	1	2	3	Root	1	2	3	Root
[illegible]	0.1A†	0.2A	0.8C		7.6A	7.8A	8.8A		24.4A	25.5A	21.7AB					
[illegible]	1.7B	1.3B	0.8C	0.6A	10.5A	9.3A	6.8A	3.4A	29.9A	24.7A	12.3A	9.1A	78.2A	54.6A	27.5A	20.6
[illegible]	1.5B	1.3B	0.6BC	0.3A	166.2B	68.9C	8.9A	13.6B	616.8B	307.4B	52.3BC	51.9B	943.5B	980.2B	919.8B	XX‡
[illegible]	0.7AB	1.0B	0.2AB	0.2A	203.0B	38.8B	6.5A	11.1B	725.7B	507.3B	143.6C	107.4C	1087.1B	3184.8B	XX	XX
[illegible]	0.9AB	1.1B	0.4A	0.5A	184.7B	85.0C	19.1B	21.5C	755.3B	419.4B	213.2C	111.2C	1116.4B	1130.6B	1074.1B	XX

†Values followed with the same letter within a column are not significantly different ($p < 0.05$), Duncan's multiple range test of log-transformed means.
‡XX = plants died or unable to recover.

Table 4. Dry matter production of alfalfa shoots and roots grown in five soils with added Se(VI).

Soil series and harvest	Se(VI) added (mg kg⁻¹) 0	0.5	1.5	3.0	LSD (0.05)
	g				
[illegible]	10.9	8.0	1.9	0.2	1.2
[illegible]	11.2	11.4	5.2	0.1	1.9
[illegible]	9.2	8.5	6.2	XX†	1.9
[illegible]	6.7	6.5	2.3	XX	1.8
[illegible]	10.3	10.4	10.5	10.6	2.1
[illegible]	11.7	12.0	12.2	12.8	1.7
[illegible]	11.6	10.9	10.8	12.2	1.4
[illegible]	7.0	7.0	6.7	8.7	2.6
[illegible]	6.3	6.5	4.2	0.8	1.5
[illegible]	9.2	9.0	6.6	0.4	3.4
[illegible]	3.4	4.1	3.1	XX	3.9
[illegible]	3.8	3.8	1.8	XX	3.3
[illegible]	9.8	9.0	4.3	1.0	1.3
[illegible]	11.3	12.6	8.4	1.1	1.4
[illegible]	10.4	10.9	8.1	0.4	0.9
[illegible]	6.4	6.5	4.0	XX	1.7
[illegible]	12.5	11.3	11.4		1.5
[illegible]	13.1	12.3	11.3		3.5
[illegible]	9.7	7.9	7.5		3.9

†XX = plants died or unable to recover.

[illegible] have been had the plants been grown in a low-SO_4^{2-} [illegible]. Antagonistic interactions between Se(VI) and SO_4^{2-} [illegible] first observed by Hurd-Karrer (1938) who found that [illegible] either elemental S or gypsum could reduce plant [illegible] of Se from soils. Since this early discovery, several [illegible]earchers have noted this antagonistic relationship [illegible]el-Nielsen, 1973; Smith and Watkinson, 1984).

CONCLUSIONS

The uptake of Se(VI) by the plants tested was proportional to the concentration of Se(VI) added to the soil. Alfalfa, barley, beet, and tomato were all capable of accumulating Se to concentrations potentially harmful to [illegible] consuming these products. Barley, beet, and [illegible] all accumulated Se in lower concentrations in the [illegible] portion compared to the generally inedible portion. [illegible] accumulated Se to very high concentrations and [illegible] accompanying yield reduction was found. The [illegible] of soluble SO_4^{2-} in the soil significantly reduced [illegible] accumulation by alfalfa.

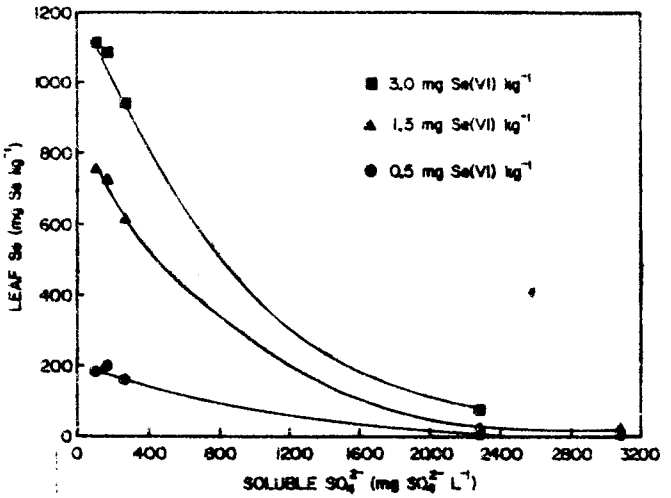

Fig. 1. The effect of soluble SO_4^{2-} in soil on Se accumulation by alfalfa shoots at three concentrations of added Se(VI).

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Disposal of Septic Tank Effluent in Calcareous Sands

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ABSTRACT

Perth, Western Australia, has 430 000 households with septic tanks discharging through sandy soils into the groundwater, which is pumped for domestic irrigation and public water supply. This study investigated the suitability of calcareous sands (Xeropsamment), one of Perth's major soil types, for treatment of septic tank effluent. Calcareous sands adjacent and below two septic tank systems were sampled to a depth of 8 m and the soil pH, soil N, and soil P contents were measured. The soil solution was sampled by an immiscible displacement technique and analyzed for N and P. Most of the NH_4-N in the effluent was oxidized to NO_3-N in the unsaturated zone just below the slime layer. Nitrate (NO_3) was present in the soil solution up to a concentration of 50 mg L^{-1} down to the maximum depth sampled of 8 m. The acidity produced during nitrification of the NH_4 dissolved carbonates from the soil changing the soil pH. Below one system, the carbonates were completely removed from the first 4 m of soil lowering soil pH from 9.5 to 5.2. The NO_3 in the soil solution was used to monitor the effluent flow pattern, which below one system had significant lateral flow indicating development of preferred flow paths. The soil P was increased by sorption and precipitation of P from the soil solution until it reached an equilibrium. At equilibrium the soil solution P was at the same concentration as in the effluent and the P sorbed on the soil was at a maximum for that concentration. Further down the profile where the sorbed soil P was not at its maximum, all the P was sorbed from the soil solution in a vertical distance of 0.5 m. The suitability of calcareous sands and limestone areas for acidic waste disposal may be limited by rapid dissolution of carbonate and the consequent release of previously sorbed P. Monitoring of effluent disposal in these calcareous soils is made more difficult by the development of preferred flow paths.

Additional Index Words: **Phosphorus, Nitrate, Acidic leachate, Preferred flow paths.**

The Western Australian city of Perth has a population of 970 000 of whom 45% have their domestic waste treated by septic tank systems. These systems discharge their effluent into either soakwells or a leach drain, both of which are made from modular concrete [illegible] to respectively form either a circular well or [illegible] open ports in the side walls, but no base.

The city and its metropolitan area are [illegible] coastal plain with an average width of 25 [illegible] the soils are derived from old sand dunes th[illegible] to the coast, and form a major unconfined [illegible] region. The watertable varies from 50 m b[illegible] level to the surface where freshwater lakes [illegible] 1981). There are three major soil types on th[illegible] (FAO, 1974); calcaric regosols (Xeropsamm[illegible] Quindalup dune system, which form the pres[illegible] dystric regosols (Xeric Quartzipsamments) [illegible] Spearwood dune system; and further inland [illegible] zols (Haplorthods) from the Bassendean [illegible] (McArthur and Bettenay, 1974). Although [illegible] Perth's population is housed on the extensive [illegible] and Spearwood sands, there is an increasing [illegible] coastal housing development on the Quin[illegible] The Quindalup sands are unconsolidated [illegible] sands with a wide range of $CaCO_3$ content [illegible] of comminuted shell fragments. The presence [illegible] has often been considered as one means of [illegible] PO_4 retention of sandy soils receiving effluent [illegible] tic tanks or sewage treatment plants (Bouwer, [illegible] Chowdhry, 1977).

The septic tank system for effluent disposal [illegible] Bassendean and neutral Spearwood dune soil[illegible] described by Whelan and Barrow (1984a, b). [illegible] tive of this study was to determine the suitability of [illegible] CO_3 unconsolidated sand for septic tank effl[illegible] disposal.

METHODS AND MATERIALS

Soil Type

Calcaric regosols (Xeropsamments) were selected for the study. These soils are deep, coarse sands with 97% of the soil particles in the 2.0- to 0.2-mm size range. These soils [illegible] to 700 g kg^{-1} of $CaCO_3$, a water pH of 9.2, an organic surface horizon of 0.02 to 0.1 m thick, and cemented soil material [illegible]

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