the clear plastic rowcover will cost about $348/acre (based on $.04/linear ft and 8712 ft of row). The cost for the wire hoops necessary to support the rowcovers is about $458/acre (2178 hoops @ $0.21/hoop). The additional labor will approach $192 per acre (4 people @ $6/h for 8 h). The total cost for this technique is about $1000/acre. The return per acre based on the total marketable yield of the rowcover treatments is shown in Table 2. The profitability of the system will be determined by the price for the early season tomatoes. Based on the results of this 1-year trial, it would seem that an early season price of about $0.60/lb would be the break-even point, assuming that later season prices are about $0.20/lb. Actual wholesale prices received for 1993 and 1994 averaged $0.46 and 0.71, respectively, for tomatoes from July 3 through July 25, the time considered early in this experiment (R.J. Battaglia, N.J. Agricultural Statistics Service, personal communication). Prices fell to about $0.20/lb for most of the rest of the season before rising again in September. Based on these prices, it seems that using rowcovers is a very cost-effective means to improve early season yield.

This experiment clearly demonstrates that rowcovers, if used at the proper time, can increase the early yield of tomatoes. Their effectiveness, however, seems to be related to allowing earlier planting rather than accelerating the ripening of later planted tomatoes. The higher temperatures under rowcovers may decrease the yield in plantings made at traditional times. The traditional planting date for tomatoes in a particular area may indicate when rowcovers should be removed. Fall bedding seems to be a viable option for growers interested in maximizing the ability to plant very early in the spring.

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Response of Bean and Broccoli to High-sulfate Irrigation Water

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ADDITIONAL INDEX WORDS. *Brassica oleracea* L., *Phaseolus vulgaris*, electrical conductivity

SUMMARY. Groundwater contaminated with sulfate (SO_4^{2-}) at concentrations greater than allowed for drinking water may be suitable for irrigation. Our objectives were to determine the growth response and mineral uptake of two vegetables grown with high SO_4^{2-} irrigation water. Bean (*Phaseolus vulgaris*) and broccoli (*Brassica oleracea* L.) were grown in a calcareous sandy loam soil irrigated with water containing 175 to 1743 mg SO_4^{2-}/L. Plants were harvested and growth was measured at 4, 8, or 12 weeks. Soil paste and dried ground plant tissue extracts were analyzed for elemental composition at each harvest by inductively coupled plasma spectroscopy. Bean shoot dry mass decreased as SO_4^{2-} concentration increased. Although pod number at 4 weeks decreased as SO_4^{2-} concentration increased, pod number at 12 weeks was not affected by irrigation treatments. Broccoli growth was not affected by increasing SO_4^{2-} concentration at any of the harvest dates, although head diameter decreased as SO_4^{2-} increased. Magnesium, sodium, and sulfur accumulated in shoot tissue (leaves and stems) of both species in proportion to their concentration in the irrigation water. Soil Na and electrical conductivity levels increased as SO_4^{2-} concentration increased even with a 20% leaching fraction. These results suggest that bean and broccoli can be successfully grown with high-SO_4^{2-} irrigation water.

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High concentrations of sulfate are found in the groundwater near the Kennecott copper mine, Copperton, Utah. In many of the test wells near the mine site, SO_4^{2-} concentration exceeds the secondary drinking water standard of 250 mg SO_4^{2-}/L set by the U.S. Environmental Protection Agency (EPA) and in some wells exceeds Utah's primary drinking water standard of 1000 mg SO_4^{2-}/L (Sverdrup Corp., 1993). With increasing urban development in this area of Salt Lake County, this water could be used to irrigate lawns and vegetable gardens. Since many vegetables require high-quality irrigation water for maximal plant productivity, our goal was to evaluate the potential for using this high-SO_4^{2-} groundwater to irrigate vegetables.

Working in the arid western United States, Scofield (1936) reported that water containing <336 mg SO_4^{2-}/L could be considered good-quality irrigation water, while water with a SO_4^{2-} concentration >960 mg·L^{-1} was not suitable for irrigation. However, soil type, climatic effects, and water source interact and influence plant growth; therefore, irrigation water standards generally apply to specific conditions. Decisions regarding the use of a particular water are best made based on field or greenhouse trials under site-specific conditions.

In soils of arid regions, sulfate concentration in the soil solution is often governed by gypsum and $CaCO_3$ solubility. Adding SO_4^{2-} to highly calcareous soils may cause gypsum to precipitate. Gypsum buffers the SO_4^{2-} concentration of the soil water. Sulfate levels in high SO_4^{2-} irrigation waters may be reduced by gypsum precipitation upon contact with the soil. However, SO_4^{2-} levels cannot drop below gypsum saturation and crops must contend with elevated soil salinity (Suarez and van Genuchten, 1981). Elevated SO_4^{2-} levels may persist even when the soil is over-irrigated to facilitate leaching due to the release of SO_4^{2-} from gypsum (Papadopoulos, 1984).

Few studies have been conducted to test the effects of high sulfate-containing waters on horticultural plant growth. Plants vary in their tolerance to SO_4^{2-} and the accumulation of sulfur-containing compounds in plant tissues (Marschner, 1995). In general, the sulfur requirement of legumes is less than that of the Cruciferae. In the mustards, concentration of mustard oils but not plant yield was shown to be closely related to sulfate supply (Marquard et al., 1968). This increase may enhance the flavor of some plants while adversely affecting flavor in others. In a greenhouse study, fresh yield of tomato and eggplant was reduced when irrigated with water containing high SO_4^{2-} (Papadopoulos, 1986). Yield of bell pepper were not affected by SO_4^{2-} levels in that study, but fruit quality deteriorated as concentration increased.

The objectives of this study were to evaluate the effects of high sulfate irrigation waters on the growth and accumulation of minerals in tissues of bean (SO_4^{2-} excluding, natrophobic) and broccoli (SO_4^{2-} accumulating, natrophilic) plants.

Materials and methods

Sulfate-contaminated groundwater was collected from test wells near the Kennecott Copper Mine in Copperton, Utah (20 miles southwest of Salt Lake City). The Kennecott Corporation, the EPA, and the Utah Department of Environmental Quality (UDEQ) agreed during consent decree negotiations to perform as focused feasibility study to evaluate possible response alternatives for addressing elevated sulfate in groundwater downstream from the copper mine (Sverdrup, 1993). The study reported here was funded to evaluate if elevated SO_4^{2-} levels in these well waters would adversely affect plant performance. The test wells, located on Kennecott land adjacent to the copper mine, were within five miles of each other. Sulfate concentrations in the selected wells were 175, 646, 862, and 1743 mg·L^{-1}. While attempts were made to minimize the variation of other elements in these waters, the concentration of salts other than sulfate varied from well to well (Table 1). This altered the electrical conductivity (EC) and the B, Ca, Mg, Na, and Zn concentrations. However, concentrations of these elements were well below published crop tolerance values (Ayers and Wescott, 1985).

Bean ('Blue Lake Bush') and broccoli ('Premium Crop') were grown in 8-L pots containing a Kidman fine sandy loam soil (coarse-loamy, mixed, mesic Calcic Haploxeroll) collected from an undisturbed site near one of the wells. The Kidman series is composed of 64% sand, 23% silt, and 13% clay and is a common agricultural soil in the area. Soluble salt concentrations of the saturated paste extract for this soil are listed in Table 1. Pots were filled with air-dried, well-mixed, sieved soil. Monocalcium phosphate, equivalent to 600 kg·ha^{-1} P, was added to each pot before planting. Potassium nitrate was added at each irrigation to supply 100 mg·L^{-1} of N and 270 mg·L^{-1} of K. Micronutrients in the soil were deemed adequate to meet the plant requirements for the duration of the study. The experiment was arranged in a randomized complete-block design with six replications.

Beans and broccoli were seeded into pots on 21 Apr. 1995 at five seeds per pot and irrigated immediately with the appropriate SO_4^{2-} water. Plants were grown in the greenhouse at 26/18 °C day/night temperatures with a

Table 1. Concentration of selected elements in soil saturation paste extract and groundwater from different test wells used for irrigating garden vegetables.

Treatment	pH	EC (dS·m^{-1})	B	Ca	Cl	Mg	Na	S	Zn	HCO_3 (meq·L^{-1})
			(mg·L^{-1})							
Water 1	7.1	1.18	<0.1	149	142	41	42	58	0.18	5.0
Water 2	7.1	1.80	<0.1	251	148	76	57	216	0.35	3.6
Water 3	7.2	2.70	0.39	238	237	98	245	288	0.55	5.7
Water 4	7.1	3.60	<0.1	554	239	170	120	582	0.85	4.6
Soil[z]	6.1	0.43	<0.1	35	39	14	23	21	---	1.6

[z]Soil was a Kidman fine sandy loam

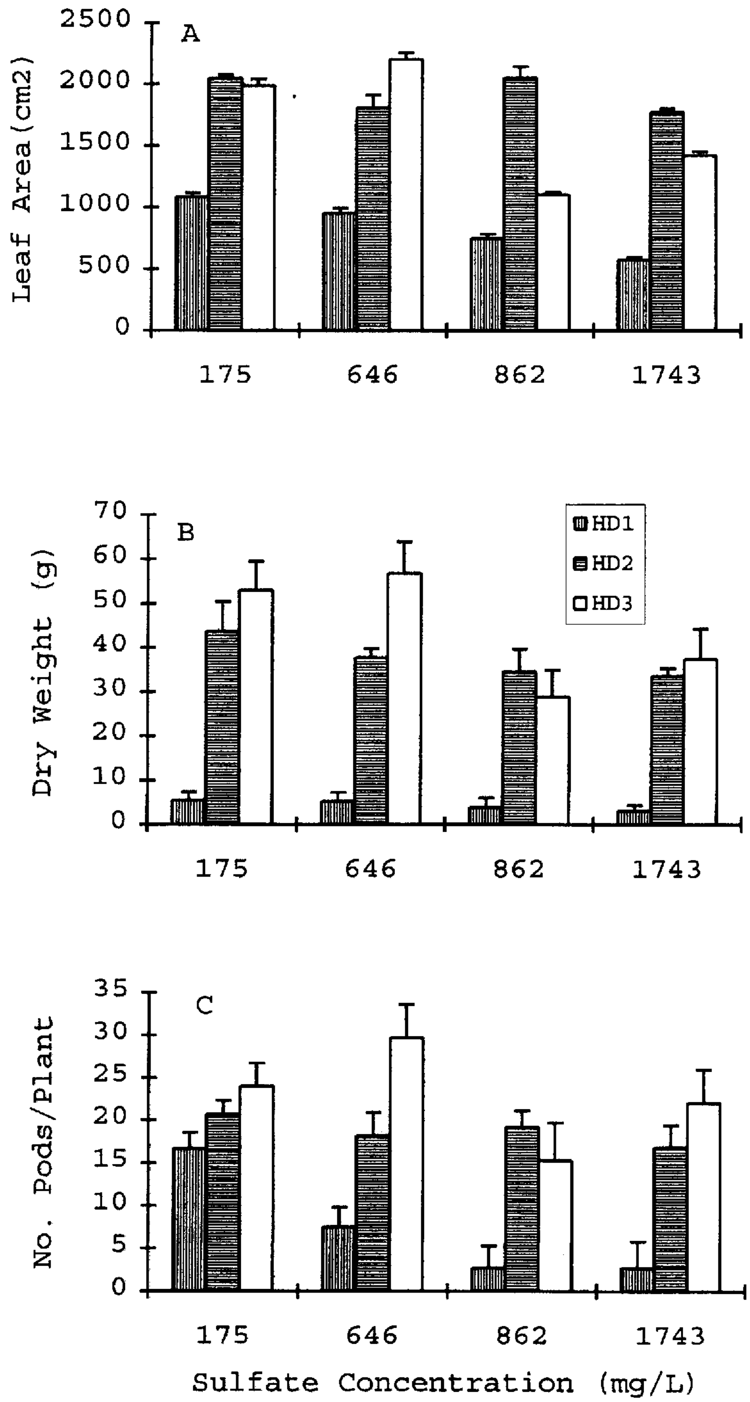

Fig. 1. Bean leaf area (A), dry mass (B), and pod number (C) as influenced by irrigation water sulfate concentration and harvest date (HD1, HD2, or HD3). Vertical bars represent SE.

15-h photoperiod. Daylength was extended to 15 h using artificial lights during the first 4 weeks of the study. Initially, plants were irrigated every 4 to 5 d. As water demand increased, plants were irrigated daily to minimize water stress effects. Sufficient water was applied at each irrigation to supply a 20% leaching fraction. Plants were destructively harvested 4, 8, or 12 weeks after emergence. After the first harvest, plants were thinned to one per pot. Leaf area (model 3100; LI-COR, Lincoln, Nebr.), bean pod number, and dry mass of leaves, stems, and heads or pods were measured at each harvest. Broccoli head diameter was measured at the final harvest. Due to poor germination of the beans, seeds from a different source were replanted on 4 June 1995 and grown as described previously.

At each harvest, the soil-saturated paste extract for each treatment was analyzed for elemental composition, pH, and EC. If available, leaf, stem, and reproductive tissues were oven dried for 48 h at 80 °C before analysis. Plant tissues were ground, digested in nitric acid, refluxed with HCl (EPA method 3050), and analyzed for S and other elements by inductively coupled plasma spectroscopy (model 9000; Jarrel-Ash) (EPA method #6010). Data were analyzed using a split-plot design for the main effect of irrigation water and the subplot of harvest dates, tissues, and their interactions. Means were separated when ANOVA showed significant differences within a species. In addition, the sums of squares were partitioned using single-degree-of-freedom linear, quadratic, and residual contrasts. No statistical comparisons were made between plant species.

Results and discussion

PLANT GROWTH. There was a significant linear ($p = 0.05$) decrease in bean leaf area with increasing SO_4^{2-} concentrations in the irrigation water at the first and third harvests but not the second harvest (Fig. 1A). This difference was due to slow initial growth in treatments receiving the high-SO_4^{2-} water and early senescence of those treatments as plants matured. Within the different SO_4^{2-} treatments, bean leaf area increased with time until the second harvest, then remained the same or declined at the third harvest. Leaf senescence, attributed to high salt concentrations in the water (Table 1), was responsible for the decrease in leaf area in 862 and 1743 $mg \cdot L^{-1}$ SO_4^{2-} at the third harvest. Few leaves senesced in the irrigation waters containing lower SO_4^{2-} concentrations.

Shoot dry mass increased over the study period for the 175, 646, and 1743 $mg \cdot L^{-1}$ SO_4^{2-} (Fig. 1B). In general, the greatest dry mass was found in bean plants receiving the lowest SO_4^{2-} concentrations. However, in the 862-$mg \cdot L^{-1}$ treatment, shoot dry mass increased until harvest two. The lack of an increase in dry mass at harvest three was due in part to elevated Na levels in this water that hastened leaf senescence and abscission and led to the reduced leaf area noted at the final harvest. Beans are known to be sensitive to Na, which reduces leaf area and shoot dry mass (Marschner, 1995).

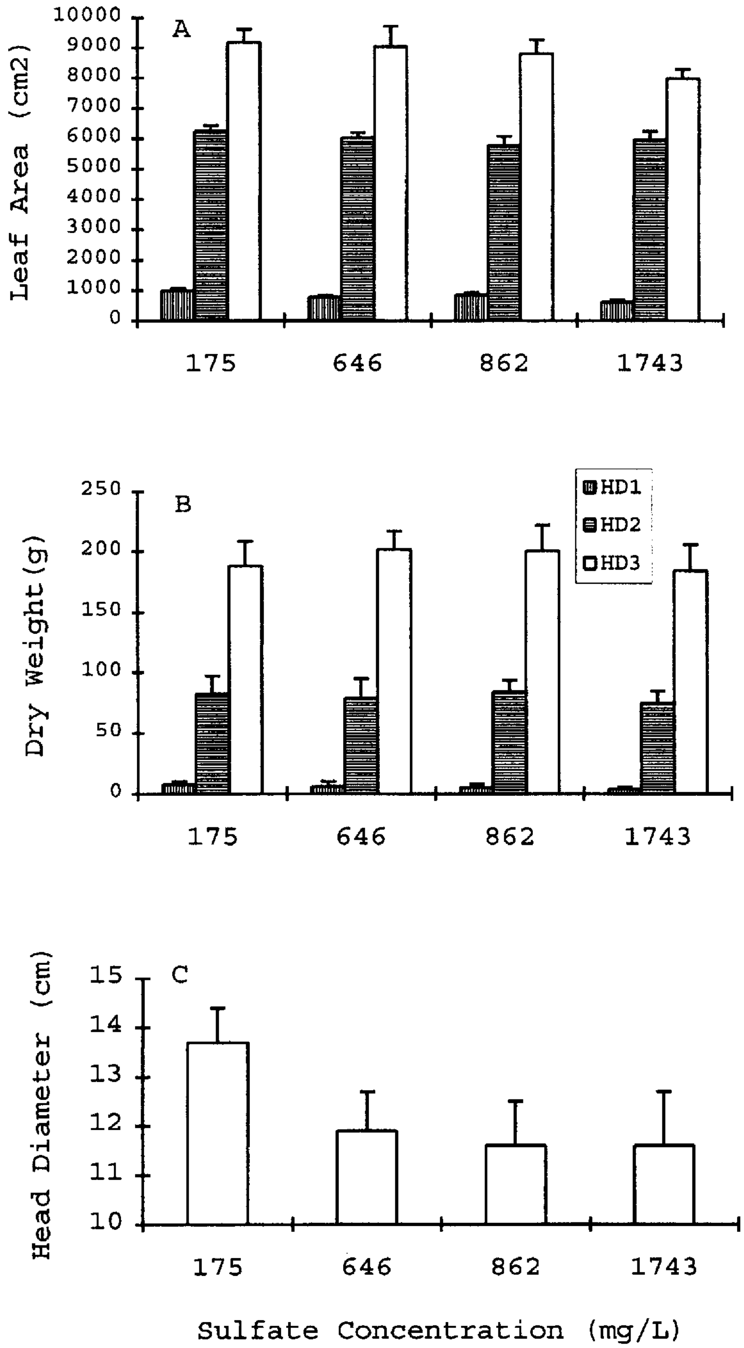

Fig. 2. Broccoli leaf area (A), dry mass (B), and head diameter (C) as influenced by irrigation water sulfate concentration and harvest date (HD1, HD2, or HD3). Vertical bars represent SE.

While there were significant differences in bean shoot dry mass between the SO_4^{2-} concentrations used, a similar proportion of dry mass was partitioned to leaves, stems, and pods in all treatments (data not shown).

Sulfate concentration had a significant effect on early (4 week) and final (12 week) pod number (Fig. 1C). Early pod number decreased quadratically as SO_4^{2-} concentration increased (Fig. 1C). Beans irrigated with 175 $mg \cdot L^{-1}$ SO_4^{2-} had two to six times as many pods as those plants irrigated with waters containing 646 $mg \cdot L^{-1}$ SO_4^{2-} or more at the first harvest. By the second harvest, there was no difference in pod number among the treatments. Over time, pod set increased in plants irrigated with 175, 646, or 1743 $mg \cdot L^{-1}$ SO_4^{2-} but decreased when irrigated with 862 $mg \cdot L^{-1}$ SO_4^{2-}. While the reduction in final pod number in the 862 $mg \cdot L^{-1}$ SO_4^{2-} at harvest three was not significantly different from harvest two, the 20% reduction was due in part to elevated Na levels in this water. Others have noted that, when beans are exposed to increased Na levels, pod numbers decrease (Wagenet et al., 1983).

Increasing SO_4^{2-} levels in irrigation water had no effect on broccoli leaf area or shoot dry mass at any harvest date (Fig. 2 A and B). For all treatments at all harvest dates, a similar proportion of shoot dry mass was partitioned to leaves and stems (data not shown). However, as SO_4^{2-} levels increased, head diameter decreased quadratically (Fig. 2C), although head mass was not affected by the treatments (data not shown). Since brassicas are known sulfur accumulators and more tolerant of saline conditions than beans (Marschner, 1995), their growth should not be adversely influenced by increasing SO_4^{2-} levels in the soil or irrigation water up to the levels used in this study.

PLANT TISSUE. Since there was no significant interaction between water source and harvest date for tissue nutrient concentration, only the main effects for each is presented. Concentrations of Mg, Na, S, and Zn increased in beans and broccoli tissues as SO_4^{2-} concentration in the irrigation water increased (Table 2) because irrigation waters with higher SO_4^{2-} levels had greater amounts of these elements as well (Table 1). Boron levels in plant tissues were highest when treated with 862 mg SO_4^{2-}/L irrigation water, which also had the greatest concentration of this element. Tissue Ca and P levels were not influenced by irrigation water sulfate content.

Tissue levels of the different elements changed over the 12 weeks of growth (Table 3). Concentrations of B, Ca, Na, and S increased while K and P decreased over time in bean tissue as plants were exposed to high SO_4^{2-} irrigation water. In broccoli, the concentrations of B, Ca, Mg, Na, P, and Zn decreased with time. Sulfur and K levels in broccoli tissue did not change during the 12-week growth period. Concentrations of all elements measured in the plant tissues fell within the sufficiency range of plant nutrients (Bennett, 1993).

SOILS. Calcium, Mg, and S levels increased linearly when soils were continually irrigated with waters containing increasing SO_4^{2-} levels (Table 4), although S levels in the soil solution

Table 2. Nutrient concentration in bean and broccoli tissue as a function of irrigation water sulfate concentration.

Sulfate	Tissue dry mass ($mg\cdot kg^{-1}$)							
(mg/L)	B	Ca	K	Mg	Na	P	S	Zn
Bean								
175	19	26922	36986	5047	563	2317	2269	29
646	23	27442	38306	6064	920	2425	4494	34
862	34	26300	37397	6839	2402	2378	6242	36
1743	28	28172	34458	9408	1777	2194	8339	37
Significance	Q^{**}	NS	Q^{*}	L^{**}	Q^{*}	NS	L^{**}	NS
Broccoli								
175	13	15058	50783	3647	2728	2831	958	16
646	14	15772	50094	4086	2559	3089	1080	19
862	31	14819	44311	4386	8587	2961	1125	18
1743	19	14703	47856	5428	3935	3017	1151	19
Significance	Q^{**}	NS	Q^{*}	L^{**}	Q^{**}	NS	L^{**}	L^{*}

^{NS,*,**}Nonsignificant or significant at $P = 0.05$ or 0.01, respectively; L = linear; Q = quadratic from planned contrasts.

Table 3. Nutrient concentration of bean and broccoli tissue as a function of harvest dates.

Harvest	Tissue dry mass ($mg\cdot kg^{-1}$)							
Date	B	Ca	K	Mg	Na	P	S	Zn
Bean								
1	23 a^{z}	20188 a	45033 a	5883 a	654 a	3590 a	4494 a	35 a
2	25 a	26965 a	31279 b	7335 a	1743 b	1881 b	5583 ab	35 a
3	31 b	34475 b	34048 b	7300 a	1849 b	1515 c	5931 b	32 a
Broccoli								
1	21a	17750 a	49981 a	5306 a	5175 a	4031 a	10813 a	27 a
2	21 a	13773 b	47827 a	3827 b	3854 b	2998 b	11235 a	17 b
3	16 b	13742 b	46975 a	4027 b	4327 b	1994 c	10306 a	11 c

^{z}Mean separation in columns by Duncans multiple range test at $P \leq 0.05$.

did not increase in direct proportion to the addition of SO_4^{2-} in the irrigation water. The behavior of the saturation paste Ca and S concentration suggests gypsum precipitation in the soil. When present in the soil, calcium carbonate minerals control Ca concentrations and gypsum controls SO_4^{2-} levels. When Ca and SO_4^{2-} are added with the irrigation water, precipitation of calcium carbonates caused Ca concentrations to decrease over time (data not shown) while permitting SO_4^{2-} levels to increase above the solubility of gypsum in pure water (1500 mg SO_4^{2-}/L).

To test for gypsum control of SO_4^{2-} concentrations, mean Ca, Mg, Na, K, and SO_4^{2-} values in the leachate collected from each treatment, pH, and a CO_2 partial pressure of 0.0003 atm (ambient) were inserted into the MINTEQA2 model (Staff, 1991). The model computed single ion activities and a saturation index for gypsum (Fig. 3). Values near 1.0 strongly suggest the presence of gypsum while values >1.0 indicate supersaturation. In all soils except those irrigated with the 175 mg SO_4^{2-}/L, gypsum saturation or supersaturation was indicated.

In addition, soil Na and EC values increased quadratically as irrigation water SO_4^{2-} concentration increased (Table 4). The highest Na and EC levels occurred in the 862-mg SO_4^{2-}/L irrigation water. The 20% leaching fraction used in this study was ineffective in controlling salinity, which agrees with the findings of Jury et al. (1978), Papadopoulos (1984), and Suarez and van Genuchten (1981).

Table 4. The composition of soil saturation paste as influenced by the sulfate containing irrigation water.

Sulfate	Saturation paste concn ($mg\cdot L^{-1}$)				EC
($mg\cdot L^{-1}$)	Ca	Mg	Na	S	($dS\cdot m^{-1}$)
Bean					
175	289	91	86	212	3.8
646	≥39	133	155	508	4.4
862	341	165	392	592	5.4
1743	514	232	161	741	5.4
Significance	L^{*}	L^{**}	Q^{*}	L^{*}	Q^{*}
Broccoli					
175	321	125	124	184	4.7
646	425	202	138	560	5.8
862	510	203	496	657	6.9
1743	581	319	251	790	6.9
Significance	L^{*}	L^{*}	Q^{*}	L^{**}	Q^{*}

*,**Significant at $P = 0.05$ or 0.01, respectively; L = linear; Q = quadratic from planned contrasts.

This study was initiated to address whether irrigation water with high SO_4^{2-} concentrations could be used to grow garden vegetables. High SO_4^{2-} concentration reduced bean growth and early but not final pod number. Broccoli growth was not significantly affected by any sulfate concentration tested. Tissue S levels increased in bean but not broccoli as irrigation water SO_4^{2-} concentrations

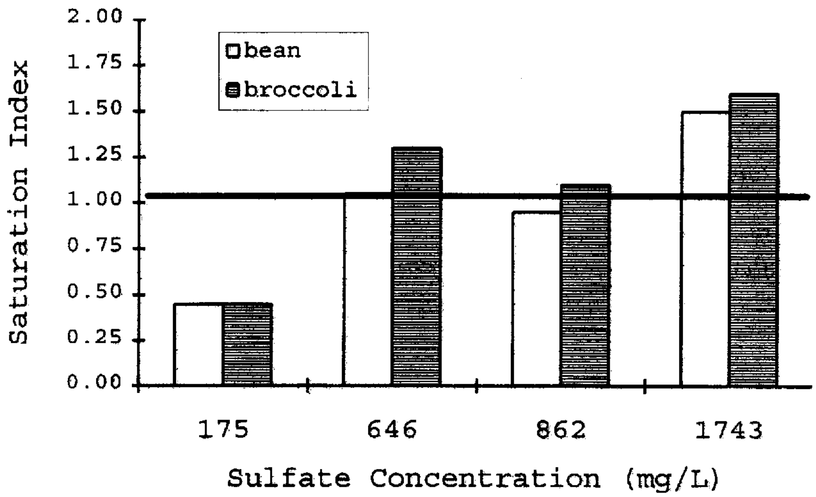

Fig. 3. MINTEQA2 calculated saturation index values for gypsum in saturation paste extracts from soil samples collected after treatment with sulfate containing irrigation water.

increased. Increasing concentrations of Ca and S in the soil suggests that gypsum saturation has been achieved in soils irrigated with waters containing >646 mg SO_4^{2-}/L. Results presented here suggest that bean and broccoli can be successfully grown in the short term using high-SO_4^{2-} waters for irrigation purposes. Further research is needed to determine the response of other vegetable crops to elevated levels of SO_4^{2-} in irrigation water and the long-term effects of using these waters on sulfate and salt accumulation in the soil.

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Critical Comparison of an Accelerometer and a Laser Doppler Vibrometer for Measuring Fruit Firmness

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Additional index words. resonance frequency, phase shift, kiwifruit, Japanese pear, citrus, apple

Summary. To examine the feasibility of using a laser Doppler vibrometer (LDV) for fruit quality evaluation, measurements of firmness derived by this method were compared with those acquired using a contact accelerometer. Apples (*Malus pumila* Miller var. Domestica Schneider 'Fuji'), kiwifruit [*Actinidia deliciosa* (A. Chev.) Liang et Ferguson, 'Hayward'], Japanese pear [*Pyrus pyrifolia* (Burm. f.) Nakai var. Rehd. 'Nijusseiki'], and Hassaku (*Citrus hassaku* Hort. ex Tanaka) were used. Fruit were subjected to sine waves at frequencies from 5 to 2000 Hz at the

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