JOURNAL OF PLANT NUTRITION, 22(9), 1443–1450 (1999)

Effect of Saline Irrigation Water Composition on Selenium Accumulation by Wheat

Catherine M. Grieve, Donald L. Suarez, and Michael C. Shannon

USDA-ARS, U.S. Salinity Laboratory, 450 W. Big Springs Road, Riverside, CA 92507

ABSTRACT

Trace amounts of selenium (Se) are essential for animal and human nutrition. However, the optimum concentration range is very narrow and outside of this range deficiencies or toxicities can occur. Potentially harmful levels of Se in soils and irrigation waters have been reported in regions where salinity is also a hazard. This study was conducted to determine the effects of irrigation water composition and salinity level on Se accumulation in leaves and grain of spring wheat (*Triticum aestivum* L. cv. 'Yecora Rojo'). Plants were grown in greenhouse sand cultures and irrigated with complete nutrient solution. Salinity treatments were initiated 4 days after planting by irrigating the seedlings with either chloride-dominated waters or with waters containing both chloride and sulfate salts. Compositions of the mixed salt waters were designed to simulate saline drainage waters commonly present in the San Joaquin Valley of California. The experimental design was a randomized complete block with two salinity types (Cl^- or mixed salts), eight salinity levels (osmotic potentials=0.07, 0 .16, 0.21, 0.30. 0.36, 0.44, 0.52, and 0.63 MPa), and three replications. Four weeks after planting, Se (1 mg L^{-1} as sodium selenate) was added to all irrigation waters. In the chloride system, the molar ratio of SO_4^{2-}:SeO_4^{2-} was approximately 110 across all salinity levels, whereas in the mixed salt system, the SO_4^{2-}:SeO_4^{2-} ratio in solution increased from about 300 to 4,700 as salinity increased. Selenium concentration was determined in fully-expanded flag leaf blades and grain. Salinity type, and to a lesser extent, salinity affected Se accumulation. In the Cl^--system, wheat accumulated Se to levels that may be potentially harmful to livestock and humans, e.g., blade-Se ranged from 435 to 295 mg kg^{-1} dry wt; grain-Se ranged from 81 to 54 mg kg^{-1} dry wt. Under the saline conditions of the mixed salt system, the inhibition of selenium uptake by sulfate reduced both blade- and grain-Se to levels that would minimize the health risk to consumers.

INTRODUCTION

Wheat (*Triticum aestivum* L.) has been rated as one of the most efficient Se-absorbing cereal crops. Hamilton and Beath (1963) measured the Se content in wheat, barley, corn, millet, oats, and rye grown in soil cultures amended with K_2SeO_4 (3 mg Se kg^{-1}). In all cases, the vegetative tissue was a more efficient Se sink than the grain. Selenium levels in wheat were 112 mg kg^{-1} in both seedlings and straw and 81 mg kg^{-1} in grain, whereas Se in the other crops ranged from 18 to 42 mg kg^{-1} in straw and 13 to 22 mg kg^{-1} in grain. Selenium in cereal grain occurs predominately as selenomethionine and concentrates in the protein-rich fractions derived from the outer endosperm (Stephen et al., 1989). Therefore, Se tends to be higher in flour and milling residue (e. g., bran and wheat germ) than in grain. Food processing and preparation may affect the content and availability of Se. Olson et al. (1970) found that the Se concentration in wheat gluten (131 mg kg^{-1}) was over 4-fold higher than the grain (31 mg kg^{-1}) from which it was prepared. However, Se in bread tends to be lower than the initial Se content in flour (Barclay and MacPherson, 1986).

Potentially harmful trace elements such as selenium often are associated with moderate to high levels of soil and water salinity. In parts of the San Joaquin Valley of California, for example, typical saline drainage waters may contain high concentrations (0.5 to 1 mg L^{-1}) of Se as well as Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} (Läuchli, 1993; Deverel et al., 1994). Plant uptake of Se depends on numerous factors including the salinity level and the ion composition of the saline media. The competitive inhibition of plant uptake of SeO_4^{2-} by SO_4^{2-} has been well documented (Hurd-Karrer, 1938; Pratley and McFarland, 1974; Läuchli, 1993), and there have been numerous studies that report significant reductions in Se uptake and accumulation by crops in response to sulfate-dominated salinity as compared with chloride salinity (Mikkelson et al., 1988; Enberg and Wu, 1995). The objective of

TABLE 1. Composition of irrigation waters used for wheat grown in greenhouse sand cultures.

Osmotic Potential (MPa)	EC_i (dSm^{-1})	Salinity Type	Ca	Mg	Na	SO_4	Cl
			-----	-----	mM	-----	-----
-0.07	1.7	Chloride	2.6	1.2	8.1	1.4	7.0
-0.16	3.9		6.8	1.7	18.9	1.4	29.4
-0.21	5.4		10.3	1.8	26.7	1.5	44.7
-0.30	7.5		15.1	3.2	36.3	1.4	66.5
-0.36	9.2		21.8	4.0	44.5	1.4	78.1
-0.44	10.9		24.1	3.5	54.9	1.4	97.8
-0.52	12.8		26.7	4.5	64.7	1.4	115.0
-0.63	15.3		34.5	3.1	78.0	1.3	146.0
-0.06	1.8	Mixed Salt	3.1	1.4	7.9	3.9	3.6
-0.16	4.3		5.9	3.3	29.0	16.0	12.0
-0.21	5.8		6.8	4.5	40.9	21.9	16.5
-0.29	7.5		9.3	7.4	54.7	29.9	23.9
-0.37	9.3		11.2	8.7	72.6	38.4	31.5
-0.43	10.6		12.7	10.8	82.1	43.7	38.8
-0.52	12.4		14.2	12.6	100.0	52.2	49.9
-0.63	14.4		14.9	14.1	121.7	59.3	57.5

this study was to determine Se accumulation in leaves and grain of wheat grown in sand cultures irrigated with either Cl^--salinity or with mixed salt (Cl^-+ SO_4^{2-}) salinity containing 1 mg L^{-1} Se.

MATERIALS AND METHODS

Yecora Rojo wheat was grown in 48 sand tanks in a greenhouse in Riverside, CA. The tanks (1.2 by 0.6 by 0.5 m deep) contained washed sand having an average bulk density of 1.2 Mg m^{-3}. At saturation, the sand had an average volumetric water content of 0.34 m^3 m^{-3}. Seeds were planted on 22 Jan 1998. Twenty-four of the tanks were irrigated with a base nutrient solution (BNS-A) consisting of 4.0 m*M* KNO_3, 1.5 m*M* $MgCl_2$, 5 m*M* NaCl, 1 m*M* Na_2SO_4. The irrigation water base nutrient composition (BNS-B) for the remaining 24 sand tanks was: 4.0 m*M* KNO_3. 1.5 m*M* $MgSO_4$, 1.5 m*M* Na_2SO_4, 3 m*M* NaCl. Micronutrient levels in both solutions were: 0.17 m*M* KH_2PO_4, 50 μ*M* Fe as sodium ferric diethylenetriamine pentaacetate (NaFeDTPA), 23 μ*M* H_3BO_3, 5 μ*M* $MnSO_4$, 0.4 μ*M* $ZnSO_4$, 0.2 μ*M* $CuSO_4$, and 0.1 H_2MoO_4. The solutions were made up in local tap water having a Ca^{2+} concentration of about 2 m*M*. All tanks were irrigated three times daily. Each irrigation cycle continued 15 min until the sand was completely saturated, after which the solution drained into 765 L reservoirs for reuse in the next irrigation. Water lost by evaporation was replenished automatically each day to maintain constant osmotic potentials in the solutions. At seedling emergence three d after planting, salinization was initiated. For the Cl^--dominated system with BNS-A, 8 salinity treatments were imposed by adding NaCl and $CaCl_2$ (2:1 molar ratio) to the irrigation reservoirs. For the 8 treatments of the mixed salt system, solution osmotic potentials, electrical conductivities and composition of the salinizing salts are shown in Table 1. At each salinity level, the Cl^- and mixed salt treatments were isoosmotic. Salinity treatments were brought to the desired levels over five consecutive days to avoid osmotic shock in the seedlings. Thirty d after the completion of salinization, Se (1 mg L^{-1}, 12.7 μM) was added to all irrigation waters as Na_2SeO_4.

Two months after planting, fully-expanded flag leaves were harvested for Se analysis. Plant samples were washed in deionized water, frozen, vacuum-dried, then ground to a fine powder in a Wiley mill. Grain was harvested at maturity, air-dried for 2 months and ground. For tissue Se analysis, the method of Briggs and Crock (1986) was followed: concentrated nitric acid (20 ml) was added to 2 g dried plant material contained in a digestion tubes and heated at 100° for 2 hr, then cooled. Hydrogen peroxide (30%, 10 mL) was added to destroy the organic material. The digestion tubes were allowed to cool and sulfuric acid (18 *N*, 1 mL) was added. The solutions were cooled, transferred to volumetric flasks and brought to volume with hydrochloric acid (6 *N*). The solutions were heated at 90° for 1 hr. The flasks were shaken and Se was determined with an atomic absorption spectrophotometer equipped with a hydride generator.

Statistical analysis of the Se data was performed using SAS release version 6.12 (SAS Institute Inc., 1997).

RESULTS AND DISCUSSION

Selenium accumulation by wheat was strongly influenced by composition of the irrigation waters. In response to chloride-dominated irrigation waters having an electrical conductivity (ECi) of 1.7 dS m^{-1} and a molar ratio of $SO_4^{2-}/SeO_4^{2-} = 110$, flag leaf-Se concentration was 388 mg kg dry wt^{-1} (Figure 1). There was no obvious trend in leaf-Se uptake with increases in Cl^--salinity, except at the highest salinity where leaf-Se was about 40% lower than the mean of the other 7 treatments.

Increases in the concentration of irrigation water-SO_4^{2-} reduced, but did not completely inhibit Se uptake even when the SO_4^{2-}:SeO_4^{2-} ratio in solution was over

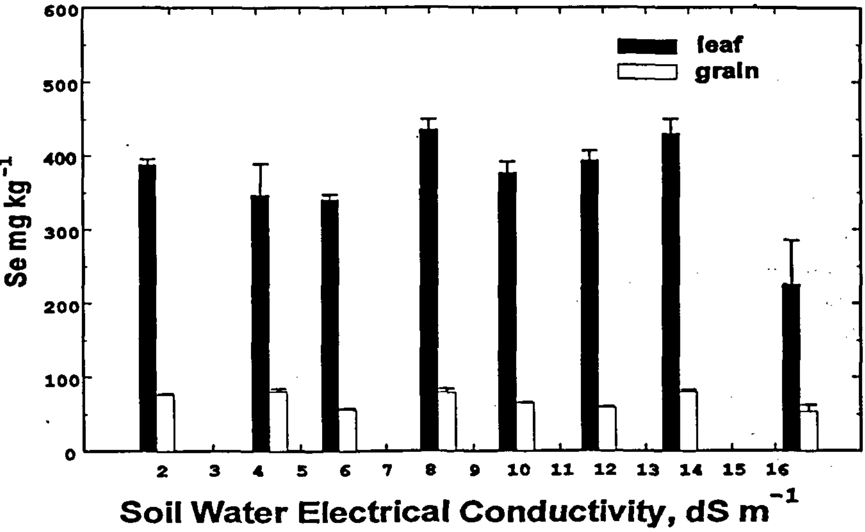

FIGURE 1. Concentration of selenium in leaves and grain of spring wheat (cv. Yecora Rojo) grown under 8 levels of chloride-dominated salinity.

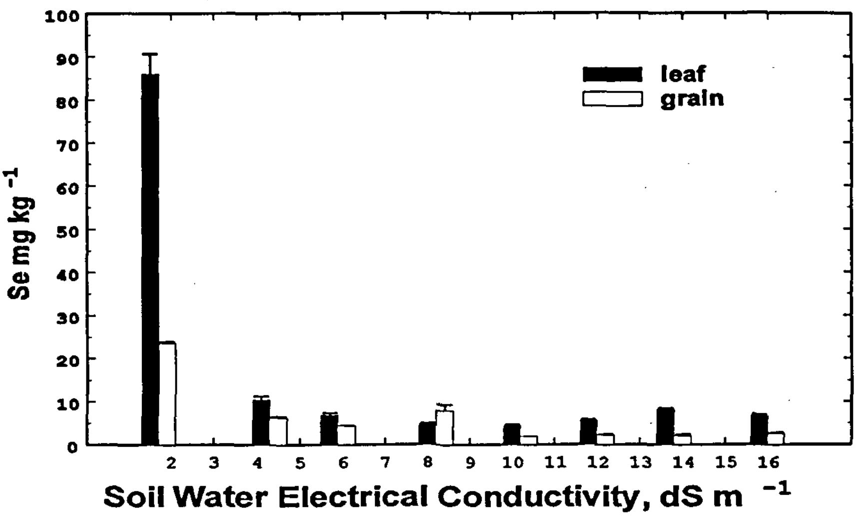

FIGURE 2. Concentration of selenium in leaves and grain of spring wheat (cv. Yecora Rojo) grown under 8 levels of mixed salt (SO_4^{2-} + Cl^-) salinity.

4,600. In response to irrigation with mixed salt solution of with low ECi (1.8 dS m^{-1}), but with SO_4^{2-}:SeO_4^{2-}=307, leaf-Se was only 22% of that obtained from the corresponding low salinity Cl^--treatment (Figure 2). An increase of mixed salt salinity from 1.7 to 4.3 dS m^{-1} resulted in an 8-fold reduction in leaf-Se. Leaf-Se was variable over the salinity range 4.3 to 16 dS m^{-1} and averaged 6.7 mg kg^{-1}.

In general, Se was more actively accumulated by wheat leaves rather than the grain (Figures 1 and 2). This preferential distribution of Se to vegetative tissues rather than to reproductive organs has been reported for numerous crops: melon and tomato (Grattan et al., 1988), cereals (Hamilton and Beath, 1963; Wan et al., 1988). Plants irrigated with Cl^--dominated waters contained 4- to 5-times less Se in the grain (mean=69 mg kg^{-1}) than the leaves and this concentration was not significantly affected by increased salt stress. The lowest mixed salt salinity (ECi=1.8 dS m^{-1}) reduced grain-Se to less than 30% of that in the leaves. With increases in salinity and substrate SO_4^{2-}, the other 7 treatments fell into 2 groups based on significant differences in grain-Se. Grain from saline water treatments ECi=4.3, 5.9, and 8.2 dS m^{-1} and SO_4^{2-}:SeO_4^{2-} ratios<2400 contained more than twice as much Se (mean=5.4 mg kg^{-1}) as grain from the four highest salinity treatments with SO_4^{2-}:SeO_4^{2-} ratios ranging from 3,000 to 4,670.

CONCLUSIONS

These findings have important implications for wheat production in saline-seleniferous regions in that wheat is capable of accumulating levels of Se that are potentially harmful to humans and livestock. The magnitude of selenium uptake by wheat depends on many environmental factors, including the composition of the external media on which it is grown (Hurd-Karrer, 1938; Pratley and McFarlane, 1974; Läuchli, 1993). In the present experiment, grain-Se in plants irrigated with Cl^- dominated saline waters contaminated with 1 mg L^{-1} Se was so high that the product would be unsuitable for livestock unless mixed with Se-free grain. The National Research Council (1980) reported that animals that consume grain containing 5 to 40 mg Se kg^{-1} over a period of several weeks may exhibit symptoms of chronic selenosis which is characterized by liver cirrhosis, hoof malformations, loss of hair, emaciation.

Increasing levels of substrate SO_4^{2-} markedly decreased Se bioaccumulation in wheat grain to concentrations that are undoubtedly safe, even beneficial, for humans according to current standards and expected daily consumption of wheat products (National Research Council, 1983; Valoppi and Tanji, 1988).

ACKNOWLEDGMENTS

The authors are indebted to Jennifer Hopper for selenium analysis and to James A. Poss for statistical analysis.

REFERENCES

Barclay, M.N. and A. MacPherson. 1986. Selenium content of wheat flour used in the UK. J. Sci. Food Agric. 37:1133-1138.

Briggs, P.H. and J.G. Crock. 1986. Automated determination of total selenium in rocks, soils, and plants. U.S. Department of Interior, Geological Survey. Report 86-40.

Deverel, S.J., J.L. Fio, and N.M. Dubrovsky. 1994. Distribution and mobility of selenium in groundwater in the western San Joaquin Valley of California. pp. 157-183. Marcel Dekker Inc., New York, NY.

Enberg, A. and L. Wu. 1995. Selenium assimilation and differential response to elevated sulfate and chloride salt concentrations in two saltgrass ecotypes. Ecotox. Environ. Safety 32:171-178.

Grattan, S.R., C. Shennan, D.M. May, and R.G. Burau. 1988. Effect of saline drainage water on yield and accumulation of selenium in melon and tomato. pp. 41-46. In: K.K. Tanji (ed.), Selenium contents in animal and human food crops grown in California. DANR Publ. 3330. University of California, Davis, CA.

Hamilton, J.W. and O.A. Beath. 1963. Selenium uptake and conversion by certain crop plants. Agron. J. 55:528-531.

Hurd-Karrer, A.M. 1938. Relation of sulphate to selenium absorption by plants. Am. J. Bot. 25:666-675.

Läuchli, A. 1993. Selenium in plants: Uptake, functions, and environmental toxicity. Bot. Acta 106:455-468.

Mikkelsen, R.L., A.L. Page, and G.H. Haghnia. 1988. Effect of salinity and its composition on the accumulation of selenium by alfalfa. Plant Soil 107:63-67.

National Research Council. 1980. *Mineral Tolerance of Domestic Animals*. Selenium. pp. 392-420. National Academy of Press, Washington, DC.

National Research Council. 1983. Selenium in Nutrition. p. 174. National Academy of Press, Washington, DC.

Olson, O.E., E.J. Novacek, E.I. Whitehead, and I.S. Palmer. 1970. Investigations on selenium in wheat. Phytochemistry 9:1181-1188.

Pratley, J.E. and J.D. McFarlane. 1974. The effect of sulphate on the selenium content in pasture plants. Aust. J. Exp. Agric. Animal Husb. 14:533-538.

SAS Institute, Inc. 1997. SAS/STAT Software. Changes and Enhancements through Release 6.12. Statistical Analysis System Institute, Cary, NC.

Stephen, R.C., D.J. Saville, and J.H. Watkinson. 1989. The effects of sodium selenate applications on growth and selenium concentration in wheat. New Zealand J. Crop Hort. Sci. 17:229-237.

Valoppi, L. and K. Tanji. 1988. Are the selenium levels in food crops and waters of concern? pp. 97-102. In: K.K. Tanji (ed.), Selenium Contents in Animal and Human Food Crops Grown in California. DANR Publ. 3330, University of California, Davis, CA.

Wan, H.F., R.L. Mikkelsen, and A.L. Page. 1988. Selenium uptake by some agricultural crops from Central California soils. J. Environ. Qual. 17:269-272.