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THE EFFECT OF BICARBONATE IN IRRIGATION WATERS ON THE EXCHANGEABLE SODIUM STATUS OF THE SOIL

By

Edward J. Williamson

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THE EFFECT OF BICARBONATE IN IRRIGATION WATERS
ON THE EXCHANGEABLE SODIUM STATUS
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This thesis is approved as a creditable independent investigation by a candidate for the degree, Master of Science, and acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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INTRODUCTION

Farmers and ranchers are becoming more interested each year in supplemental irrigation, particularly where water sources such as permanent streams, rivers and underground aquifers are available. Many of these waters are of doubtful quality and if used for irrigation along with improper management could induce quite unfavorable soil conditions, both chemical and physical. Western United States has numerous examples of irrigation projects that have failed because of the use of waters of inferior quality.

Several of the surface flowing waters in western South Dakota are abnormally high in total soluble salts and contain high concentrations of sodium and bicarbonate. The Moreau River Project was abandoned by the Bureau of Reclamation because of the high salt and high sodium content of the waters of this river, and development of the Grand River Project is being held in abeyance pending further investigations which are in progress at the present time. A development farm near the Shadehill reservoir on the Grand River has been established to study on a field basis the effects such water has on the soils of this locality.

The nature of the Grand River water is such that a moderately high sodium ion content is combined with a bicarbonate ion content approximately equivalent to the alkaline earths. The principal objective of the study reported herewith is to determine to what extent the ratio of the concentration of bicarbonate ion to the sum of calcium plus magnesium ions affects the exchangeable sodium and soluble salt status of the soil. When irrigation water becomes the soil solution it suffers a shrinkage in volume, because of transpiration and evaporation, resulting frequently in precipitation of the least soluble constituents, which in this case are calcium and magnesium carbonates. The soluble sodium percentage[1] of the soil solution then increases, favoring adsorption of sodium in the cation exchange complex of the soil. Adsorption of sodium by the cation exchange complex beyond the point of 12 to 15 percent of the cation exchange capacity results almost without exception in deleterious physical and chemical effects. These effects are those characteristically associated with true alkali soils, for example, extreme swelling and shrinkage, high plasticity, poor aeration, poor tilth, high pH and dispersion of organic and inorganic colloids.

REVIEW OF LITERATURE

The precipitation of calcium and magnesium in the form of carbonates and the accompanying effect on the soluble sodium concentration of the soil solution is a relatively recently recognized aspect of irrigation water management.

Eaton (2) was probably the first to relate the significance of carbonate and bicarbonate content of irrigation waters to alkali formation. He reported that in the Nile Valley alkali conditions are prevalent, but salinity without alkali characterised the soils of the Euphrates Valley. These differences were explained on the basis of the bicarbonate content of the two waters. In the Nile water the bicarbonate concentration on chemical equivalent basis, exceeds the sum of calcium plus magnesium, while in the Euphrates the reverse is true. He postulated that calcium and magnesium were precipitated in the soil as carbonates, leaving sodium as the principal soluble cation. The remaining bicarbonate, after calcium and magnesium precipitation, combines

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[1] Refer to appendix for glossary of terms.

with sodium to give "residual sodium carbonate". This, in turn, builds up the level of sodium saturation of base exchange minerals and other colloidal matter in the soil. It was Way (6) in 1850 who discovered that soils have the power of exchanging cations with solutions. The seat of these exchange reactions was later established to be the surfaces of the finer clay particles and some of the decomposition products of plant and microbial material in the soil.

Fireman et al (3) attributed the existing alkalinity problem of the Emmett Valley Area of Idaho to the high bicarbonate content of the Payette River water. The total salt concentration of this river water is low but the salts are chiefly bicarbonates of sodium and calcium. Upon application to the soil the volume of water decreases because of plant use and evaporation, with ultimate precipitation of calcium carbonate. The loss of soluble calcium increases the soluble sodium percentage of the soil solution and this results in a decrease in exchangeable calcium and increase in exchangeable sodium of the soil. These investigators found that for the 868 soil samples of the Emmett Valley analyzed, exchangeable sodium ranged from 3 to 100 per cent of the cation exchange capacity, with an average for all samples of 36.8 per cent. This average amounts to approximately 8.5 milliequivalents of exchangeable sodium per 100 grams of soil. The values for exchangeable sodium content and exchangeable sodium percentage at which plant growth is seriously affected are not known for many crops. However, both the level of 2 milliequivalents of sodium per 100 grams of soil and 15 per cent sodium saturation of the cation exchange capacity have been used. By either criterion, 60 to 65 per cent of the surface samples and 75 to 79 per cent of the subsoil samples contain excessive amounts of exchangeable sodium for satisfactory plant growth.

Various other investigators (1, 4, 5, 7) have recommended the consideration of Eaton's bicarbonate theory in irrigation water quality standards.

METHODS

Samples of the various major surface waters of South Dakota have been analyzed. The results of the analyses are presented in Table 1. The majority of the streams of western South Dakota evidence a bicarbonate:calcium plus magnesium ratio greater than one, and thus have "residual sodium carbonate". The Grand River is typical of those waters, and inasmuch as a reservoir has already been constructed in anticipation of irrigation, it seemed pertinent to conduct a study of the effect of this water on soil.

To accelerate the use of water and the anticipated deleterious processes, greenhouse experiments were conducted. The hypothesis was tested by means of soil analysis before and after use of low quality waters, by analyses of soil solutions and by analyses of drainage waters from the cultures.

Two cultures, one of sunflowers and one of sudan grass, were grown in succession in the greenhouse in five-quart oil cans. Barnes loam soil was used; a characterization of this soil is given in Table 2.

The waters applied were made up by the use of certain salts to embrace the quality of the water anticipated in the Shadehill reservoir. The six water qualities used in these studies consisted of two sodium levels, as regards sodium percentages of total cations in milliequivalents per liter, 65 per cent and 75 per cent, and three bicarbonate:calcium ratios, 0, 1 and 1.8, in all possible combinations. Both the sodium levels and

Table 1. Analyses of various surface waters in South Dakota.

Source	Conductivity mmhos/cm.	Total Dissolved Salts p.p.m.	% Sodium Found	% Sodium Possible	$HCO_3^-:Ca^{++}+Mg^{++}$ Ratio	Residual Na_2CO_3 m.e./l.	pH	Date Collected	Location
Grand River	2020	1341	77.3	97.9	1.79	3.16	8.5	9/14/50	Mouth of North Fork
Shadehill Reservoir	730	432	58.1	61.8	1.63	1.37	8.0	9/5/52	Shadehill Reservoir
Little White River	230	200	29.9	74.7	1.31	0.47	7.3	9/13/52	Westover S. Dak.
White River	1010	730	74.3	99.2	1.58	1.52	7.4	9/1/52	Westover S. Dak.
Bad River	1400	1022	38.0	49.0	0.38	0.00	7.9	7/9/52	Ft. Pierre S. Dak.
Rabbit Creek	2150	1336	86.4	100.0	4.10	9.59	8.5	10/26/51	Harding County
James River	1440	950	50.7	88.8	0.80	0.00	8.6	9/10/51	Redfield Farm
Cheyenne River	2130	1670	27.8	32.5	0.21	0.00	8.0	8/24/50	Eagle Butte S. Dak.
Moreau River	1520	1030	79.5	100.0	1.64	2.48	8.0	7/4/48	Faith S. Dak.
Rapid Creek	500	337	5.6	16.7	0.68	0.00	8.5	1/16/50	Rapid City S. Dak.
Missouri River	460	318	36.2	53.7	0.52	0.00	6.9	7/21/49	Rosseau S. Dak.

Table 2. Characterization of soil used in greenhouse experiments.

Factor	Description
Soil type	Barnes loam
Great soil group	Chernozem
Natural vegetation	Tall grasses
County	Brookings
Horizon studied	A
Depth represented	6 inches
Horizon description	Dark brown friable loam
Parent material	Till, Iowan substage of Wisconsin glaciation
pH	6.1
Per cent base saturation	90
Exchange capacity (m.e./100 g.)	24.13
Exchangeable sodium percentage	0.24
Soluble sodium percentage	9.50

Mechanical analysis and mineral identity

Separate size	Per cent	Predominant mineral*
> 5u	74.24	Not determined
5 - 2u (Fine silt)	2.09	Quartz with trace of Vermiculite and Mica
2 - 0.2u (Coarse clay)	3.30	Quartz, considerable Mica and little Montmorillonite
0.2 - 0.08u (Med. clay)	8.34	Montmorillonite plus 5 per cent Quartz
< 0.08u (Fine clay)	5.20	Montmorillonite

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* Qualitative analysis as estimated from X-ray powder diffraction patterns by Dr. M. L. Jackson of University of Wisconsin.

the ratios are on a chemical equivalent basis. The magnesium ion was left out for convenience in making up these synthetic waters. Table 3 gives the ionic content of the waters used. Each treatment was replicated four times making a total of twenty-four variates in the study.

Table 3. Synthetic irrigation waters*.

Na %	$HCO_3:Ca^{++}$ Ratio	Ionic Content, m.e./l.				Residual Na_2CO_3
		Na^+	Ca^{++}	HCO_3^-	Cl^-	
65	0	13.6	7.3	0	20.8	0
	1	11.7	6.3	6.3	11.7	0
	1.8	10.4	5.6	10.1	5.9	4.5
75	0	15.6	5.2	0	20.8	0
	1	14.1	4.7	4.7	14.1	0
	1.8	12.9	4.3	7.7	9.5	3.4

* All waters contain 1200 p.p.m. of total dissolved salts.

The oil cans, painted to prevent rusting, were uniformly filled with fifty-five hundred grams of soil and planted to sunflowers on October 23, 1951. A quarter-inch copper tube two inches in length was centrically located in the bottom of each can to provide for drainage of the soil column. The distribution of the various irrigation treatments was randomised in each replicate. Plants were thinned to six per pot at the two-week stage of growth. Watering was done as often as needed until the plants were six to eight inches in height. Beginning at this stage, watering was done only as often as symptoms of wilting were noted. This was done to promote carbonate precipitation of the calcium and to simulate field conditions. The pots were rotated periodically during the growth period to eliminate possible effects from differential lighting and temperatures of the greenhouse.

Twice during the growth period of the first culture sufficient water was applied to cause drainage water to appear. The drainage or percolation occurred to the extent that water was added in excess of field capacity. The first drainage was caused thirty days after starting the study and the second at maturity. Sufficient excess water was added to cause drainage to occur to the extent of ten per cent of the total water applied. The drainage water at each period was sampled for analysis. The ten per cent drainage goal has been proposed as a method of maintaining favorable salt balance. The actual volume collected at each period varied slightly from the ten per cent goal.

The first sunflower crop was harvested on January 17, 1952 after eighty-seven days of growth. The plants were cut off at the soil line, dried in the oven, and the weights of dry matter for each pot recorded. The soil was sampled at this point by use of a soil probe. Five systematic probes were taken in two layers, 0-4 and 4-8 inch depths, for laboratory analyses. The sampling holes were filled with stock soil and tamped to prevent abnormal infiltration during the subsequent culture.

The second crop using sudan grass, was planted on January 19, 1952. Drainage of this culture likewise was caused after thirty days of growth and prior to harvesting at maturity. The harvesting was done on April 21, 1952. The second culture growth period comprised ninety-four days.

The analyses of the drainage waters consisted of determination of soluble salts by conductivity, using a Solu-Bridge, and determination of soluble sodium using the Perkin Elmer flame photometer. The soil samples were analyzed for soluble sodium, exchangeable sodium, cation exchange capacity and conductivity of the saturation extract. The methods used were those adopted by the USDA Regional Salinity Laboratory (8).

In Figure 1 are shown sudan grass plants grown in cans in the greenhouse.

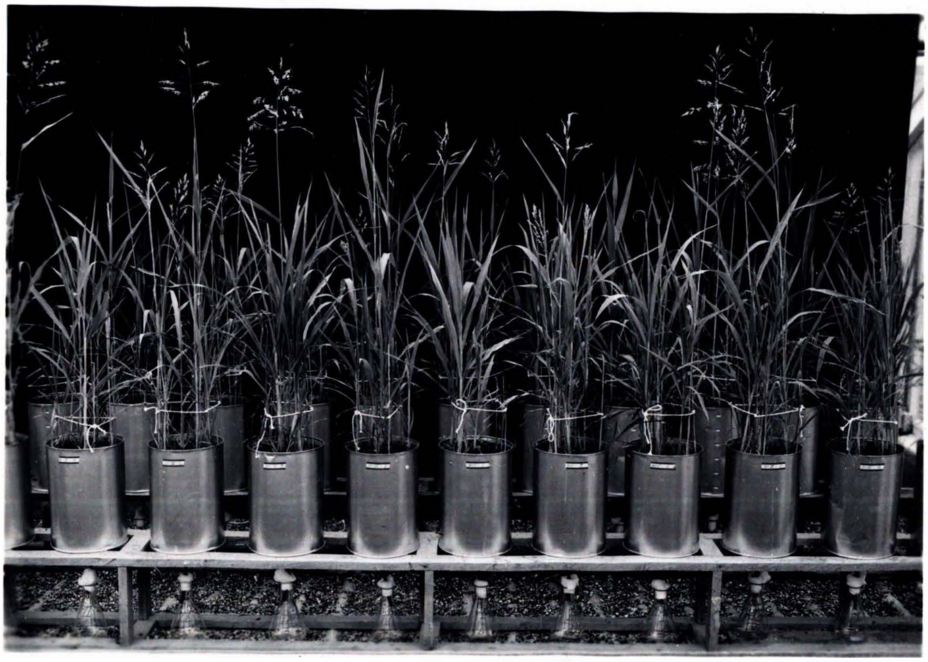

Figure 1. A greenhouse view of the second culture phase with sudan grass as the crop grown.

EXPERIMENTAL RESULTS AND DISCUSSION

Plant Studies

The synthetic waters used in this study were prepared to represent the anticipated quality of the Shadehill Reservoir. This involved the use of two sodium levels each in combination with three bicarbonate: calcium ratios. All waters carried 1200 p.p.m. of total dissolved salts. The harvest yields and total inches of water applied for each water quality used during the two successive greenhouse cultures are presented in Table 4.

Table 4. Effect of irrigation water quality on harvest yields. Values are means of four replications.

Water Quality		Treatment Number	Water Applied, inches		Dry Matter Yield Grams	
Na %	$HCO_3^-:Ca^{++}$ Ratio		First Culture	Second Culture	First Culture	Second Culture
65	0	1	16.4	13.4	26.1	22.3
	1	2	17.1	16.1	27.0	27.9
	1.8	3	17.2	16.4	27.8	29.1
75	0	4	16.2	14.0	26.4	24.5
	1	5	16.2	15.6	26.5	27.3
	1.8	6	17.1	16.2	27.3	28.0

As indicated in Table 4, yields of dry matter increased as the bicarbonate:calcium ratio of the synthetic water was increased. The salt contents were the lowest however, in those cultures with the greatest yields (Table 5). Figure 2 shows the differences in appearance of the plants between two treatments, 4 and 6. On the left are shown the plants when grown under treatment 4 (75 per cent sodium water with bicarbonate:calcium ratio of 0), while on the right are shown the plants from treatment 6 (75 per cent sodium water with a bicarbonate:calcium

Treatment No. 4

Treatment No. 6

Figure 2. A comparison of effects of treatment with two qualities of synthetic waters on growth of sudan grass.

ratio of 1.8). These pictures were taken just prior to harvesting; it is noted that the plants in treatment 6 were more mature than those in treatment 4. It is believed that salt concentration in treatment 4 is the reason for this difference. The conductivity of the saturation extract for treatment 4 was 9.8 mmhos/cm. while that for treatment 6 was 5.4 mmhos/cm. (Table 5). Recent unpublished data of the USDA Salinity Laboratory (9) indicate that soluble salts composed chiefly of calcium chloride are more toxic to plant growth than chlorides of other alkali earth and alkali metals. It is very likely that such a condition existed in treatment 4. Sudan grass is considered to have only a moderate degree of salt tolerance; consequently, with the conductivity approaching 10 mmhos/cm., reductions in growth and retardation of maturity would be expected.

The sunflower yields showed the same trend and likewise, are considered to have only a moderate degree of salt tolerance.

Soil Studies

The primary data obtained from the soil analyses are presented in Table 5. Various parts of the data were subjected to statistical analyses, consisting of linear regression relations, correlations and analysis of variance computations.

The linear regression and correlation coefficients were computed and studied for the following relationships:

1. Relation of soluble sodium percentage of the saturation extract to the exchangeable sodium percentage.
2. Relation of soluble sodium percentage to the conductivity of soil extract.

3. Relation of soluble sodium percentage of the leachate to the exchangeable sodium percentage of the soil.
4. Relation of soluble sodium percentage to the conductivity of the leachate.
5. Relation of bicarbonate:calcium ratios to the exchangeable sodium percentage.

The exchangeable sodium percentage data for the two synthetic water sodium levels were tested by analysis of variance.

Table 5 shows that an increase in soluble sodium and exchangeable sodium developed as the bicarbonate:calcium ratio increased with either sodium level of synthetic water. The 75 per cent sodium water resulted in greater increases in exchangeable sodium percentage than did the 65 per cent sodium water. This is congruous in as much as the soluble sodium percentage of the soil solution was greater in the 75 per cent sodium cultures. The lag in increase of exchangeable sodium percentage in the 4-8 inch soil depth can be attributed to lack of equilibrium with the soil solution during the first culture period. This is illustrated by the difference in soluble sodium concentration of the leachates in the first and second cultures (Table 7). The soluble sodium percentage of the second culture leachate was approximately ten per cent greater than that of the first culture leachate, indicating that the soil was approaching an equilibrium with the soil solution.

The salt content of the soil decreased as the bicarbonate:calcium ratio was increased in the synthetic waters. This trend towards an increase in exchangeable sodium and a decrease of soluble salts is characteristic of the formation of non-saline alkali soils.

Figure 3 presents in graphic form the effects of bicarbonate:calcium

Table 5. Effect of irrigation water quality on soluble sodium, exchangeable sodium and salt content of Barnes loam soil after two successive greenhouse cultures. Values are means of four replications.

Water Quality Na %	Water Quality HCO$_3$:Ca Ratio	Treatment Number	Depth Inches	Cation Exchange Capacity m.e./100 g.	Soluble Sodium Percentage Orig.	Soluble Sodium Percentage 1st Cult.	Soluble Sodium Percentage 2nd Cult.	Exchangeable Sodium Percentage Orig.	Exchangeable Sodium Percentage 1st Cult.	Exchangeable Sodium Percentage 2nd Cult.	Conductivity mmhos/cm. Orig.	Conductivity mmhos/cm. 1st Cult.	Conductivity mmhos/cm. 2nd Cult.
	0	1	0-4	24.07	9.5	54.8	50.8	0.24	4.85	4.52	0.4	9.3	10.1
			4-8	24.07	9.5	33.1	44.9	0.24	2.82	5.31	0.4	7.9	9.2
65	1	2	0-4	24.07	9.5	55.8	58.4	0.24	4.85	6.19	0.4	8.7	5.9
			4-8	24.07	9.5	36.1	62.7	0.24	3.52	5.59	0.4	5.8	5.3
	1.8	3	0-4	24.07	9.5	66.1	74.7	0.24	7.29	7.93	0.4	4.9	3.4
			4-8	24.07	9.5	48.3	65.0	0.24	3.93	6.67	0.4	2.7	4.6
	0	4	0-4	24.07	9.5	56.1	59.3	0.24	6.04	5.58	0.4	10.5	9.8
			4-8	24.07	9.5	34.3	56.6	0.24	4.09	6.14	0.4	7.8	9.6
75	1	5	0-4	24.07	9.5	58.3	66.2	0.24	6.05	7.35	0.4	9.9	7.5
			4-8	24.07	9.5	41.7	62.3	0.24	4.40	7.28	0.4	6.0	7.4
	1.8	6	0-4	24.07	9.5	68.7	76.0	0.24	8.15	9.09	0.4	6.4	5.4
			4-8	24.07	9.5	40.5	70.0	0.24	3.57	8.38	0.4	4.1	5.7

ratios in the synthetic water at the 65 per cent and 75 per cent sodium level on the exchangeable sodium percentage of the 0-4 and 4-8 inch depths of soil. The effects of these synthetic waters on the exchangeable sodium status of the soil, presented in Table 5, are more clearly depicted in this graph. This is especially true of the lag that exists in exchangeable sodium percentage between the first and second cultures at the 4-8 inch soil depth.

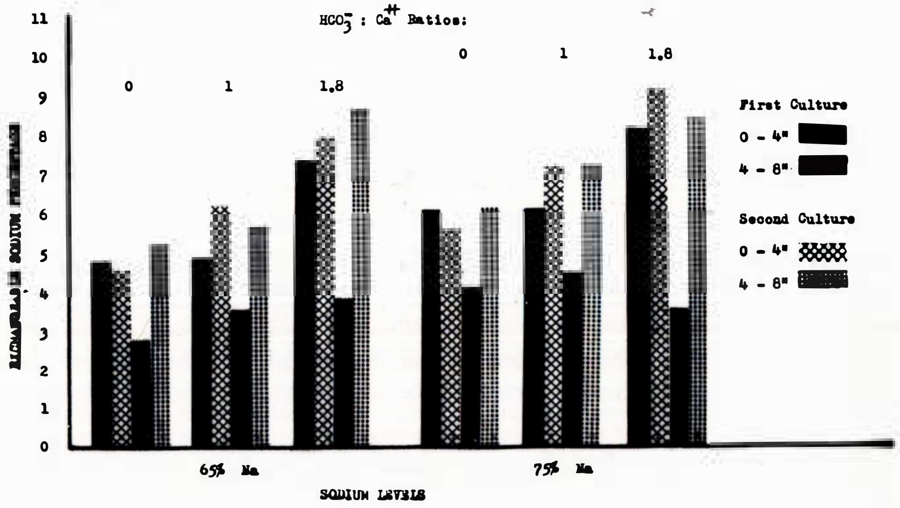

Figure 3. Effect of bicarbonate:calcium ratios in synthetic water on the exchangeable sodium percentage in Barnes loam in pot cultures.

A linear regression of the soluble sodium percentage in the saturation extract on the exchangeable sodium percentage in the soil colloids is presented in Figure 4. Regression lines are shown for both the 65 per cent and 75 per cent sodium levels in the synthetic waters. Correlation coefficients are highly significant indicating that the exchangeable sodium percentage of the soil is closely related to the soluble sodium percentage of the saturation extract.

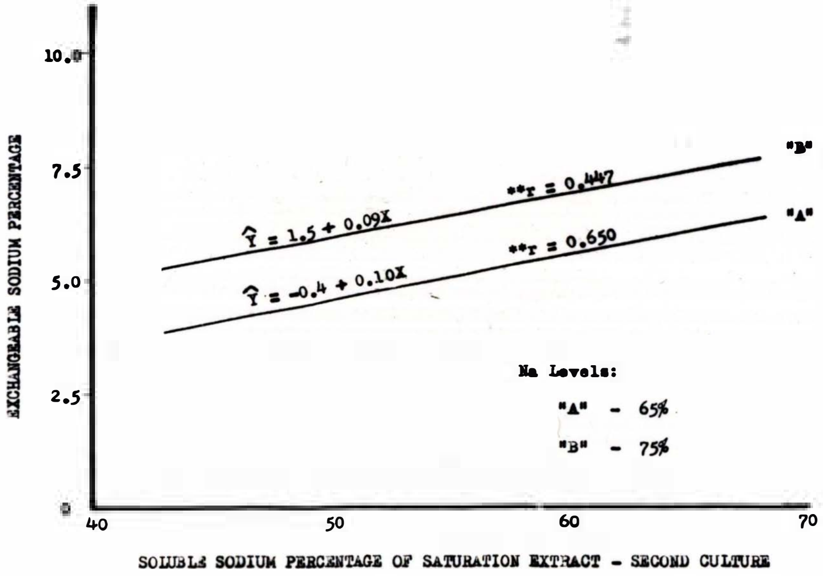

Figure 4. Linear regression of soluble sodium percentage of the saturation extract on the exchangeable sodium percentage in the soil.

Figure 5 presents the linear regression relationship between soluble sodium percentage and conductivity of the saturation extract.

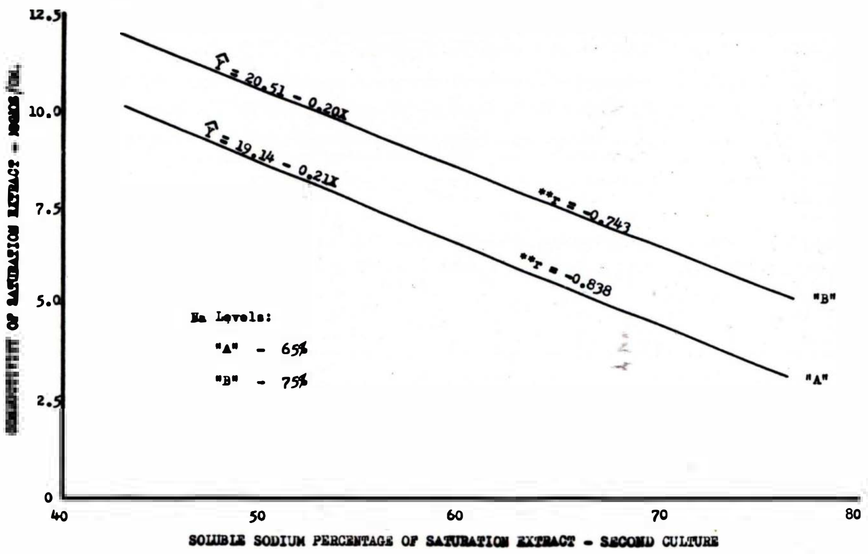

Figure 5. Linear regression of soluble sodium percentage of the saturation extract on the conductivity of the saturation extract.

As indicated by the highly significant negative correlation coefficient, soluble sodium percentage is inversely related to conductivity of the saturation extract. A ten per cent increase in soluble sodium is accompanied by a decrease in the conductivity of approximately 2.5 mmhos/cm. This relationship is apparently a result of the bicarbonate precipitation of calcium in the form of carbonates in the soil solution. The depletion of soil water by transpiration of plants and surface evaporation increases the soil solution concentration to the point where the least soluble salts commence to precipitate out. Calcium carbonate, being the least soluble, would precipitate first.

It is apparent from the data in Figure 6 that the bicarbonate:calcium ratio of an irrigation water has a direct bearing on the exchangeable sodium status of the soil colloids. The synthetic water possessing 65 per cent soluble sodium increased the exchangeable sodium percentages of the soil from an original 0.24 per cent to 4.4 per cent and 7.8 per cent when the bicarbonate:calcium ratio of the water was 0 and 1.8, respectively. Similar results were found for the 75 per cent sodium water, but with even greater increases in exchangeable sodium percentage.

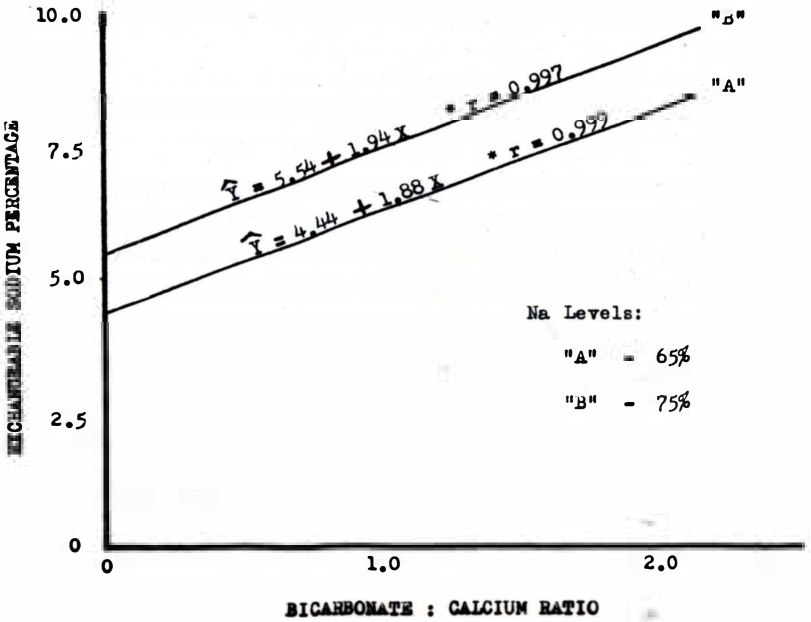

Figure 6. Linear regression of bicarbonate:calcium ratios of the synthetic waters on the exchangeable sodium percentage in the soil.

Table 6 presents the analysis of variance in the data on the exchangeable sodium percentages as found in the soil at the end of the second culture. A highly significant *F* value for "between bicarbonate:calcium ratios" was obtained.

Table 6. Analysis of variance, exchangeable sodium percentages in the 0-4 and 4-8 inch soil depths of the second culture.

Source of Variation	Degrees of Freedom	Mean Square	
		0-4"	4-8"
Total	23		
Replicates	3	0.5987	2.0934
Na	1	7.6388	3.3004
HCO_3:Ca	2	24.9780**	16.9099**
Na X Reps.	3	2.2211	2.2709
HCO_3:Ca X Reps.	6	0.4753	0.8715
Na X HCO_3:Ca	2	0.0066	0.4852
Na X HCO_3:Ca X Reps.	6	0.6661	1.0098

** Level of significance one per cent.

This analysis of variance lends considerable support to the data of Figure 5 in that the bicarbonate:calcium ratio is demonstrated to be the most important factor in exchangeable sodium build-up. In previous classifications of irrigation waters, soluble sodium percentage has been regarded as the primary factor in such build-up. In this study in all cases where residual bicarbonate was greater than zero, the most important factor is not the soluble sodium percentage, but the bicarbonate:calcium ratio.

Leachate Studies

The drainage waters, toluene treated to retard bacterial action, were analyzed for soluble sodium and soluble salt content. These data were statistically tested for linearity of the relationship of soluble sodium percentage to conductivity and to the exchangeable sodium percentage. Table 7 presents the primary data from the leachate analyses.

Table 7. Leachate analyses. Values are means of four replications.

Water Quality			Leachate			
			Soluble Na%		Conductivity mmhos/cm.	
Na %	$HCO_3^-:Ca^{++}$ Ratio	Treatment Number	First Culture	Second Culture	First Culture	Second Culture
65	0	1	4.5	30.0	13.5	24.1
	1	2	4.7	36.5	9.0	19.5
	1.8	3	4.1	41.1	5.1	13.2
75	0	4	4.2	32.4	13.5	24.5
	1	5	4.7	41.2	10.9	16.4
	1.8	6	4.7	44.9	6.5	13.0

The principles established by this phase of the study are very similar to those established by the saturation extract data. Figure 7 presents the linear regression of the soluble sodium percentage of the leachate on the exchangeable sodium percentage of the soil for both sodium levels combined. The slope of this line is steeper than that found for the saturation extract data. Apparently, there is a much closer degree of association between exchangeable sodium percentage and soluble sodium percentage of the leachate than there is between exchangeable sodium percentage and soluble sodium percentage of the saturation extract. The lower soluble sodium percentage in the leachate than in the saturation extract indicates again that the soil has not reached complete equilibrium with the soil solution.

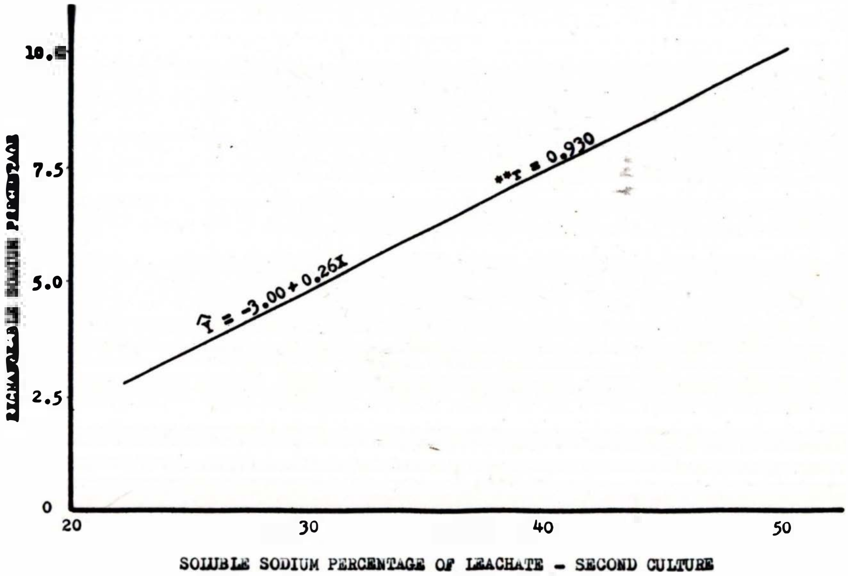

Figure 7. Linear regression of soluble sodium percentage of the leachate on the exchangeable sodium percentage in the soil.

Figure 8 presents the linear regression relationship between soluble sodium percentage and conductivity of the leachate. The highly significant negative correlation coefficient indicates that with an increase in soluble sodium percentage, one may expect a decrease in conductivity. Apparently, this is a result of bicarbonate precipitation of calcium in the form of carbonates, lowering the total soluble salt concentration.

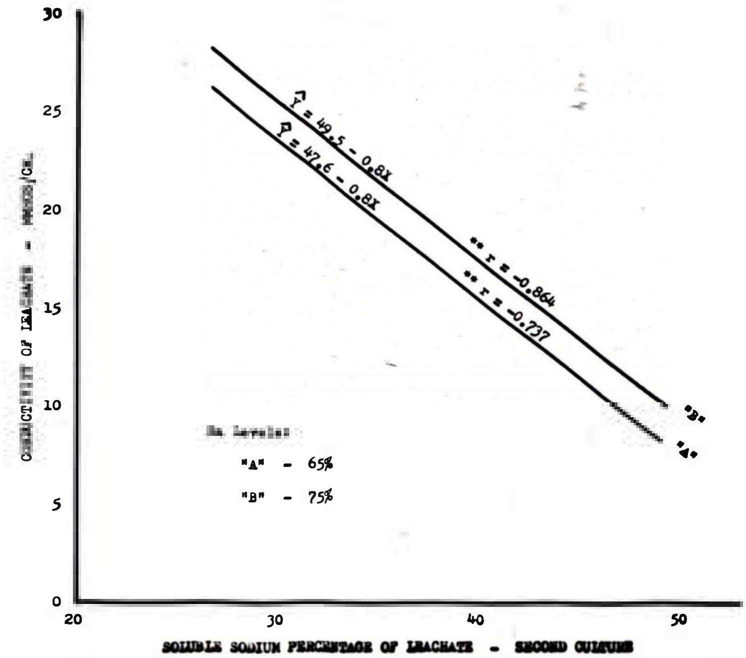

Figure 8. Linear regression of soluble sodium percentage of the leachate on the conductivity of the leachate.

SUMMARY AND CONCLUSIONS

Greenhouse experiments were conducted and laboratory analyses of soils were made to study the effect of bicarbonate content of irrigation waters upon the exchangeable sodium status of soils. Synthetic irrigation waters of two sodium levels, 65 per cent and 75 per cent, each in combination with three ratios of bicarbonate:calcium, 0, 1 and 1.8, were used for growing sunflowers and sudan grass in two successive cultures. Drainage waters and periodic soil samples of the cultures were analysed and each crop harvested, dried and weighed.

An increase of exchangeable sodium level in the soil resulted from all treatments, the greatest increase deriving from water having a 1.8 bicarbonate:calcium ratio and 75 per cent sodium. Bicarbonate:calcium ratio of unity for both sodium levels of water gave the next highest exchangeable sodium values, and zero bicarbonate:calcium the least. Increases in exchangeable sodium percentages ranging from 1780 to 2200 per cent, based on the original soil, resulted from use of the 65 per cent and 75 per cent sodium waters without bicarbonate. The use of waters having bicarbonate:calcium ratios of 1.8 resulted in increases in exchangeable sodium ranging from 3200 to 3680 per cent. These effects occurred after use of only 30 to 33 surface inches of water. This is approximately the amount of water that would be used in two years of irrigation.

An increase in soluble salt content of approximately 2900 per cent, based on the original soil, resulted from the use of synthetic waters free of bicarbonate. The least accumulation of salts occurred with the use of waters of the highest bicarbonate:calcium ratio, 1.8. The low concentrations of soluble salt found in soils treated with the high bicarbonate waters are apparently the result of bicarbonate precipitation of calcium in the form of carbonate from the soil solution.

It is believed that the higher yields of plant tissue in the 1.6 bicarbonate:calcium ratio treatments were at least partially a result of the low soluble salt contents of the soil in these treatments. Another explanation possible is the absence of large amounts of calcium chloride in the soil solution of these treatments.

In conclusion, it appears quite evident that waters high in bicarbonate:alkaline earth metals could cause serious damage to soils if used extensively over prolonged periods of time. The increase in exchangeable sodium percentage in the soils treated with synthetic water having residual Na_2CO_3 (high bicarbonate:calcium ratio) was approximately 60 per cent greater than the increase in the soils treated with waters not having residual Na_2CO_3. It is recognized that high sodium content alone in irrigation waters is easily capable of increasing exchangeable sodium in the soil, but evidence of this study indicates that high bicarbonate:alkaline earth metals greatly enhance this build-up.

LITERATURE CITED

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APPENDIX

Glossary of Terms

1. Alkali soil or Nonsaline-alkali soil —— a soil in which the exchangeable sodium percentage is greater than 15 and the conductivity of the saturation extract is less than 4 millimhos per cm.

2. Cation exchange capacity —— the number of milliequivalents of cations per 100 gms. of soil which can be held by surface forces and can be replaced by other cations.

3. Electrical conductivity (EC) —— a unit for measuring conductance of a water or soil solution to electricity. Addition of a salt to the water or soil solution increases its conductance. It is the reciprocal of the electrical resistivity. The resistivity is the resistance in ohms of a conductor which is 1 cm. long and has a cross-sectional area of 1 sq. cm. EC (mhos/cm.) has been multiplied by 10^3 (1000) so as to avoid use of large decimal values, hence, EC X 10^3 (millimhos/cm. or mmhos/cm.)

4. Exchangeable sodium percentage —— degree of saturation of the soil-exchange-complex with sodium, defined as follows:

$$ESP = \frac{\text{Exchangeable sodium (m.e./100 gm. soil)}}{\text{Cation exchange capacity (m.e./100 gm. soil)}} \times 100$$

5. Field capacity —— the amount of water retained in a soil against a force of gravity at any specific time (about 24 to 36 hours) after flooding.

6. Milligram equivalent (m.e.), or milliequivalent per liter (m.e./l.) —— a unit used in water and soil analyses. Chemical elements combine with each other in definite weight ratios. Thus 23 grams sodium ion will combine with 35.5 grams chloride ion, or 1 sodium ion will combine with 1 chloride ion to form sodium chloride, written chemically NaCl. An equivalent of sodium is therefore 23 grams, which will combine with its chemical equivalent of chloride ion, sulfate, or other substance. A milligram equivalent (m.e.) is 0.001 of an equivalent, or 0.023 gram of sodium or 0.0355 gram of chloride. The milliequivalent per liter of sodium is therefore 0.023 gram of sodium in a liter of water.

7. Parts per million (p.p.m.) —— the parts of salt or any one salt constituent per million parts of solution.

8. Saline-alkali soil —— a soil in which the conductivity of the saturation extract is greater than 4 millimhos per cm. and the exchangeable sodium percentage is greater than 15.

9. Saline soil —— a soil in which the conductivity of the saturation extract is greater than 4 millimhos per cm. and the exchangeable sodium percentage is less than 15.

10. Saturation extract —— the solution obtained by pressure or vacuum filtration of a soil paste that has been made up to a saturated condition by adding water while stirring.

11. Soil solution —— the moisture bathing the soil particles and containing dissolved minerals and air.

12. Soluble sodium percentage —— a term used in connection with irrigation waters and soil extracts to indicate the proportion of sodium ions in solution in relation to the total cation concentration and is defined as follows:

$$\text{SSP} = \frac{\text{Soluble sodium concentration (m.e./l.)}}{\text{Total cation concentration (m.e./l.)}} \times 100$$

For irrigation water it may be expressed as Sodium Percentage "present".

13. Sodium percentage "possible" —— a term used in connection with irrigation waters found by subtracting the milliequivalents per liter of carbonate plus bicarbonate from the milliequivalents per liter of calcium plus magnesium, then re-calculating the sodium percentage as follows:

$$\underset{\text{"possible"}}{\text{Na \%}} = \frac{\text{Na (m.e./l.)}}{\text{Ca} + \text{Mg} - (\text{CO}_3 + \text{HCO}_3) + \text{Na} + \text{K (m.e./l.)}} \times 100$$

14. Residual sodium carbonate —— a term used in connection with irrigation waters and found by subtracting the milliequivalents per liter of calcium plus magnesium from the milliequivalents per liter of carbonate plus bicarbonate, and expressing the remaining milliequivalents per liter of carbonate and bicarbonate as milliequivalents per liter Na_2CO_3.