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SULFATE UPTAKE BY SALINITY-TOLERANT PLANT SPECIES

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ABSTRACT: High soluble-sulfate (SO_4) concentrations affect water quality, soil chemistry, plant sulfur (S) levels, and possibly ruminant-animal health. The objective of this greenhouse pot study was to determine the potential for accumulating high levels of S by tansy mustard (*Descurainia pinnata* (Walt.) Britton), kochia (*Kochia scoparia* L. Schrad.), yellow sweet clover (*Melilotus officinalis* L.), slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners), and sunflower (*Helianthus annuus* L.). Plants were grown on both a Brinegar (fine-loamy Ultic Argixeroll) and Portneuf (coarse silty Durixerollic Calciorthid) soil. Each species received five-SO_4 levels. The saturation extract electrical conductivity (EC) of the cropped soils ranged from 6 to 16 dS/m, while the soluble SO_4 varied from 16 to 200 $mmol_c$/kg soil. Soil solutions were saturated or very nearly saturated with respect to gypsum at the conclusion of each study. Plant dry matter yield, except of grass growing on the non-calcareous soil, was not reduced by SO_4 treatment nor by the sulfate-induced decrease in mole fraction of calcium (Ca)/(sum cations) to values less than 0.10 for kochia and grass. Sulfur concentration in the plants ranged from 2.5 mg/g in grass to 10 mg/g in mustard and for each species was linearly related to the SO_4 treatment and soil-SO_4 activity. Plant SO_4-S values ranged from 70 µg/g in the grass to nearly 900 µg/g in mustard. Total nitrogen (N):organic S was 4.4, 7.5, 11.4, 16.5, and 5.8 for mustard, kochia, clover, grass, and sunflower, respectively. It was concluded that these species could accumulate high levels of S in the above ground tissue.

INTRODUCTION

High sulfate (SO_4) concentrations occur in soils and waters associated with many Cretaceous geological formations in the Prairie Provinces, Northern Great Plains, and Colorado Plateau of North America. In these areas, ground water may contain 30,000 mg SO_4/L (3.1 molar) (Brown et al., 1983). Ruminant animal intake of large amounts of SO_4 and perhaps total S in feed and water, may cause clinical abnormalities including polioencephalomalacia characterized by depression, incoordination, and blindness (Beke and Hironaka, 1990; Dickie et al., 1979; Hamlen et al., 1993). The problem is also observed when feeding high-SO_4 feed supplements (Gooneratne et al., 1989; Gould et al., 1991; Raisbeck, 1982; Sadler et al., 1983). Beke and Hironaka (1990) reported that saline water con- tributed about 20%, grain supplement 20%, and hay 60% to the total dietary S intake of heifers having symptoms of polioencephalomalacia. However, little is known about the potential S uptake by herbage plants. This study reports SO_4 and total S accumulations by five plant species grown in five SO_4 levels in soil.

MATERIAL AND METHODS

Soils: A Brinegar (fine-loamy, mixed, frigid pachic Ultic Argixeroll) soil and Portneuf (coarse, silty, Durixerollic Calciorthid) soil (0-15 cm depth) were used in this greenhouse experiment. The chemical characteristics are shown in Table 1. Four kilograms of air-dry soil was added to 5-L pots and water content maintained between 160 and 260 g/kg water content, corresponding to a matric potential of approximately -50 to -15 kPa, respectively. All pots were irrigated with distilled water except when SO_4 treatments were being applied. The experiments were conducted from March through July at 18 to 25°C air temperatures in the greenhouse. Each plant species was treated as a separate study, because growing periods did not coincide. Upon concluding each study, stubble and roots were removed and the soil from triplicated treatments was combined, mixed, and subsampled for later soil analyses.

Plants: Five salt-tolerant species selected for this study were tansy mustard, kochia, yellow sweet clover, slender wheatgrass, and sunflower. Volunteer mustard seedlings were transplanted from the field to the greenhouse and three plants were grown in each pot. Seeds of other species were germinated in the soil

TABLE 1. Water Content and pH of Saturated Soil Paste and the Electrical Conductivity and Elemental Composition of the Extract.

Soil	Water content	pH	EC	Ca	Mg	Na	K	SO_4	Cl	NO_3	HCO_3
	g/kg	-	dS/m	- - - - - - - -	- - - - - - - -	- - - - - - - -	mmol$_c$/L	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -
Brinegar	305	6.4	1.0	6.4	3.2	0.8	0.4	0.9	0.2	5.7	2.0
Portneuf	293	8.1	3.8	23.5	12.4	5.6	1.1	4.0	5.5	27.0	3.0

pots. Kochia and yellow sweet clover seed were obtained locally. Prior slender wheatgrass seed was obtained from the USDA Plant Materials Center, Bridger, MT. Seed of an oil-type sunflower (Interstate 894) was obtained from Interstate Seed, West Fargo, ND.

Mustard plants were about 45-cm tall and were flowering when harvested 38 days after transplanting. Kochia seedlings were thinned to 10 per pot. They were harvested 54 days after seeding (DAS) when the vegetative plants were about 40-cm high. Clover seedlings were thinned to 25 plants per pot and herbage harvested at 50 and again at 133 DAS when regrowth was about 15-cm tall and plants were beginning to bud. Grass seedlings were thinned to about 50 plants per pot, and clipped at 46 and again at 94 DAS when vegetative plants were about 12-cm high. Sunflower seedlings were thinned to 10 plants per pot, and five plants were harvested at 50 DAS and the other five at 65 DAS when they were 45-cm tall and beginning to bud. Plants were harvested at 3-cm stubble height, dried in forced air at 64°C until dry, ground to pass a 1-mm stainless steel screen using a Wiley Mill and later analyzed.

Treatments: Applications of a 16:7:8:7 (N:P:K:S) fertilizer in 3 g/pot applications were made to meet plant nutrient requirements and to further elevate the base level of available SO_4. The fertilizer was added on DAS as follows: mustard, 31; kochia, 38 and 46; clover, two applications before planting; grass, two applications before planting plus on DAS 52 and 69; and sunflower, 13 and 48 DAS (Table 2).

Sulfate treatments were applied by dissolving SO_4 salts in distilled water and then applied as part of an irrigation. The formulated SO_4-solution contained 25.26 g magnesium sulfate ($MgSO_4$)/L and 3.55 g sodium sulfate (Na_2SO_4)/L, typical of some well waters in northcentral Montana. Sulfate treatments consisted of adding in each application: 0, 47, 94, 141, or 188 mmolc of SO_4 to individual pots. These portions were added on DAS as follows: mustard 20, 31; kochia 27, 38, 42, 46; grass 30, 45; and sunflower 20, 34, 42, and 50. Clover and wheatgrass were planted in soil pots that previously received two SO_4 applications. Wheatgrass then received two additional SO_4 treatments on DAS 30 and 45. The added salts accumulated in the pots because there was no opportunity for drainage. Cumulative SO_4-treatment levels are shown in Table 2.

TABLE 2. Sulfate ($mmoles_c$) Added to Soil Pots Either as Blanket Fertilizer or in the SO_4-Water Irrigations.

Treatment No.	Mustard	Kochia	Clover[1/]	Grass[2/]	Sunflower
	--------------	---- $mmol_c$ SO_4/kg soil	----	----	--------------
1	3	6	6	11	6
2	30	53	53	53	53
3	53	100	100	100	100
4	77	147	147	147	147
5	100	194	194	194	194

[1/]These SO_4 applications were made prior to cropping.

[2/]One-half of the SO_4 was applied to soil prior to planting grass.

Plant Analyses: Plant samples were digested in HNO_3-$HClO_4$ (3:1). Cations were analyzed by atomic absorption, except K, which was determined by emission spectroscopy. Calcium, Mg, K, and Na were determined in a 1 g/L lanthanum (La) matrix. Total S was determined colorimetrically by flow injection analysis using a 40 ml/L $HClO_4$ carrier stream (QuikChem Method No. 12-116-10-1-C, LACHAT Instruments, Milwaukee, WI). Total P was determined colorimetrically as molybdovanado phosphoric acid. Water soluble anions were extracted by shaking 0.5 g plant tissue with 50 mL H_2O for 30 minutes, followed by filtering through #42 Whatman filter paper. Addition of carbon black was unnecessary and was therefore omitted. The anions Cl, NO_3, and SO_4 were quantified on a Waters ILC-1 liquid ion chromatograph using a model 430 conductivity detector and an ICPAC anion column. The carrier stream was 6 mmolar potassium benzoate. The retention times for the Cl, NO_3, and SO_4 peaks were about 3, 5.5, and 10 minutes, respectively. Total N, including NO_3, was determined by Kjeldahl analysis. Total S minus SO_4 will be considered as organic S. Data are presented for the single harvest of mustard and kochia and for the second harvest of clover, grass, and sunflower.

Soil Analyses: Soil pH and electrical conductivity (EC) were determined on the saturated soil paste and the extract, respectively. Calcium and Mg cations in this extract were analyzed by atomic absorption in a 1 g La/kg matrix and Na and K were analyzed by flame emission spectroscopy. Anions in the water extract were determined by ion chromatography as described above. Ion activity values were computed for 160 and 260 g/kg water contents using values presented by Adams (1971) and Suarez (1977). Ionic strength was calculated by the method of Griffin and Jurinak (1973).

Experimental Design: Each study was conducted as a completely randomized design having two soils, five SO_4-S levels, and three replications. Data were tested by the type III sums of squares and linear, quadratic, and cubic contrasts computed by PC-SASGLM 1990 and correlations computed by SASCORR 1990 (SAS Institute Inc., Cary, NC).

RESULTS

Soils: The SO_4 treated soils had final SO_4 values from 16 to 202 $mmol_c/kg$ values (Table 3) and a range of EC values from 6 to 16 dS/m (Table 4). The original untreated Portneuf had a higher EC than did the Brinegar (Table 1). The EC values and soluble SO_4 values for treatment 1 reflect the effect of incubation, crop growth, and the NPKS fertilizer additions. Relative EC differences continued for the treated soils over the range of SO_4 treatments.

After cropping, the Brinegar soil contained 18 to 202 with an average of 70 $mmol_c$ SO_4/kg in the saturation extracts and the calcareous Portneuf soil had 16 to 101, with an average of 41 $mmol_c$ SO_4/kg (Table 4). The greater concentration of soluble Ca in the Portneuf soil led to a greater proportion of SO_4 precipitation as gypsum (Adams 1971). The gypsum ion activity products were calculated from saturation paste extraction data that had been converted to 160 and 260 g water/kg soil values (Table 5). These water levels represented the upper and lower limits maintained during the studies. The data suggest that all soil solutions were saturated or very nearly saturated with respect to gypsum at the end of the study. Only four of the Brinegar treatments had $CaSO_4$ ion activity product means below the 2.4 E-05 K_{sp} value, and that was immediately following irrigation. Even those four exceeded the gypsum K_{sp} as evapotranspiration reduced the soil water

TABLE 3. Water-Soluble SO_4 in Saturation Paste Extract after Cropping.

Soil	SO_4 treatment	Soluble SO_4 after given crop				
		Mustard	Kochia	Clover	Grass	Sunflower
		---------- $mmol_c$ SO_4/kg soil ----------				
Brinegar	1	18	23	18	19	27
	2	28	38	33	44	45
	3	45	68	61	61	66
	4	73	132	101	77	101
	5	96	202	142	112	127
Portneuf	1	17	20	16	17	24
	2	28	24	20	25	33
	3	38	35	47	30	39
	4	54	67	56	40	53
	5	64	101	72	42	71

Table 4. Electrical Conductivity (EC) of the Saturated-Soil-Paste Extract after Cropping.

Soil	SO_4 treatment	EC following given cropping system				
		Mustard	Kochia	Clover	Grass	Sunflower
		---------- dS/m ----------				
Brinegar	1	6.7	7.0	5.7	12.8	5.9
	2	7.1	7.1	6.3	12.5	6.4
	3	7.8	8.9	8.1	13.8	6.9
	4	8.5	10.9	8.7	14.8	8.1
	5	10.0	13.4	12.4	14.6	9.7
Portneuf	1	8.5	11.5	9.1	15.9	8.7
	2	9.3	11.0	9.9	14.5	10.0
	3	9.7	11.7	10.1	15.6	9.8
	4	10.3	15.7	10.6	16.2	9.4
	5	10.0	12.4	10.9	14.5	10.2

TABLE 5. The Gypsum Ion Activity Product[1/] Computed at Two Water Levels for Each Soil and Cropping Treatment from Saturation Paste Extract Ion Values.

Soil	SO_4 tmt	Mustard	Kochia	Clover	Grass	Sunflower
		Ion activity product at 160 g/kg water content, E-05				
Brinegar	1	3.5	4.4	3.6	3.9	5.0
	2	4.3	4.2	4.3	6.2	5.8
	3	5.2	4.8	4.9	5.8	6.1
	4	5.8	4.6	4.8	4.4	5.1
	5	6.0	3.9	4.5	5.1	4.9
Portneuf	1	4.6	6.4	4.8	6.3	7.1
	2	6.7	6.4	5.3	8.6	7.5
	3	6.7	6.6	9.0	9.1	7.3
	4	7.4	8.4	7.3	9.5	7.5
	5	7.0	8.0	6.5	9.0	6.8
		Ion activity product at 260 g/kg water content, E-05				
Brinegar	1	1.9	2.4	2.0	2.1	2.8
	2	2.4	2.3	2.4	3.3	3.2
	3	2.9	2.6	2.7	3.1	3.4
	4	3.3	2.5	2.7	2.4	2.9
	5	3.3	2.1	2.5	2.7	2.9
Portneuf	1	2.5	3.5	2.6	3.3	3.9
	2	3.6	3.5	2.9	4.6	4.1
	3	3.6	3.5	4.9	4.8	4.0
	4	4.0	4.5	4.0	5.0	4.1
	5	3.8	4.3	3.5	4.7	3.7

[1/]Solubility product (K_{sp}) for gypsum is 2.4E-05.

content. The ion activity product cannot, however, be used to evaluate the Ca or SO_4 ion concentration in the soil solution since it is a product of the two and does not imply equality between Ca and SO_4 ion activity. Other ions in solution also increase gypsum solubility by other Ca or SO_4 ion pairing with other ions and by indifferent ion effects on solution ionic strength. This explains the difference in the trends between the values in Tables 3 and 5. Likewise, SO_4 addition in excess of Ca addition will decrease Ca availability for chemical and biological reactions (Adams, 1971; Curtin et al., 1993; Robbins et al., 1980).

Plants: Dry matter yields (Tables 6 and 7) were significantly ($P<0.05$) lower for all plants grown on the Portneuf than on the Brinegar (Tables 6 and 8). This could be from the higher salinity in the Portneuf than the Brinegar soil. There was no significant treatment effect on yield. There was, however, a significant ($P<0.01$) soil x treatment interaction for grass yield. Yields of grass (Table 6) grown on the Brinegar soil were reduced ($P<0.05$) by increasing SO_4 levels, whereas those on the Portneuf increased ($P<0.10$). The reduced solubility of the added SO_4 in the Portneuf treatments (Table 4) accounted for the significant soil x treatment effect (Table 8).

Elevating the SO_4 concentrations such that plant yields would be reduced was achieved only with the grass grown on the Brinegar soil. The stresses visible on other plants were probably diurnal osmotic stresses that were tolerated without yield reductions. The fertilizer salts plus the SO_4 treatments did not elevate the EC's sufficiently high to reduce shoot yield. Some added SO_4 was precipitated, consequently not contributing to an increase in EC.

Sulfur concentrations were higher in plants grown on the Brinegar than for those grown on the Portneuf soil (Tables 6 and 8). This is explained by the greater reduction of soluble SO_4 following gypsum precipitation in the calcareous Portneuf soil. This phenomenon causes the soil x treatment interactions that were evidenced when SO_4 was applied in the presence of the excess Ca in the calcareous Portneuf. Treatment contrasts were significantly linear ($P<0.03$) for all species (Table 8).

Total N: Organic S ratios were affected by soil type and SO_4 treatment level (Tables 6 and 8). The soil x treatment interaction was significant ($P<0.05$) for mustard and sunflower. These interactions again may be explained by the

TABLE 6. Mean Shoot Yield, SO_4-S, Organic-S, and Total N:Organic-S in Tissues for Five Species Grown on Five-S Levels and Two Soils.

Species	SO_4-S treatment	Yield Brinegar	Yield Portneuf	SO_4-S Brinegar	SO_4-S Portneuf	Organic-S Brinegar	Organic-S Portneuf	Total N:organic-S Brinegar	Total N:organic-S Portneuf
		- - - g/pot - - -		- - - µg/g - - -		- - - mg/g - - -			
Mustard	1	5.9	4.7	310	220	7.2	8.4	5.5	5.0
	2	5.4	3.9	330	460	8.4	8.3	4.9	4.6
	3	5.7	4.5	550	440	10.0	8.9	4.1	5.0
	4	5.7	4.8	890	540	13.5	9.1	3.1	4.6
	5	5.8	4.8	660	530	12.7	9.8	3.5	3.8
Kochia	1	15.4	11.2	400	360	5.7	5.0	7.7	9.3
	2	15.5	11.6	490	370	6.1	5.4	7.5	8.7
	3	14.7	12.5	580	430	6.9	5.4	6.5	8.7
	4	15.8	12.6	610	540	7.9	5.5	5.6	8.4
	5	15.4	13.7	680	580	8.4	6.2	5.2	7.3
Clover	1	3.9	2.8	320	630	3.3	2.3	12.3	15.6
	2	4.0	2.5	340	490	3.9	2.8	9.6	13.9
	3	4.9	2.9	250	420	2.9	2.5	14.9	14.7
	4	3.4	4.2	300	740	3.7	2.9	9.5	11.9
	5	3.1	2.4	400	530	4.5	3.2	10.0	12.4
Grass	1	2.2	0.9	70	140	2.5	2.1	15.8	19.6
	2	2.1	0.9	80	170	2.6	2.3	14.9	18.9
	3	2.0	1.0	80	170	2.5	2.3	16.2	17.5
	4	1.5	1.2	90	180	2.7	2.2	14.3	17.9
	5	1.4	1.1	90	150	2.9	2.1	13.3	17.8
Sunflower	1	9.9	8.0	300	240	3.8	2.9	9.0	8.2
	2	8.7	7.9	500	460	5.8	6.1	6.1	4.6
	3	8.9	8.2	600	410	7.0	4.4	5.2	6.1
	4	10.1	6.9	680	800	7.4	7.2	4.9	4.0
	5	7.7	7.1	790	520	9.0	4.9	4.0	5.6

TABLE 7. Mean Dry Matter Yield and Ion Concentration in Each of Five Species Across SO_4 Treatments.

Species	Yield	Na	K	Mg	Ca	C-A[1/]	C1	NO_3-N	SO_4-S	P	N	S
	g/pot	- - - -	- - - -	mg/g	- - - -	mol_c/g	- - - -	- - - -	mg/g	- - - -	- - - -	- - - -
Mustard	5.1	0.64	24	5.0	14.5	1.58	1.77	0.15	0.49	3.7	40	9.6
Kochia	13.8	3.86	65	9.4	9.0	2.79	3.85	0.47	0.50	4.4	45	6.2
Clover	3.4	0.58	25	8.1	15.3	1.96	1.26	0.04	0.44	4.4	38	3.1
Grass	1.4	0.87	29	3.4	6.9	1.24	2.29	0.30	0.12	4.4	40	2.4
Sunflower	8.3	0.62	48	7.2	12.2	2.25	2.80	0.38	0.53	3.1	31	5.8

[1/] Cations minus inorganic anions.

TABLE 8. Significance Values (P>F) for Experiment ANOVA and Treatment Contrasts[1] of Yield, SO_4-S, Organic-S, and N:Organic-S Across Soils and SO_4 Treatments for Each Species.

Statistic		Mustard	Kochia	Clover	Grass	Sunflower
				Yield		
Source	Soil	<.01	<.01	.04	<.01	.01
	Treatment	.25	.65	.45	.08	.45
	Soil x tmt	.87	.60	.24	<.01	.47
Treatment contrasts	Linear	.45	.14	.67	<.01	.12
				SO_4-S		
Source	Soil	.23	<.01	<.01	<.01	<.04
	Treatment	.05	<.01	.33	.23	<.01
	Soil x tmt	.59	<.04	.46	.51	.05
Treatment contrasts	Linear	<.01	<.01	.71	.16	<.01
				Organic-S		
Source	Soil	<.09	<.01	<.01	<.01	<.01
	Treatment	.04	<.01	<.01	.17	<.01
	Soil x tmt	.26	.04	.28	.04	<.01
Treatment contrasts	Linear	<.01	<.01	<.01	.04	<.01
				Total N:organic-S		
Source	Soil	.10	<.01	<.01	<.01	.60
	Treatment	<.01	<.01	<.01	.13	<.01
	Soil x tmt	.04	.47	.28	.37	<.01
Treatment contrasts	Linear	<.01	.01	.02	.01	<.01

[1] Quadratic contrasts were only significant (P<.01) for treatment effects on organic-S and total N:organic-S for sunflower. Cubic contrasts were not significant (P<.01).

reduction of soluble SO_4 in the Portneuf soil-solution. The linear treatment contrasts were significant for all species, and the quadratic treatment contrast was significant for sunflower, but the cubic was not significant for any of them.

The significant linear treatment effects on both S concentration and N:organic S ratios suggest that these plants may take up even higher concentrations of S than were measured in this study. Only with clover, sunflower, and possibly grass is there an indication that the point of diminishing response may have been achieved at the higher SO_4 rates on the Portneuf soil (Table 6). Nevertheless, high concentrations of S were measured in mustard, kochia, and sunflower (Tables 6 and 7). These plants also have low N:organic-S values, suggesting that much of the S is present in the plant in non-protein, organic forms.

Mustard, clover, and sunflower accumulate Ca in excess of 12 mg/g. Kochia, however, accumulated large concentrations of Na (Table 7). Trace elements and their concentrations across the tested species in mg/kg were: Cu, 9 to 12; Fe, 60 to 120; Mn, 64 to 350; and Zn, 31 to 54 (not shown). The ratio of (P+S)/(Ca+Mg+K+Na) as $mmol_c/g$ for each species was mustard, 1:1.8; kochia, 1:3.6; clover, 1:3.2; grass, 1:2.9; and sunflower, 1:3.5 (not shown). Of interest is the large cation composition (3.6 $mmol_c/g$) of the kochia. The anion bicarbonate (HCO_3) was not measured. These mineral anions, plus the organic anions, would balance the cation composition. The microcations composed less than 0.05 $mmol_c/g$. For each of the individual soil x species matrices, the sum of P and S ($mmol_c/g$) was highly correlated ($r^2 = 0.73$-0.98) with S treatments. The sum of macro cations was significantly correlated ($r^2 = 0.90$) with S in mustard but not in the other species.

Plant total S concentrations were correlated with post-harvest soil SO_4 activity for all plants grown on the Brinegar soil and mustard and kochia grown on the Portneuf (Table 9).

DISCUSSION

Absorption, transport, and metabolic reactions of S by plants occur predominately as SO_4. Although SO_4 may account for less than 10% of the total S in non-gypsiferous surface soils, the amounts in subsoils may represent a significant portion of the total (Harward and Reisenauer, 1966). Behavior of SO_4

TABLE 9. Correlation (r^2) of Plant-Tissue S Concentration on SO_4 Activity in Soils.

Soil	df	Mustard	Kochia	Clover	Grass	Sunflower
Brinegar	13	0.89	0.99	0.43	0.75	0.95
Portneuf	13	0.96	0.91	0.24	0.00	0.15
Both	28	0.81	0.80	0.54	0.69	0.62

in arid soils involves gypsum dissolution and precipitation reactions. This was a factor in our study of SO_4 additions to these soils. The main factors controlling solubility are Ca and SO_4 concentration, soil moisture content, common ion effects and ionic strength (Adams, 1971) (Tables 5 and 10).

Concern about S uptake by plants has centered on defining soil and plant-tissue concentrations relating to optimum plant growth. Previous studies have defined plant tissue critical concentrations as 2.0 to 2.2 mg S/g for alfalfa (whole above-ground plant); 2.6 for white clover; and 2.6 to 3.0 for cool season grasses (Ensminger and Freney, 1966; Martin and Walker, 1966). Martin and Walker (1966) showed that alfalfa at bloom stage could accumulate as much as 3.8 mg S/g when excess S fertilizer was applied. The S concentration can become higher in salt tolerant plants (halophytes). Thomas et al. (1950) sampled various halophytes in 11 western states and found as much as 30 mg S/g in some of those plants. Many halophytes belong to the chenopodiaceae family that includes kochia. Rennenberg (1984) concluded that plants generally absorb excess S, since avoidance is the exception. Once excess S enters a plant's cell, it may be translocated out of the cell directly or after conversion into a transport form. The excess S may be translocated to other parts of the plant or released into the environment in some volatile form.

The N:S ratios are useful as indicators of S nutrition in legumes and non-legumes. The ratio of protein N to protein S ranges from 40 in legumes to 50 in gramineous plants (Rennenberg, 1984) and is relatively constant for a given

TABLE 10. Sulfate Ion Activity Computed at Two Water Levels for Each Soil and Cropping Treatment.

Soil	SO_4 tmt	Mustard	Kochia	Clover	Grass	Sunflower
			at 160 g/kg water content, mmoles/L			
Brinegar	1	2.8	3.9	3.0	2.3	4.9
	2	4.9	6.5	5.8	6.0	8.0
	3	7.3	10.9	9.8	8.1	11.6
	4	12.3	15.0	13.8	10.8	14.9
	5	15.3	20.3	20.4	14.1	16.7
Portneuf	1	2.6	2.3	2.0	1.5	3.4
	2	4.1	2.9	2.7	2.5	4.4
	3	5.8	4.4	7.1	2.8	5.6
	4	8.6	9.2	8.6	4.2	8.5
	5	10.6	15.6	11.6	4.8	12.1
			at 260 g/kg water content, mmoles/L			
Brinegar	1	2.2	3.0	2.4	1.8	3.8
	2	3.8	5.0	4.5	4.6	6.1
	3	5.6	8.3	7.5	6.3	8.8
	4	9.4	11.4	10.6	8.3	11.2
	5	11.6	15.4	15.4	10.7	14.1
Portneuf	1	2.0	1.9	1.6	1.3	2.7
	2	3.3	2.4	2.2	2.1	3.5
	3	4.6	3.6	5.6	2.4	4.4
	4	6.7	7.3	6.7	3.5	6.6
	5	8.2	12.0	8.9	4.0	9.3

TABLE 11. Molar Ratio of Ca:Sum Cations, Analysis of Variance, and Contrasts for Treatment Effects on Plant Tissue Cation Composition.

		Treatment means of Ca:sum cations				
Soil	SO_4 tmt	Mustard	Kochia	Clover	Grass	Sunflower
Brinegar	1	0.35	0.11	0.30	0.14	0.22
	2	.34	.11	.24	.11	.16
	3	.29	.06	.20	.13	.13
	4	.24	.05	.14	.07	.12
	5	.25	.05	.13	.05	.10
Portneuf	1	.34	.15	.44	.27	.26
	2	.37	.12	.36	.23	.21
	3	.26	.10	.33	.17	.17
	4	.28	.09	.29	.18	.14
	5	.31	.07	.24	.19	.13
Statistic		Probability greater than F value				
Soil		.15	.0001	.0001	.0001	.0001
Treatment		.005	.0001	.0001	.003	.0001
S x tmt		.25	.72	.84	.12	.03
Contrast						
Linear		.0002	.0001	.0001	.0002	.0001
Quadrate?		.20	.24	.15	.34	.0001
Cubic		.02	.32	.97	.89	.4

species. Plants supplied with sufficient N showed no further increase in yield with increasing S supply, such that the N:S ratios would decrease below these respective values. Smaller N:S values reflect the presence of excess S. The N:S values in this study range from 4 to 20, indicating excess S uptake (Rennenberg, 1984).

One of the effects of SO_4 salinity is the precipitation of $CaSO_4$, thereby reducing plant-available Ca. Curtin et al. (1993) noted that reduced plant growth and dry matter yield could result from induced Ca deficiency. This would likely occur when the molar ratio of Ca:sum cations, in plant tissue, fell below 0.10. In this study, the ratio decreased as increasing amounts of SO_4 were added to the soils (Table 11). Ratios less than 0.10 occurred only in plants grown on the Brinegar and then only for kochia and grass. A yield reduction was noted in grass grown on the Brinegar, but not for the kochia (Tables 6 and 8). Herbage Ca levels were lower for these two species compared to the others (Table 7).

Some plants, including those in this study, can take up excess SO_4 when it is available. Some of these plants are eaten by ruminants and the S contained in this herbage would contribute to total S intake. Kochia scoparia is often recommended as an alternative forage crop, in spite of documented poisoning of cattle (Dickie and Berryman, 1979). The ability of kochia to accumulate high concentrations of S and its common use as a forage crop explain why this plant has been associated with the occurrence of polioencephalomalacia in ruminants (Beke and Hironaka, 1990; Dickie and James, 1983; Hamlen et al., 1993).

Most of the field reports of polioencephalomalacia seem related to drinking-water SO_4, but the S or SO_4 eaten in the forage should be included in computing the quantity of ingested S. A 450-kg cow drinking 75 L water containing 5,000 mg SO_4/L and eating 10 kg herbage containing 4 mg/g SO_4-S would have a total 125 g S in water and 40 g S in herbage. Thus, herbage could contribute significantly to S intake by ruminants.

Epsom's salts ($MgSO_4 \cdot 7H_2O$) and Glauber's salts ($Na_2SO_4 \cdot 10H_2O$) are prominent constituents in the ground water found in some Cretaceous formations and in the related soils (Brown et al., 1983). These salts influence soil chemistry and subsequent fertility by developing SO_4 salinity. It is in such areas where the livestock's consumption of excess SO_4 may lead to the development of