A STUDY OF THE EFFECT OF IRRIGATION WATER COMPOSITION ON SOIL PROPERTIES

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Lysimeter experiments designed to study the quality of irrigation waters were initiated in 1953. The principal objective was to observe the effects of Na^+ and HCO_3^- in the water on the chemical properties of the soil. After being cropped to alfalfa for four years, the soil was found to have significant salt gradients with depth. In many cases, there was an appreciable formation of exchangeable Na^+, and "excess cation saturation" had been induced. Extensive chemical analyses are reported.

A STUDY OF THE EFFECT OF IRRIGATION WATER COMPOSITION ON SOIL PROPERTIES[1]

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INTRODUCTION

ALL WATERS used to irrigate plants contain dissolved salts. Thus, if irrigation water is repeatedly evaporated and transpired by plants in a given mass of soil, the salt content of the soil will increase until it eventually becomes injurious to plants. Extensive research has been done on the amount of leaching necessary to prevent such salt accumulation, and on related problems.

When the cation content of irrigation water is characterized by a high proportion of Na^+, the use of such water may increase the exchangeable Na^+ content of the soil, resulting in injury to plants and possibly a poor soil condition. Eaton (1950)[6] suggested that such effects may be aggravated if the irrigation water contains HCO_3^- ions. As water containing Ca^{++} and HCO_3^- evaporates, CO_2 is lost from the system, and $CaCO_3$ precipitates according to the reaction:

$$Ca^{++} + 2HCO_3^- \rightleftharpoons CaCO_{3(s)} + H_2O + CO_2$$

Thus, as a soil containing soluble Ca^{++} and HCO_3^- dries out, $CaCO_3$ is precipitated, and the ratio of Na^+ to Ca^{++} ions in the soil solution increases. This in turn results in an increase in the exchangeable Na^+ content. Effects of this kind have been clearly demonstrated (Richards, 1954). Eaton (1950) has therefore suggested that irrigation waters be evaluated on the basis of the "possible" sodium percentage of the water. That is, where the $(HCO_3^- + CO_3^=)$ does not exceed $(Ca^{++} + Mg^{++})$, "possible" Na^+ percentage =

$$\frac{Na^+}{(Ca^{++} + Mg^{++} + Na^+) - (HCO_3^- + CO_3^{--})} \times 100.$$

This represents the Na percentage which results when part of the Ca^{++} and Mg^{++} is precipitated as carbonates. When the $(HCO_3^- + CO_3^=)$ exceeds the $(Ca^{++} + Mg^{++})$, the possible Na^+ percentage is taken as 100.

Workers at the United States Salinity Laboratory at Riverside, California, have developed a method of predicting the ultimate equilibrium exchangeable sodium percentage (ESP) that will result from the prolonged use of a given irrigation water (Richards, 1954). They define the sodium absorption ratio (SAR) of the water as:

$$SAR = \frac{Na^+}{\sqrt{\dfrac{Ca^{++} + Mg^{++}}{2}}}$$

(cation concentrations in m.e./l). With the value of SAR known, an empirical nomogram may be used to obtain the equilibrium ESP.

The present paper reports the results of some lysimeter experiments designed to determine the effects on soil of irrigation waters containing various proportions of Na^+ and CA^{++} and of Cl^- and HCO_3^-.

MATERIALS AND METHODS

The lysimeters consisted of thirty-six 32-gallon, galvanized steel containers (fig. 1) packed (with water) to a depth of 2 feet with thoroughly mixed, Columbia very fine sandy loam. An analysis of the soil appears in table 1. Drainage was provided for, and leachates were collected at the bottoms of the containers. All containers were surrounded by a soil buffer (see fig. 1).

Nine synthetic irrigation waters were applied in fourfold replication to a total of 36 lysimeters. All waters had a total salt concentration of 10 m.e. per liter. Their compositions are given in table 2.

In March, 1953, the lysimeters were seeded to alfalfa, and the crop was established by irrigation with tap water. Irrigation with the synthetic waters began in July, 1953, and continued until September, 1957. Water was applied whenever the plants showed signs of wilt, and the same amount of water was applied to each tank with each irrigation. The irrigations were so conducted that, in each case, approximately 10 per cent of the applied water passed through the soil and was collected in a pan at the bottom of the

TABLE 1
ANALYSIS OF COLUMBIA VERY FINE SANDY LOAM USED IN
LYSIMETER EXPERIMENT*

Water-soluble ions							Exchangeable cations			
Ca^{++}	Mg^{++}	Na^+	K^+	CO_3^-	HCO_3^-	Cl^-	Ca^{++}	Mg^+	K^+	Na^+
m.e. per liter of saturation extract							*m.e./100 gm.*			
1.25	0.86	0.73	0.045	....	0.091	0.88	10.7	3.9	0.15	0.11

* Saturation moisture percentage, 44; pH of saturation extract, 6.7; conductivity of saturation extract, 0.29 mmho/cm at 25° C; cation exchange capacity, 13.1 m.e./100 gm.
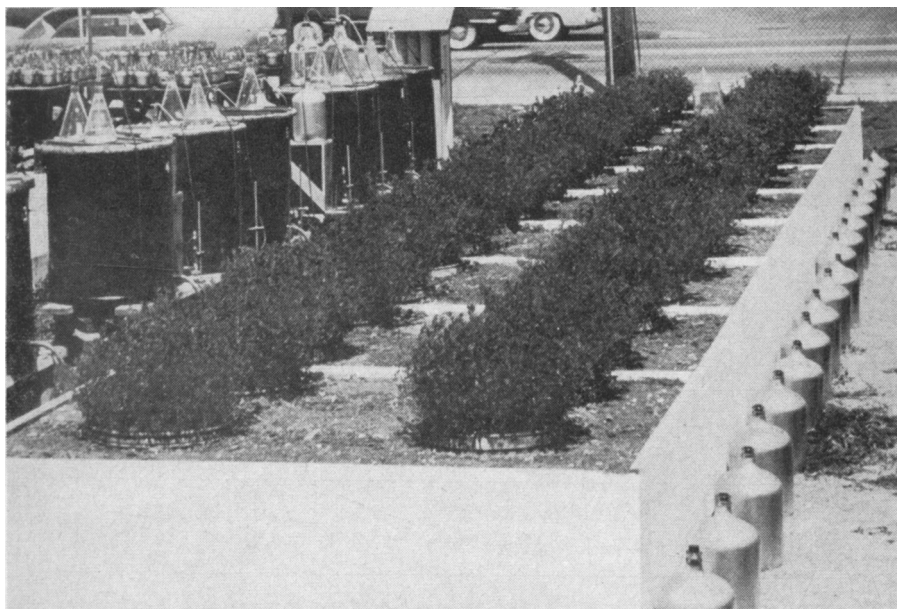
Fig. 1. Lysimeter installation and tanks containing the irrigation waters.

lysimeter. During periods of rain, the soils were protected by suitable covers. Because a preliminary investigation indicated that the soil was phosphate-deficient, $(NH_4)H_2PO_4$ was applied from time to time. Over the whole period of the experiment, the total $(NH_4)H_2PO_4$ applied was at the rate of 1,836 pounds per acre. As the tanks were cropped, yield data were obtained, some of which are shown in table 5.

In September, 1957, soil samples were taken at depths of from 0 to 6 inches, 6 to 18 inches, and 18 to 24 inches. They were air dried, and ground

TABLE 2

COMPOSITION OF APPLIED IRRIGATION WATERS*

Irrigation water no.	Ionic concentration				Ion ratios	
	Na^+	Ca^{++}	Cl^-	HCO_3^-	$\dfrac{Ca^{++}}{Na^+}$	$\dfrac{HCO_3^-}{Cl^-}$
	m.e./l	*m.c./l*	*m.e./l*	*m.e./l*		
1...................................	5.0	5.0	10.0	0	1.0	0
2...................................	7.5	2.5	10.0	0	0.33	0
3...................................	10.0	0	10.0	0	0	0
4...................................	5.0	5.0	5.0	5.0	1.0	1.0
5...................................	7.5	2.5	5.0	5.0	0.33	1.0
6...................................	10.0	0	5.0	5.0	0	1.0
7...................................	5.0	5.0	3.33	6.67	1.0	2.0
8...................................	7.5	2.5	3.33	6.67	0.33	2.0
9...................................	10.0	0	3.33	6.67	0	2.0

* All waters contained a total of 10 m.e. per liter of salt.

TABLE 3

CHEMICAL ANALYSES OF SOIL SAMPLES TAKEN AT CONCLUSION OF LYSIMETER EXPERIMENTS

(Average of 4 replicates)

Sample no.	Depth	Soluble Cl⁻	Soluble HCO₃⁻	Soluble CO₃⁻	Soluble Ca⁺⁺	Soluble Mg⁺⁺	Soluble K⁺	Soluble Na⁺	Exchangeable Ca⁺⁺	Exchangeable Mg⁺⁺	Exchangeable K⁺	Exchangeable Na⁺	Exchange capacity
	inches	m.e./l*	m.e./l*	m.e./l*	m.e./l*	m.e./l*	m.e./l*	m.e./l*	m.e./100 gm	m.e./100 gm	m.e./100 gm	m.e./100 gm	m.e./100 gm
1	0-6	6.58	0.67	0.00	2.77	0.18	0.094	5.38	12.6	0.50	0.15	0.79	13.4
1	6-18	17.2	0.28	0.00	5.44	0.70	0.078	11.4	11.4	0.95	0.11	1.18	12.9
1	18-24	29.0	0.30	0.00	6.82	3.28	0.089	19.9	9.71	2.50	0.10	1.68	12.8
2	0-6	5.07	1.07	0.00	0.77	0.10	0.054	6.38	11.2	0.84	0.14	1.67	12.9
2	6-18	18.7	0.30	0.00	2.00	0.86	0.064	16.4	8.80	2.50	0.10	2.43	12.6
2	18-24	33.4	0.28	0.00	3.40	2.21	0.080	30.2	8.17	2.95	0.10	3.21	12.3
3	0-6	7.08	1.01	0.00	0.22	0.15	0.048	9.76	6.81	2.12	0.13	4.53	13.2
3	6-18	23.4	0.30	0.00	0.86	0.62	0.050	23.5	7.02	2.34	0.09	4.72	13.0
3	18-24	38.0	0.35	0.00	1.89	1.39	0.070	34.8	7.42	2.63	0.11	5.00	12.9
4	0-6	2.91	2.82	0.00	2.85	0.10	0.046	5.69	16.0	0.88	0.15	1.19	13.3
4	6-18	7.48	0.91	0.00	1.31	0.51	0.032	7.55	12.4	2.68	0.10	1.76	12.9
4	18-24	16.6	0.74	0.00	1.23	0.90	0.033	16.2	9.96	4.01	0.08	3.42	12.8
5	0-6	3.15	2.94	0.00	0.78	0.15	0.031	7.74	13.9	1.56	0.12	2.54	12.8
5	6-18	9.85	0.86	0.00	0.40	0.30	0.024	11.6	9.42	3.12	0.11	4.39	12.5
5	18-24	17.9	0.80	0.00	0.48	0.33	0.030	19.6	8.43	2.96	0.10	6.27	12.4
6	0-6	4.24	2.50	0.00	0.32	0.12	0.022	10.1	7.94	2.40	0.19	6.04	13.2
6	6-18	11.3	1.02	0.00	0.33	0.13	0.024	14.0	7.58	2.54	0.17	6.36	13.0
6	18-24	19.4	1.69	0.00	0.58	0.25	0.029	22.4	7.71	2.87	0.16	6.54	12.8
7	0-6	2.22	2.77	0.00	1.26	0.10	0.039	5.29	16.1	0.66	0.10	1.15	13.4
7	6-18	5.64	1.34	0.00	0.94	0.24	0.028	6.78	12.2	2.86	0.08	1.96	12.9
7	18-24	12.8	1.60	0.00	0.93	0.57	0.038	13.8	10.2	3.98	0.08	3.46	12.7
8	0-6	2.35	3.60	0.04	0.86	0.17	0.032	7.64	13.7	1.79	0.10	2.43	13.3
8	6-18	6.23	1.29	0.00	0.34	0.14	0.024	8.64	9.88	2.94	0.09	4.13	12.8
8	18-24	12.8	1.68	0.14	0.42	0.12	0.029	14.5	8.95	3.20	0.08	5.70	12.7
9	0-6	2.63	3.32	0.00	0.28	0.20	0.030	9.10	8.48	2.62	0.12	6.06	12.6
9	6-18	7.42	1.72	0.00	0.25	0.14	0.026	10.9	7.72	2.80	0.10	6.56	12.2
9	18-24	12.9	3.39	0.47	0.37	0.24	0.030	18.1	8.02	3.28	0.09	7.28	12.4

to pass a 2-mm sieve. The following determinations were made: pH and electrical conductivity of the saturation extract; soluble ions in the saturation extract; per cent lime; NH_4Ac-extractable cations; and the NH_4Ac exchange capacity. Average results for the four replicates are given in tables

TABLE 4

CHEMICAL ANALYSES OF SOIL SAMPLES TAKEN AT CONCLUSION
OF LYSIMETER EXPERIMENT

(Average of 4 replicates)

Sample no.	Depth	pH*	Conduc-tivity*	Lime	SAR*	ESP		Sum of exch. bases	Base sat.
						est.†	actual		
	inches		*mmho/cm*	*% CaCO₃*	$\sqrt{mm/l}$			*m.e./100 g*	*per cent*
1................	0–6	6.1	0.88	0.00	4.41	4.9	5.89	14.1	105
1................	6–18	5.8	2.01	0.00	7.86	9.1	9.13	13.7	106
1................	18–24	6.1	3.23	0.00	11.6	14	13.1	14.3	111
2................	0–6	6.3	0.74	0.00	9.66	11	12.9	13.8	107
2................	6–18	6.0	2.19	0.00	13.7	16	19.2	13.8	110
2................	18–24	6.2	3.57	0.00	18.1	20	26.1	14.4	118
3................	0–6	6.7	1.08	0.00	22.7	25	34.3	13.6	103
3................	6–18	6.4	2.54	0.00	35.6	34	36.3	14.2	109
3................	18–24	6.7	3.99	0.00	27.2	28	38.9	15.2	118
4................	0–6	7.8	0.82	0.04	4.90	5.5	8.92	18.2	137
4................	6–18	7.6	1.05	0.01	7.92	9.2	13.7	16.8	130
4................	18–24	7.6	2.04	0.01	15.7	18	26.8	17.5	135
5................	0–6	7.9	0.82	0.01	11.3	13	19.9	18.1	142
5................	6–18	7.7	1.34	0.00	19.6	22	35.1	17.0	136
5................	18–24	7.8	2.23	0.01	37.0	35	50.8	17.7	144
6................	0–6	7.6	1.00	0.01	21.5	23	45.7	16.6	126
6................	6–18	7.6	1.57	0.01	29.2	29	49.0	16.6	128
6................	18–24	8.0	2.47	0.02	34.7	33	51.2	17.3	136
7................	0–6	7.9	0.70	0.04	5.19	6.0	8.59	18.0	135
7................	6–18	7.9	0.85	0.02	8.83	10	15.2	17.0	132
7................	18–24	8.0	1.64	0.03	15.9	18	27.2	17.7	139
8................	0–6	8.0	0.80	0.02	10.6	12	18.2	18.0	136
8................	6–18	8.0	0.97	0.01	17.6	20	32.2	17.0	133
8................	18–24	8.0	1.65	0.02	27.9	28	44.8	17.9	141
9................	0–6	8.0	0.91	0.00	18.6	21	48.2	17.3	138
9................	6–18	8.0	1.21	0.02	24.6	26	53.7	17.2	140
9................	18–24	8.3	1.97	0.10	32.8	32	58.9	18.7	151

* Saturation extract, 25° C.
† From the analyses of the extracts.

3 and 4. The complete chemical data are given in Appendix Table A, pages 166 to 169.

Sodium and potassium were determined by flame photometry, and Ca^{++} and Mg^{++} were determined in duplicate by titration with versenate. The saturation water content in all cases was 44 per cent. Lime was determined by the method of Hutchinson and MacLennan (1914), and corrected for soluble HCO_3^- and CO_3^{--}. The values given for exchangeable Ca^{++} have been corrected for the lime dissolved in the extraction with NH_4Ac. (This correction assumes

that all of the insoluble lime found by the method of Hutchinson and Mac-Lennan dissolves in NH_4Ac. If less lime than this actually dissolved, the values for exchangeable Ca^{++} given are low.) The cation exchange capacity was determined with NH_4Ac at pH 7.0.

RESULTS AND DISCUSSION

The analytical results (tables 3 and 4) show that the amount of soluble salts increased in all cases and at all depths. The lowest conductivity observed was 0.7 mmho/cm, in contrast to the value of 0.29 mmho/cm on the original soil. The highest values approached 4 mmho/cm, reflecting a salt content which may be injurious to very sensitive crops. In the field, therefore, greater leaching would apparently be desirable.

As expected, the soluble Na^+ and Cl^- contents increased everywhere over the amounts initially found in the soil since all of the irrigation waters contained NaCl. The soluble Ca^{++} increased where the high Ca^{++}, all-chloride water (treatment 1) was used, but decreased in most of the other treatments. The greatest decrease occurred when the high-HCO_3^- waters were used. The soluble Mg^{++} decreased in the surface of the soils treated with the Cl^- waters, but increased with depth. Wherever water containing HCO_3^- was used, soluble Mg^{++} decreased throughout the soil profile. The content of HCO_3^- ions in the soil increased throughout.

The conductivity values (table 4) increased with depth in all cases. Similar results were obtained by Harding *et al.* (1958). This condition was evidently produced by the following processes: The salt carried into the soil by a given irrigation was uniformly distributed with depth to a first approximation. Because the water loss from the system was primarily via transpiration by the plants, and since the alfalfa roots were distributed throughout the lysimeters, there was probably little salt redistribution as the soils dried. During the next irrigation, the infiltrating water displaced salts downward, and the repetition of this process in the course of many irrigations produced the downward gradients. The distribution is thus quite different from that to be expected if appreciable amounts of water were removed from the surface by evaporation.

The soluble Na^+ and Cl^- contents increased with depth by appreciable factors in all cases, whereas the soluble Ca^{++} increased with depth only when the purely Cl^- waters (treatments 1, 2, 3) were used. In the other cases, soluble Ca^{++} and HCO_3^- decreased with depth. No general pattern of soluble Ca^{++} distribution emerged where HCO_3^- waters were applied. The soluble Mg^{++} increased with depth following the use of purely Cl^- waters, probably as a result of the exchange of Mg^{++} from the soil and its downward displacement. Where waters containing HCO_3^- were used, the soluble Mg^{++} either increased much less rapidly with depth or actually decreased.

In all cases, the exchangeable Na^+ content increased over the amount initially present in the soil. As expected, the increases were greatest when Ca^{++} was not added to the irrigation water (treatments 3, 6, 9). The highest exchangeable Na^+ percentages were produced when HCO_3^- was added. For a given level of HCO_3^- concentration, decreasing Ca^{++} in the irrigation water

resulted in an increase in exchangeable Na^+ in the soil. However, for a given cation ratio in the irrigation water, the amount of exchangeable Na^+ produced does not appear closely related to the amount of HCO_3^- in the water (compare treatments 2, 5, and 8, for example). This is in contrast to what might be expected from Eaton's (1950) principle. It is of further interest that the $CaCO_3$ analyses do not reflect levels that bear any relationship to the amounts of exchangeable Na^+ produced. (To see this, 0.01 per cent lime $\approx$ 0.20 m.e./100 gm of soil.) The failure of $CaCO_3$ to precipitate was probably the result of the high CO_2 partial pressure caused by root respiration. (It is of interest in this connection that, in many instances, $CaCO_3$ was observed to precipitate in the leachates after a short period of standing in the pans.)

The amounts of exchangeable Ca^{++} tended to increase when the irrigation waters were high in Ca^{++} (treatments 1, 4, 7), and decreased when Ca^{++} was absent (treatments 3, 6, 9). Again, these changes appear to be more closely related to the cation ratio than to the anion composition of the irrigation water. In fact, when waters of comparable cation ratios were used, a greater exchangeable Ca^{++} resulted in the case of water high in HCO_3^- (treatment 7) than in the case of the purely Cl^- water (treatment 1). This was also true when Ca^{++} was not added to the water (compare treatments 3 and 9). These results also are not consistent with Eaton's (1950) principle.

As expected from the fact that Mg^{++} was absent in the irrigation waters, the exchangeable Mg^{++} of the soils was generally decreased by exchange and leaching. Exchangeable K^+ was either essentially unchanged or decreased.

As with the soluble constituents, appreciable increases occurred in the exchangeable Na^+ content with depth. These gradients were weakest where purely Na^+ waters were applied (treatments 3, 6, 9). These results are contrary to what would be expected from ion-exchange chromatographic effects which are thought to occur when Na^+-bearing waters are applied to a Ca^{++}-dominated soil. The explanation is apparently connected with the well-known "cation-dilution effect" (for example, see Reitemeier [1946]). According to this principle, when a soil containing Ca^{++} and Na^+ ions is diluted, some exchangeable Na^+ is replaced on the exchange complex by Ca^{++}. The exchangeable Na^+ thus decreases on dilution, and there is an increase in the exchangeable Ca^{++}. The increases in exchangeable Na^+ with depth observed in the lysimeters presumably resulted from a reversal of this process. The salt concentration increases with depth, as a result of the mechanism described above, and produces increasing exchangeable Na^+ contents.

The values of the SAR determined on the saturation extracts are given in table 4 together with the values of the ESP predicted from the nomogram used by the Salinity Laboratory. At low values of ESP, the predicted values agree well with those obtained experimentally, but serious discrepancies appear when the ESP is high. This may be connected with the apparent excess base saturation indicated in table 4 and discussed further below.

The exchangeable Ca^{++} content of the soil decreased appreciably with depth except where purely Na^+ waters were applied (treatments 3, 6, 9). It is in just such cases as the latter that the greatest decreases would be ex-

pected on the basis of chromatographic effects, again illustrating the significance of the salt-movement mechanism and cation-dilution principle discussed above.

It has been emphasized that the increases in exchangeable Na^+ and decreases in exchangeable Ca^{++} occurring in this soil were not the result of $CaCO_3$ precipitation. It is interesting to note that wherever the application of HCO_3^- waters produced an increase in exchangeable Na^+, an apparent excess base saturation was also encountered. Excess base saturation, for which several explanations are possible, has been noted in neutral and alkaline soils for many years. The fixation of NH_4^+ during the exchange-capacity determination would lead to apparent excess saturation, but this is clearly not the explanation in the present case since the NH_4Ac exchange capacities are essentially independent of the treatments. It has been pointed out that leaching soils having a high pH with NH_4Ac at pH 7.0 will increase the amounts of exchangeable hydrogen held and therefore introduce a discrepancy between the bases extracted and the NH_4Ac exchange capacity. It is difficult, however, to imagine that the Columbia soil used in this experiment would be 25 per cent H^+ saturated at pH 7.0. (Additional evidence to be reported elsewhere supports this view.) The chelation of Ca^{++} or Mg^{++} by soil organic matter may account for excess saturation, but independent evidence not presented here indicates that such effects will not account for the magnitude of excess saturation encountered. On the basis of their experimental evidence, Bower and Truog (1940) have postulated that, in neutral soils, calcium and magnesium can be adsorbed as the ion species $(CaOH)^+$ and $(MgOH)^+$. The data obtained in this experiment are consistent with the assumption that such ion species account for an apparent excess cation adsorption. If this is the case, $(CaOH)^+$ and $(MgOH)^+$ must be much more strongly adsorbed than are Ca^{++} and Mg^{++}. For example, Harned and Owen (1950) give the following value for the dissociation constant of $(CaOH)^+$:

$$\frac{(Ca^{++})\ (OH^-)}{(CaOH)^+} = 3.1 \times 10^{-2}$$

Thus, in solution at pH 8.0, the ratio $\dfrac{Ca^{++}}{(CaOH)^+}$ has the value of 3.1×10^4; yet at this pH, appreciable excess cation adsorption is noted, indicating that very significant amounts of $(CaOH)^+$ may be adsorbed.

Where the amounts of applied HCO_3^- are equal to or greater than the amounts of Cl^- applied, comparable degrees of accumlation of the two ions would be expected. The Cl^- accumulation, however, is much more marked. This disappearance of HCO_3^- possibly indicates that $(CaOH)^+$ is formed by the following reaction:

$$H_2O + Ca^{++} + HCO_3^- = (CaOH)^+ + H_2CO_3$$
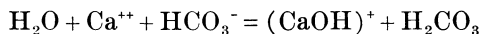
CO_2 would then be lost from the system through the dissolution of H_2CO_3 to CO_2 and H_2O. The equilibrium for this reaction would lie to the right since the $(CaOH)^+$ formed is adsorbed.

It is of interest to note that wherever HCO_3^- waters were applied, the pH and degree of excess cation adsorption did not show much change, either with the water used or with depth. The constancy of the pH probably results from the fact that where the exchangeable Na^+ is high, the salt concentration is also high, and there is a repression of the hydrolysis of Na^+. The absence of depth gradients in excess base saturation conceivably reflects the fact that, where exchangeable Ca^{++} decreases appreciably with depth, exchangeable Mg^{++} increases. It is expected that the $(MgOH)^+$ complex would be less dissociated than the $(CaOH)^+$.

The data on total yields (table 5) appear to indicate significant differences among the treatments. These differences, however, are actually the result of

TABLE 5

TOTAL YIELD OF ALFALFA PER LYSIMETER, AND
YIELDS FOR TWO HARVESTS

(Average of 4 replicates)

Treatment no.	Total yield per lysimeter	Average yield per lysimeter	
		Harvested Dec. 6, 1955	Harvested June 21, 1956
	gm dry wt	*gm dry wt*	*gm dry wt*
1	1,870	34.8	184
2	1,957	38.0	183
3	1,984	41.5	165
4	2,176	48.5	198
5	2,255	52.0	199
6	2,351	50.0	182
7	2,214	50.2	188
8	2,231	51.5	184
9	2,405	55.8	184

fertility problems induced by the treatments. The harvest of December 6, 1955, for example, shows the greatest yields in the tanks containing the highest exchangeable Na^+ content. These apparently anomalous results do not appear in the harvest of June 21, 1956, which was made following a fertilization with $NH_4(H_2PO_4)$.

Examples of the leachate data obtained are given in table 6. During the course of the experiment, the ratio of $Ca^{++} + Mg^{++}$ to Na^+ in the leachates dropped from very high values to values below that of the applied water in cases where HCO_3^- was present. This possibly reflects the formation and adsorption of $(CaOH)^+$ in the soil.

In summary, the results of the experiment show that the application of HCO_3^--bearing waters results in an increase in exchangeable Na^+ content and the production of apparently excess cation adsorption. Following a cropping regime, the soluble salts and exchangeable Na^+ were found to increase markedly with depth. The mechanism of exchangeable Na^+ production involves the cation dilution effect and possibly the production of $(CaOH)^+$ and $(MgOH)^+$, rather than $CaCO_3$ precipitation, at least under the conditions of

this experiment. Thus, the estimation of the exchangeable sodium percentage in equilibrium with a given irrigation water, based on exchange equations or on Eaton's (1950) principle, may not serve to predict field behavior when a crop is grown. Furthermore, the presence of a crop may reverse expected chromatographic effects.

TABLE 6

VOLUME OF LEACHATE RECOVERED FROM LYSIMETERS, AND ANALYSES OF LEACHATES OF JANUARY 10, 1954, AND JUNE 10, 1956

(Average of 4 replicates)

Treatment no.	Total volume irrigation water applied	Total leach recovered		Cation ratio $\dfrac{Ca^{++} + Mg^{++}}{Na^+}$		
				in H_2O applied	leachate 1/10/54	leachate 6/10/56
	liters	*liters*	*per cent of applied*			
1...............................	1,664*	202	12.1	1.0	15.0	1.33
2...............................	1,664	189	11.4	0.30	12.9	0.53
3...............................	1,664	173	10.4	0	10.0	0.21
4...............................	1,664	128	7.74	1.0	24.9	0.44
5...............................	1,664	132	7.98	0.30	14.2	0.18
6...............................	1,664	129	7.80	0	12.8	0.10
7...............................	1,664	138	8.34	1.0	16.9	0.24
8...............................	1,664	147	8.90	0.30	8.78	0.11
9...............................	1,664	137	8.30	0	16.4	0.08

* With the lysimeters used. this amount of water corresponded to 30.2 feet.

**Appendix Table A begins on
the following page.**

CHEMICAL ANALYSES OF SOIL SAMPLES TAKEN FROM EACH TANK AT END OF THE EXPERIMENT

(Average values areg iven in text tables 3 and 4.)

Sample no.*	Depth	Soluble Cl⁻	Soluble HCO₃⁻	Soluble CO₃⁻⁻	Soluble Ca⁺⁺	Soluble Mg⁺⁺	Soluble K⁺	Soluble Na⁺	Exch. Ca⁺⁺	Exch. Mg⁺⁺	Exch. K⁺	Exch. Na⁺	Exch. cap.	pH†	Conductivity†	Lime	ESP
	inches	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./100 gm	m.e./100 gm	m.e./100 gm	m.e./100 gm	m.e./100 gm		mmho/cm	per cent CaCO₃	
1:																	
A	0–6	8.53	0.66	0.00	3.90	0.27	0.089	6.00	12.5	0.42	0.15	0.78	13.1	6.0	1.07	0.00	5.96
B	0–6	5.84	0.61	0.00	2.43	0.15	0.139	5.10	12.6	0.42	0.15	0.82	13.4	6.2	0.72	0.00	6.12
C	0–6	5.55	0.78	0.00	2.18	0.10	0.067	4.75	12.7	0.54	0.14	0.76	13.5	6.0	0.78	0.00	5.63
D	0–6	6.39	0.64	0.00	2.58	0.20	0.080	5.65	12.8	0.62	0.15	0.80	13.7	6.1	0.94	0.00	5.84
1:																	
A	6–18	17.7	0.31	0.00	5.32	0.81	0.084	11.8	11.4	0.95	0.10	1.33	12.8	6.1	2.03	0.01	10.4
B	6–18	17.3	0.31	0.00	5.64	0.57	0.076	11.7	11.5	0.89	0.11	1.20	13.0	6.2	2.06	0.00	9.23
C	6–18	18.2	0.25	0.00	5.28	0.78	0.080	12.0	11.0	1.02	0.12	1.26	12.9	5.4	2.13	0.00	9.78
D	6–18	15.5	0.25	0.00	5.52	0.64	0.071	10.3	11.8	0.94	0.11	0.93	13.0	5.7	1.83	0.00	7.15
1:																	
A	18–24	27.6	0.31	0.00	6.82	3.61	0.080	17.5	10.0	2.62	0.10	1.66	12.9	6.1	3.05	0.00	12.9
B	18–24	29.1	0.32	0.00	6.67	3.29	0.093	20.0	9.53	2.50	0.10	1.69	13.0	6.1	3.28	0.00	13.0
C	18–24	30.4	0.29	0.00	5.58	3.01	0.089	22.8	9.31	2.62	0.09	2.07	12.6	6.4	3.34	0.00	16.4
D	18–24	28.8	0.27	0.00	8.21	3.19	0.093	19.3	10.0	2.28	0.11	1.29	12.9	5.8	3.23	0.00	10.0
2:																	
A	0–6	4.38	1.23	0.00	0.95	0.08	0.062	7.20	11.3	0.77	0.14	1.68	12.7	6.3	0.79	0.00	13.2
B	0–6	6.10	0.89	0.00	0.64	0.02	0.042	5.80	11.4	0.79	0.12	1.67	12.6	6.4	0.65	0.00	13.3
C	0–6	4.34	1.29	0.00	0.72	0.17	0.062	6.00	11.0	0.84	0.15	1.55	13.0	6.3	0.68	0.00	11.9
D	0–6	5.45	0.88	0.00	0.78	0.13	0.051	6.50	11.0	0.98	0.14	1.77	13.3	6.3	0.82	0.00	13.3
2:																	
A	6–18	18.9	0.28	0.00	1.95	0.83	0.071	16.8	8.97	2.12	0.10	2.58	12.2	5.8	2.21	0.00	21.1
B	6–18	18.2	0.27	0.00	2.36	0.90	0.060	16.0	8.40	3.14	0.10	2.15	12.3	6.0	2.16	0.00	17.5
C	6–18	13.4	0.42	0.00	1.17	0.46	0.055	13.0	9.01	2.23	0.11	2.37	12.9	6.2	1.63	0.01	18.4
D	6–18	24.2	0.25	0.00	2.50	1.27	0.071	20.0	8.84	2.51	0.10	2.62	13.2	6.0	2.75	0.00	19.9
2:																	
A	18–24	31.3	0.35	0.00	2.66	1.65	0.076	29.4	8.08	2.77	0.10	3.62	12.0	6.1	3.56	0.00	30.1
B	18–24	34.0	0.19	0.00	4.63	2.84	0.089	30.9	8.34	2.85	0.10	2.54	11.9	6.4	3.86	0.00	20.6

A.............	0–6	7.58	1.04	0.00	0.22	0.08	0.053	20.0	6.59	1.93	0.12	4.76	12.9	6.6	1.12	0.00	36.9
B.............	0–6	7.46	0.79	0.00	0.18	0.12	0.035	9.40	6.86	2.04	0.11	4.78	13.1	6.6	1.07	0.00	36.5
C.............	0–6	6.68	1.18	0.00	0.22	0.22	0.053	10.0	6.85	2.31	0.15	4.44	13.5	6.9	1.08	0.01	32.9
D.............	0–6	6.62	1.04	0.00	0.24	0.18	0.051	9.65	6.94	2.18	0.14	4.15	13.4	6.7	1.05	0.00	30.9
3:																	
A.............	6–18	26.5	0.29	0.00	0.82	0.61	0.057	26.4	6.82	2.25	0.09	5.13	12.9	6.3	3.01	0.00	39.7
B.............	6–18	29.2	0.34	0.00	1.37	0.87	0.062	29.0	7.35	2.26	0.10	4.33	13.0	6.3	3.33	0.00	33.3
C.............	6–18	23.5	0.34	0.00	0.80	0.59	0.044	23.7	7.17	2.52	0.09	4.14	13.0	6.7	2.03	0.01	31.5
D.............	6–18	14.6	0.25	0.00	0.44	0.41	0.037	14.9	6.74	2.33	0.09	4.28	13.0	6.4	1.76	0.01	32.9
3:																	
A.............	18–24	14.4	0.32	0.00	1.73	1.29	0.062	37.6	7.34	2.59	0.08	5.38	12.6	6.7	4.42	0.00	42.7
B.............	18–24	46.2	0.33	0.00	3.18	2.18	0.103	42.0	7.99	2.65	0.10	4.74	13.2	6.7	5.18	0.00	35.9
C.............	18–24	36.4	0.48	0.00	1.67	1.43	0.062	35.0	7.18	2.82	0.14	5.22	12.7	6.9	3.53	0.01	41.1
D.............	18–24	25.0	0.27	0.00	0.99	0.66	0.051	24.6	7.18	2.47	0.12	4.67	13.0	6.5	2.85	0.00	35.9
4:																	
A.............	0–6	2.34	3.20	0.00	3.16	0.06	0.055	6.30	15.6	0.80	0.14	1.16	13.5	7.8	0.92	0.05	8.59
B.............	0–6	2.61	3.17	0.00	2.34	0.06	0.037	5.25	16.2	0.91	0.12	1.43	13.8	7.8	0.75	0.03	10.4
C.............	0–6	2.80	2.44	0.00	2.13	0.09	0.037	5.10	16.1	0.86	0.17	1.08	12.9	7.8	0.71	0.03	8.37
D.............	0–6	3.89	2.45	0.00	2.68	0.20	0.055	6.10	15.9	0.96	0.16	1.09	13.1	7.8	0.88	0.04	8.32
4:																	
A.............	6–18	8.49	0.91	0.00	1.51	0.55	0.042	8.00	12.1	2.70	0.09	1.71	13.1	7.6	1.16	0.01	13.0
B.............	6–18	5.92	0.81	0.00	1.00	0.43	0.021	6.20	12.4	2.69	0.08	1.72	13.2	7.7	0.85	0.01	13.0
C.............	6–18	7.36	0.79	0.00	1.15	0.48	0.028	7.55	12.5	2.63	0.10	1.87	12.5	7.7	1.02	0.01	15.0
D.............	6–18	8.14	1.12	0.00	1.57	0.57	0.037	8.45	12.4	2.72	0.12	1.75	12.7	7.6	1.17	0.02	13.8
4:																	
A.............	18–24	18.1	0.72	0.00	1.35	0.97	0.035	17.6	9.73	4.09	0.08	3.47	13.2	7.7	2.20	0.01	26.3
B.............	18–24	13.9	0.71	0.00	1.00	0.79	0.026	13.6	10.0	4.03	0.07	3.25	13.2	7.7	1.74	0.01	24.6
C.............	18–24	18.1	0.80	0.00	1.35	0.99	0.035	17.8	10.0	4.04	0.09	3.56	12.4	7.6	2.20	0.01	28.7
D.............	18–24	16.4	0.74	0.00	1.23	0.85	0.035	16.0	10.1	3.87	0.10	3.40	12.4	7.6	2.02	0.01	27.5
5:																	
A.............	0–6	3.35	3.22	0.00	0.72	0.09	0.030	7.85	13.2	1.52	0.11	2.72	12.6	7.9	0.80	0.01	21.6
B.............	0–6	2.88	2.50	0.00	0.95	0.22	0.033	7.40	13.5	1.65	0.12	2.18	12.4	7.9	0.82	0.01	17.6
C.............	0–6	3.39	3.42	0.00	0.77	0.16	0.033	8.15	13.4	1.60	0.13	2.77	13.0	7.9	0.86	0.01	21.3
D.............	0–6	2.98	2.62	0.00	0.70	0.13	0.028	7.55	15.5	1.59	0.12	2.51	13.1	7.8	0.80	0.00	19.2

* A, B, C, D = replications.
† Saturation extract.

Sample no. *	Depth	Soluble Cl⁻	Soluble HCO₃⁻	Soluble CO₃⁻	Soluble Ca⁺⁺	Soluble Mg⁺⁺	Soluble K⁺	Soluble Na⁺	Exch. Ca⁺⁺	Exch. Mg⁺⁺	Exch. K⁺	Exch. Na⁺	Exch. cap.	pH†	Conductivity†	Lime	ESP
	inches	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./lt	m.e./100 gm	m.e./100 gm	m.e./100 gm	m.e./100 gm	m.e./100 gm		mmho/cm	per cent CaCO₃	
5:																	
A	6-18	13.8	0.81	0.00	0.54	0.34	0.028	15.0	9.22	3.03	0.12	4.94	12.3	7.6	1.76	0.01	40.2
B	6-18	9.30	0.78	0.00	0.38	0.18	0.030	11.2	9.22	3.07	0.10	4.33	12.2	7.6	1.29	0.00	35.5
C	6-18	8.24	1.03	0.00	0.36	0.41	0.019	10.3	9.71	3.11	0.10	4.37	12.7	7.8	1.18	0.00	34.4
D	6-18	8.06	0.82	0.00	0.30	0.26	0.021	9.80	9.52	3.25	0.12	3.91	12.9	7.6	1.15	0.00	30.3
5:																	
A	18-24	26.0	0.68	0.00	0.76	0.51	0.037	27.8	8.24	2.91	0.09	6.47	12.0	7.7	3.07	0.01	53.9
B	18-24	12.3	0.86	0.00	0.36	0.20	0.021	14.4	8.19	2.93	0.09	6.15	11.9	7.9	1.66	0.01	51.7
C	18-24	18.8	0.81	0.00	0.48	0.33	0.033	20.3	8.70	3.04	0.09	6.32	12.7	7.8	2.34	0.01	49.8
D	18-24	14.5	0.86	0.00	0.34	0.27	0.028	16.0	8.59	2.96	0.14	6.15	12.8	7.7	1.84	0.00	48.0
6:																	
A	0-6	5.84	2.50	0.00	0.32	0.10	0.024	10.4	8.23	2.38	0.20	5.91	13.3	7.7	1.08	0.00	44.4
B	0-6	3.70	2.38	0.00	0.30	0.08	0.019	9.50	7.70	2.37	0.18	6.37	13.2	7.8	0.95	0.00	48.2
C	0-6	3.47	2.57	0.00	0.36	0.18	0.024	10.4	8.04	2.37	0.19	5.85	13.2	7.5	0.98	0.00	44.3
D	0-6	3.94	2.70	0.00	0.30	0.14	0.019	10.2	7.77	2.50	0.20	6.02	13.1	7.6	1.01	0.01	46.0
6:																	
A	6-18	13.1	0.86	0.00	0.32	0.16	0.024	15.4	7.46	2.44	0.17	6.24	12.7	7.6	1.74	0.01	49.1
B	6-18	11.2	1.29	0.00	0.34	0.10	0.021	13.8	7.40	2.60	0.17	6.45	13.1	7.8	1.57	0.01	49.2
C	6-18	8.67	1.11	0.00	0.28	0.12	0.024	11.8	7.57	2.44	0.16	6.31	13.0	7.3	1.30	0.00	48.5
D	6-18	12.3	0.81	0.00	0.38	0.14	0.026	14.8	7.90	2.61	0.17	6.46	13.1	7.7	1.68	0.00	49.3
6:																	
A	18-24	27.4	0.85	0.00	0.77	0.42	0.037	29.3	7.93	2.88	0.16	6.13	12.9	7.7	3.25	0.02	47.5
B	18-24	13.0	2.60	0.00	0.46	0.12	0.024	17.2	7.48	2.83	0.16	6.58	12.6	8.2	1.87	0.04	52.2
C	18-24	14.6	2.06	0.00	0.52	0.18	0.026	18.0	7.70	2.89	0.16	6.90	12.9	8.2	1.98	0.02	53.5
D	18-24	22.7	1.25	0.00	0.58	0.27	0.028	24.9	7.73	2.87	0.17	6.53	12.6	8.0	2.77	0.02	51.8
7:																	
A	0-6	2.57	3.16	0.00	2.30	0.08	0.044	5.45	17.0	0.68	0.12	1.08	13.8	7.9	0.75	0.02	7.83
B	0-6	1.87	2.61	0.00	1.71	0.08	0.033	5.45	15.9	0.59	0.10	1.16	13.4	8.0	0.65	0.04	8.65
C	0-6	2.47	2.61	0.00	1.85	0.23	0.039	5.70	15.9	0.72	0.10	1.32	13.3	7.9	0.74	0.07	9.93
D	0-6	1.99	2.70	0.00	2.00	0.02	0.039	4.55	16.1	0.67	0.10	1.04	13.1	7.9	0.64	0.04	7.94
7:																	
A	6-18	5.57	1.45	0.00	0.81	0.28	0.026	6.80	12.6	2.94	0.08	1.98	13.1	7.9	0.86	0.00	15.1
B	6-18	4.13	1.51	0.00	0.64	0.13	0.021	5.95	11.9	2.76	0.08	2.13	12.9	8.0	0.73	0.01	16.5

	Range																
B	18-24	12.6	1.59	0.00	0.74	0.39	0.030	13.4	10.4	3.74	0.07	3.24	12.9	8.1	1.68	0.03	25.1
C	18-24	16.1	1.26	0.00	1.25	0.87	0.062	16.0	10.0	3.98	0.08	3.27	12.2	7.8	2.02	0.02	26.8
D	18-24	10.1	1.76	0.00	0.81	0.47	0.030	11.5	10.3	4.05	0.08	3.22	12.8	8.0	1.21	0.04	25.2
8:																	
A	0-6	2.42	3.52	0.00	0.87	0.08	0.033	7.65	13.7	1.64	0.10	2.50	13.5	8.1	0.80	0.02	18.5
B	0-6	1.91	3.56	0.15	0.91	0.17	0.033	7.20	13.8	1.69	0.11	2.28	13.3	8.1	0.79	0.03	17.1
C	0-6	2.06	3.61	0.00	0.73	0.18	0.030	7.10	13.6	1.83	0.09	2.39	13.2	8.0	0.66	0.04	18.1
D	0-6	3.02	3.70	0.00	0.93	0.25	0.033	8.60	13.8	2.00	0.11	2.54	13.3	7.9	0.95	0.01	19.1
8:																	
A	6-18	7.15	1.08	0.00	0.42	0.10	0.028	9.05	9.75	2.61	0.08	4.01	12.7	8.0	0.92	0.01	31.6
B	6-18	6.01	1.27	0.00	0.38	0.10	0.024	8.45	9.90	2.91	0.08	3.87	12.8	8.0	0.99	0.01	30.2
C	6-18	6.30	1.58	0.00	0.30	0.18	0.021	8.45	10.1	3.21	0.10	4.08	12.8	7.8	0.99	0.00	31.9
D	6-18	5.46	1.24	0.00	0.28	0.20	0.024	8.60	9.78	3.02	0.10	4.56	12.9	8.0	0.97	0.01	35.3
8:																	
A	18-24	12.9	1.32	0.00	0.46	0.20	0.028	14.8	9.08	3.01	0.08	5.38	12.7	8.0	1.72	0.01	42.4
B	18-24	11.3	1.89	0.28	0.46	0.12	0.028	14.6	8.74	3.20	0.08	6.03	12.6	8.2	1.64	0.03	47.8
C	18-24	12.9	1.00	0.00	0.40	0.31	0.030	14.8	9.10	3.30	0.07	5.39	12.8	7.9	1.73	0.01	42.1
D	18-24	10.3	2.50	0.28	0.36	0.26	0.030	13.8	8.87	3.28	0.09	6.00	12.8	8.2	1.51	0.04	46.9
9:																	
A	0-6	2.26	3.42	0.00	0.28	0.22	0.030	9.80	8.49	2.78	0.11	6.51	13.0	8.1	0.92	0.01	50.1
B	0-6	3.74	3.09	0.00	0.30	0.22	0.033	9.80	8.86	2.56	0.10	6.43	13.0	8.0	1.02	0.03	49.5
C	0-6	2.26	3.84	0.00	0.28	0.20	0.030	8.75	8.18	2.60	0.13	5.82	12.2	8.0	0.88	0.01	47.7
D	0-6	2.26	2.93	0.00	0.24	0.14	0.028	8.05	8.41	2.54	0.12	5.49	12.1	8.1	0.83	0.00	45.4
9:																	
A	6-18	5.61	1.95	0.00	0.20	0.18	0.024	9.50	7.88	2.61	0.08	6.62	12.0	8.1	1.04	0.00	55.2
B	6-18	11.6	1.35	0.00	0.32	0.10	0.030	14.2	7.89	2.88	0.09	6.85	12.2	7.7	1.63	0.01	56.1
C	6-18	6.47	2.12	0.00	0.24	0.18	0.026	10.8	7.22	2.87	0.12	6.54	12.4	8.1	1.18	0.05	52.7
D	6-18	6.00	1.50	0.00	0.24	0.12	0.026	9.20	7.88	2.86	0.12	6.24	12.3	7.9	1.03	0.01	50.7
9:																	
A	18-24	10.4	3.15	0.60	0.36	0.22	0.026	15.8	8.20	3.33	0.07	7.54	12.3	8.4	1.72	0.09	61.3
B	18-24	14.5	3.12	0.34	0.40	0.24	0.033	19.0	8.31	3.17	0.08	7.40	12.7	8.3	2.13	0.07	58.3
C	18-24	13.2	3.44	0.40	0.34	0.26	0.028	18.8	7.20	3.32	0.11	7.23	12.0	8.4	1.99	0.14	60.2
D	18-24	13.6	3.65	0.54	0.38	0.24	0.033	18.8	8.37	3.32	0.11	6.96	12.5	8.3	2.02	0.08	55.7

* A, B, C, D = replications.
† Saturation extract.

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