HILGARDIA

JOURNAL OF AGRICULTURAL SCIENCE PUBLISHED BY
THE CALIFORNIA AGRICULTURAL EXPERIMENT STATION

Volume 42, Number 1 · May, 1973

Depth Distribution of Salts in Soils Irrigated by Means of Permanent Furrows

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HILGA4 42(1) 1-16 (1973)

UNIVERSITY OF CALIFORNIA DIVISION OF AGRICULTURAL SCIENCES

Analyses of saturation extracts of soil samples from six treatments of a long-term fertility trial, in which irrigation was by gravity flow into permanent furrows, indicated considerable retention of salt within the root zone. Most of the salt retention was within the 0- to 8-foot depth, but some extended into the 10- to 15-foot depth. Salt concentrations within the root zone were correlated with leaching fractions. Analyses of samples from below the 10-foot depth showed that drainage waters had much lower salt contents than the water of the root zone, and suggest that the drainage waters effectively by-passed soil volumes of higher salt concentration in the root zone. Because of salt retention in the root zone of the permanent-furrow gravity-flow irrigation system, higher leaching fractions are required to prevent accumulation of adverse salt concentrations than would be the case for many other systems.

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Depth Distribution of Salts in Soils Irrigated by Means of Permanent Furrows[1]

INTRODUCTION

NUTRIENT AVAILABILITY, salt toxicity, and composition of drainage water are related to depth distribution of soluble salts and soluble nutrient ions. The heterogeneity of salt distribution is perhaps maximum where permanent furrows are maintained, where water is distributed by gravity flow down these furrows, and where rainfall is insufficient to upset the salt-distribution patterns produced by the irrigation system. The permanent-furrow irrigation system used in citrus production in the Santa Ana River Valley of southern California has these essential conditions for heterogeneity of depth distribution of salt.

Harding *et al.* (1958) studied depth distribution of salt in 4-foot profiles of a number of treatments in the long-term fertility trial used for the study reported herein. They found minimum salt concentrations at the 6- to 12-inch depth, with salt concentration increasing with increase in depth to the third or fourth foot. In a detailed study of the three dimensional distribution of salt in 4-foot profiles of the same fertility trial, Harding and Ryan (1961) found that furrow ridges and areas under these ridges had more salt than the furrows and the area under them, and that plots having permanent furrows had more salt than cultivated plots. Differences in salt content between furrow ridges and furrows were small in tilled plots. Harding (1954) found relatively large surface accumulations of NO_3^- and soluble salts in the furrow ridges of a number of citrus groves in southern California.

This paper describes salt-distribution patterns in deep profiles of six treatments in a long-term fertility trial and also discusses the results in terms of mechanisms for salt retention within the root zone of the trees, the residual effects of N fertilizers, and the leaching of salts. Data for NO_3^- and Cl^- in 100-foot profiles of the same treatments have been presented elsewhere (Pratt *et al.*, 1972, and Pratt, 1972).

EXPERIMENTAL AREA

The soil profiles sampled were in a long-term fertility trial with Washington navel oranges. The trees were planted in 1917 and differential fertilizer treatments were started in 1927. From 1927 to 1939 the rate of application of N in most treatments was 1 pound per tree per year, or about 100 pounds per acre per year. In the winter of 1939–40 the basic rate of application of N was increased to 3 to 5 pounds per tree per year or about 300 to 500 pounds per acre per year. The lower rate of application was used to compare different sources of N; the higher rate was used to completely eliminate available N as a factor and thus measure responses to other elements and to measure the secondary effects of various fertilizers in a shorter period of time. The estimated volume of irrigation water infiltrating into the soil varied from 34 to 41 surface inches per year; no estimate of intake of rainwater was available. Average

[1] Submitted for publication September 1, 1972

rainfall was 11 inches per year, mostly during winter, and estimated evapotranspiration was 24 surface inches of water per year during the irrigation season. Drainage volumes were estimated at 10 to 17 surface inches per year.

The soil in the long-term fertility trial is a Hanford sandy loam having little if any evidence of a textural B horizon. To approximately the 10-foot depth the texture was a sandy loam with alternate layers of loamy sand to silt loams and loams below this depth. Strata of sands were found in a few areas. There was no evidence of a restricting layer that would cause drainage water to move laterally. The 0- to 2-foot depth of soil was originally slightly acid, but at the time of sampling the whole profile was slightly calcareous as a result of accumulation of $CaCO_3$ from Ca^{++} and HCO_3^- ions of the irrigation water.

Starting in the 1963 irrigation season all treatments were discontinued and a uniform rate of 150 pounds N per acre per year was imposed. Thus, for six seasons, prior to the sampling in the spring of 1969, all plots received uniform applications of N. Irrigation schedules were also uniform so that water intake was dependent on infiltration characteristics of the individual plots, which characteristics were in turn dependent largely on residual effects of pre-1963 treatments (Jones *et al.*, 1961) and on basic soil characteristics. Six treatments thought to have had residual effects of fertilizer N rates and sources were selected for this work. Table 1 gives data from these treatments.

TABLE 1

NITROGEN FERTILIZER TREATMENTS FOR SIX TREATMENTS SELECTED FOR STUDY

Treatment number	Fertilizer N treatments			
	Prior to 1963		1936 to 1969 inclusive	
	Annual rate of N applied	Source*	Annual rate of N applied	Source*
	1 lb per acre		*1 lb per acre*	
1	50	Irrigation water	150	NH_4NO_3
6	50	Irrigation water	150	NH_4NO_3
21	350	$Ca(NO_3)_2$	150	NH_4NO_3
23	550	$Ca(NO_3)_2$	150	NH_4NO_3
26	350	$NaNO_3$	150	NH_4NO_3
30	350	Steer manure	150	NH_4NO_3

* The average amount of N added as NO_3^- in the irrigation water is included in these rates.

The long-term average composition of the irrigation water, in meq per liter, was: Ca, 2.43; Mg. 0.76; Na, 1.46; Cl, 0.65; SO_4, 1.03; and HCO_3, 3.00. The average electrical conductivity (EC) was 0.45 mmhos per liter. Only minor variations from this composition occurred during the years of the experiment, but the amount of NO_3^- in the water gradually increased from < 1 to about 7 mg $NO_3^- - N$ per liter. Along with this increase in NO_3^- concentrations, soluble cations Ca^{++}, Mg^{++}, and Na^+ also increased slightly over the years.

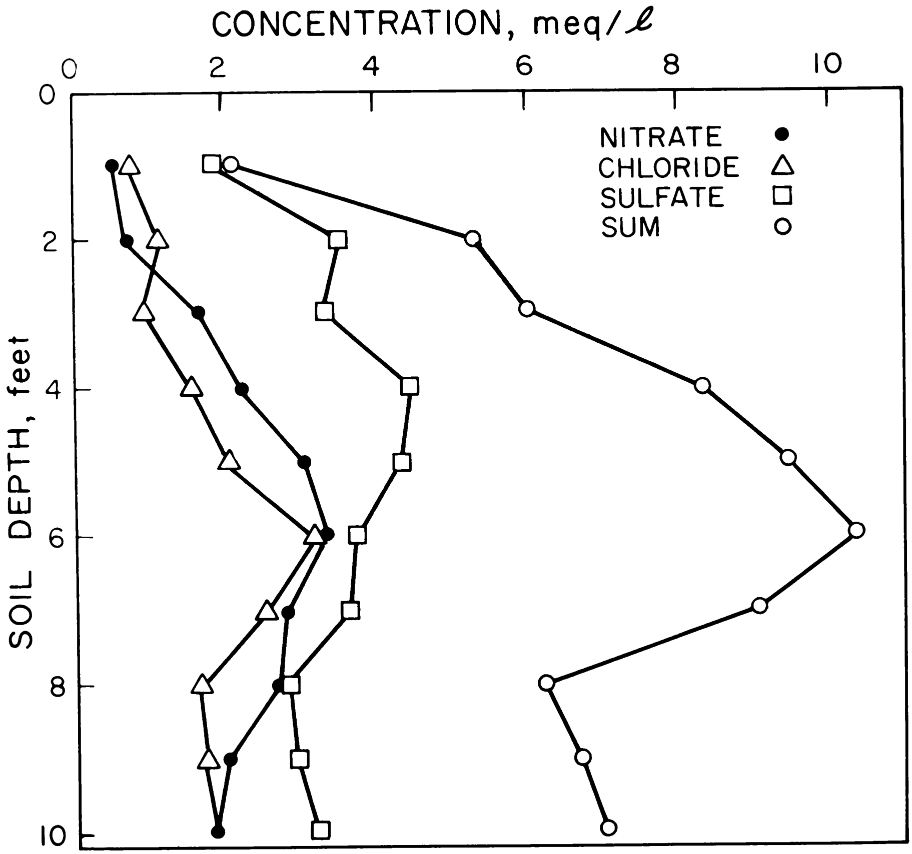

Fig. 1. Depth distribution patterns for soluble anions in saturation extracts of samples from treatment 1.

METHODS

Soil samples were taken in 1969 from two plots for each of six treatments. Samples were taken from the center irrigation furrow using a power-driven 24-inch bucket auger which had enough diameter so that part of the samples came from under the furrow ridges. There was some variation in positioning the drilling rig, so the samples probably represented a good average of the soil under furrow ridges and furrows. The data herein presented are averages of six holes. Samples were taken at 1-foot intervals to the 10-foot depth, and at 5-foot intervals from the 10- to 100-foot depth. Following rapid air-drying, samples were mixed with distilled water to make a saturation paste and saturation extracts were obtained by suction. Extracts were analayzed for NO_3^-, Cl^-, $SO_4^=$ and HCO_3^- and the electrical conductivity (EC) was determined. Below the 10-foot depth only NO_3^-, and Cl^- and electrical conductivity were determined. Leaching fractions (the drainage volume expressed as a fraction of the irrigation water intake) were calculated as the ratio of the Cl^- concentration of the irrigation water—the average Cl^- concentration in the water in the soil material of the 10- to 100-foot depth.

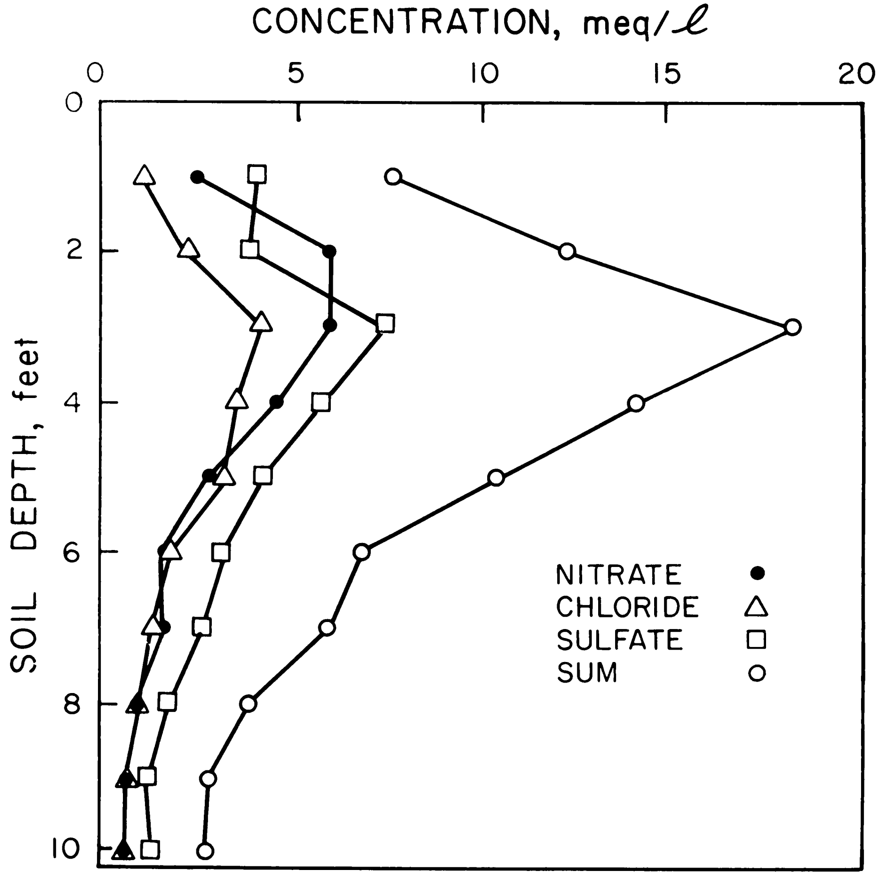

Fig. 2. Depth distribution patterns for soluble anions in saturation extracts of samples from treatment 6.

RESULTS AND DISCUSSION

Figures 1 through 6 show the patterns of depth distribution of NO_3^-, Cl^-, $SO_4^=$ and the sum of these three anions for six treatments. Peaks of concentration are mostly in the 3-, 4-, and 6-foot depth with some variation among the anions within some of the profiles. The patterns are somewhat similar for treatments 1, 6, 21, and 30 even though the maxima are at different depths, whereas patterns for treatments 23 and 26 are different with consistently high total anion concentrations in the 0- to 4-foot depth. This difference is largely a result of the accumulation of $SO_4^=$ in surface layers of treatments 23 and 26, in which the $SO_4^=$ concentration in the surface foot of soil is sufficiently high that the precipitation of $CaSO_4$ is likely. The field water range would most likely give concentrations two to four times greater than in saturation extracts or concentrations of about 35 to 70 meg $SO_4^=$ per liter in the surface foot of soil of these two treatments. These concentrations are typical for soils saturated with $CaSO_4$.

Figures 7 and 8 show, respectively, distribution patterns for electrical conductivity and for soluble HCO_3^-. Patterns for electrical conductivity are es-

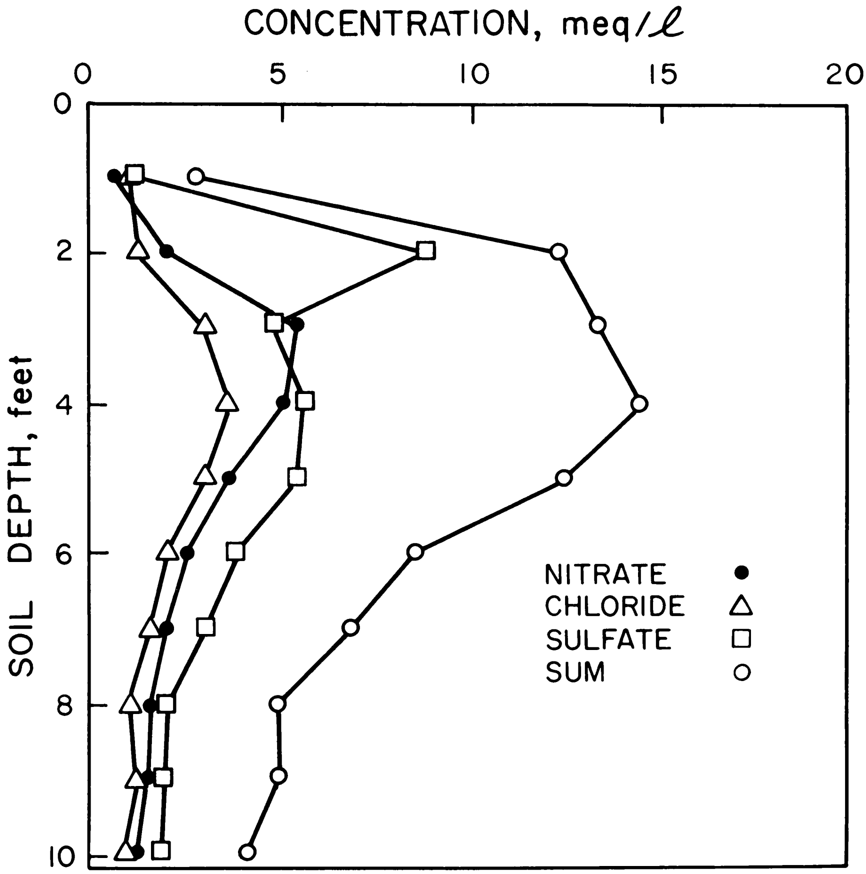

Fig. 3. Depth distribution patterns for soluble anions in saturation extracts of samples from treatment 21.

sentially the same as for the sum of NO_3^-, Cl^- and $SO_4^=$, but the depth distribution of HCO_3^- is radically different with highest concentrations at the surface where biological activity might be expected to be highest. Data for HCO_3^- are presented separately because the concentration of this anion is dependent on solubility of $CaCO_3$, CO_2 pressure, and pH, whereas concentrations of the other anions are dependent on water movement, leaching fraction, and salt cycling in the soil profile.

Figure 9 shows relationships between EC of saturation extracts and soil depth to the 100-foot depth for two treatments; figure 10 shows relationships for NO_3^- concentration and depth for the same depth for two treatments. These relationships are typical of all six treatments. Relatively high concentrations were found in the first few feet, with decreasing concentrations to about the 15-foot depth and a relatively constant concentration for the 15- to 100-foot depth, inclusive. Data for the 100-foot profiles suggest clearly that depth-distribution patterns shown in figures 1 through 6 reflect processes of salt accumulation in the soil-root zone that have been in operation for a number of years.

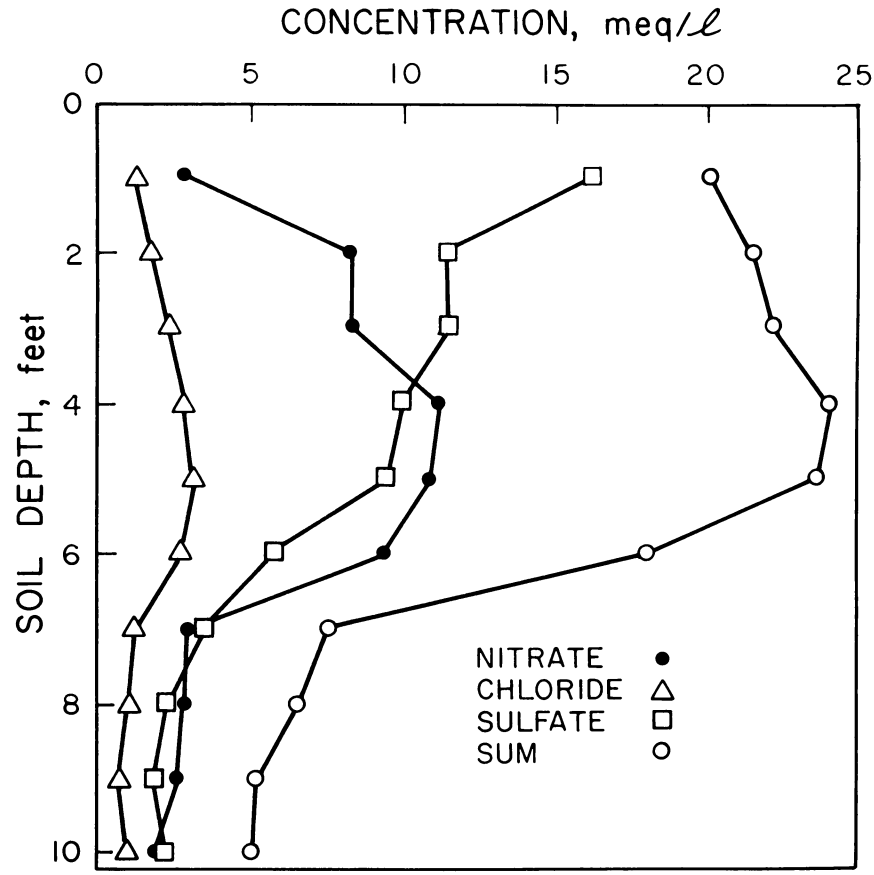

Fig. 4. Depth distribution patterns for soluble anions in saturation extracts of samples from treatment 23.

Anion distribution patterns suggest that cycling of salt in the root zone of the trees is mostly in the 0– to 8-foot depth, and that water moving below this depth is probably beyond recall of the tree-root system. Cahoon *et al.* (1959), studying the same field trial, found that most roots occurred in the first 3 feet and that less than 10 per cent occurred in the 4th foot. This conclusion is also supported by data for 100-foot profiles. Assuming that the root system, as measured by the depth of recall of water, is in the 0- to 8-foot depth, the average concentration of soluble anions (excluding HCO_3^-) would be a measure of the relative amounts of salt retained as a result of salt cycling processes. Table 2 presents such data along with data for leaching fractions; figure 11 shows the relationships between NO_3^-, $SO_4^=$, and the sum of NO_3^-, Cl^-, and $SO_4^=$ and leaching fractions. All correlation coefficients shown are significant at the 0.05 probability level.

Figure 12 shows the relationships of the concentration of NO_3^-, $SO_4^=$, and Cl^- to individual anions and the sum of these anions. Sulfate and NO_3^- are the dominant anions. Cl^- concentration in the irrigation water was 0.65 meq per liter whereas the NO_3^- concentration was approximately 0.5 meq per liter. The ratio of Cl^- to NO_3^- to $SO_4^=$ in the irriga-

TABLE 2

AVERAGE CONCENTRATION OF NITRATE, CHLORIDE, AND SULFATE, AND AMOUNT OF THESE ANIONS IN SATURATION EXTRACTS IN RELATION TO CHLORIDE CONCENTRATIONS IN IRRIGATION AND DRAINAGE WATER AND LEACHING FRACTION

Treatment number	Average concentration*			Amount of anions*	Chloride in:		Leaching fraction
	Nitrate	Chloride	Sulfate		Water	Drainage†	
	meg per liter						
1	2.0	1.7	3.4	7.1	0.65	1.62	0.40
6	3.3	2.4	4.2	9.9	0.65	1.81	0.36
21	2.9	2.2	3.9	9.0	0.65	1.58	0.41
23	7.1	2.1	8.8	18.0	0.65	1.91	0.34
26	8.1	2.3	11.4	21.8	0.65	2.51	0.26
30	3.0	2.3	6.3	11.6	0.65	1.81	0.36

* 0- to 8-foot depth.
† 10-to 100-foot depth.

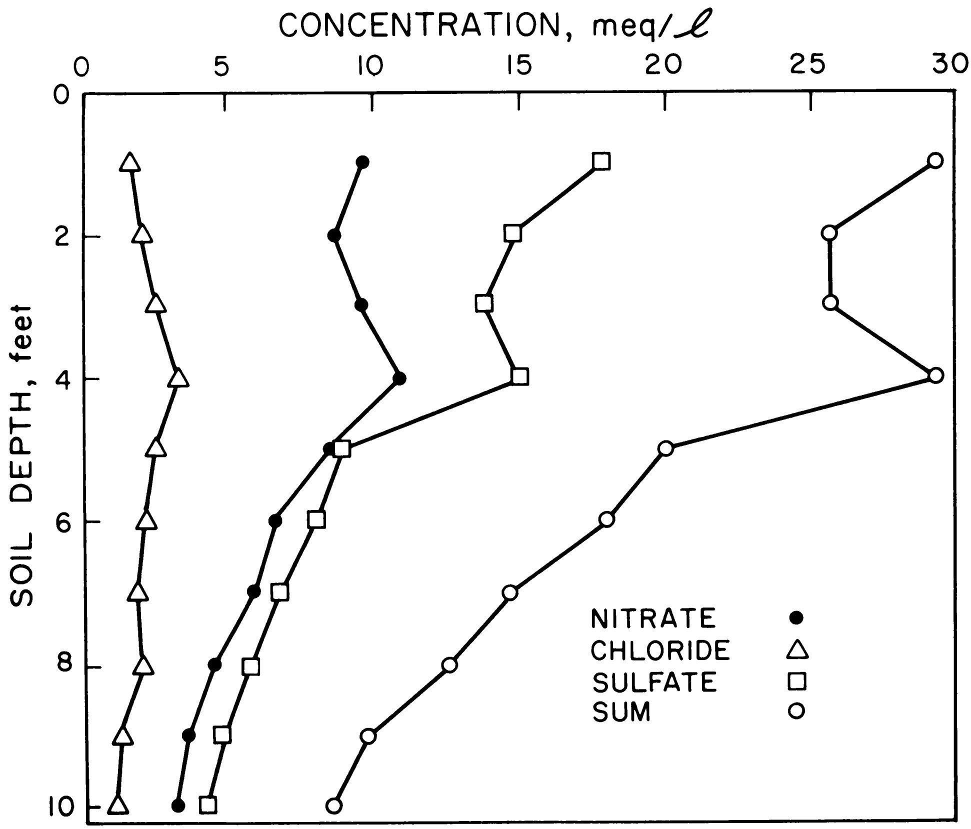

Fig. 5. Depth distribution patterns for soluble anions in saturation extracts of samples from treatment 26.

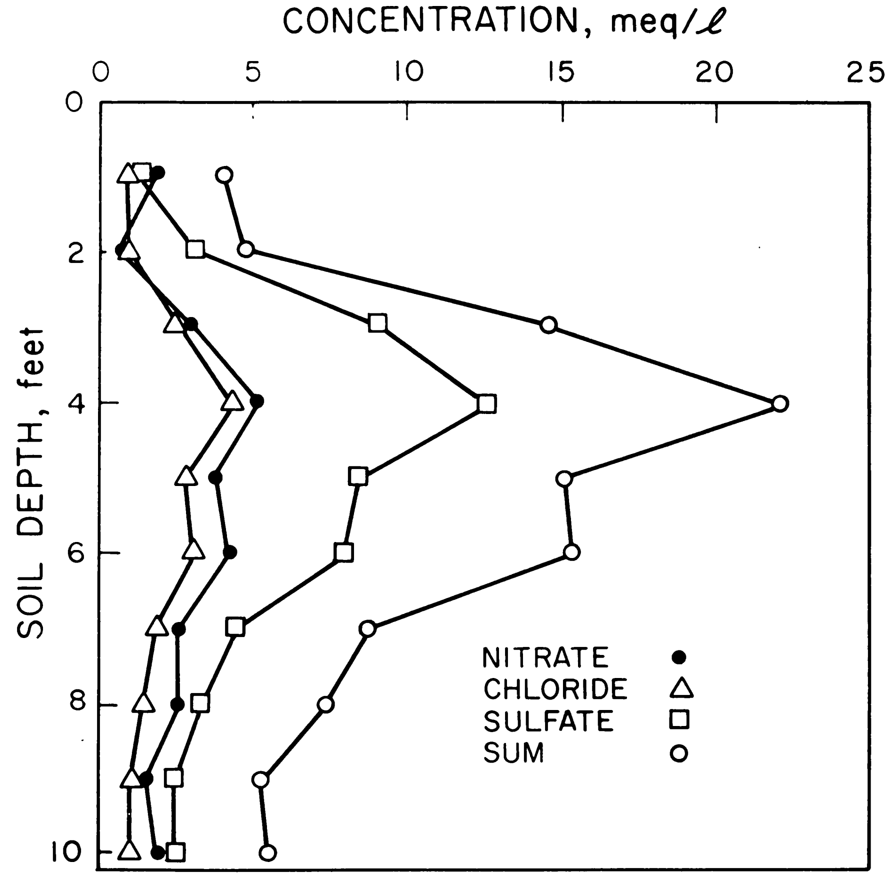

Fig. 6. Depth distribution patterns for soluble anions in saturation extracts of samples from treatment 30.

tion water was approximately 1.0:0.8: 1.6; the average ratio in saturation extracts of the 0- to 8-foot depth of soil was 1.0:2.0:2.9, with a high ratio of 1.0:3.5:4.9 in treatment 26 and low ratio of 1.0:1.2:1.9 in treatment 1. In comparison to Cl^- the soil-root system retains $SO_4^=$ much more efficiently.

Calculated amounts of NO_3^- – N in the 0- to 8-foot depth of soil are approximately 275, 450, 400, 970, 1100, and 400 pounds per acre, respectively, for treatments 1, 6, 21, 23, 26 and 30. These values are not highly correlated with fertilizer rates prior to 1963, but they have a higher correlation with leaching fractions. Because the $SO_4^=$ and the sum of NO_3^-, Cl^- and $SO_4^=$ are also correlated with the leaching fractions and because the only source of $SO_4^=$ was the irrigation water, one might conclude that the accumulation of NO_3^- within the root zone is largely a result of variations in leaching fractions. However, in support of the idea of a residual effect from the pre-1963 period, one must mention that in the 1963 to 1969 period the amount of N added was 900 pounds per acre. Assuming fruit removal of about 240 pounds of N in 6 years and some small losses, some carry-over of N from the pre-1963 period is obvious. Thus, both

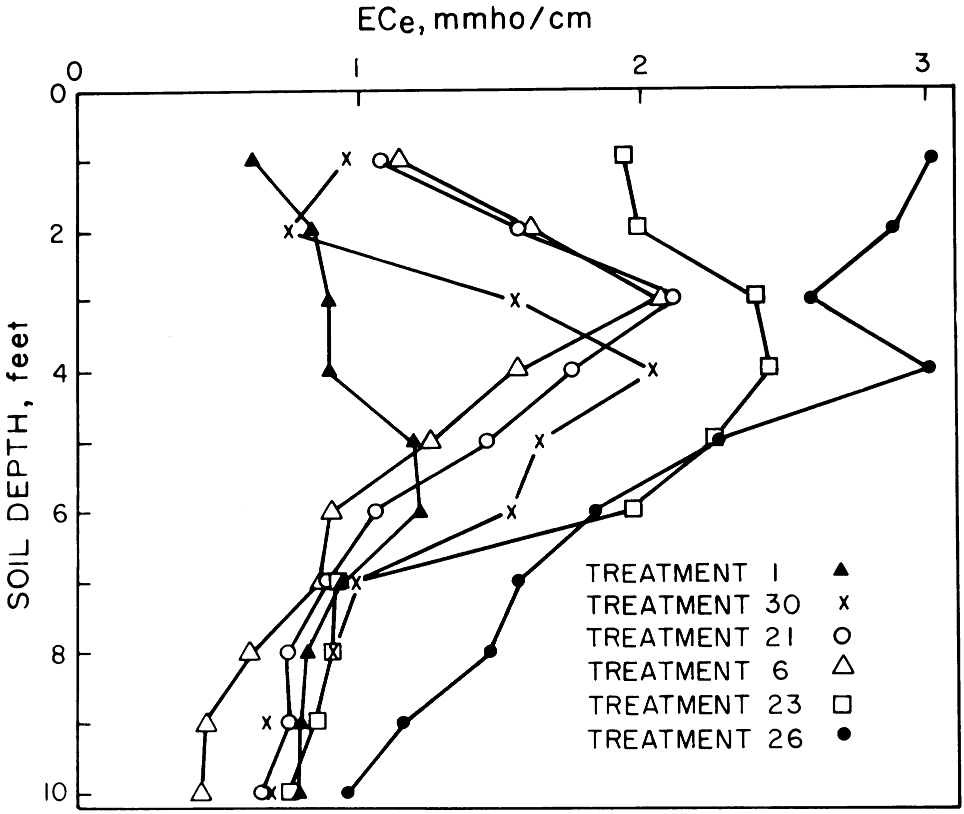

Fig. 7. Relationship between the electrical conductivity of saturation extracts and soil depth.

residual N from the pre-1963 treatments and leaching fractions are likely involved. Perhaps the large residual effect for treatments 23 and 26 were possible only because of relatively low leaching fractions.

The logical explanation for salt-distribution patterns obtained in these plots is that drainage water bypasses the macro- and/or micro-volumes of soil containing the highest salt concentrations. The salt distribution under furrow ridges versus under the furrows, and the cycle of water movement in soils as related to irrigation and drying cycles, are probably contributing factors in the bypass process. This explanation is consistent with modern concepts of water movement in soil pores presented in recent literature (Nielsen, *et al.*, 1972).

Judging from the three-dimensional salt-distribution patterns of Harding and Ryan (1961), water added in the furrows and rainwater that also concentrates in the furrows moves down into soil having the least concentration of soluble salts. From this zone of low salt concentration the water moves toward the furrow ridges and the area under the ridges, thus tending to keep these areas higher in salt; this produces and maintains narrow strips of high salt concentration alternating with strips of less salinity under the furrows. The water that moves down has low

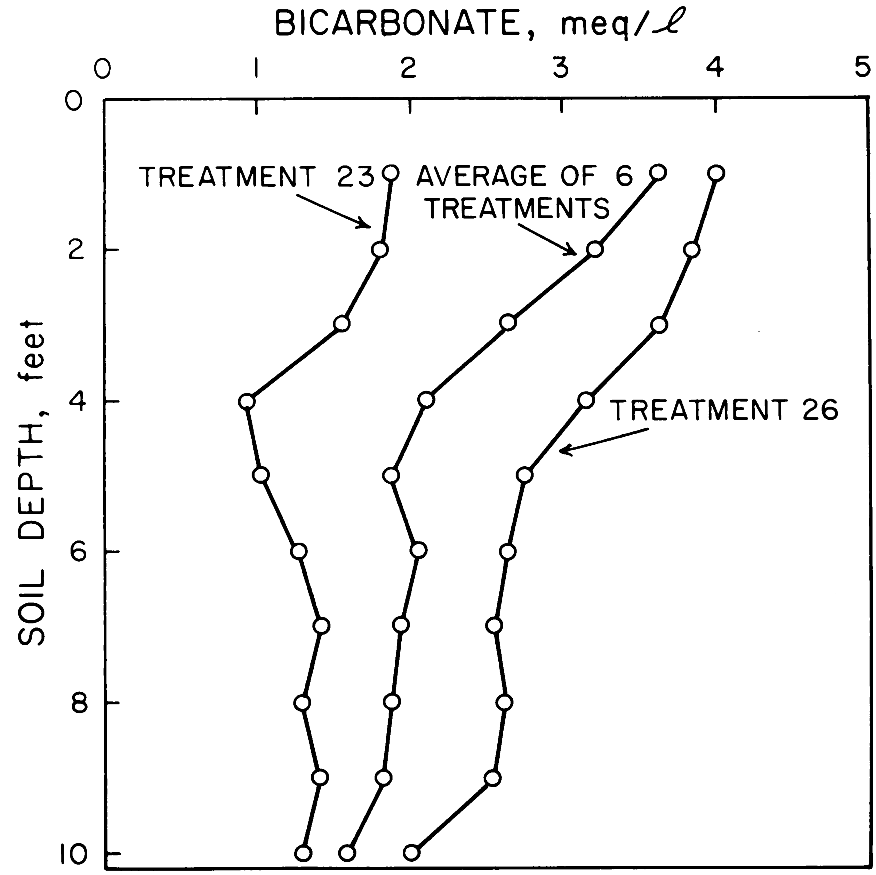

Fig. 8. Relationship between soluble HCO_3^- concentration in saturation extracts and soil depth.

salt concentration; if it escapes from the root zone it carries a low salt concentration and produces a drainage water of lower salt concentration than the average concentration found in the root zone.

When water is added to the soil it not only moves down through soil with lower salt concentration but it moves down rather rapidly through large pores, and consequently has a relatively low efficiency of salt transport. After the downward movement of water has stopped the trees continue to transpire water, and water continues to evaporate from the soil surface. Thus, between irrigations, water moves back up towards the surface and towards the root system. This upward movement is more efficient in salt transport because it occurs at lower rates and because it takes place via smaller pores.

Basing our conclusions on the data presented by Harding and Ryan (1961) and the data presented in this report, we propose that the leaching waters in this field trial passed rapidly through the large pores of the soil under the furrows and reflect the salt concentration under the furrows rather than the average salt concentration in the total soil volume. This means that when leaching

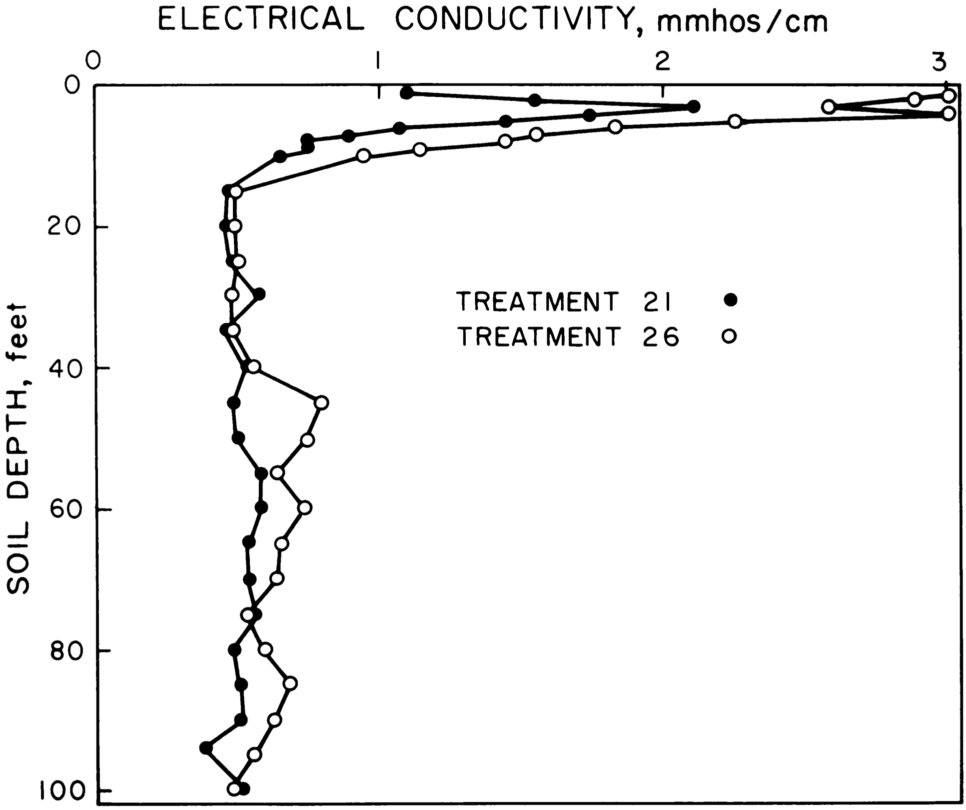

Fig. 9. Relationship between EC of the saturation extract and depth for two treatments.

occurs, water movement is too rapid for diffusion processes to have a large influence in equalizing salt concentration throughout the soil volume. However, the total salt under the furrows evidently is influenced by the salt under the furrow ridges, or otherwise the correlation between salt in the soil-root zone and LF would not exist. Thus the salt movement from the furrow area to the ridge area is not a one-way process.

Judging from the idealistic leaching theory that the LF is equal to the EC of the irrigation water divided by the EC of the drainage water, we should have found EC values no higher than about 0.8 mmhos in saturation extracts in the soil-root zone (EC of saturation extracts from below the 10-foot depth were all about 0.8 mmhos or less). Comparisons of this 0.8 mmhos value against peak values shown gives some idea of the order of magnitude of salt retention.

The salt retention in permanent furrow irrigation systems where irrigation is by gravity flow means that higher LF must be obtained with this system, as compared to other systems, to prevent accumulation of adverse levels of salt in the root zone.

In other orchards having permanent furrow-irrigation systems, Jones and Embleton (1960, 1967) have shown that it takes from 2 to 10 years after termin-

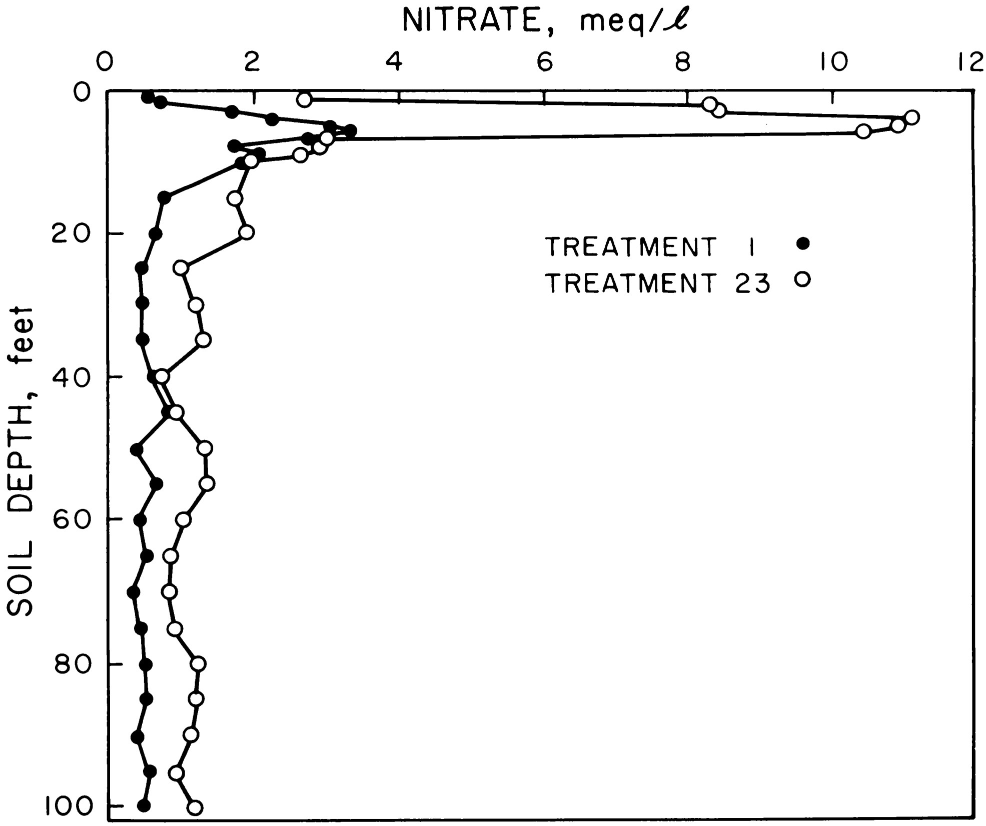

Fig. 10. Relationship between NO_3^- concentration in the saturation extract and depth for two treatments.

ation of fertilizer applications for Washington navel or Valencia orange trees to show nitrogen stress. One reason for this long residual effect could be the recycling and retention of NO_3^- in the soil-root zone as discussed above.

If salt bypass as discussed here is common to lands on which conventional irrigation systems are used, sampling of soils to assess the movement of salts and nutrients from the soil-root zone should be sufficiently deep to get below the zone of higher salt concentration. In our work on leaching of NO_3^- from the soil root-zone under citrus we found that we needed to sample below the 10-foot depth. Samples taken from the root-zone might give a valuable assessment of nutrient availability and potential salt damage to crops, but they might provide a large over-estimate of the concentrations of ions in the drainage water that will move from the root-zone to the groundwater.

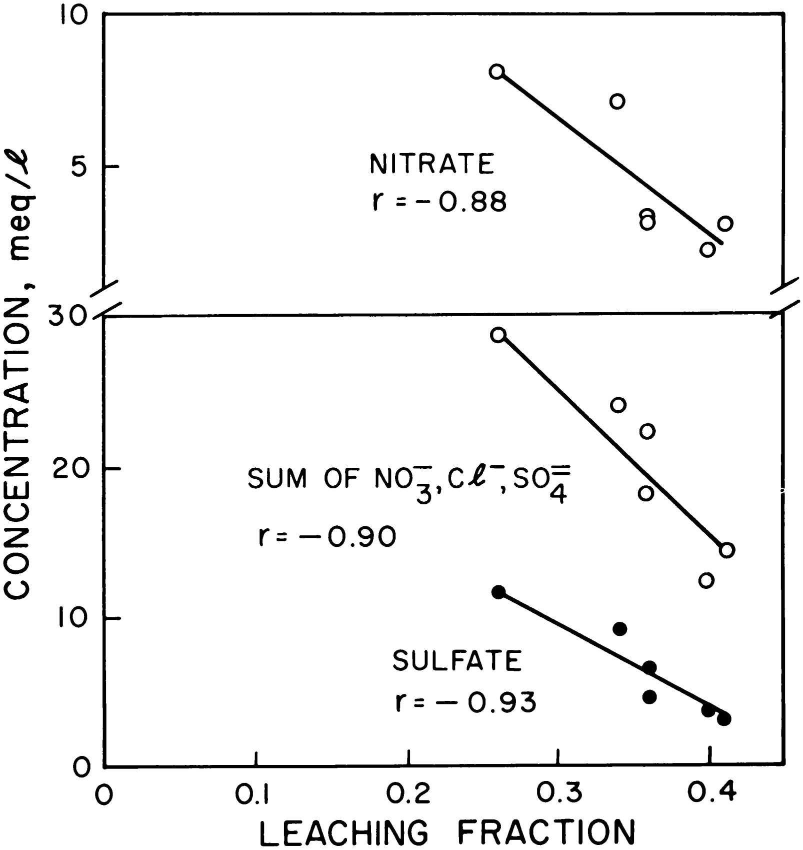

Fig. 11. Relationship between average saturation-extract concentrations of NO_3^-, $SO_4^=$ and sum of NO_3^-, Cl^-, and $SO_4^=$ in the 0- to 8-foot depth to leaching fractions.

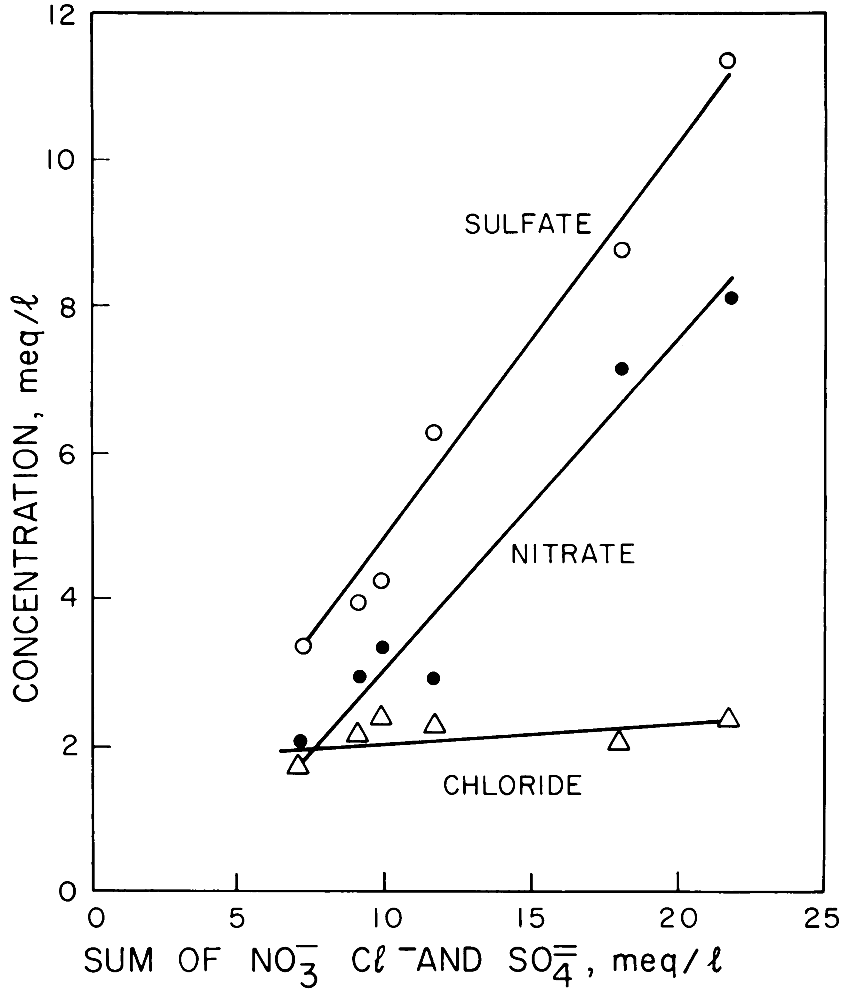

Fig. 12. Relationship between concentration of individual anions and the sum of these anions in saturation extracts for the 0- to 8-foot depth of soil.

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