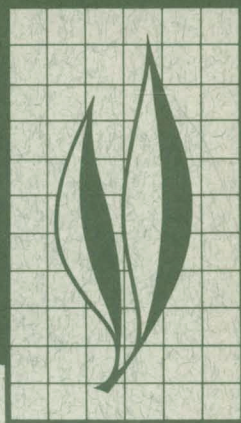


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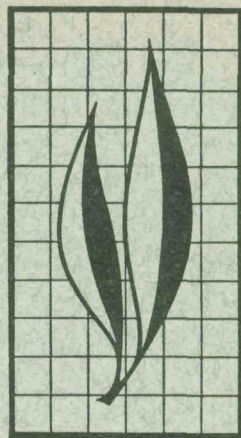


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## Effect of Three Nitrogen Fertilizers on Gains, Losses, and Distribution of Various Elements in Irrigated Lysimeters

P. F. Pratt, G. H. Cannell,  
M. J. Garber, and F. L. Bair





Nitrogen from three sources— $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{Ca}(\text{NO}_3)_2$ ,  $\text{NH}_4\text{OH}$ —was applied to four irrigated soils during a five-year lysimeter experiment. Effects on yields, irrigation water used, salinity of soil and drainage water, and soil acidity were studied. Gains or losses of other elements were also recorded. Yields of Swiss chard and corn were not affected by the  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{Ca}(\text{NO}_3)_2$ , and  $\text{NH}_4\text{OH}$  materials, but the  $\text{Ca}(\text{NO}_3)_2$  resulted in higher nitrogen content of plants. The  $(\text{NH}_4)_2\text{SO}_4$  acidified the soil, caused higher losses of Ca in the drainage water of one soil, and produced higher total salt in all soils. The  $\text{Ca}(\text{NO}_3)_2$  and  $\text{NH}_4\text{OH}$  materials produced similar effects. The Ca in  $\text{Ca}(\text{NO}_3)_2$  was largely precipitated.

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#### THE AUTHORS:

P. F. Pratt is Professor of Soil Science, and Chemist in the Experiment Station, Riverside.

G. H. Cannell is Lecturer in Vegetable Crops, and Associate Soil Physicist in the Experiment Station, Riverside.

M. J. Garber is Professor of Biometry, and Biometrician, Computer Center, Riverside.

F. L. Bair is Laboratory Technician, Department of Soils and Plant Nutrition, Riverside.

# Effect of Three Nitrogen Fertilizers on Gains, Losses, and Distribution of Various Elements in Irrigated Lysimeters<sup>1</sup>

## INTRODUCTION

LYSIMETERS have been used for many years to measure losses of water and mineral elements as a result of cropping and of leaching. Kohnke, Dreibelbis and Davidson (1940) provided a thorough review of the literature and the construction of lysimeters up to that date. Newer types of construction are illustrated in the report by Harrold and Dreibelbis (1958). Most reports on lysimeters have dealt with humid, non-irrigated areas; very few studies have been conducted on gains and losses of mineral elements in irrigated soils. Earlier work at the Citrus Research Center and Agricultural Experiment Station in Riverside has been reported by Chapman, Liebig, and Rayner (1949); Broadbent and Chapman (1949); and Pratt, Branson and Chap-

man (1960). Pratt and Chapman (1961) reported gains and losses of elements during a 20-year lysimeter experiment. Their source of irrigation water was the same as that used in the experiment reported here, and the soil was similar to one of the four soils in the present experiment. In the earlier work, however, only one fertilizer was used.

This paper reports results of a five-year lysimeter experiment with four soils and three nitrogen fertilizers. Input of irrigation water, composition of drainage water, crop yields, and gains or losses of various elements were studied. Depletion or accumulation of the trace elements boron, copper, molybdenum, and zinc, in this experiment, has already been reported (Pratt and Bair, 1964).

## MATERIALS AND METHODS

Twenty-four steel lysimeters, each 4 feet in diameter and 6 feet deep, were installed in a terrace in the winter of 1957-1958. Each was lined with polyethylene to prevent contamination of the contents by the metal container. Polyethylene drains conducted the water from the bottoms of the lysimeter tanks to polyethylene receiving tanks at the bottom of the terrace. Each tank was first covered with a 3-inch layer of pea gravel, after which soil was added 6 inches at a time. After each addition,

the soil was walked over in order to pack it. When the tanks were full, the soil was settled by adding water until it appeared in the drainage lines. The tanks were again filled and rewetted. The final depth of soil plus gravel layer was approximately 69 inches, with 3 inches left for a water reservoir at the top.

The four surface soil materials are described in table 1. Analysis of each load of soil indicated that the material was quite uniform in the characteristics

<sup>1</sup> Submitted for publication May 12, 1966.

TABLE 1  
CHARACTERISTICS OF LYSIMETER SOILS, AND THEIR CATION-EXCHANGE  
CAPACITY AT pH 8

Soil no. and series	pH	CaCO <sub>3</sub>	Total N content	Water at saturation	CEC
		<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>m.e./gm</i>
1. Moreno sandy loam .....	7.3	0.28	0.04	28	0.14
2. Greenfield sandy loam .....	6.8	<0.01	0.04	25	0.08
3. Altamont clay loam .....	7.2	0.10	0.15	48	0.27
4. Holtville clay loam .....	7.8	6.60	0.06	44	0.17

noted in the table. Starting in the winter of 1958–1959, a crop of Swiss chard was grown during each fall and winter, and a crop of sweet corn in each spring and summer. The chard was planted in October and harvested in February. The corn was harvested when the ears were ripe for marketing. Total aboveground parts of the plants were harvested and their dry weight recorded. Plant materials were analyzed, and total removal of elements by plants calculated.

Both irrigation and drainage waters were analyzed for chemical content, and input and removal of the elements found were calculated. The irrigation water contained (m.e. per liter): 2.43 Ca; 0.76 Mg; 1.46 Na; 0.63 Cl; 1.03 SO<sub>4</sub>; 3.00 HCO<sub>3</sub>; and 0.07 K.

Soils were sampled and analyzed for pH and soluble and exchangeable ions before and after the experiment.

Tensiometers were placed at the 8-inch depth in each tank, and water was applied when the suction reached 0.7 to 0.8 bar. Five other tensiometers, placed at 1-foot intervals to indicate water loss between irrigations, were used to determine the amount of water to be added at each irrigation. In the spring, between crops, the tanks were leached to give a volume of drainage about equal to 7 per cent of the volume of irrigation

water applied during the previous year.

Fertilizer treatments consisted of applications of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, Ca(NO<sub>3</sub>)<sub>2</sub>, and NH<sub>4</sub>OH in amounts required to supply N at the same rates. The sulfate and nitrate were dissolved in water and added to the surface soil; irrigation water moved them into the soil. The NH<sub>4</sub>OH was added at the 4-inch level by means of a pipette. About 30 holes were made in the moistened soil, and the pipette delivered NH<sub>4</sub>OH at the bottom of each hole. The holes were then plugged to prevent escape of NH<sub>3</sub>. Following applications of (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and NH<sub>4</sub>OH, the surface soil was kept moist to prevent loss of NH<sub>3</sub> to the atmosphere.

Two replications were made with the soils, and treatments were randomized within each replication.

The rate of N application averaged 3.9 gm equivalents per tank per year or, on an area basis, 420 pounds N per acre per year (470 kg per hectare). During the first year of operation, the rate was 200 pounds per acre. The rate was increased to 600 pounds during the last year in order to maintain high yields as the readily decomposable organic residues in the soils became exhausted. Since each tank had a large border, and neither fertilizer nor water was a limit-



ing factor, very large populations were possible and high yields were obtained. Rates of planting were high, and final stands were dense—45 plants per tank for chard, and 12 for corn. On an acre basis, the corn had 42,000 plants per acre (104,000 per hectare).

The metric system is used to express results. Equivalents used are gram equivalents. Because of the tremendous border effect obtained in growth of

plants, extrapolation to field conditions (acre or hectare basis) is not justified. To convert to an area basis, add 50 per cent to the 12.5 square feet of soil surface of the tanks to adjust arbitrarily for the border effect. We have expressed the data on a tank basis to allow for comparisons within the experiment. Most data, except the means for the soils and treatments, represent averages of two replications.

## RESULTS

**Crop yields.** Data on total dry weight of the aboveground parts of corn plants during the five years of the experiment are presented in table 2. Soils 1 and 3 showed no statistically significant differences in treatment means. In soil 2, yields were highest with  $(\text{NH}_4)_2\text{SO}_4$ ; with the  $\text{Ca}(\text{NO}_3)_2$  and  $\text{NH}_4\text{OH}$ , yields were almost alike. In soil 4, however, the  $\text{Ca}(\text{NO}_3)_2$  produced the highest yield, and  $(\text{NH}_4)_2\text{SO}_4$  produced the lowest. The overall effect of treatments was small, and because there was a treatment-soil interaction the treatment mean differences are difficult to interpret. The means for soils show statistically significant differences, with soil 3 producing the highest yields and soil 2 the lowest. It is unlikely that the differences in yields from the various soils resulted from poor nutrition, because the concentration of all essential elements was optimum in all cases. Assuming the absence of nutrient element deficiencies, some physical or biological problems must have been the limiting factors in production. Although no quantitative data are available, observations indicated that soil 2 had the highest bulk densities and the lowest hydraulic conductivity, and soil 3 had the lowest density and the highest hydraulic conductivity.

Data for dry weight of Swiss chard are presented in table 3. There were

TABLE 2  
AVERAGE DRY WEIGHT OF ABOVE-GROUND PARTS OF CORN PLANTS DURING A FIVE-YEAR LYSIMETER EXPERIMENT

Soil no.	Dry wt. with fertilizer treatments of:			Soil means*
	$(\text{NH}_4)_2\text{SO}_4$	$\text{Ca}(\text{NO}_3)_2$	$\text{NH}_4\text{OH}$	
	kg/tank	kg/tank	kg/tank	
1.....	12.4	13.1	12.1	12.5 <sup>b</sup>
2†.....	12.4 <sup>a</sup>	11.0 <sup>b</sup>	10.5 <sup>b</sup>	11.3 <sup>c</sup>
3.....	14.3	13.4	13.2	13.6 <sup>a</sup>
4‡.....	11.2 <sup>b</sup>	12.6 <sup>a</sup>	11.5 <sup>ab</sup>	11.8 <sup>b</sup>
Treatment means...	12.6	12.5	11.8	12.3

\* Soil means not having a letter in common differ at the 0.01 level.

† For soil 2 only, treatment means not having a letter in common differ at the 0.05 level.

‡ For soil 4 only, treatment means not having a letter in common differ at the 0.05 level.

TABLE 3  
AVERAGE DRY WEIGHT OF SWISS CHARD DURING A FIVE-YEAR LYSIMETER EXPERIMENT

Soil no.	Dry wt. with fertilizer treatments of:			Soil means*
	$(\text{NH}_4)_2\text{SO}_4$	$\text{Ca}(\text{NO}_3)_2$	$\text{NH}_4\text{OH}$	
	kg/tank	kg/tank	kg/tank	
1.....	2.6	3.6	3.7	3.3 <sup>b</sup>
2.....	2.3	2.3	2.6	2.4 <sup>c</sup>
3.....	4.6	3.9	3.8	4.1 <sup>a</sup>
4.....	4.0	3.6	3.9	3.8 <sup>ab</sup>
Treatment means...	3.4	3.4	3.5	3.4

\* Soil means not having a letter in common differ at the 0.01 level.

no statistically significant differences among fertilizer treatments in any of the soils. The yield differences among soils were the same as for corn—soil 3 produced the highest yields and soil 2, the lowest. One reason for the low yields on soil 2 was a crop failure during the fifth year of the experiment, resulting from low germination and lack of seedling survival. Even with an additional 0.6 kg (the average yield for four years), the yield would have been only 3 kg per tank—75 per cent of the yield for soil 3.

The absence of differences in yield as a result of treatments indicates that all three N sources supplied sufficient N to the crops. The rates of application were high, but perhaps not excessive, judging from the fact that relatively small amounts of N appeared in the drainage water from soils 1 and 4, both of which had very low organic matter and thus low rates of mineralization of N from organic sources.

**Irrigation and drainage water.** Data on the added irrigation water are presented in table 4. For the five-year period, the average water added minus average drainage water (table 5) was 7,077 liters, equivalent to 240 surface inches, or 20 surface feet. Since the average rainfall was 6.2 inches per year, the total evapotranspiration was slightly in excess of 4.5 surface feet per year.

Soil 3 was highest in irrigation water applied and also in drainage. Variation between added irrigation water and drainage was very small, ranging from soil 4, with 6,816 liters difference, to soil 3, with a difference of 7,339 liters.

Data not presented here, on quantities of water added during growth (exclusive of seedling stage) of corn and chard, show highly significant variation among years and between years and soil type. With corn, water applications were significantly related to soils, the largest amounts being applied to soil 3.

TABLE 4  
IRRIGATION WATER APPLIED TO  
LYSIMETERS DURING A FIVE-YEAR  
PERIOD

Soil no.	Irrigation water applied with fertilizer treatments of:			Soil means*
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Ca(NO <sub>3</sub> ) <sub>2</sub>	NH <sub>4</sub> OH	
	<i>l/tank</i>	<i>l/tank</i>	<i>l/tank</i>	
1†.....	7,171 <sup>b</sup>	7,945 <sup>a</sup>	8,050 <sup>a</sup>	7,722 <sup>ab</sup>
2.....	7,538	7,127	7,638	7,434 <sup>b</sup>
3.....	8,250	8,009	7,884	8,048 <sup>a</sup>
4.....	7,611	7,473	7,006	7,363 <sup>b</sup>
Treatment means....	7,642	7,639	7,644	7,642

\* Soil means not having a letter in common differ at the 0.01 level.

† For soil 1 only, treatment means not having a letter in common differ at the 0.05 level.

TABLE 5  
DRAINAGE WATER COLLECTED AS  
PER CENT OF IRRIGATION WATER  
APPLIED

Soil no.	Amt. of drainage water with fertilizer treatments of:			Five-year average
	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Ca(NO <sub>3</sub> ) <sub>2</sub>	NH <sub>4</sub> OH	
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
1.....	8.0	7.2	7.2	7.5
2*.....	6.7 <sup>ab</sup>	8.0 <sup>a</sup>	6.6 <sup>b</sup>	7.1
3.....	7.6	7.5	8.0	7.7
4.....	6.8	8.0	7.6	7.4
Average....	7.3	7.7	7.3	7.4

\* The treatment means for soil 2 not having a letter in common differ at the 0.01 level.

In the ratios of yield to water application, however, no significant differences were apparent with relation to either soils or treatments.

For the corn crop, the average ratio of yield to water added was 0.00292. Since there was no rain during the corn growth period, and no drainage water was collected, the water added represents the evapotranspiration, and the ratio of yield to water added represents the efficiency of water use. Thus, the efficiency of water use was independent of soils and treatments.

Leaching percentages for the five years, presented in table 5, were fairly

uniform, varying from 6.6 to 8 per cent, with an average of 7.4. No differences resulting from treatment or soil type were found except with soil 2, which showed a higher leaching percentage with  $\text{Ca}(\text{NO}_3)_2$  than with  $\text{NH}_4\text{OH}$ .

A substantial portion of the salts added in irrigation water was removed by the crops. Salts in the irrigation water used for evapotranspiration amounted to 32.5 equivalents per tank. (Total cation concentration of the water was 4.65 m.e. per liter.) Crop removal of cations averaged about 25 equivalents per tank, which represents 77 per cent of the salt added in the water. This removal by crops reduced the need for leaching to remove salt. The leaching requirement (L.R.), assuming no removal by crop or by precipitation in the soil, and assuming a concentration of 120 m.e. of cations per liter in the drainage water, was 3.9 per cent, whereas after adjustment for removal by crops it was 0.93 per cent—one-fourth that considered ideal.

Assuming the evapotranspiration, as the salinity of the water increases, and the salt removal by crops to be constants, the relative importance of removal of salts by crops can be calculated. Within limits, these assumptions are justified because use of water is independent of dry-weight production within a wide range of crop yields, and as yields decrease as a result of salts in the soil, the plants contain higher concentrations of salts.

Using the formula of Bower (1961):

$$V_i C_i - V_d C_d - Sc = 0 \quad (1)$$

for a system that is not gaining nor losing salt, where  $V$  equals volume of water,  $C$  equals concentration of salts, subscripts  $i$  and  $d$ , respectively, refer to the irrigation water and drainage, and  $Sc$  equals crop removal of salt, the L.R. can be calculated and compared with the simple L.R., which is  $C_i/C_d$ . From equation (1) and the assumption that  $V_i$  equals consumptive use or evapo-

transpiration plus  $V_d$ , the L.R. becomes:

$$\text{L.R.} = \frac{100 \left( \frac{V_e C_i - Sc}{C_d - C_i} \right)}{V_e + \left( \frac{V_e C_i - Sc}{C_d - C_i} \right)} \quad (2)$$

where  $V_e$  equals evapotranspiration.

The relations between L.R. and the cation concentration of the irrigation water, based on  $C_i/C_d$  or on equation (2), are presented in figure 1. A  $C_d$  value of 120 m.e. cations per liter was used in all of the calculations. The relationships presented show that if the irrigation water contained less than 4 m.e. total salts per liter, no leaching would be required with the type of crop management system used in the lysimeters and with comparable yields. As the salt concentration increases, however, the need for leaching increases, and the relative difference between the two L.R. values decreases. The relative difference in L.R. values at 20 m.e. salt per liter is only 14 per cent, which is probably smaller than the departure from ideal behavior in leaching efficiency. Thus, when salinity of water is high, the removal of salt by crops does not contribute greatly to reducing the L.R.

In some very impermeable soils, however, where water of low salt content is used, removal by crops can be important, and different cropping patterns can be expected to have a significant effect on salt accumulation in the soil.

#### Composition of drainage water.

Data on the relationship between Mn and nitrate contents of the drainage water during the first year fell into two groups, and are plotted differently (fig. 2). In the case of soil 3, the reducing conditions essential for putting Mn in solution did not reduce the  $\text{NO}_3$  to as low a level as in the other three soils. This difference was probably a result of a much higher  $\text{NO}_3$  content of soil 3. In spite of a high  $\text{NO}_3$  content there

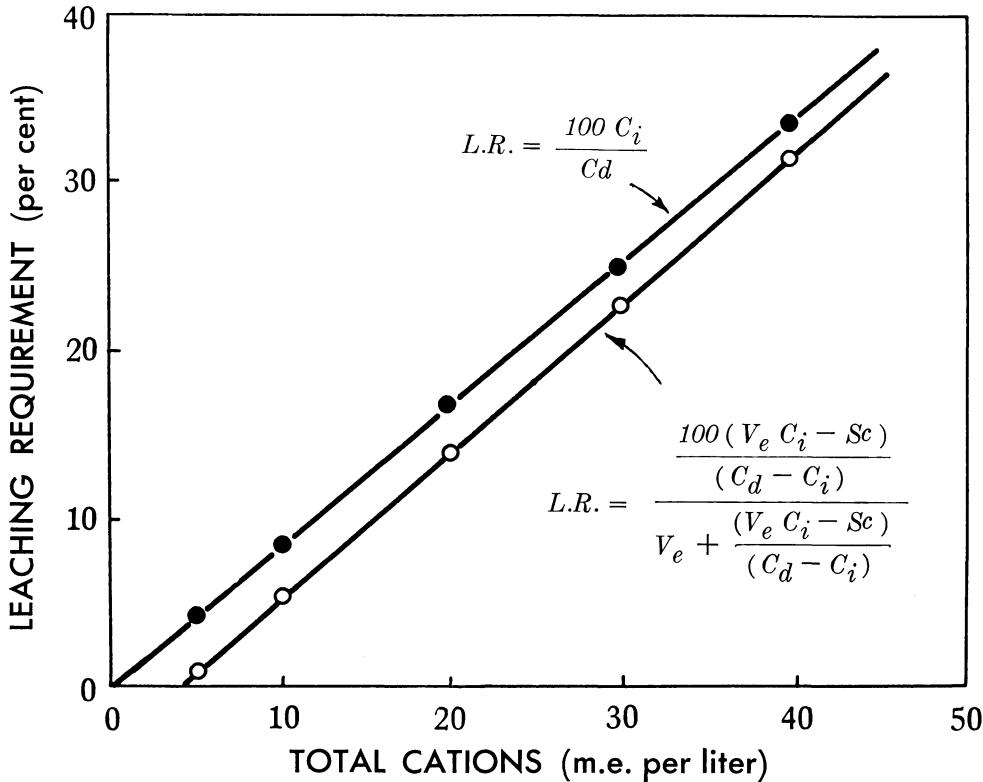


Fig. 1. Relationships between leaching requirement and total cation concentration of irrigation water adjusted for removal of salts by crops, as compared with the simple L.R., which =  $100 C_i / C_d$ .

was a tendency for lower  $\text{NO}_3$  with higher Mn.

In the other soils there was a significant reduction in  $\text{NO}_3$  with increase in soluble Mn. Each tank seemed to operate individually in so far as soluble Mn and  $\text{NO}_3$  contents were concerned. This fact is well documented in table 6 which presents data on the Mn, Fe,  $\text{NO}_3\text{-N}$ ,  $\text{SO}_4\text{-S}$  contents and volume of drainage water. The tanks from which these paired comparisons were taken had received the same treatment following the time at which they were filled with soil. Yet some factor created much more reduction in one than the other. In each case in which the soluble Mn content was high there was evidence of reduction of  $\text{SO}_4$  and  $\text{NO}_3$ . In the case of soil 4, the  $\text{SO}_4\text{-S}$  concentration of the drain-

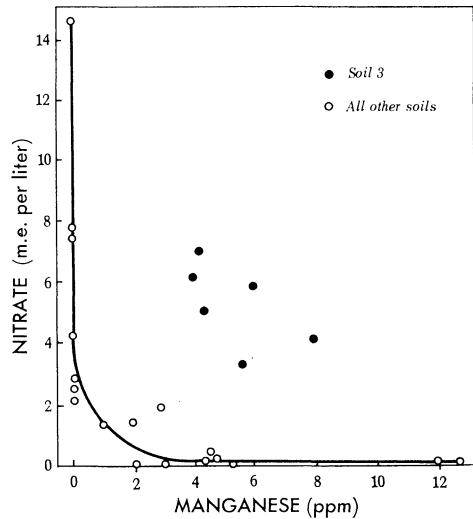


Fig. 2. Relationship between nitrate and Mn contents of drainage water during the first year of operation of the lysimeters.



TABLE 6  
CONTENT AND VOLUME OF DRAINAGE WATER DURING FIRST YEAR OF  
LYSIMETER EXPERIMENT\*

Soil no.	Tank no.	Fertilizer treatment	Soluble				Volume of drainage water
			Mn	Fe	SO <sub>4</sub> -S	NO <sub>3</sub> -N	
			<i>ppm</i>	<i>ppm</i>	<i>ppm</i>	<i>m.e./l</i>	<i>liters</i>
1.....	5	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.0	0.02	62	7.8	153
	21	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	4.4	4.31	19	0.2	122
2.....	12	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.0	0.02	23	2.0	114
	17	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	12.0	4.45	6	0.2	117
2.....	27	NH <sub>4</sub> OH	0.0	0.03	33	2.9	139
	11	NH <sub>4</sub> OH	12.7	5.51	9	0.1	116
4.....	16	NH <sub>4</sub> OH	0.0	0.02	930	7.3	139
	1	NH <sub>4</sub> OH	3.0	0.03	882	0.2	116
4.....	6	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.0	0.02	930	4.3	160
	19	Ca(NO <sub>3</sub> ) <sub>2</sub>	4.8	0.56	908	0.4	150

\* Paired comparisons for tanks given the same management.

TABLE 7  
AVERAGE VOLUME AND CONCENTRATION OF VARIOUS IONS IN DRAINAGE  
WATER DURING FIFTH YEAR OF LYSIMETER EXPERIMENT

Soil no.	Fertilizer treatment	Volume of drainage water	NO <sub>3</sub>	SO <sub>4</sub>	Cl	Ca	Mg	K	Na	B
		<i>liters</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>ppm</i>
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	50.0	2.34	38.5	0.70	35.8	9.30	0.88	1.38	0.24
	Ca(NO <sub>3</sub> ) <sub>2</sub>	57.0	1.46	16.2	1.16	19.9	5.40	0.71	0.38	0.25
	NH <sub>4</sub> OH	63.0	0.90	17.4	1.39	19.6	5.60	0.78	0.58	0.18
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	42.0	6.68	16.8	1.46	23.0	5.85	1.12	2.89	0.36
	Ca(NO <sub>3</sub> ) <sub>2</sub>	56.0	8.64	10.4	2.72	16.8	4.45	0.82	2.22	0.22
	NH <sub>4</sub> OH	54.0	3.94	12.9	2.34	17.8	4.60	1.06	2.65	0.24
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	59.5	2.38 <sup>b</sup> *	20.9	1.90	23.8	8.20	0.40	2.55	0.26
	Ca(NO <sub>3</sub> ) <sub>2</sub>	47.5	18.14 <sup>a</sup>	10.8	2.90	25.8	8.80	0.40	2.51	0.34
	NH <sub>4</sub> OH	46.0	19.56 <sup>a</sup>	10.8	2.95	26.4	9.35	0.42	2.46	0.16
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	60.5	0.48	61.0	1.16	26.6	26.45	0.88	24.65	0.54
	Ca(NO <sub>3</sub> ) <sub>2</sub>	48.0	1.71	56.2	1.90	23.4	23.95	0.86	25.10	0.95
	NH <sub>4</sub> OH	45.0	1.11	48.4	1.20	20.2	20.45	0.82	22.30	0.92
Treatment means:										
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....		53.0	2.97	34.3 <sup>a</sup> *	1.30	27.3 <sup>a</sup> †	12.45	0.82	7.87	0.35
Ca(NO <sub>3</sub> ) <sub>2</sub> .....		52.1	7.49	23.4 <sup>b</sup>	2.17	21.5 <sup>b</sup>	10.65	0.70	7.55	0.44
NH <sub>4</sub> OH.....		52.0	6.38	22.4 <sup>b</sup>	1.97	21.0 <sup>b</sup>	10.00	0.77	7.00	0.38
Soil means:										
1.....		56.7	1.57	24.0 <sup>b</sup> *	1.08 <sup>b</sup> *	25.1	6.77 <sup>b</sup> c*	0.79 <sup>a</sup> *	0.78 <sup>b</sup> *	0.22 <sup>b</sup> *
2.....		50.7	6.42	13.4 <sup>b</sup>	2.17 <sup>a</sup> b	19.2	4.97 <sup>c</sup>	1.00 <sup>a</sup>	2.59 <sup>b</sup>	0.27 <sup>b</sup>
3.....		51.0	13.36	14.2 <sup>b</sup>	2.58 <sup>a</sup>	25.3	8.78 <sup>b</sup>	0.41 <sup>b</sup>	2.51 <sup>b</sup>	0.26 <sup>b</sup>
4.....		51.2	1.10	55.2 <sup>a</sup>	1.42 <sup>a</sup> b	23.4	23.62 <sup>a</sup>	0.85 <sup>a</sup>	24.02 <sup>a</sup>	0.81 <sup>a</sup>

\* Values within each soil set of entries not having a letter in common differ at the 0.01 level.

† Values within each soil set of entries not having a letter in common differ at the 0.05 level.

TABLE 8  
TOTAL SOLUBLE CATIONS IN SATURATION EXTRACT OF SOIL SAMPLES  
BEFORE AND AFTER TREATMENT OF LYSIMETERS WITH THREE N SOURCES  
DURING A FIVE-YEAR EXPERIMENT

Soil no. and type	Depth	Soluble cation conc. with fertilizer treatments of:			Av. conc. before treatment*
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Ca(NO <sub>3</sub> ) <sub>2</sub>	NH <sub>3</sub> OH	
	<i>cm</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>	<i>m.e./l</i>
1. Moreno					
sandy loam.....	0-15	9.7	7.6	8.6	8.7
	15-30	13.1	6.6	8.0	....
	30-60	22.8	11.3	10.6	....
	60-90	26.2	9.6	11.2	....
	90-120	31.0	10.0	10.4	....
	120-150	27.8	8.1	9.3	....
2. Greenfield					
sandy loam.....	0-15	16.4	7.8	10.2	10.3
	15-30	30.6	8.9	10.0	....
	30-60	38.9	15.4	12.2	....
	60-90	40.4	23.8	19.5	....
	90-120	34.7	26.0	23.6	....
	120-150	22.1	16.9	18.4	....
3. Altamont					
clay loam.....	0-15	39.6	9.3	12.2	13.2
	15-30	26.3	10.6	14.6	....
	30-60	27.6	14.8	14.2	....
	60-90	31.2	22.0	21.8	....
	90-120	30.0	24.0	27.0	....
	120-150	21.4	19.0	21.0	....
4. Holtville					
clay loam.....	0-15	9.3	7.0	7.7	61.3
	15-30	18.6	9.0	10.1	....
	30-60	24.4	13.5	13.5	....
	60-90	38.7	26.0	17.8	....
	90-120	53.2	55.6	48.2	....
	120-150	59.2	60.7	59.6	....

\* For all tanks of each soil.

age water was 930 ppm or above in all tanks except those in which soluble Mn was high. This soil was saturated with gypsum, and would be expected to show a high soluble SO<sub>4</sub>-S in the drainage water. The decrease in SO<sub>4</sub>-S noted may have taken place after the drainage water left the soil, and while it was passing through the gravel pack and the drainage lines.

During the second year of operation of the lysimeters, soluble Mn and Fe appeared in the drainage water of only a few tanks, and the concentrations were much lower than during the first year. During the third to fifth years, this phenomenon was not found. Since readily decomposable organic matter is essential for development of strongly

reductive conditions, it might be assumed that the readily decomposable organic matter in the soil of the lower portion of the soil columns, that would presumably be saturated during drainage, was oxidized by the end of the second year.

Data on volume and concentration of various ions in the drainage water during the fifth year are presented in table 7. Most of the differences shown are those among soil means. However, two differences among fertilizer treatments are important. Both the SO<sub>4</sub> and Ca concentrations were higher with the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> as compared with the other two treatments. Evidently the acidification from (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> was sufficiently effective in preventing Ca precipitation

TABLE 9  
SOLUBLE CATIONS, RATIO OF SOLUBLE Ca TO SOLUBLE Mg, AND SAR  
FOR SOIL 2

Fertilizer treatment	Depth	Soluble cations			Ratio of Ca to Mg	SAR*
		Ca	Mg	Na		
	cm	m.e./l	m.e./l	m.e./l		(mmoles/l) <sup>1/2</sup>
(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub> .....	0-15	8.3	2.5	5.3	3.3	2.3
	15-30	19.0	4.5	7.0	4.3	2.0
	30-60	22.3	5.3	10.9	4.2	2.9
	60-90	21.7	5.2	12.7	4.1	3.4
	90-120	21.6	5.2	6.7	4.1	1.8
	120-150	15.1	3.8	2.2	4.0	0.7
Ca(NO <sub>3</sub> ) <sub>2</sub> .....	0-15	4.6	0.9	2.2	5.1	1.3
	15-30	4.5	0.8	4.1	5.6	2.5
	30-60	7.9	1.7	6.1	4.5	2.8
	60-90	12.1	3.9	8.3	4.2	3.0
	90-120	15.4	3.8	8.4	4.0	2.7
	120-150	11.0	2.9	2.2	3.8	0.8
NH <sub>4</sub> OH.....	0-15	5.1	1.7	3.2	3.1	1.8
	15-30	4.5	1.2	4.2	3.7	2.5
	30-60	4.4	1.1	6.6	4.1	4.0
	60-90	7.5	1.7	9.8	4.4	4.6
	90-120	13.3	3.1	6.4	4.2	2.2
	120-150	12.2	3.1	2.2	4.0	0.8
Av. before treatment		6.7	1.2	1.3	5.4	0.7

\* SAR =  $\frac{\text{Na}}{\sqrt{\text{Ca} + \text{Mg}}} \text{ (mmoles/l)}^{1/2}$

so that in the fifth year of the experiment a higher Ca concentration was found in drainage from the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> treatment. Furthermore, the absence of a higher Ca concentration in drainage from the Ca(NO<sub>3</sub>)<sub>2</sub> as compared with the NH<sub>4</sub>OH treatment suggests that the Ca from Ca(NO<sub>3</sub>)<sub>2</sub> was largely precipitated. As shown in the section on salinity, the soils receiving these two fertilizer treatments had practically the same amounts of soluble Ca.

Data on the HCO<sub>3</sub> content of the drainage water are not presented. In all cases CaCO<sub>3</sub> precipitated in the drainage water as soon as it was exposed to the air for an hour or more, indicating that the CO<sub>2</sub> pressure in the soil was higher than in the atmosphere above the water in the receiving tanks. Anions other than HCO<sub>3</sub> were determined on a nonacidified sample of drainage wa-

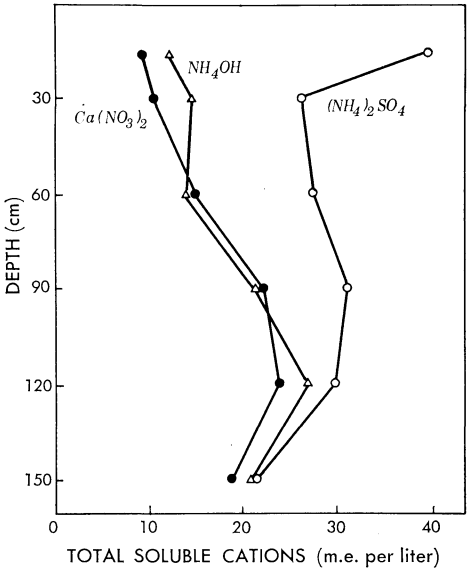


Fig. 3. Relationships between soluble cations and soil depth for soil number 3, treated with three N sources for five years.

TABLE 10  
pH OF SOIL PASTE ON SAMPLES TAKEN BEFORE AND AFTER FIVE YEARS OF  
TREATMENT WITH THREE N SOURCES

Soil no.	Depth	pH with fertilizer treatments of:			pH before treatment
		(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Ca(NO <sub>3</sub> ) <sub>2</sub>	NH <sub>4</sub> OH	
	<i>cm</i>				
1.....	0-15	6.6	7.8	7.5	7.4
	15-30	7.6	7.8	7.8	7.4
	30-60	7.6	7.7	7.8	7.4
	60-90	7.6	7.8	7.6	7.4
	90-120	7.6	7.8	7.6	7.4
	120-150	7.4	7.8	7.6	7.4
2.....	0-15	4.7	7.8	6.5	6.8
	15-30	6.0	7.9	7.4	6.8
	30-60	6.6	7.8	7.8	6.8
	60-90	6.7	7.2	7.3	6.8
	90-120	6.6	6.9	6.8	6.8
	120-150	6.4	7.0	6.6	6.8
3.....	0-15	5.6	7.6	6.8	7.2
	15-30	7.0	7.5	7.2	7.2
	30-60	7.2	7.4	7.4	7.2
	60-90	7.1	7.4	7.3	7.2
	90-120	7.0	7.2	7.2	7.2
	120-150	7.2	7.2	7.0	7.2
4.....	0-15	7.8	7.8	7.9	7.8
	15-30	8.0	8.0	8.0	7.8
	30-60	8.0	8.0	8.0	7.8
	60-90	7.9	7.8	8.0	7.8
	90-120	7.8	7.8	7.9	7.8
	120-150	7.8	7.8	7.9	7.8

ter, and the cations on a sample acidified with HCl to dissolve the CaCO<sub>3</sub>. The HCO<sub>3</sub> was not determined directly but was calculated as the difference between cations and anions. No significant differences in HCO<sub>3</sub> content of the drainage water were associated with treatments or soils, except that the water from the Holtville soil had much higher HCO<sub>3</sub> content than the others.

**Salinity.** Data on the salinity of the soils, in terms of total soluble cations in the saturation extract before and after the experiment, are presented in table 8. Those for soil 3 are shown in figure 3. No consistent differences in total soluble cations between the Ca(NO<sub>3</sub>)<sub>2</sub> and NH<sub>4</sub>OH treatments were noted, but the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> produced consistently higher soluble cations than did the other fertilizers, except in the 90- to

150-cm depth of soil 4, where some of the original high salinity remained. Soil 4 was saturated with gypsum at the start, and the 90- to 150-cm depth was still saturated after the five-year experiment.

The higher salinity with (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> was undoubtedly a result of acidification, which prevented CaCO<sub>3</sub> precipitation, and of the introduction of the SO<sub>4</sub> anion, which is stable and is not absorbed in large amounts by plants nor precipitated until relatively high concentrations are present. In the case of Ca(NO<sub>3</sub>)<sub>2</sub>, the anion was largely absorbed by plants and the Ca was mainly precipitated as CaCO<sub>3</sub>. The N from NH<sub>4</sub>OH was mostly absorbed by plants in the NH<sub>4</sub> or NO<sub>3</sub> state; thus its contribution to the salinity in the soil was low.



TABLE 11  
N ADDED TO LYSIMETERS IN FERTILIZERS AND IRRIGATION WATER, AND  
REMOVED IN CROPS AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	N added in fertilizer and irrigation water	N removed in:		Added N minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	21.6	20.0 <sup>b†</sup>	1.1	0.5
	Ca(NO <sub>3</sub> ) <sub>2</sub>	21.9	23.6 <sup>a</sup>	1.7	— 3.4
	NH <sub>4</sub> OH	21.9	20.7 <sup>b</sup>	0.5	0.7
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	21.7	18.8	3.0	— 0.1
	Ca(NO <sub>3</sub> ) <sub>2</sub>	21.6	21.6	3.6	— 3.6
	NH <sub>4</sub> OH	21.8	19.2	2.9	— 0.3
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	21.9	35.8 <sup>a†</sup>	6.0	—19.9
	Ca(NO <sub>3</sub> ) <sub>2</sub>	21.9	33.4 <sup>ab</sup>	8.9	—20.0
	NH <sub>4</sub> OH	21.8	31.6 <sup>b</sup>	5.3	—15.1
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	21.8	21.8	0.6	— 0.6
	Ca(NO <sub>3</sub> ) <sub>2</sub>	21.7	25.2	0.9	— 4.4
	NH <sub>4</sub> OH	21.7	23.1	0.8	— 2.2
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	21.8	24.1	2.7	— 5.0 <sup>b†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	21.8	26.0	3.8	— 7.9 <sup>a</sup>
	NH <sub>4</sub> OH	21.8	23.6	2.4	— 4.2 <sup>b</sup>
Soil means:					
1.....		21.8	21.4 <sup>bce†</sup>	1.1 <sup>bce†</sup>	— 0.7 <sup>b†</sup>
2.....		21.7	19.9 <sup>c</sup>	3.2 <sup>b</sup>	— 1.3 <sup>b</sup>
3.....		21.9	33.6 <sup>a</sup>	6.7 <sup>a</sup>	—18.3 <sup>a</sup>
4.....		21.7	23.4 <sup>b</sup>	0.8 <sup>c</sup>	— 2.4 <sup>b</sup>

\* All units are equivalents per tank.  
† Values within each soil set not having a letter in common differ at the 0.05 level.  
‡ Values within each soil set not having a letter in common differ at the 0.01 level.

Data on the soluble Ca, Mg, and Na ratios of soluble Ca to soluble Mg, and SAR (sodium adsorption ratio) values for soil 2 are given in table 9. The (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> treatment produced higher soluble Ca in the saturation extract, but the increase in total soluble cations was well distributed among the three cations in proportion to their exchange constants. The ratios of Ca to Mg and SAR values did not differ greatly as a result of treatment, but the Ca to Mg ratios were slightly higher with the Ca(NO<sub>3</sub>)<sub>2</sub>.

If acidification from (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> was highly effective in keeping Ca from precipitating, we should expect to find not just more Ca in the drainage, but more of all three cations. Drainage data for the fifth year (table 7) show this to be the case, but also show that the differ-

ences in Ca were statistically significant, whereas those for Mg and Na were not. The five-year average shows that only in soil 1 was the Ca removed in the drainage higher in the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> than in the other two treatments.

Data for the other three soils show the same pattern as that for soil 2 (table 9). None of the differences in ratio of Ca to Mg and in SAR values could be attributed to the fertilizer treatments.

**Acidity.** The pH values for soil samples taken before and after the five-year period of the experiment are given in table 10. The Ca(NO<sub>3</sub>)<sub>2</sub> increased the pH in all soils except soil 4, which had a pH of 7.8 at the start; thus accumulation of CaCO<sub>3</sub> had no effect. The NH<sub>4</sub>OH had a very slight acidifying effect in the surface (0 to 15 cm) depth

TABLE 12  
Cl ADDED TO LYSIMETERS IN IRRIGATION WATER, AND REMOVED IN CROPS  
AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	Cl added in irrigation water	Cl removed in:		Added Cl minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	4.85	5.16	0.94	-1.24
	Ca(NO <sub>3</sub> ) <sub>2</sub>	5.44	5.52	0.96	-1.04
	NH <sub>4</sub> OH	5.46	5.31	0.84	-0.70
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	5.12	4.92	0.97	-0.77
	Ca(NO <sub>3</sub> ) <sub>2</sub>	5.17	4.54	1.34	-0.70
	NH <sub>4</sub> OH	5.15	4.78	1.09	-0.71
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	5.60	5.84	1.60	-1.84
	Ca(NO <sub>3</sub> ) <sub>2</sub>	5.44	5.06	1.65	-1.26
	NH <sub>4</sub> OH	5.32	4.74	2.00	-1.42
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	5.16	6.89	3.70	-5.46
	Ca(NO <sub>3</sub> ) <sub>2</sub>	5.07	6.52	5.56	-7.02
	NH <sub>4</sub> OH	5.08	6.29	4.97	-6.18
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	5.18	5.70 <sup>a†</sup>	1.80	-2.33
	Ca(NO <sub>3</sub> ) <sub>2</sub>	5.28	5.41 <sup>ab</sup>	2.38	-2.50
	NH <sub>4</sub> OH	5.26	5.28 <sup>b</sup>	2.22	-2.25
Soil means:					
1.....		5.25	5.33 <sup>b†</sup>	0.92 <sup>b†</sup>	-0.99 <sup>b†</sup>
2.....		5.15	4.74 <sup>c</sup>	1.13 <sup>b</sup>	-0.73 <sup>b</sup>
3.....		5.46	5.21 <sup>c</sup>	1.75 <sup>b</sup>	-1.51 <sup>b</sup>
4.....		5.10	6.57 <sup>a</sup>	4.74 <sup>a</sup>	-6.22 <sup>a</sup>

\* All units are equivalents per tank.

† Values within each soil set not having a letter in common differ at the 0.05 level.

‡ Values within each soil set not having a letter in common differ at the 0.01 level.

of soils 2 and 3, but none on soils 1 and 4 at any depth because of their higher CaCO<sub>3</sub> contents. It caused small increases in pH in all other depths of soils 2 and 3. The overall effect of the NH<sub>4</sub>OH was a slight increase in pH. The (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> produced large decreases in pH of the surface 0 to 30-cm depth for soil 2 and 0 to 15-cm depth for soils 1 and 3.

Evidently the amount of acidification from NH<sub>4</sub>OH was less than the alkalinity provided by the HCO<sub>3</sub> of the irrigation water, but the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> produced more acid than could be counteracted by alkalinity of the water. The average quantity of HCO<sub>3</sub> added in the water was 22.9 equivalents per tank. On the basis of values from Millar and Turk (1951) for residual acidity for the fertilizer materials, the acid formed

would have been approximately 10 and 30 equivalents per tank, respectively, for NH<sub>4</sub>OH and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. Thus, the results obtained in this experiment are consistent with previously reported data.

In an earlier experiment, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> at 390 pounds N per acre per year, applied in a citrus orchard irrigated with water from the same source as used in this lysimeter experiment, produced extreme acidification of the surface 0 to 30-cm depth of soil (Pratt *et al.*, 1959). The rate of application of N for the lysimeters was 420 pounds of N per acre per year, but the rate of water application could have been 100 per cent higher than the field trial; therefore, more HCO<sub>3</sub> was added in the lysimeter test.

**Nitrogen.** Data on the N added in

TABLE 13  
S ADDED TO LYSIMETERS IN IRRIGATION WATER, AND REMOVED IN CROPS  
AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	S added in fertilizer and irrigation water	S removed in:		Added S minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	28.6	1.8	9.7	17.0
	Ca(NO <sub>3</sub> ) <sub>2</sub>	10.1	2.0	5.3	2.8
	NH <sub>4</sub> OH	10.3	2.0	7.0	1.4
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	29.1	2.0 <sup>a†</sup>	4.1	22.9
	Ca(NO <sub>3</sub> ) <sub>2</sub>	9.0	1.6 <sup>b</sup>	2.7	4.7
	NH <sub>4</sub> OH	9.7	1.7 <sup>b</sup>	2.7	5.3
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	30.0	2.5 <sup>a†</sup>	4.2	23.3
	Ca(NO <sub>3</sub> ) <sub>2</sub>	10.2	2.1 <sup>b</sup>	3.0	5.1
	NH <sub>4</sub> OH	10.0	2.1 <sup>b</sup>	2.9	5.0
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	29.2	2.0	28.9	— 2.3
	Ca(NO <sub>3</sub> ) <sub>2</sub>	9.7	2.0	28.5	—20.8
	NH <sub>4</sub> OH	9.4	1.9	32.5	—25.3
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	29.2 <sup>a†</sup>	2.1	11.7	15.2 <sup>a†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	9.8 <sup>b</sup>	1.9	9.9	— 2.0 <sup>b</sup>
	NH <sub>4</sub> OH	9.9 <sup>b</sup>	1.9	11.3	— 3.4 <sup>b</sup>
Soil means:					
1.....		16.3 <sup>ab†</sup>	1.9 <sup>bce†</sup>	7.3 <sup>b†</sup>	7.1 <sup>b†</sup>
2.....		15.9 <sup>b</sup>	1.8 <sup>c</sup>	3.2 <sup>c</sup>	11.0 <sup>a</sup>
3.....		16.7 <sup>a</sup>	2.2 <sup>a</sup>	3.4 <sup>c</sup>	11.1 <sup>a</sup>
4.....		16.1 <sup>b</sup>	2.0 <sup>b</sup>	30.1 <sup>a</sup>	—16.1 <sup>c</sup>

\* All units are equivalents per tank.  
† Values within each soil set not having a letter in common differ at the 0.01 level.

fertilizer and irrigation water, removed by crops and in drainage water are shown in table 11. Of the average of 21.8 equivalents of N added during the course of the experiment, 19.5 came from fertilizer and 2.3 from the irrigation water. No differences in added N were related to treatments or soils.

Although the effect of treatment on N removed by crops was not significant, the ratio of N removal to total crop yield was consistently higher with the Ca(NO<sub>3</sub>)<sub>2</sub> treatment as compared with the NH<sub>4</sub> sources. Also, the average amounts of N in plants were 2.07, 2.66, and 2.16 per cent, respectively, for (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, Ca(NO<sub>3</sub>)<sub>2</sub>, and NH<sub>4</sub>OH. Thus, there was some indication that the Ca(NO<sub>3</sub>)<sub>2</sub> was the most effective in keeping N available to plants, although the difference was small and did not produce differences in plant growth.

The largest amount of N removed by crops and in drainage water, as well as the highest negative balance or depletion, occurred with soil 3. This soil was relatively high in organic matter, undoubtedly the source of the removed N. Soils 1, 2, and 4 are more typical of the irrigated soils of southern California.

**Chloride.** Data on added, removed, and depleted Cl are given in table 12. The removal by crops and by drainage was, in all treatments of all soils, greater than the quantity added in the water; thus Cl was depleted rather than accumulated. Chard removed slightly more Cl than did corn.

The fertilizer treatments had no measurable effect on Cl, except that with the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, crops removed slightly more than with the NH<sub>4</sub>OH. There is no apparent reason for the SO<sub>4</sub> anion to promote Cl absorption,

TABLE 14

Ca ADDED TO LYSIMETERS IN FERTILIZER AND IRRIGATION WATER, AND  
REMOVED IN CROPS AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	Ca added in: water and fertilizer	Ca removed in:		Added Ca minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	19.7 <sup>c†</sup>	3.0	13.4 <sup>a†</sup>	3.3 <sup>c†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	41.4 <sup>a</sup>	3.6	9.1 <sup>b</sup>	28.6 <sup>a</sup>
	NH <sub>4</sub> OH	22.1 <sup>b</sup>	3.2	10.0 <sup>b</sup>	8.9 <sup>b</sup>
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	20.7 <sup>b†</sup>	2.8	7.9	10.0 <sup>b†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	39.1 <sup>a</sup>	3.4	7.8	27.9 <sup>a</sup>
	NH <sub>4</sub> OH	21.0 <sup>b</sup>	2.8	7.0	11.2 <sup>b</sup>
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	22.7 <sup>b†</sup>	4.8	13.2	4.7 <sup>b†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	41.5 <sup>a</sup>	4.3	13.6	23.6 <sup>a</sup>
	NH <sub>4</sub> OH	21.7 <sup>b</sup>	4.2	13.0	4.5 <sup>b</sup>
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	20.9 <sup>b†</sup>	2.9	14.7	3.3 <sup>b†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	40.1 <sup>a</sup>	3.1	16.2	20.8 <sup>a</sup>
	NH <sub>4</sub> OH	20.7 <sup>b</sup>	2.9	14.7	3.1 <sup>b</sup>
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	21.0 <sup>b†</sup>	3.4	12.3	5.3 <sup>c†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	40.5 <sup>a</sup>	3.6	11.7	25.2 <sup>a</sup>
	NH <sub>4</sub> OH	21.4 <sup>b</sup>	3.3	11.2	6.9 <sup>b</sup>
Soil means:					
1.....		27.7 <sup>a†</sup>	3.3 <sup>b†</sup>	10.9 <sup>c†</sup>	13.6 <sup>b†</sup>
2.....		26.9 <sup>b</sup>	3.0 <sup>b</sup>	7.6 <sup>d</sup>	16.4 <sup>a</sup>
3.....		28.6 <sup>a</sup>	4.5 <sup>a</sup>	13.2 <sup>b</sup>	10.9 <sup>c</sup>
4.....		27.2 <sup>b</sup>	3.0 <sup>b</sup>	15.2 <sup>a</sup>	9.1 <sup>d</sup>

\* All units are equivalents per tank.

† Values within each soil set not having a letter in common differ at the 0.01 level.

and since (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> resulted in no consistently higher yields, the conclusion may be drawn that the differences in Cl removal by crops were random and therefore independent of fertilizer treatment.

The difference in soil means for Cl removal and depletion are mostly a result of the much higher Cl content of soil 4 at the start of the five-year period of data collection.

**Sulfur.** Data on the S added, removed, and accumulated or depleted are presented in table 13. Removal of S by crops was higher in two of the four soils with the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> treatment than with the other two, but the overall effect of removal by crops was very small. Evidently the irrigation water provided nearly as much as the plants could absorb and translocate to the harvested portion. The treatments had no

measurable effect on removal of SO<sub>4</sub> in the drainage water. Thus, the 19.5 equivalents of SO<sub>4</sub> added as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> mostly accumulated as soluble SO<sub>4</sub> in the soil.

The differences in soil means are mostly a result of higher yields and higher water use by soil 3, except the higher S removal in the drainage water from soil 4, which resulted from the high original CaSO<sub>4</sub> content of this soil.

In contrast to the data on Cl, more S was removed in the drainage water than by crops, and more by corn than by chard. There was, except for soil 4, an accumulation rather than a depletion.

**Calcium.** Data on added, removed, and accumulated Ca are presented in table 14. Removal of Ca was much greater by drainage than by crops.



TABLE 15  
Mg ADDED TO LYSIMETERS IN IRRIGATION WATER, AND REMOVED IN CROPS  
AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	Mg added in irrigation water	Mg removed in:		Added Mg minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	6.32	2.78	3.61	-0.08
	Ca(NO <sub>3</sub> ) <sub>2</sub>	7.01	3.60	2.69	0.72
	NH <sub>4</sub> OH	7.12	3.29	3.18	0.64
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	6.64	2.58	2.70 <sup>ab†</sup>	1.36 <sup>‡</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	6.25	3.65	3.82 <sup>a</sup>	-1.16 <sup>b</sup>
	NH <sub>4</sub> OH	6.73	2.74	2.00 <sup>b</sup>	2.00 <sup>a</sup>
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	7.04	4.79	4.97	-2.72
	Ca(NO <sub>3</sub> ) <sub>2</sub>	7.05	4.63	4.44	-2.02
	NH <sub>4</sub> OH	6.94	4.21	4.96	-2.22
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	6.72	3.50	13.00 <sup>b†</sup>	-9.79 <sup>a‡</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	6.58	4.16	15.28 <sup>a</sup>	-12.87 <sup>b</sup>
	NH <sub>4</sub> OH	6.59	3.78	11.58 <sup>c</sup>	-8.77 <sup>a</sup>
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	6.68	3.42 <sup>b†</sup>	6.07 <sup>ab†</sup>	-2.81 <sup>a‡</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	6.72	4.01 <sup>a</sup>	6.56 <sup>a</sup>	-3.83 <sup>b</sup>
	NH <sub>4</sub> OH	6.84	3.50 <sup>b</sup>	5.43 <sup>b</sup>	-2.09 <sup>a</sup>
Soil means:					
1.....		6.82 <sup>ab†</sup>	3.23 <sup>c†</sup>	3.16 <sup>c†</sup>	0.43 <sup>a‡</sup>
2.....		6.54 <sup>b</sup>	2.99 <sup>c</sup>	2.84 <sup>c</sup>	0.73 <sup>a</sup>
3.....		7.01 <sup>a</sup>	4.54 <sup>a</sup>	4.79 <sup>b</sup>	-2.32 <sup>b</sup>
4.....		6.63 <sup>b</sup>	3.82 <sup>b</sup>	13.29 <sup>a</sup>	-10.48 <sup>c</sup>

\* All units are equivalents per tank.

† Values within each soil set not having a letter in common differ at the 0.05 level.

‡ Values within each soil set not having a letter in common differ at the 0.01 level.

However, removal by drainage was not influenced by fertilizer treatment except in soil 1, where removal was greatest with the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. This result is consistent with data on Ca content of drainage water for the fifth year of the experiment, in which the Ca removed was greatest with the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> treatment. The 19.5 equivalents of Ca per tank, added in the form of Ca(NO<sub>3</sub>)<sub>2</sub>, were mostly accumulated in the soil, and did not show as soluble Ca. The Ca was presumably precipitated as CaCO<sub>3</sub>.

**Magnesium.** Data on the added and removed Mg are given in table 15. Except for soil 4, which had relatively high salinity at the start, the amount of Mg removed was about equally distributed between removal by crops and that by drainage. In soils 3 and 4, Mg

was depleted under all treatments, whereas in soils 1 and 2 it tended to accumulate. No evidence in these data supports the idea that Mg was precipitated in the soil.

In soils 2 and 4 there was evidence that the Ca(NO<sub>3</sub>)<sub>2</sub> treatment caused greater Mg removal in the drainage and thus greater total removal as compared with the other two N sources. However, this greater depletion of Mg with the Ca(NO<sub>3</sub>)<sub>2</sub> did not show in decreased soluble or exchangeable Mg.

**Sodium.** Data on Na are given in table 16. Except for soil 4, Na was removed mostly by crops, and nearly all by the chard. Soils 1, 2, and 3 accumulated Na, whereas soil 4 lost Na. The accumulated Na, however, was not sufficient to show as increased exchangeable Na in the soil.

TABLE 16  
Na ADDED TO LYSIMETERS IN IRRIGATION WATER, AND REMOVED IN CROPS  
AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	Na added in irrigation water	Na removed in:		Added Na minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	11.4 <sup>b†</sup>	2.59 <sup>b‡</sup>	0.56	8.2
	Ca(NO <sub>3</sub> ) <sub>2</sub>	12.6 <sup>a</sup>	4.38 <sup>a</sup>	0.34	7.8
	NH <sub>4</sub> OH	12.7 <sup>a</sup>	3.58 <sup>ab</sup>	0.45	8.7
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	11.9	3.08	0.92	7.9
	Ca(NO <sub>3</sub> ) <sub>2</sub>	11.2	4.26	0.95	5.9
	NH <sub>4</sub> OH	12.0	3.09	0.78	8.2
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	13.0	7.37 <sup>a‡</sup>	1.54	4.2
	Ca(NO <sub>3</sub> ) <sub>2</sub>	12.7	6.20 <sup>ab</sup>	1.29	5.2
	NH <sub>4</sub> OH	12.4	5.60 <sup>b</sup>	1.38	5.5
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	12.0	5.81	14.52 <sup>b†</sup>	- 8.3 <sup>a†</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	11.8	6.99	19.93 <sup>a</sup>	-15.1 <sup>b</sup>
	NH <sub>4</sub> OH	11.8	6.78	18.10 <sup>a</sup>	-13.0 <sup>b</sup>
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	12.1	4.71 <sup>b‡</sup>	4.38	3.0 <sup>a‡</sup>
	Ca(NO <sub>3</sub> ) <sub>2</sub>	12.1	5.46 <sup>a</sup>	5.63	1.0 <sup>b</sup>
	NH <sub>4</sub> OH	12.3	4.76 <sup>b</sup>	5.18	2.3 <sup>ab</sup>
Soil means:					
1.....		12.2 <sup>ab†</sup>	3.52 <sup>b†</sup>	0.45 <sup>b†</sup>	8.2 <sup>a†</sup>
2.....		11.7 <sup>b</sup>	3.48 <sup>b</sup>	0.88 <sup>b</sup>	7.3 <sup>ab</sup>
3.....		12.7 <sup>a</sup>	6.39 <sup>a</sup>	1.40 <sup>b</sup>	4.7 <sup>b</sup>
4.....		11.9 <sup>b</sup>	6.53 <sup>a</sup>	17.51 <sup>a</sup>	-12.1 <sup>c</sup>

\* All units are equivalents per tank.  
† Values within each soil set not having a letter in common differ at the 0.01 level.  
‡ Values within each soil set not having a letter in common differ at the 0.05 level.

**Potassium.** Data on added, removed, and depleted K are presented in table 17. The fertilizer treatments had no effect on K removal except for soil 3 in which the (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> resulted in removal of more K by crops as compared with the NH<sub>4</sub>OH. Differences among soils were significant in all columns (table 17), and were related to differences in yield and to native supply of available K. Differences in added K, however, were related to the quantity of water added. There was an inverse relationship between K removed by crops and that removed by drainage water. About 85 per cent was removed by corn and 16 per cent by chard.

The relations between depth and NH<sub>4</sub>OAc-extracted K at start and end of the experiment for soils 1 and 4 are shown in figure 4; relations for soils 2

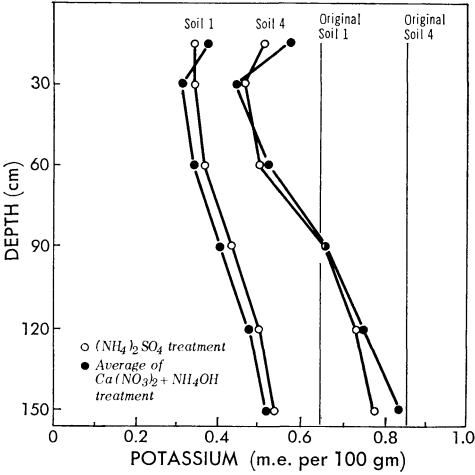


Fig. 4. Relationships between soil depth and NH<sub>4</sub>OAc-extracted K at start and at end of the experiment for soils 1 and 4.

TABLE 17  
K ADDED TO LYSIMETERS IN IRRIGATION WATER, AND REMOVED IN CROPS  
AND DRAINAGE WATER\*

Soil no.	Fertilizer treatment	K added in irrigation water	K removed in:		Added K minus removed
			Crops	Drainage	
1.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.50 <sup>b†</sup>	11.4	0.41	-11.3
	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.56 <sup>a</sup>	12.7	0.36	-12.5
	NH <sub>4</sub> OH	0.56 <sup>a</sup>	12.3	0.40	-12.1
2.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.52	10.8	0.58	-10.8
	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.50	10.8	0.50	-10.8
	NH <sub>4</sub> OH	0.54	10.7	0.50	-10.7
3.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.58	15.7 <sup>a†</sup>	0.24	-15.4
	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.56	14.1 <sup>ab</sup>	0.23	-13.8
	NH <sub>4</sub> OH	0.55	13.6 <sup>b</sup>	0.24	-13.3
4.....	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.53	12.0	0.43	-11.8
	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.52	12.2	0.48	-12.1
	NH <sub>4</sub> OH	0.49	11.5	0.44	-11.4
Treatment means	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	0.53	12.4	0.42	-12.3
	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.54	12.4	0.39	-12.3
	NH <sub>4</sub> OH	0.54	12.0	0.40	-11.9
Soil means:					
1.....		0.54 <sup>ab†</sup>	12.1 <sup>b†</sup>	0.39 <sup>b†</sup>	-12.0 <sup>b†</sup>
2.....		0.52 <sup>b</sup>	10.8 <sup>c</sup>	0.53 <sup>a</sup>	-10.8 <sup>c</sup>
3.....		0.56 <sup>a</sup>	14.5 <sup>a</sup>	0.24 <sup>c</sup>	-14.2 <sup>a</sup>
4.....		0.52 <sup>b</sup>	11.9 <sup>b</sup>	0.45 <sup>ab</sup>	-11.8 <sup>b</sup>

\* All units are equivalents per tank.

† Values within each soil set not having a letter in common differ at the 0.05 level.

‡ Values within each soil set not having a letter in common differ at the 0.01 level.

and 3 were similar. The differences between the K values at the start and at the end represent the reduction in exchangeable K, mostly as a result of removal by crops. These reductions amounted to approximately 5.1, 3.6, 6.3, and 5.4 equivalents per tank, respectively, for soils 1 through 4. This decrease in exchangeable K represented 33 to 46 per cent of the total depletion of K from the tank. Potassium depletion minus the decrease in exchangeable K must represent the release from non-exchangeable forms.

Because the soils, at the start of the experiment, were uniform in K content at all depths, the decrease in K during cropping should represent a root-activity distribution pattern. Table 18 shows distribution of root activity as indicated by percentages of total exchange-

TABLE 18  
ROOT ACTIVITY OF CHARD AND CORN AT VARIOUS DEPTHS IN FOUR LYSIMETER SOILS, AS INDICATED BY REMOVAL OF EXCHANGEABLE K FROM SOIL

Soil depth	Exchangeable K removed from soil no.:			
	1	2	3	4
cm	per cent	per cent	per cent	per cent
0-30.....	27	44	24	34
30-60.....	26	34	25	32
60-90.....	21	15	22	19
90-120.....	15	4	16	11
120-150.....	11	3	13	4

able K removed from the soil. Root distribution in soils 1 and 3 was fairly uniform as compared with soils 2 and 4, in which root activities were more highly concentrated in the surface

layers. Soil 2, with the least root activity in the lower depths, produced the lowest yields of both crops. Observations during the irrigation and during

periods of leaching indicated that soil 2 had the lowest water intake rate and the lowest rate of water conductivity through the columns.

## SUMMARY

**Crop yields.** Treatments made with  $(\text{NH}_4)_2\text{SO}_4$ ,  $\text{Ca}(\text{NO}_3)_2$ , or  $\text{NH}_4\text{OH}$  produced no differences in yield of corn grown during the spring and early summer or in Swiss chard grown during the autumn and winter. The rate of N application, which was the same for all sources, was sufficient to prevent deficiencies, but was not excessive, judging from the low level of  $\text{NO}_3$  in drainage waters. Variations in yields of crops from different soils were probably caused by the physical or biological differences among soils.

**Irrigation and drainage water.** Total irrigation water used was largely determined by yields of crops and thus was related to soils rather than to treatments. The drainage water represented 6.6 to 8 per cent of the water added (average, 7.4).

Crops removed a large fraction of the salt added to the soil in irrigation water. When salt in the irrigation water was low, removal by crops was a significant factor in reducing the need for leaching, but this effect lessened with water of higher salt content.

During the first year of operation of the lysimeters the drainage water from certain tanks had relatively high Mn and Fe concentrations and relatively low  $\text{NO}_3$  and  $\text{SO}_4$  concentrations, indicating losses of N and S by reduction. During the second year, this was less pronounced, and did not occur thereafter.

The drainage water during the fifth year of operation showed higher Ca concentration from tanks treated with  $(\text{NH}_4)_2\text{SO}_4$  than from tanks treated with  $\text{Ca}(\text{NO}_3)_2$  or  $\text{NH}_4\text{OH}$ . Since the  $\text{Ca}(\text{NO}_3)_2$ - and  $\text{NH}_4\text{OH}$ -treated tanks produced the same amount of Ca in the

drainage water, the Ca added as  $\text{Ca}(\text{NO}_3)_2$  was either precipitated or accumulated as soluble salt.

**Salinity.** The  $(\text{NH}_4)_2\text{SO}_4$  produced a much higher soluble-salt content in the soil than did the other N sources. The absence of differences between  $\text{Ca}(\text{NO}_3)_2$  and  $\text{NH}_4\text{OH}$  treatments suggests that the Ca added as  $\text{Ca}(\text{NO}_3)_2$  was precipitated, presumably as  $\text{CaCO}_3$ . The acidification from  $(\text{NH}_4)_2\text{SO}_4$  was evidently responsible for keeping a higher total salt content in the soil.

**Acidity.** The  $\text{Ca}(\text{NO}_3)_2$  increased soil pH except where the original pH was 7.8 or higher. The  $(\text{NH}_4)_2\text{SO}_4$  produced more acidity than the alkalinity of the water could counteract, whereas  $\text{NH}_4\text{OH}$  produced less.

**Nitrogen.** The N sources produced no differences in yields, but  $\text{Ca}(\text{NO}_3)_2$  resulted in higher total N in crops. One soil with a high total organic matter contributed large amounts of  $\text{NO}_3$  to the drainage water, but amounts from the other three soils were low.

**Chloride.** Depletion of Cl resulted mostly from removal by crops.

**Sulfur.** Sulfur added in  $(\text{NH}_4)_2\text{SO}_4$  accumulated in the soil mainly as soluble  $\text{SO}_4$ . General accumulation of  $\text{SO}_4$  occurred with all treatments and in all soils except one, which had a solid-phase  $\text{CaSO}_4$ , and lost  $\text{SO}_4$  during the experimental period.

**Calcium.** This element accumulated in all cases. In one soil, loss of Ca was greater from the  $(\text{NH}_4)_2\text{SO}_4$  than from  $\text{Ca}(\text{NO}_3)_2$  and  $\text{NH}_4\text{OH}$  treatments. The Ca from  $\text{Ca}(\text{NO}_3)_2$  accumulated mainly in an insoluble form.

**Magnesium.** In most soils and treatments, Mg was depleted. Removal by crops and in drainage was about equal



except for one soil, which had a relatively high salt content at the start of the experiment.

**Sodium.** Three soils accumulated Na, but one showed a large net loss of this element.

**Potassium.** Net losses of K were great in all cases, mostly as a result of removal

by crops. Decreases in exchangeable K represented 33 to 46 per cent of that removed by crops. Release from nonexchangeable forms represented 54 to 67 per cent. Distribution of exchangeable K at the end of the experiment indicated a correlation between root depth and yield in corn.

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