Nitrification and Denitrification of Municipal Wastewater Effluents Disposed to Land

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NITRIFICATION AND DENITRIFICATION
OF MUNICIPAL WASTEWATER EFFLUENTS DISPOSED TO LAND

DIVISION OF PLANNING AND RESEARCH
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TABLE OF CONTENTS

FOREWORD

Standard Agreement No. 3–2–59 for this report, *Nitrification and Denitrification of Municipal Wastewater Effluents Disposed to Land,* was entered into on July 1, 1974 between the State Water Resources Control Board and the University of California at Davis.

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The findings reported herein are those of the contractor and do not necessarily reflect the opinion or policies of the State Water Resources Control Board.

NITRIFICATION AND DENITRIFICATION OF MUNICIPAL WASTEWATER EFFLUENTS DISPOSED TO LAND

SUMMARY

A study was conducted to evalute the effects of nitrification of nitrogen in wastewater applied to soil on movement of calcium, magnesium, and other ions. The study involved experiments with laboratory soil columns, analysis of field soils with a long history of wastewater or sludge application, and evaluation of the collected data.

Synthetic sewage containing all its nitrogen in either the ammonium or nitrate form was applied to laboratory columns of soil at the rate of 7.5 cm per week for 41 weeks. Total application was equivalent to 1838 lbs N/acre and 11 acre feet of water. Concentrations of calcium and magnesium in the column effluents were higher with ammonium sewage than with nitrate sewage. Similar results were obtained with sewages from treatment plants applied to several different soils representing a wide range of textures and other properties where the level of input ammonium was augmented before application to soil. Where the level of input ammonium was not changed, concentrations of calcium, magnesium and other bases in effluents of soil columns were the same whether the input sewage was nitrified prior to application on soil or not.

Significant losses of nitrogen, up to 32% of the applied N, occurred during the passage of sewage through soil columns as a result of denitrification even though the columns were in an aerobic condition most of the time. Sewage input nitrogen was distinguished from soil nitrogen by use of ^{15}N-enriched tracer materials.

Analysis of soil obtained from a field site where wastewater had been used to irrigate the crop for a period of 36 years showed that the sewage had brought about a marked improvement in the cation status of the soil, which was a saline alkali soil in the virgin condition. Most of the exchangeable sodium in the top 3 ft. of soil had been replaced by calcium as a result of wastewater application.

Comparison of soil taken from a sludge pit with that from an untreated area showed little effect of the sludge on soil properties, except for an increase in calcium and organic matter near the surface and the presence in the profile of considerable ammonium and nitrate.

It is concluded that nitrification does not exert a dominant effect on the acidity of wastewaters or on soils to which they are applied. After nitrification the bicarbonate content of wastewaters was decreased indicating that these are self-buffering to some extent. Consequently the dissolution of calcium and magnesium as a result of nitrification is less than would be expected on the basis of the stoichiometry of the reactions in nitrification. Total dissolved solids, as reflected by equivalent conductance values, in effluents from soil columns receiving nitrified sewage were only 10-15% lower than in effluents from columns receiving ammonium sewage.

Nitrification had no effect on concentrations of calcium in effluents from columns of two different soils treated with wastewater containing 2.5 meq N/l, which suggests that at low levels of input ammonium the acidifying effects of nitrification are counterbalanced by denitrification and reaction with bicarbonate followed by escape of carbon dioxide from the soil. Thus, it seems likely that wastewater application to soil can be managed so as to minimize any effects of nitrification on groundwater hardness. Such management should utilize alternate wetting and drying cycles to favor the nitrification-denitrification sequence and permit escape of cardon dioxide from the soil.

I. INTRODUCTION

Statement of Problem

In recent years there has been a tremendous upsurge in interest in disposal of wastewaters on land as an alternative to the more common practices of discharge to surface waters or ocean outfalls. A recent EPA survey (Sullivan et. al. 1973) of projects on land disposal shows that many communities are utilizing this means of disposing of wastewater.

One of the problems associated with land disposal involves the transformation of nitrogenous components of the wastewater. Secondary effluents commonly have most of the nitrogen present as ammonium ion which, when the wastewater is applied to soil, is subject to nitrification. In nitrification, two hydrogen ions are produced for each nitrate ion as follows:

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O$$

Similarly, in the conversion of organic nitrogen to nitrate, one hydrogen ion is produced for each nitrate ion:

$$\text{organic N} \rightarrow NH_3$$

$$NH_3 + H_2O \rightarrow NH_4OH$$

$$NH_4OH + 2\,O_2 \rightarrow NO_3^- + H^+ + 2H_2O$$

Thus, nitrification has the effect of increasing soil acidity with the potential for bringing insoluble carbonates into solution such as those of calcium and magnesium. In this way, an increase in carbonate content of water percolating down through the soil may eventually contribute to hardness of ground water.

On the other hand, denitrification generates hydroxyl as follows:

$$\text{Organic matter} + NO_3^- \rightarrow \uparrow N_2 + H_2O + OH^- + \uparrow CO_2$$

It can be seen that denitrification has the effect of decreasing the soil acidity with the possibility of precipitating calcium and magnesium ions out of solution. The relative balance between nitrification and denitrification will therefore have an influence on changes in soil acidity or alkalinity in wastewaters containing nitrogen when applied to soil.

Virtually all soils are well supplied with nitrifying bacteria, which require oxygen in order to function. The rate of nitrification is generally higher in calcareous soils than in neutral or acidic ones because the acid produced is neutralized as rapidly as it is formed. If the rate of diffusion of oxygen to the small pores in the soil is slower than the rate of utilization by bacteria and other organisms in these pores then denitrification can occur. In conditions where oxygen supply is limited the rate of denitrification is governed primarily by the supply of available organic matter. Wastewater containing some decomposable organic matter when applied to soils may favor denitrification by furnishing energy materials for denitrifying bacteria.

Thus, the question arises whether an application of ammonium-containing wastewaters to soil is comparable to the application of ammonic fertilizers, the acidifying effects of which are well known. It has been suggested that sewage treatment plants should nitrify the ammonium in wastewaters before they are released from the plant, thus avoiding the possibility of acidification in soils to which the wastewater may ultimately be applied. On the other hand, consideration must also be given to the potential contribution of nitrates to ground waters, which may be greater from nitrified sewage owing to the greater mobility of nitrate than of ammonium.

Purpose of the Investigation

The objective of this study was to evaluate the effects of physical, chemical and biological processes in soils on the chemical characteristics of solutions passing through soils when wastewater containing ammonium or nitrate is spread on land. In order to achieve this objective, two approaches were followed. The first of these involved the treatment of laboratory columns of soil with wastewater containing nitrogen either in the ammonium or nitrate form, but otherwise of similar composition, and measuring the concentrations of various components of the effluents from the columns which would eventually contribute to ground water in a natural situation. In most of these experiments, the nitrogen level of the collected sewage was augmented in order to maximize the effects of nitrification on the composition of the column effluents. Several different soils of varying properties were utilized in the column studies in order to obtain results which might be applicable to a broad range of soils in the field. The second general approach involved analyzing the properties of soils which had been treated with wastewater or sludge over long periods of time and comparing these properties with corresponding values from nearby soils, which had not been treated with wastewater or sludge. These comparisons were used as a basis for determining whether long term application of wastewater or sludge had resulted in significant removal of cations from the soil, particularly calcium and magnesium.

II. BACKGROUND

Definitions of Terms

Some terms used in the report:

Effluent - Solution collected at the bottom of soil columns treated with wastewater.

Exchangeable cations - Positively charged ions which are adsorbed by the negatively charged soil colloids and which may be displaced by other cations in the soil solution. The exchangeable cations considered in this report include calcium, magnesium, potassium, sodium, and ammonium.

Bases - Cations which can hydrolyze to produce a basic reaction. In this report ammonium is not regarded as a base because it has a transitory existence in soil, being rapidly converted to nitrate.

Alkaline - A chemical term referring to basic reaction where the pH reading is above 7, as distinguished from acidic reaction where the pH reading is below 7.

Electrical conductivity - The reciprocal of the electrical resistivity. The resistivity is the resistance in ohms of a conductor 1 cm long with 1 cm^2 cross sectional area. Electrical conductivity of solutions is directly related to total dissolved salts.

Equivalent - The weight in grams of an ion or compound that combines with or replaces 1 gram of hydrogen. The atomic weight or formula weight divided by the valence.

Milliequivalent - One-thousandth of an equivalent.

Saturation extract - The solution extracted from a soil at its saturation percentage, which is the moisture content of a saturated soil paste.

Calcareous soil - A soil or soil layer containing free calcium carbonate.

A-horizon - Surface layer of soil from which material has been removed, but which may contain an accumulation of soil organic matter.

C-horizon - Parent material from which the soil originated.

Nitrification - The conversion of ammonium to nitrate by bacteria in soil or waters.

Denitrification - The reduction of nitrate to nitrogen gas by bacterial action.

Nitrogen mineralization - The decomposition of organic substances containing nitrogen resulting in the liberation of ammonia.

Substrate - Organic material used as a source of energy by organisms.

BOD - Biochemical oxygen demand, a measure of the amount of easily decomposable organic material in waters.

Stabilized - A term referring to the condition of wastewaters after most of the BOD or easily decomposable organic material has been removed.

Description of Soils

The soils used were collected from the Central Valley of California. The range of textures and other properties is representative of many soils in central and southern California. Some of the soil properties are given in Table 1.

1-Salado series

The Salado series is a member of a coarse-loamy,

Table 1: Some properties of soils used in soil columns.

Soil	Org. C, %	$CaCO_3$ %	Org. N %	Clay %	Silt, %	Sand, %	WHC* %
Salado fine sandy loam	1.07	0.20	.100	22.2	26.7	51.1	32.2
Salado subsoil	0.43	4.60	.033	22.0	23.3	54.7	35.3
Panoche sandy loam	0.68	1.54	.040	18.2	16.9	64.9	34.5
Panoche loam	0.56	5.10	.046	25.8	32.2	42.0	40.5
Panoche clay loam	0.72	7.98	.056	24.4	47.8	27.8	54.3
Columbia fine sandy loam	1.18	0.39	.091	11.1	23.1	65.8	37.5
Panoche loam (non-cal.)	0.66	0.44	.068	24.0	24.8	51.2	39.8

*Water holding capacity

mixed, calcareous thermic family of Typic Xerothents. The soils have brown, slightly acid to mildly alkaline A horizons and brown or pale brown, moderately alkaline stratified C horizons. Salado soils occur on the apex of alluvial fans near present stream channels or former stream channels. Their sediments are principally from sedimentary and metamorphic rocks of the Coast Range in California. These soils are well drained with slow runoff and moderately rapid permeability. They occur on the west side of the lower San Joaquin valley in association with Vernalis, Myers and Stomar series. Surface texture varies from sandy loam to loam.

2-Panoche Series

The Panoche series is a member of a fine loamy mixed, calcareous, thermic family of Typic Torriorthents. They have developed in loamy, calcareous alluvium from sedimentary formations.

The color of the A horizons ranges from pale brown and light yellowish brown to about grayish brown and brown. Textures range from sandy loam to silty clay loam. The 10 to 40 inch zone has 18 to 35 percent clay and less than 55 percent silt. The soils are moderately alkaline and calcareous throughout. The upper few inches and a few sandy strata may not be effervescent with acid.

Panoche soils occur on nearly level to sloping fans and flood plains and develop in alluvium from sedimentary alluvium. All of the Panoche soils used in the experiment were taken from the valley floor at the lower elevations. The soils occur at elevations of 200 to 2,000 feet in an arid, Mesothermal climate having a mean annual precipitation of 4 to 12 inches with hot, dry summers and cool, moist winters; an average January temperature of 45°F., an average July temperature of 82°F., a mean annual temperature of 63°F., and an average frost-free season of about 265 days.

The soils are well drained to moderately well drained; runoff is medium; permeability is moderate.

The Panoche soils are used for cotton, alfalfa, grain and many other irrigated crops and dry range. All of the soils used were taken from irrigated land.

3 - Columbia Series

The Columbia series is a member of the coarse-loamy, mixed, nonacid, thermic faimly of Aquic Xerofluvents. Typically, Columbia soils have pale brown, mottled, fine sandy loam C horizons stratified with sand, silt loam, and loam.

The average clay content of the 10 to 40 inch control section is 10 to 18 percent with 68 to 70 percent fine sand or coarser. Organic matter decreases irregularly with depth. The A horizon is pale brown, brown, light yellowish brown, grayish brown or light brownish gray. It has less than 1 percent organic matter and it is hard and massive when dry. It is slightly acid to mildly alkaline. The soil samples were taken from the top 6 inches.

Columbia soils are on nearly level flood-plains or natural levees and formed in mixed recent alluvium from a wide variety of rocks. They are at elevations of less than 150 feet. The climate is semiarid, mesothermal with hot dry summers and cool moist winters. Mean annual precipitation is 12 to 25 inches. Mean annual temperature is about 63°F., average January temperature is about 45°F., and average July temperature about 81°F. The frost free season averages about 270 days.

The soils are somewhat poorly drained; slow to very slow runoff; moderately rapid permeability.

Most of the soils are used for alfalfa, orchard, field and row crops. The soils used in the experiment came from a pear orchard.

Nitrification In Wastewater Prior To Application On Land

One of the peculiarities of the nitrifying bacteria is that the nitrite oxidizers, in particular, are sensitive to ammonium ion and even more so to free ammonia, with the result that in aqueous systems there is frequently an accumulation of nitrite until the ammonium concentration has become very low, at which point the nitrite oxidizers find conditions more to their liking and increase in activity. The typical course of nitrification in municipal wastewater during aeration is given in Table 2 showing changes in four different sewages from the Santa Ana Region. First, there is a lag phase of a few days before nitrite appears, then a period of nitrite accumulation, and finally, after ammonium concentration has reached low values, nitrate appears. Eventually most of the inorganic nitrogen is converted to nitrate, although some losses may occur during aerobic incubation.

This pattern is altered somewhat when wastewaters come into contact with soil. Ammonium is adsorbed on cation retention sites of the organic and inorganic soil colloids so that the concentration of this species in solution becomes quite low. Consequently the inhibitory effect on Nitrobacter is eliminated and nitrite rarely accumulates.

Effect of Environmental Factors on Nitrification

The influence of environmental variables on nitrification in soils has been studied very thoroughly over a long period of time and will not be reviewed in detail here. Of the variables likely to effect rate of nitrification in wastewater application temperature is important because of the desirability in many situations

Table 2. Changes of inorganic nitrogen in four sewage samples during aerobic oxidation. All values in ppm.

Days	0	4	10	17	24	31
Riverside						
NH_4-N	8.1	9.6	0.3	0.4	0.0	0.0
NO_2-N	0.0	0.0	8.2	3.6	0.0	0.0
NO_3-N	0.0	0.5	0.7	3.03	5.06	5.06
Sum	8.1	10.5	9.2	7.0	5.1	5.1
Ontario						
NH_4-N	10.8	10.8	9.8	0.4	0.0	0.0
NO_2-N	0.0	0.0	1.7	4.5	0.7	0.5
NO_3-N	0.0	0.3	0.3	0.0	12.5	10.6
Sum	10.8	11.1	11.8	4.9	13.2	11.1
Redlands						
NH_4-N	18.2	18.4	0.3	0.3	0.0	0.0
NO_2-N	0.0	0.0	15.5	6.9	0.0	0.0
NO_3-N	0.0	0.8	1.3	5.1	11.9	14.3
Sum	18.2	19.2	17.1	12.3	11.9	14.3
Sun City						
NH_4-N	19.3	18.4	0.4	0.3	0.0	0.0
NO_2-N	tr	0.0	19.3	9.2	0.0	0.0
NO_3-N	0.0	0.6	1.5	4.2	14.0	22.2
Sum	19.3	19.0	21.2	13.7	14.0	22.2

of disposing of wastewater on land throughout the year. The optimum temperature for nitrification usually is within the range between 25 and 35°C depending on the location. There is some evidence that nitrifying bacteria are able to adapt themselves to the climatic circumstances in which they occur (Mahendrappa et al, 1966). Rates of nitrification are retarded by decreasing the temperature, but measureable oxidation of ammonium and nitrite has been reported as low as 2°C (Frederick, 1956).

The pH optimum for nitrifying bacteria usually is in the range from pH 6 to 8. Under acid conditions activity falls off quite sharply. The well known stimulating effect of calcium carbonate on nitrification is probably due largely to maintenance of the soil pH within an optimum range during the process, which generates some acid. The pH of municipal wastewater usually is in the range which is optimum for nitrification. During nitrification out of soil wastewater may become more alkaline by one or more pH units, as is illustrated in Table 3.

Another change which accompanies nitrification in wastewaters is alteration in the bicarbonate concentration and the buffering capacity of the wastewater. Figure 1 shows titration curves of two municipal wastewaters initially and after 10 days of aerobic incubation. It is clear that the buffer capacity has decreased substantially. These changes, together with

Table 3. pH values of four secondary sewage samples during aerobic incubation.

Sewage	Days Incubation					
	0	4	10	17	24	31
Riverside	7.30	8.60	8.80	8.75	8.72	8.55
Ontario	7.45	8.75	8.78	8.80	9.00	8.50
Redlands	7.45	8.80	8.58	8.60	8.40	8.30
Sun City	6.45	8.65	8.15	8.20	8.00	7.80

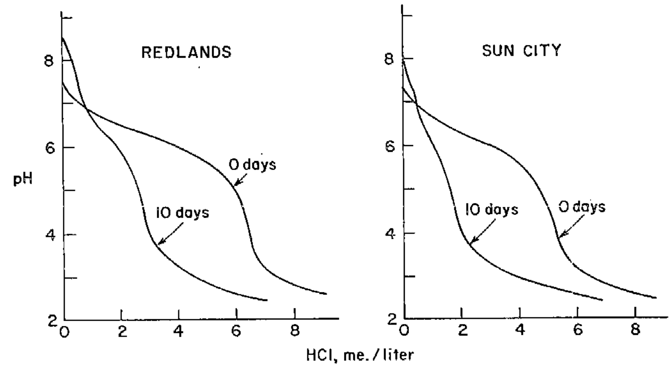


Fig. 1. Titration curves of two secondary sewages during aerobic incubation.

the associated increase in pH, suggest a decrease in bicarbonate, precipitation of phosphates, and decomposition of organic acids, leaving the associated cations such as sodium remaining in solution.

When wastewaters are applied to soil the pH of the soil is likely to dominate the situation, because soils are normally much more buffered than are wastewaters. However, with prolonged application of wastewater the tendency is for acidic soils to be made neutral or even alkaline as has been shown in the application of wastewater on extremely acidic soil (Sopper, 1973). In some instances where the pH is initially too low even to permit the growth of plants, application of wastewater not only increases the pH but contributes nutrients to the soil which makes growth of plants possible.

Mineral Nutrition

Nitrifying bacteria require among other elements, magnesium, potassium, phosphorus, sulfur, and iron. Molydenum and copper have been shown to stimulate the activity of Nitrobacter (Kiesow, 1962). Of these essential nutrients, one which is likely to become deficient in anaerobic wastewater treatment is iron because of its precipitation as the sulfide or its chelation by organic components of sludge resulting in an effluent which is very deficient in iron. In particular, the oxidation of nitrite is sensitive to iron deficiency. Aleem and Alexander (1960) reported the tripling of nitrite oxidation rate by addition of only 7 ppb of iron in solution culture. In wastewater nitrifying activity responds to substantially higher levels of iron. For example, Figure 1 shows nitrite oxidation curves of a wastewater in which there was a response up to 75 ppm iron added as ferric chloride.

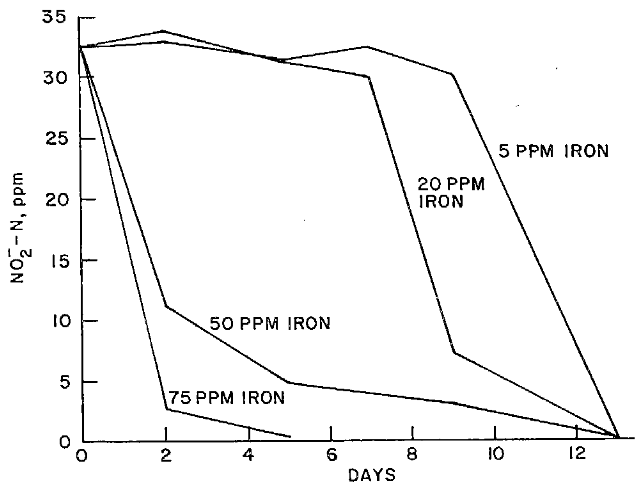


Fig. 2. Effect of added iron on nitrite oxidation in wastewater.

Effect of Size of Nitrifying Population

Although most soils are abundantly supplied with bacteria capable of carrying out nitrification, there may be some soils to which wastewater is applied where the nitrifying population is initially small. This may occur in situations where soil has been subjected to prolonged periods of drying or where topsoil has been removed and the subsoil has a low bacterial count. In such cases the effect of application of ammonium containing wastewater is a temporary accumulation of ammonium ion near the soil surface during a period when nitrifying bacteria are proliferating. The result is a lag period of a few days or a few weeks before nitrate is formed in appreciable concentration, followed by a wave of nitrate substantially higher in concentration than the ammonium concentration of the input sewage, owing to the influence of the soil colloids in accumulating ammonium in a localized region of the soil.

Effect of Environmental Variables on Denitrification

The rate and extent of denitrification during application of wastewater on land are likely to be governed in large measure by the quantity of available substrate or organic matter and the supply of oxygen in the microsites in which denitrifying bacteria function. Wastewaters typically contain some dissolved organic matter, but normally are applied after having been stabilized, with a consequence that the BOD is relatively low. On this account, the organic matter status of the soil to which the water is applied is likely to be more important than that of the wastewater itself. Woldendrop et al (1966) have pointed out the important role that the roots of growing plants may play in relation to denitrification rates. This role is a two-fold one in which substrate may be contributed through root secretions or sloughed off root tissue. Plants may also play a secondary role by utilizing available oxygen and increasing the concentration of carbon dioxide in the soil, thereby favoring the activities of the denitrifiers.

Oxygen concentration is inversely related to the moisture content of soil and the degree to which denitrification occurs will be altered to a substantial degree by the manner in which wastewater is applied. Continuous application of wastewater resulting in a saturated soil condition may initially tend to favor the denitrification process, but if continued for prolonged periods nitrification of the input ammonium may be severely inhibited, with the result that denitrification is also of minor significance. The relative balance between nitrification and denitrification can be modified by management of of wastewater application. For example, if wastewater is applied intermittently rather than continuously, cycles which are alternately aerobic and anaerobic can develop in the soil. During the aerobic cycle between periods of wastewater application, soil pores tend to fill with air and nitrification can take place. After the nitrate is produced, if the soil is then flooded to eliminate oxygen and to provide conditions favorable for denitrification, a considerable part of the nitrate may disappear through denitrification. This is illustrated in the work of Lance and Whisler (1972) who found that short cycles of flooding soil columns with secondary sewage effluent caused no net removal of nitrogen but transformed almost all the nitrogen to nitrate. With longer cycles during which the soils were flooded from 9-23 days and then allowed to dry for 5 days net nitrogen removal from the system was 30%. Net N removal ceased after 80 days of continuous flooding. Alternate flooding and drying periods were necessary for consistent N removal.

III. EXPERIMENTAL PROCEDURES

Laboratory Column Studies

Phase 1 - Experiments with synthetic sewages

Duplicate columns of Salado sandy loam and its calcareous subsoil were set up using PVC pipe 5 cm in diameter and 120 cm in length. The columns were filled with soil to a depth of 1 meter. Two samples of synthetic sewage were prepared by mixing inorganic salts to approximate the average composition of four secondary sewages from treatment plants in the Santa Ana basin. These two synthetic sewages were identical in composition except that one contained all the nitrogen (3 meq/l) in the ammonium form with chloride as balancing ion, while the other contained an equal amount of nitrate with potassium as the balancing ion. Composition of the two solutions are given in Table 4. These synthetic sewages were applied to soil columns in sufficient amount to wet the soil initially, after which weekly applications of 7.5 cm were made. After addition of each weekly application the columns were allowed to drain and the effluents collected for subsequent analysis.

Table 4. Composition of synthetic sewage applied to columns of Salado fine sandy loam and Salado subsoil

	Ca^{++}	Mg^{++}	K^{+}	Na^{+}	NH_4^{+}	NO_3^{-}
	meq/liter					
NH_4-sewage	1.78	1.44	0.32	4.17	3.02	0
NO_3-sewage	2.06	1.50	3.17	4.22	0	2.87

Calcium, magnesium, potassium and sodium were determined by atomic absorption procedures, ammonium by steam distillation, nitrite and nitrate by colorimetric techniques, and bicarbonate, carbonate and chloride by titration procedures.

Usually, drainage ceased within two days after the sewage was added. The applications were continued over a period of 41 weeks, so that a total of 348 cm of sewage containing N equivalent to 1461 kg/ha, or 1305 lbs/acre, was put on the soil. It was necessary to make up additional lots of input sewage before the 41-week period elapsed, resulting in small changes in input composition during the experiment.

At the end of the application period the columns were cut into sections 20 cm in length with the exception of two 10 cm sections at the surface. These sections were analyzed for exchangeable calcium, magnesium and sodium.

Experiment with ^{15}N-labeled synthetic sewage

In order to obtain more definitive information on nitrogen transformations in soil columns, an experiment with synthetic sewage containing ammonium nitrogen labeled with the stable ^{15}N isotope was performed with Salado surface soil and subsoil. The procedure was identical with that described for the preceding experiment except that ammonium and nitrate in the column effluents were analyzed in the mass spectrometer in order to determine their isotopic composition.

Phase 2 - Experiments with treatment plant sewages

a. Experiment with septicized sewage.

Sewage effluent from the city of Davis treatment plant was collected and ^{15}N-labeled ammonium chloride added to bring the ammonium concentration to 5.07 meq/l. Half the sewage was frozen immediately for subsequent addition to soil columns as ammonium sewage. The other half was vigorously aerated after inoculation with nitrifying bacteria to promote nitrification. After 22 days the ammonium concentration had dropped below 0.01 meq/l; however, about half the original nitrogen had been lost during nitrification since the sum of nitrite and nitrate was only 2.53 meq/l. This sewage was then frozen for later application to soil columns as nitrate sewage. Composition of these sewages is given in Table 5. Triplicate columns of the calcareous Salado subsoil were treated with ammonium or nitrate sewage at the rate of 7.5 cm per week for a total of 24 weeks. As described previously, effluents were collected weekly and analyzed for several constituents. At the conclusion of the experiment the columns were sectioned and analyzed for exchangeable bases. Use of ^{15}N-labeled nitrogen in the input sewage permitted a complete accounting of the added nitrogen.

b. Secondary sewage applied to Panoche sandy loam.

An experiment with secondary sewage from the UCD treatment plant at a lower level of input nitrogen was conducted with columns of Panoche sandy loam soil. In this case sufficient ^{15}N-labeled ammonium chloride was added to bring the ammonium concentration to 1.17 meq/l. Since there was 0.56 meq/l nitrate in the sewage, total inorganic N was 1.73 meq/l. Half this sewage was frozen immediately and the other half vigorously aerated after inoculation with nitrifying bacteria and addition of 5 ppm iron. Previous experience had shown that nitrite oxidation in sewage might be retarded by lack of iron due to precipitation of most of the iron as insoluble sulfides in the sludge. After 10 days this sewage contained no ammonium, 0.22 meq/l nitrite and 0.83 meq/l nitrate. During nitrification a loss of 0.69 meq/l inorganic N was sustained due to ammonia volatilization or denitrification. The nitrified sewage was then frozen for storage. Composition of these sewages is given in Table 6. The two sewages were applied to triplicate columns of Panoche sandy loam at the rate of 7.5 cm per week over a period of 24 weeks. Analyses of effluents and exchangeable cations in the soil columns were performed as before.

c. Comparison of effluents from columns of five different soils receiving ammonium sewage, nitrate sewage, or well water.

Five different field soils were collected to represent a broad range of textures from sandy loam to clay, as well as variations in other soil properties such as organic matter content. Three of the soils were calcareous, Panoche sandy loam, Panoche loam, and Panoche clay, while two, Columbia fine sandy loam and an atypical Panoche loam, were non-calcareous. A sixth soil, Merced clay, was initially included in the experiment, but it proved to be so impermeable that it was not satisfactory for application of sewage.

Secondary sewage was collected from the UCD treatment plant and divided into two portions. Ammonium chloride was added to half the sewage to bring the ammonium concentration to 4.0 meq/l and potassium nitrate was added to the other half to bring the nitrate concentration to the same value. Thus, unlike the preceding experiments involving a period of nitrifying activity, the nitrogen concentrations were the same in ammonium and nitrate sewages. Samples of each sewage were applied to triplicate columns of the five soils at the rate of 7.5 cm per week for 24 weeks. In addition, another set of columns received well water at the same rate. Table 8 gives the composition of the sewages and well water. Effluents of all columns were analyzed as before, and exchangeable cations were determined in sections of the soil columns at the conclusion of the experiments.

d. Experiments with nitrified and non-nitrified sewages at natural levels of nitrogen.

Since in a practical situation ammonium or nitrate levels of wastewater disposed on land would not be augmented, a column experiment was conducted with two soils to determine whether the effects observed with artificially elevated levels of ammonium in input sewage would be manifest. Sewage collected from the UCD treatment plant containing 2.41 meq/l ammonium and 0.30 meq/l nitrate was divided into two portions, one of which was immediately frozen and the other aerated to promote nitrification. After nitrification this sewage contained 0.04 meq/l ammonium and 2.28 meq/l nitrate. Concentrations of other ions are listed in Table 9. Samples of these sewages were applied to columns of Panoche clay and Columbia fine sandy loam at 7.5 cm per week for 24 weeks. Analyses of column effluents and sections of the soil columns were conducted as before.

Table 5. Composition of sewage from City of Davis applied to calcareous Salado subsoil.

	Ca^{++}	Mg^{++}	K^+	Na^{++}	NH_4^+	NO_2^-	NO_3^-	Cl^-	pH	E.C.
				meq/liter						mmhos/cm
NH_4-sewage	2.15	5.81	0.26	7.35	4.73	.007	0	10.49	8.18	1.79
NO_3-sewage	1.98	4.78	0.22	7.11	0.08	2.24	0.23	8.90	7.80	1.36

Table 6. Composition of sewage from UCD applied to Panoche sandy loam.

	Ca^{++}	Mg^{++}	K^+	Na^+	NH_4^+	NO_2^-	NO_3^-	Cl^-	pH	E.C.
						meq/liter				
NH_4-sewage	1.09	1.83	0.19	6.01	1.06	.002	0.47	4.08	7.97	0.87
NO_3^--sewage	0.94	1.64	0.16	5.63	.003	.316	0.783	3.83	8.12	0.71

Table 7. Inorganic N and exchangeable bases in soils prior to treatment with wastewater.

Soil	NH_4^+-N	NO_3^--N	Ca	Mg	K	Na	Σ bases
				meq/100 g			
Salado fine sandy loam	.002	.028	10.8	4.26	0.84	0.07	16.0
Salado subsoil	.011	.009	14.7	3.74	0.29	0.17	18.9
Panoche sandy loam	.042	.369	11.9	3.16	2.60	0.65	18.3
Panoche loam	.067	.111	15.4	5.02	0.75	0.21	21.4
Panoche clay loam	.009	.072	12.4	10.3	0.80	0.69	24.2
Columbia fine sandy loam	.006	.038	5.84	4.24	0.61	0.34	11.0
Panoche loam (non-cal.)	0	.080	13.0	4.18	0.88	0.41	18.5

Table 8. Composition of input sewages and well water applied to columns of five soils.

	Ca^{++}	Mg^{++}	K^+	Na^+	NH_4^+	NO_2^-	NO_3^-	Cl^-	HCO_3^-	pH	E.C.
				meq/liter							mmhos/cm
NH_4-sewage	0.99	1.79	0.17	5.10	3.91	0.014	0.42	6.41	4.51	8.00	1.08
NO_3-sewage	1.00	1.86	4.01	4.92	0.01	0.014	4.04	2.34	4.46	8.25	1.13
Well water	0.75	1.42	0.045	3.42	0.01	0.0	0.02	1.21	4.03	7.85	0.53

Table 9. Composition of unamended sewage applied to Panoche clay loam and Columbia fine sandy loam.

	Ca^{++}	Mg^{++}	K^+	Na^+	NH_4^+	NO_3^-	Cl^-	HCO_3^-	pH	E.C.
					meq/liter					
NH_4-sewage	1.66	6.54	0.23	8.67	2.41	0.3	9.44	10.21	8.27	1.69
NO_3-sewage	1.93	6.33	0.24	9.01	0.04	2.28	10.83	5.85	8.55	1.68

Field Studies

Bakersfield site

Soil samples were taken from a cotton field near Bakersfield where wastewater from a sewage treatment plant has been used to irrigate crops since 1938. Samples were also obtained from an adjacent location where the soil had never been farmed and no wastewater had been applied. A third sample was obtained from a nearby farmer's field where canal water had been used for irrigation of crops. These samples were analyzed at various depths for exchangeable cations and composition of the saturation extract determined.

Ontario sludge disposal site

Soil core samples were taken to a depth of 6 ft. from sludge disposal pits at the Ontario sewage treatment plant where sludge has been applied on a regular basis over a period of many years. The soil is sandy and has a low cation exchange capacity. Also taken at the same time were samples from the adjacent grassy area which has been irrigated with wastewater, and from an area at the edge of the property representing untreated soil. The composition of the sludge applied in the pits over the years is unknown, but a current sample of sludge was found to contain in excess of 400 ppm ammonium nitrogen. These soil samples were analyzed for ammonium, nitrate and exchangeable calcium, magnesium and sodium.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Laboratory Column Studies

Phase 1 - Experiments with synthetic sewages

Figure 3 shows the calcium concentrations in effluents from the Salado surface soil. It will be noted that the columns receiving ammonium sewage had slightly higher calcium concentrations throughout the experimental period, but the differences were never large. Calcium concentrations in effluents from both treatments tended to level off at values substantially higher than those of the input sewages. Similar observations can be made regarding magnesium concentrations in effluents from the surface soil

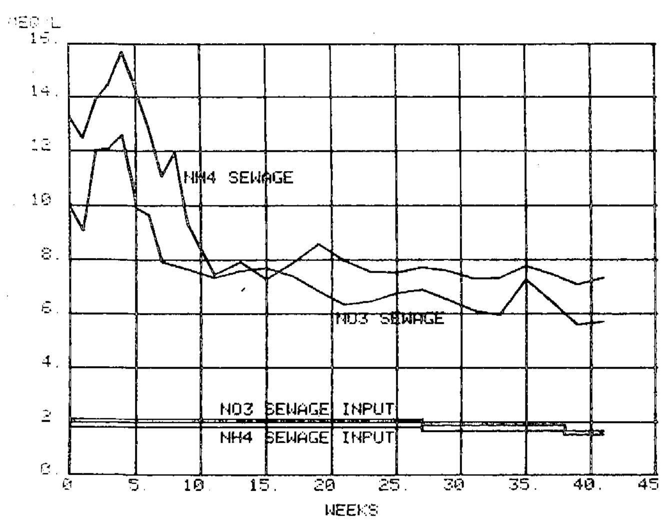


Fig. 3. Calcium concentrations in effluents from Salado surface soil treated with synthetic sewages.

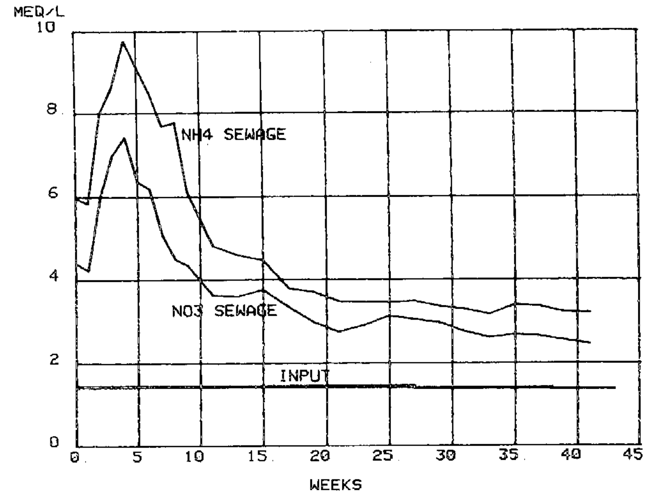


Fig. 4. Magnesium concentrations in effluents from Salado surface soil treated with synthetic sewages.

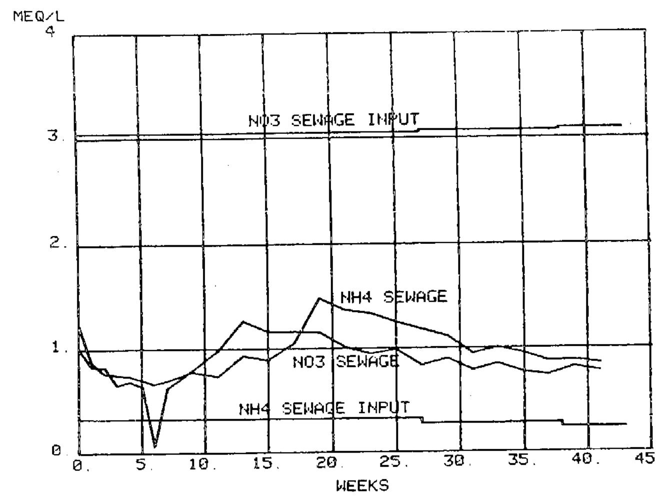


Fig. 5. Potassium concentrations in effluents from Salado surface soil treated with synthetic sewages.

(Figure 4) except that the final output concentrations were not a great deal higher than input levels.

Potassium concentrations in the effluents (Figure 5) were low and quite similar in both treatments in spite of the fact that the input level of potassium was much higher for the nitrate sewage. This can be attributed to potassium fixation in the soil, which contains some vermiculite and other clay minerals capable of potassium fixation. Sodium concentrations, shown in Figure 6, rose between 6 and 25 weeks and then leveled off at values corresponding closely to those of the input sewages. Temporary differences between sodium concentrations in columns treated with ammonium vs. nitrate sewage tended to disappear toward the end of the experimental period.

The summation of bases shown in Figure 7, yields curves much like those for calcium and magnesium. Effluents from columns treated with ammonium sewage consistently had concentrations one or two meq/l higher than those receiving nitrate sewage.

Concentrations of inorganic nitrogen in effluents, shown in Figure 8, are of particular interest. Initially for a period of about 8

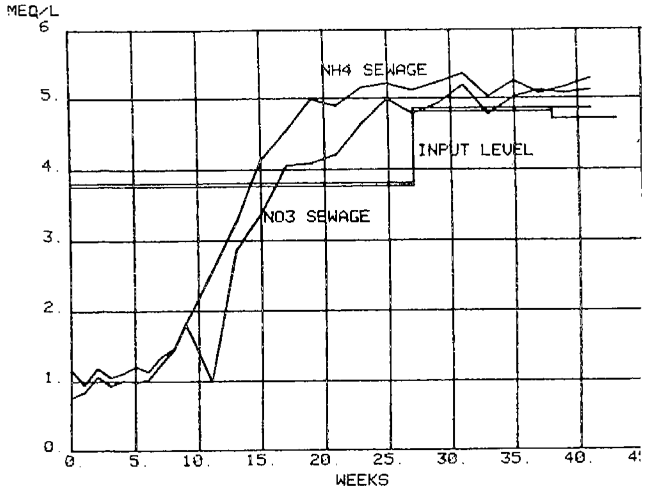


Fig. 6. Sodium concentrations in effluents from Salado surface soil treated with synthetic sewages.

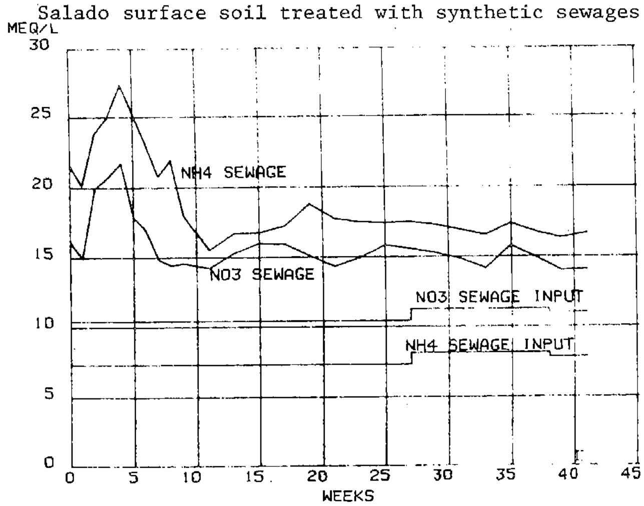


Fig. 7. Sum of bases in effluents from Salado surface soil treated with synthetic sewages.

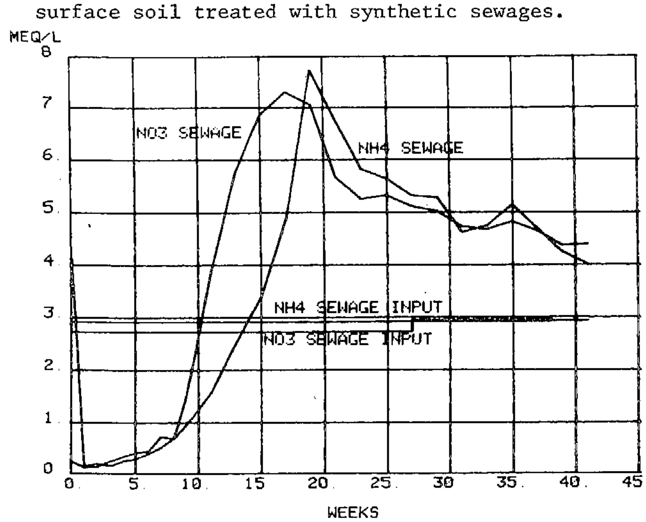


Fig. 8. Inorganic N concentrations in effluents from Salado surface soil treated with synthetic sewages.

weeks, concentrations were very low, indicating that most of the input N was lost through denitrification or some other means. Subsequently there was a sharp increase in nitrate in the effluent from columns receiving both sewages, suggesting that most of the organic matter in the soil which was previously available to drive the denitrification process had now been depleted, permitting the passage of nitrate through the columns. After reaching a peak between 15 and 20 weeks inorganic nitrogen concentrations declined, tending to level off at values somewhat higher than the 3 meq/l input concentration. This can be explained on the basis of mineralization of organic nitrogen in the soil. The fact that effluent nitrogen concentrations were virtually identical with ammonium and nitrate sewages indicates that there was no deficiency of nitrifying bacteria in the soil columns.

Data on effluents from columns of calcareous Salado subsoil are presented in Figures 9-14 inclusive. The curves for calcium and magnesium shown in Figures 9 and 10 are much like those for the surface soil and the same comments are applicable. There was virtually no removal of potassium from the subsoil (Figure 11). Figure 12 shows that the sum of four bases, Ca, Mg, K and Na, was affected more by treatment in the Salado subsoil than in the surface soil; that is, differences between effluents from ammonium and nitrate columns were larger. Here the input was somewhat lower with ammonium sewage than with nitrate sewage, but the output concentrations were higher, possibly due to solution of $CaCO_3$ present in the subsoil.

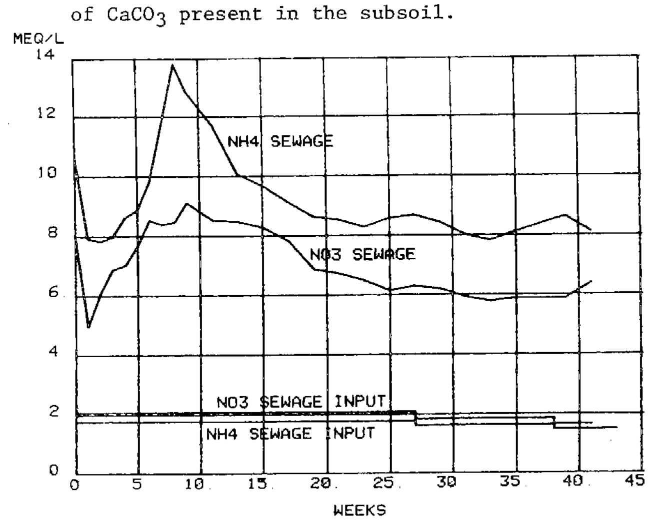


Fig. 9. Calcium concentrations in effluents from Salado subsoil treated with synthetic sewages.

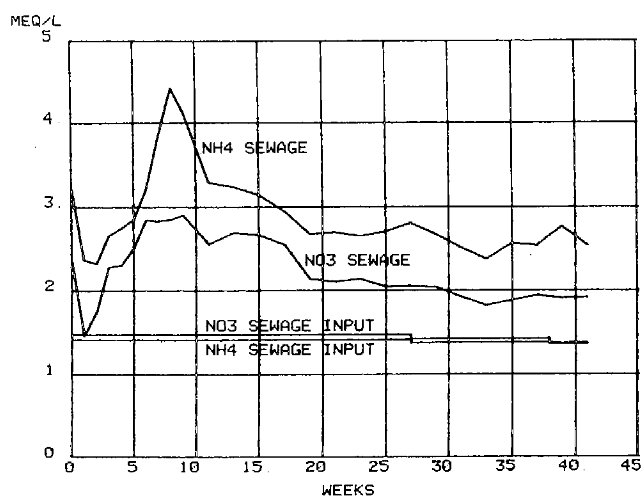


Fig. 10. Magnesium concentrations in effluents from Salado subsoil treated with synthetic sewage.

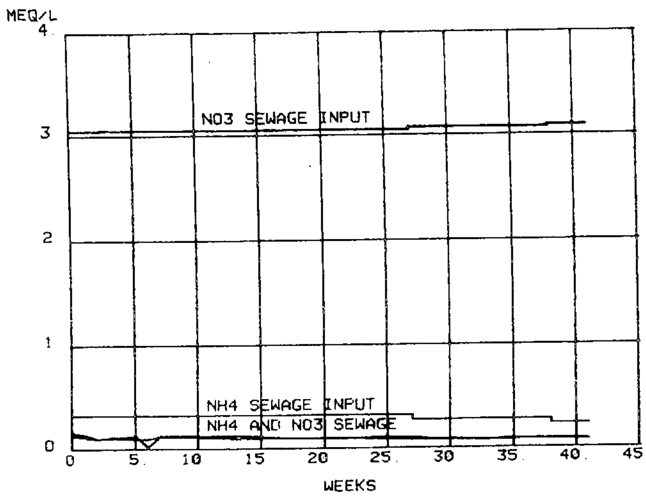


Fig. 11. Potassium concentrations in effluents from Salado subsoil treated with synthetic sewages.

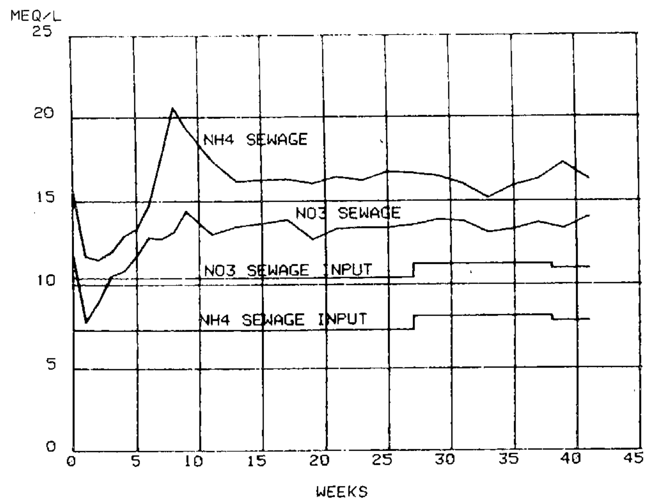


Fig. 12. Sum of bases in effluents from Salado subsoil treated with synthetic sewages.

Figure 13, showing inorganic nitrogen in the effluents (primarily nitrate since ammonium leaches only slightly) displays evidence for a lag in the initiation of nitrification. After the nitrifying population had built up, a peak in nitrate concentration was observed as a result of rapid oxidation of accumulated ammonium, followed by a quick decline to a level only slightly higher than input values. Here the contribution of nitrogen due to mineralization of organic matter was very small, as might be expected in a subsoil of low organic matter content.

Cumulative balances for the Salado surface soil and subsoil over the 41 week period of sewage application are presented in Table 10. The net change columns indicate that there were substantial losses of calcium and magnesium from both soils, and that these were higher with ammonium sewage than with nitrate sewage. The net loss of all bases from the surface soil was about 26 meq higher with ammonium sewage than with nitrate sewage, and the corresponding difference in the subsoil was about 30 meq. However, the input of potassium was approximately 13 meq higher in the nitrate sewage, and little of this potassium appeared in the output owing to fixation in the soil. If the contribution of input potassium to the balance of bases is excluded, the differences between ammonium and nitrate sewage are reduced by nearly one half.

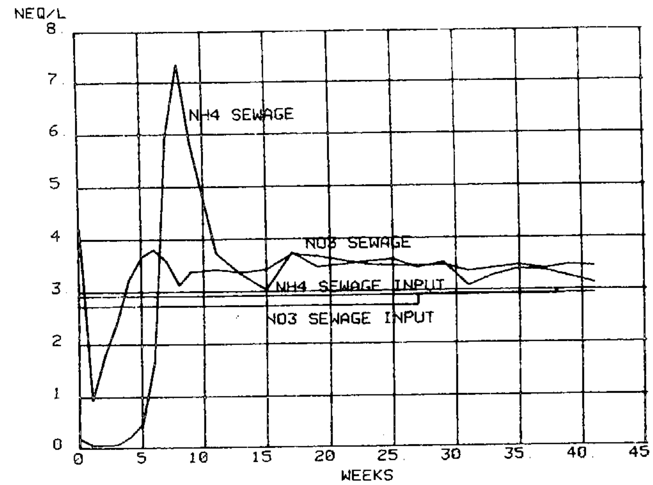


Fig. 13. Inorganic N concentrations in effluents from Salado subsoil treated with synthetic sewages.

Summarizing, synthetic sewage containing 13.6 meq ammonium produced a loss of about 11 meq more calcium and magnesium than sewage containing 12.9 meq nitrate when 348 cm of these sewages was applied to Salado surface soil. In the subsoil the difference was about 15 meq. These differences cannot be attributed solely to nitrification, since calcium and magnesium may be displaced from the soil exchange complex by other cations in the input sewage, such as potassium or sodium.

At the conclusion of the 41-week leaching period the soil columns previously treated with synthetic sewage were sliced into sections according to depth and analyzed for exchangeable cations. The distribution of exchangeable calcium, magnesium and sodium as a function of depth in Salado surface soil is shown in Figure 14 and for Salado subsoil in Figure 15. In the surface soil it appears that there was some depletion of exchangeable calcium in the top 10 cm, but differences below this depth were minimal. In the subsoil exchangeable calcium and magnesium were higher in the ammonium sewage columns than in those receiving nitrate sewage.

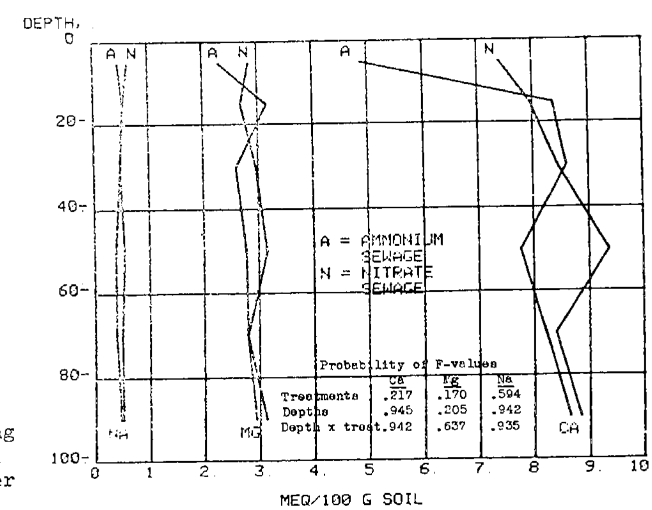


Fig. 14. Exchangeable calcium, magnesium and sodium in Salado surface soil after synthetic sewage application.

Table 10. Cumulative balances for Salado surface soil and subsoil treated with 348 cm of synthetic sewage containing N as NH_4^+ or NO_3^- over a period of 41 weeks.

Ion	Input, meq	Surface Soil Output, meq	Surface Soil Net change, meq	Subsoil Output, meq	Subsoil Net change, meq
			NH_4^+ - Sewage		
Ca^{++}	8.00	46.97	-38.97	49.94	-41.94
Mg^{++}	6.50	24.75	-18.25	16.08	- 9.58
K^+	1.43	5.36	- 3.93	0.52	+ 0.91
Na^+	18.77	21.19	- 2.42	21.99	- 3.22
Σ bases	34.70	98.27	-63.57	88.53	-53.83
NH_4^+	13.59	2.97	+10.62	0.09	+13.50
NO_3^-	0.00	17.42	-17.42	17.15	-17.15
Σ N	13.59	20.39	- 6.80	17.24	- 3.65
			NO_3^- - Sewage		
Ca^{++}	9.29	41.66	-32.37	39.64	-30.35
Mg^{++}	6.75	20.13	-13.38	12.14	- 5.39
K^+	14.26	4.91	+ 9.35	0.50	+13.76
Na^+	18.99	19.95	- 0.96	20.90	- 1.91
Σ bases	49.32	86.65	-37.33	73.18	-23.86
NH_4^+	0.00	1.50	- 1.50	0.14	- 0.14
NO_3^-	12.90	22.13	- 9.23	18.73	- 5.83
Σ N	12.90	23.63	-10.73	18.87	- 5.97

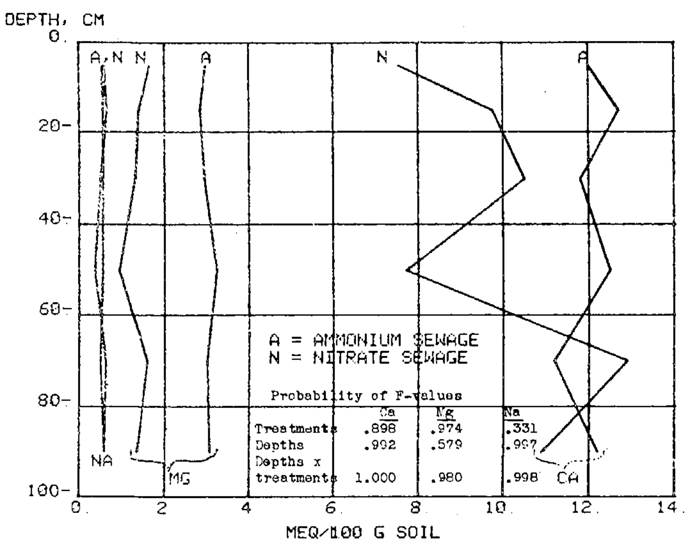


Fig. 15. Exchangeable calcium, magnesium and sodium in Salado subsoil after synthetic sewage application.

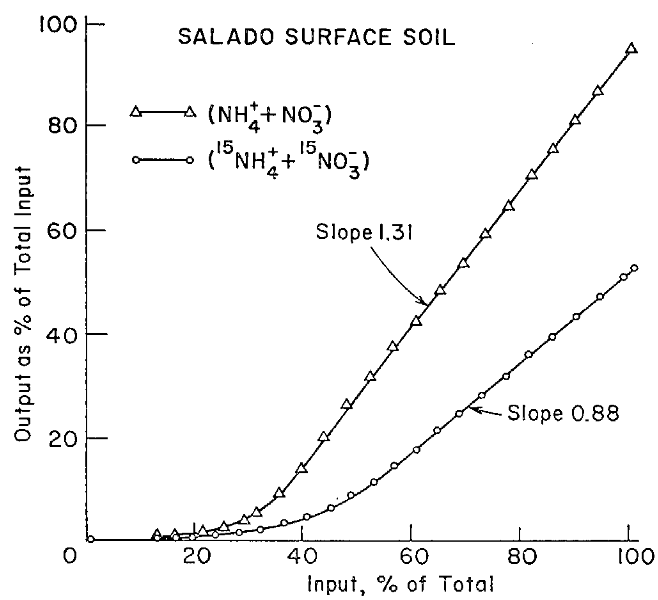


Fig. 16. Recovery of nitrogen in effluents from Salado surface soil.

b. Experiment with ^{15}N-labeled synthetic sewage.

Nitrogen recovery data are summarized in Figures 17 and 18 in which the output of inorganic nitrogen is plotted as a percentage of total input, with separate curves for total nitrogen and labled nitrogen. With this type of plot, complete recovery of input nitrogen would give a straight line of slope 1.00. Figure 16 shows that up to about 30% of total input there was virtually no output, indicative of nearly quantitative denitrification. Thereafter, output was a linear function of input, with a slope of 1.31, showing that a considerable quantity of organic nitrogen in the soil was mineralized and appeared in the effluent along with the input nitrogen. Considering the labeled nitrogen curve, the slope after the initial period of predominant denitrification was 0.88, indicating that after depletion of the initial supply of available soil carbon denitrification still accounted for loss of about 12% of the input nitrogen. Overall recovery of labeled nitrogen, including that remaining in the soil at the conclusion of the experiment, was 67.8% for the Salado surface soil.

In Figure 17 it may be observed that there was a shorter initial period of rapid denitrification, reflecting a lower organic matter content in the Salado subsoil, and the slopes of the lines for total and tagged nitrogen were essentially the same, both being close to unity. Clearly, there was not only a lower contribution to the effluent of mineralized soil nitrogen, but also a lower degree of denitrification due to less organic matter in this subsoil. Overall recovery of labeled nitrogen in this experiment was 86.9%, or about 20% higher than in the surface soil. These data indicate that a considerable quantity of the nitrogen in wastewater applied to soil can be lost through denitrification under conditions not intended to favor this process.

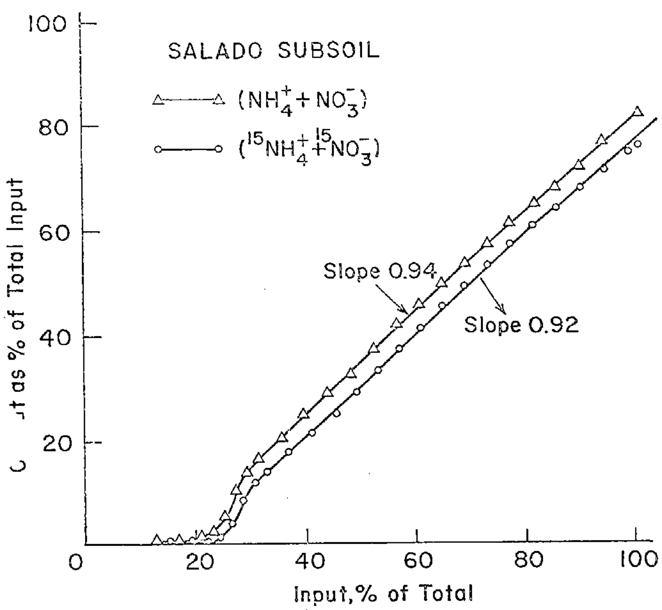


Fig. 17. Recovery of nitrogen in effluents from Salado subsoil.

Phase 2 - Experiments with treatment plant sewages

a. Experiments with septicized sewage

Calcium concentrations in effluents from calcareous Salado subsoil are shown in Figure 18. These were the same for both ammonium and nitrate sewage except for the period between 6 and 14 weeks, when values were considerably higher in effluents from columns receiving ammonium sewage. Magnesium concentrations (Figure 19) show the same pattern. As will be noted later, this was the period of most rapid nitrifying activity. Calcium concentrations seemed to level off at a value well above the input concentration, whereas magnesium concentrations in the effluent were below the input concentration during much of the experimental period. Sodium concentrations shown in Figure 20 continued to rise throughout the period of application, with ammonium sewage again showing higher concentrations. Reference to Figure 21 shows that the period of maximum nitrification of ammonium sewage was between 6 and 14 weeks, the same period when calcium and magnesium concentrations increased significantly in the column effluents. The high peak of nitrate in the ammonium-sewage columns was due to buildup of adsorbed ammonium early in the application period when the

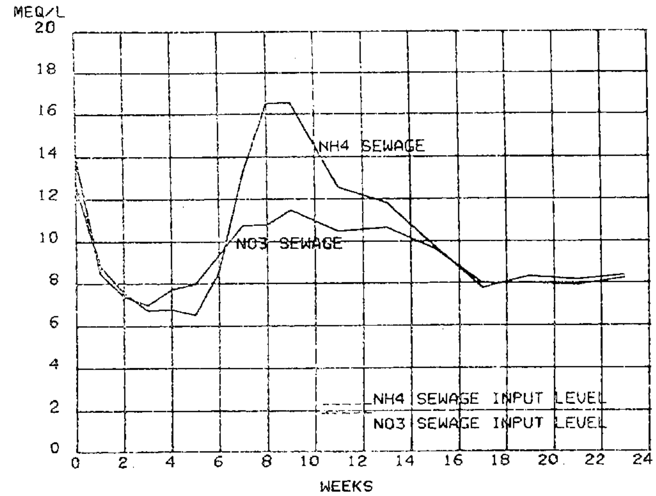


Fig. 18. Calcium concentrations in effluents from Salado subsoil treated with Davis sewage.

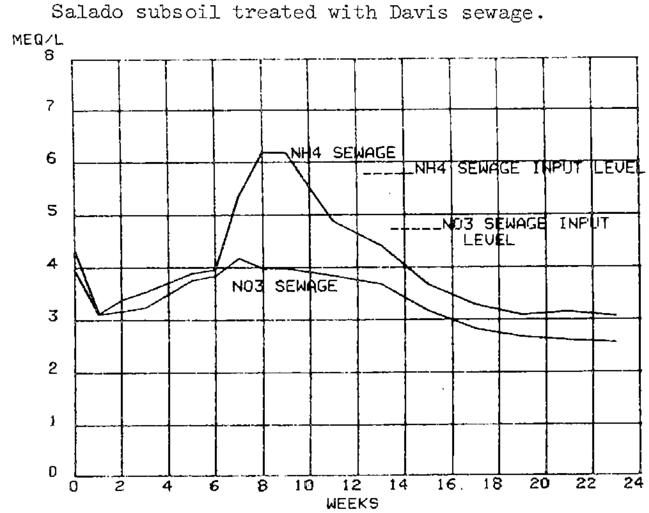


Fig. 19. Magnesium concentrations in effluents from Salado subsoil treated with Davis sewage.

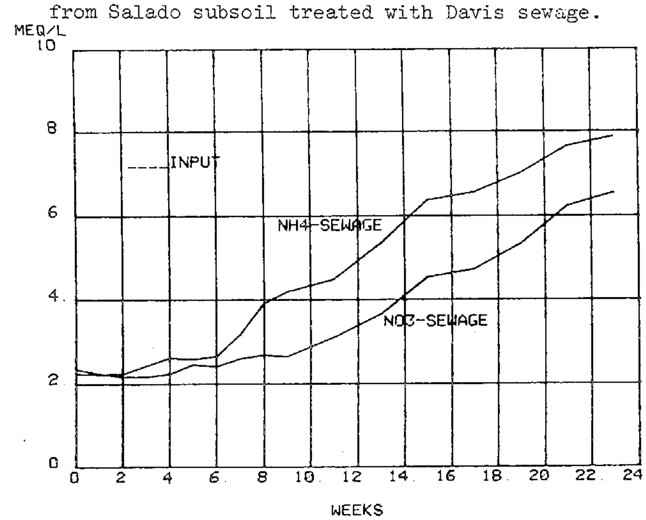


Fig. 20. Sodium concentrations in effluents from Salado subsoil treated with Davis sewage.

nitrifying population in this subsoil was apparently low, followed by a wave of nitrate when the nitrifiers became very active. After 14 weeks

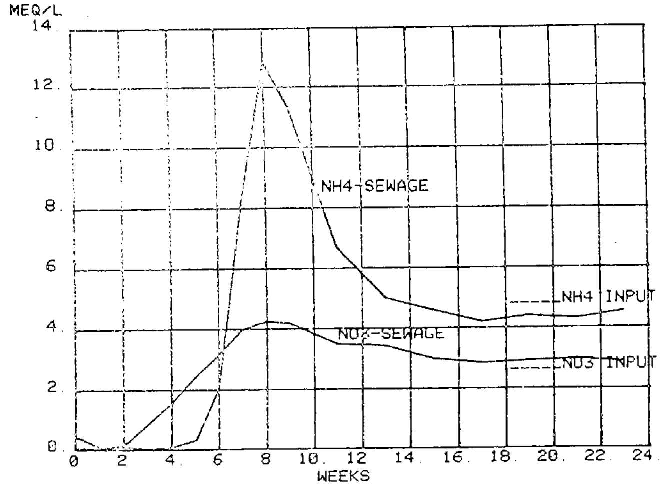


Fig. 21. Nitrate concentrations in effluents from Salado subsoil treated with Davis sewage.

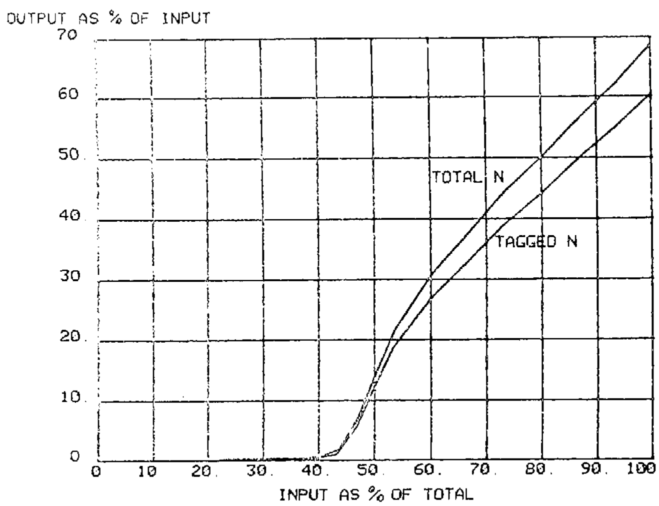


Fig. 22. Recovery of nitrogen in effluents from Salado subsoil treated with ammonium sewage.

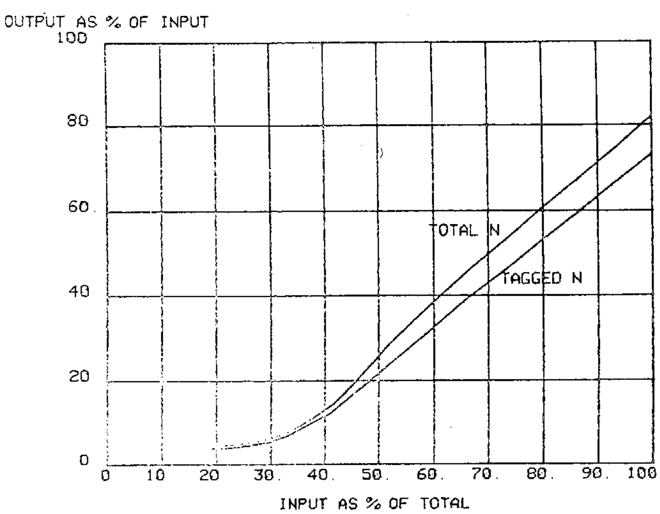


Fig. 23. Recovery of nitrogen in effluents from Salado subsoil treated with nitrate sewage.

nitrate concentrations leveled off at concentrations close to those for input nitrogen.

Recovery of nitrogen from columns of Salado subsoil treated with ammonium sewage is detailed in Figure 22, where output is plotted as per cent of total input. Recovery was nil up to about 45% of total input, then increased rapidly until an equilibrium was attained. The linear portion of the curve between 60 and 100% of total input has a slope of 0.982, indicating quantitive nitrification of the ammonium in the sewage with very little loss in transit through the soil, or more correctly, compensation for any losses by mineralization of soil organic nitrogen. The slope for the linear portion of the tagged nitrogen curve in Figure 22 is 0.871, showing a continuous loss of about 13% of input nitrogen in the equilibrium condition. Overall recovery of labeled nitrogen, including that remaining in the soil at the conclusion of the experiment, was 82.7%. Similar data for Salado subsoil treated with nitrate sewage are given in Figure 23. Here equilibrium was attained after about 40% of total input. The slope of the curve for total N after equilibrium was reached is 1.15, indicating some contribution of nitrogen from soil organic matter. Slope of the tagged N curve was 1.04, showing passage of the input nitrate through the soil without loss. Overall recovery of tagged N from the columns receiving nitrate sewage was 90.8%.

In order to estimate the degree of variability in concentrations of effluents from replicate columns standard deviations for calcium and magnesium data were calculated. These ranged from 3.1 to 14.3% of the mean for calcium and from 2.0 to 11.9% for magnesium over the 24-week period. The average standard deviation for calcium in analysis of 17 different periods was 8.7% of the mean and the corresponding figure for magnesium was 6.3%.

Cumulative balances for effluents from the Salado subsoil are given in Table 11. The most significant feature of these data is the small difference between treatments. Total bases showed a net increase, rather than a decrease as found with synthetic sewage. The close agreement between input and output of chloride shows that there was no holdup in the columns of ions not subject to adsorption.

Exchangeable calcium, magnesium, and sodium in the soil columns after leaching with sewage are shown in Figures 24, 25, and 26. These indicate some decrease of exchangeable calcium in the ammonium sewage columns as compared to those receiving nitrate sewage, but these are not statistically significant owing to variability among replicates. This variability is associated with the well-known difficulty of determining exchangeable calcium in soils containing a large excess of calcium carbonate. There were no treatment differences in the distribution of exchangeable magnesium and sodium. To put these observations in persepective, attention is directed to the net change of total bases in Table 11, which was on the order of 7-8 meq as determined by leachate analysis. By comparison, total exchangeable bases in a column containing 2.5 kg of soil is about 350 meq so the net change was about 2% of the total bases in the column.

Table 11. Cumulative balances for Salado fine sandy loam subsoil treated with 215 cm of nitrified or un-nitrified sewage from the City of Davis anaerobic treatment plant over a period of 23 weeks. Initial NH_4 level augmented to 5.07 meq/ℓ

	NH_4^+ - Sewage			NO_3^- - Sewage		
Ion	Input, meq	Output, meq	Net Change, meq	Input, meq	Output, meq	Net Change, meq
Ca^{++}	9.37	31.86	-22.49	8.60	29.58	-20.98
Mg^{++}	25.30	12.58	12.72	20.78	10.63	10.15
K^+	1.13	0.398	0.732	0.97	0.415	0.555
Na^+	31.98	16.07	15.91	30.92	12.36	18.56
Σ bases	67.78	60.91	6.87	61.27	52.99	8.28
NH_4^+	20.59	0.056	20.53	0.338	0.038	0.30
NO_3^-	0.03	14.11	-14.08	10.75	9.08	1.67
Σ N	20.62	14.17	6.45	11.09	9.12	1.97
Cl^-	45.65	44.91	0.74	38.73	39.70	- 0.97

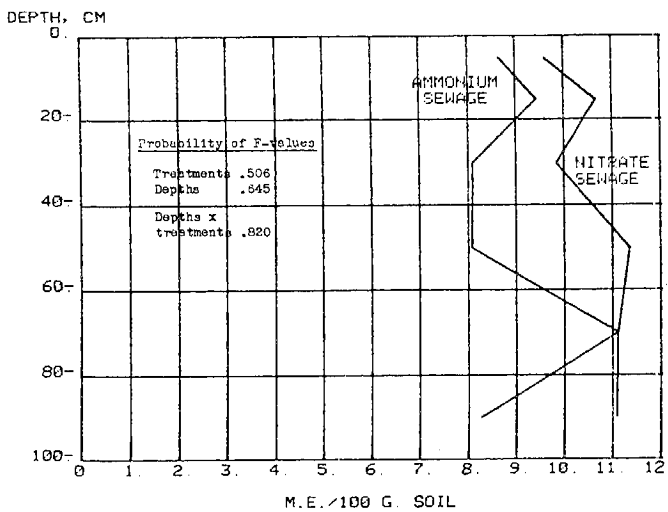


Fig. 24. Exchangeable calcium in Salado subsoil after treatment with Davis sewage.

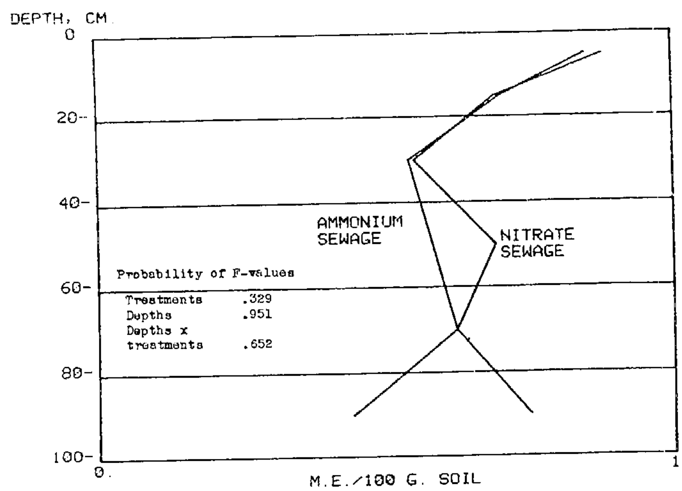


Fig. 26. Exchangeable sodium in Salado subsoil after treatment with Davis sewage.

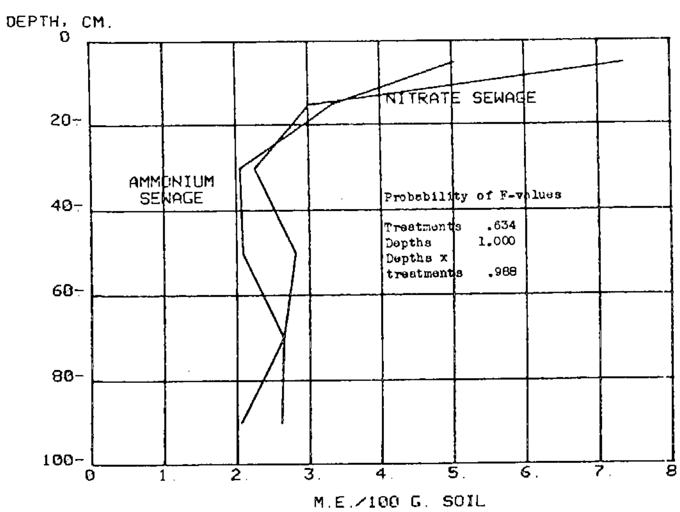


Fig. 25. Exchangeable magnesium in Salado subsoil after treatment with Davis sewage.

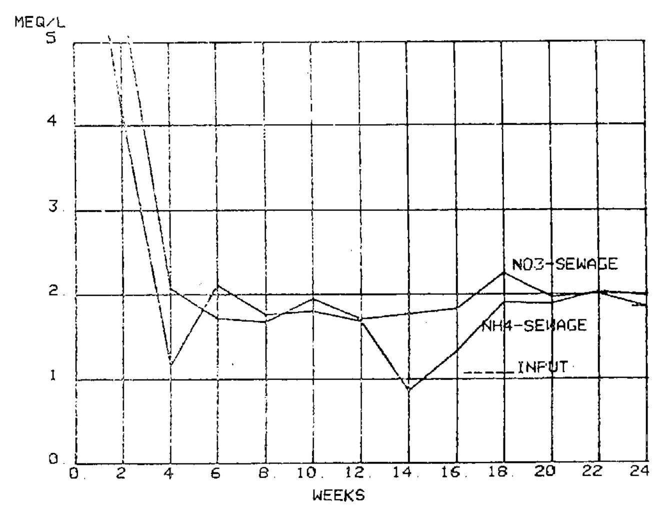


Fig. 27. Calcium concentrations in effluents from Panoche sandy loam treated with UCD sewage.

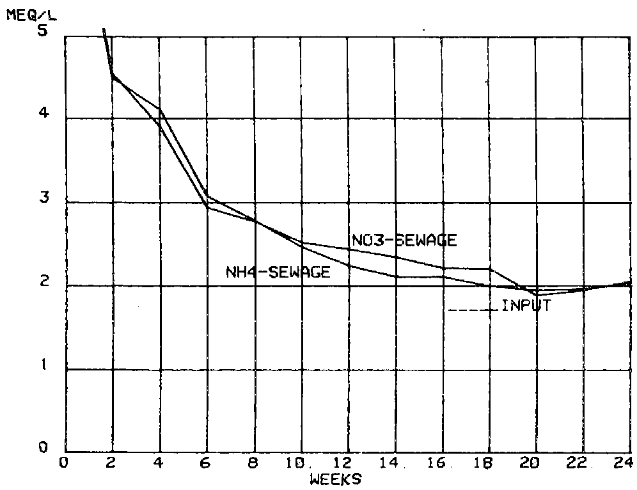


Fig. 28. Magnesium concentrations in effluents from Panoche sandy loam treated with UCD sewage.

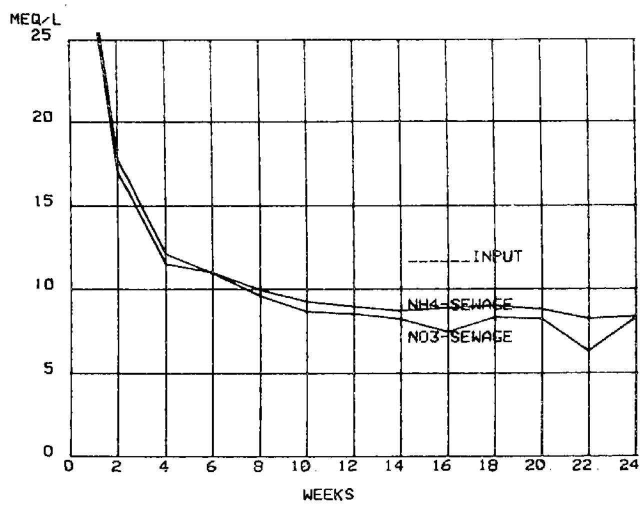


Fig. 29. Sodium concentrations in effluents from Panoche sandy loam treated with UCD sewage.

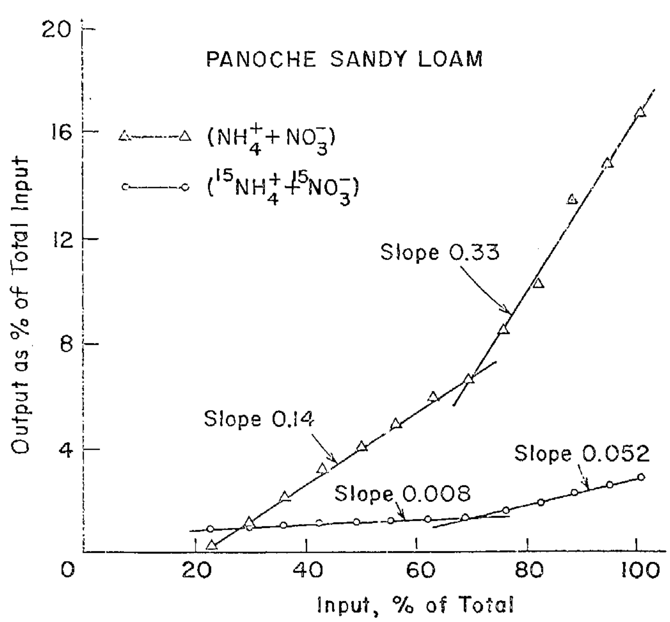


Fig. 30. Nitrogen recovery in effluents from Panoche sandy loam treated with UCD sewage.

b. Secondary sewage applied to Panoche sandy loam.

Concentrations of calcium, magnesium and sodium in column effluents are shown in Figure 27, 28, and 29 respectively. There were essentially no differences in concentrations of these cations between columns treated with ammonium or nitrate sewage. These minimal differences are further confirmed by the cumulative balance data given in Table 12. Loss of calcium was slightly higher from columns treated with nitrate sewage.

An accounting of nitrogen in the effluent from columns of Panoche sandy loam treated with ammonium sewage is shown in Figure 30. The recovery curves are resolved into two linear portions, both with very small slopes indicative of very active denitrification resulting in loss of most of the input nitrogen. An overall recovery of tagged input nitrogen of 19.3% was obtained. The fact that this recovery is higher than the 5.2% slope of the line in Figure 30 is due to the fact that most of the recovered ^{15}N was residual in the soil after the experiment was concluded. Only 1% of the input nitrogen actually appeared in the leachate. Data for the columns receiving nitrate were very similar, with a final recovery of 19.4% of input.

Exchangeable calcium, magnesium, and sodium remaining in the soil at the conclusion of the experiment are shown in Figures 31, 32, and 33 respectively.

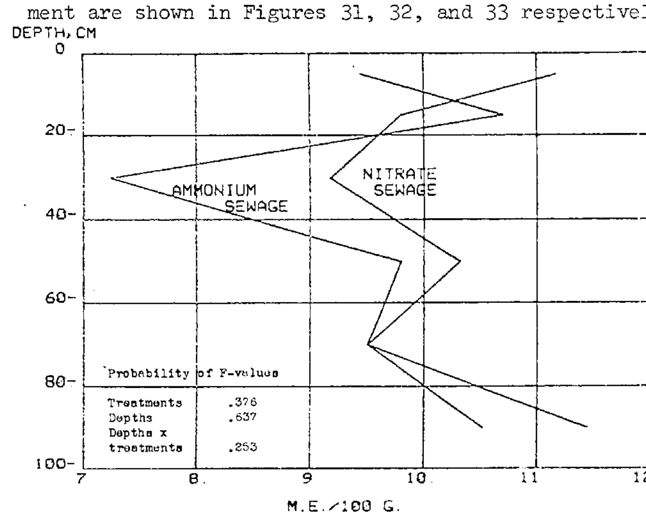


Fig. 31. Exchangeable calcium in Panoche sandy loam after treatment with UCD sewage.

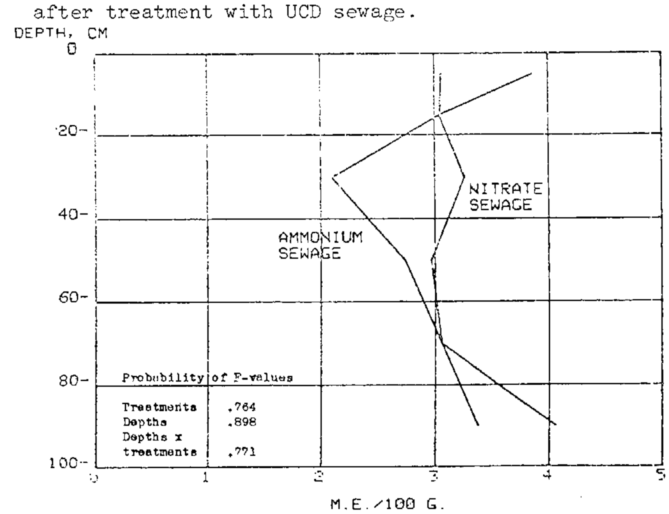


Fig. 32. Exchangeable magnesium in Panoche sandy loam after treatment with UCD sewage.

Table 12. Cumulative balances for Panoche sandy loam treated with 222 cm of nitrified or un-nitrified UCD sewage over a period of 24 weeks

	NH_4 - Sewage			NO_3 - Sewage		
Ion	Input, meq	Output, meq	Net Change, meq	Input, meq	Output, meq	Net Change meq
Ca^{++}	4.92	15.65	-10.73	4.23	16.50	-12.27
Mg^{++}	8.28	11.79	- 3.51	7.38	11.81	- 4.43
K^{+}	0.840	1.57	- 0.73	0.73	1.58	- 0.85
Na^{+}	27.22	37.67	-10.45	25.32	36.26	-10.94
Σ bases	41.26	66.68	-25.42	37.66	66.15	-28.49
NH_4^{+}	4.81	0.80	4.01	0.02	0.63	- 0.61
NO_3^{-}	2.15	9.06	- 6.91	4.95	8.48	- 3.53
Σ N	6.96	9.86	- 2.90	4.97	9.11	- 4.15
Cl^{-}	18.46	19.14	- 0.68	17.26	18.91	- 1.65

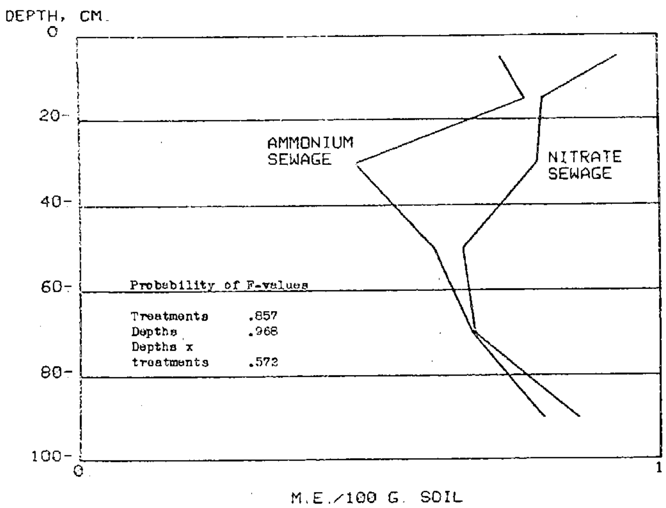


Fig. 33. Exchangeable sodium in Panoche sandy loam after treatment with UCD sewage.

There appears to have been some depletion of these cations from the 20-40 cm layer of columns treated with ammonium sewage, but this is not reflected in differences in column effluents.

c. Comparison of effluents from columns of five different soils receiving ammonium sewage, nitrate sewage, or well water.

Calcium concentrations in effluents of the five soils are shown in Figures 34-38 respectively. These consistently showed highest concentrations in effluents from ammonium sewage columns, followed by nitrate sewage and well water in that order. These differences persisted throughout the experimental period. Effluent concentrations remained well above input levels in all treatments. Magnesium concentrations (Figures 39-43 inclusive) followed the same trends as did calcium but differences among treatments were smaller than for calcium. Data for sodium presented in Figures 44-48 inclusive indicate differences between ammonium and nitrate treatments were very small in all five soils, and only in the two non-calcareous soils were sodium concentrations in

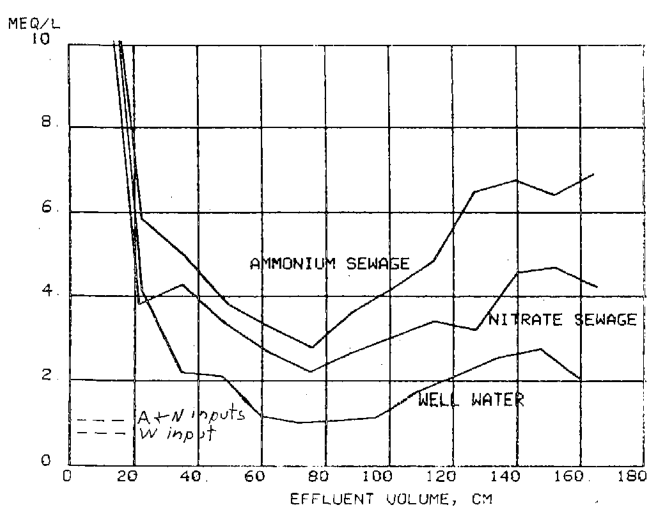


Fig. 34. Calcium concentrations in effluents from Panoche sandy loam treated with sewages or well water.

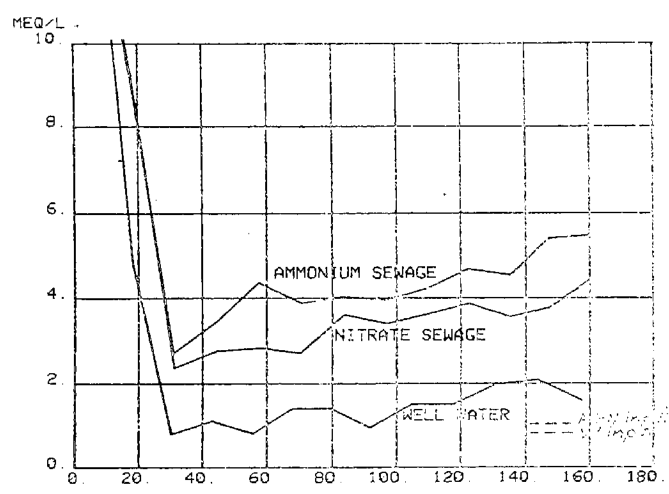


Fig. 35. Calcium concentrations in effluents from Panoche loam treated with sewages or well water.

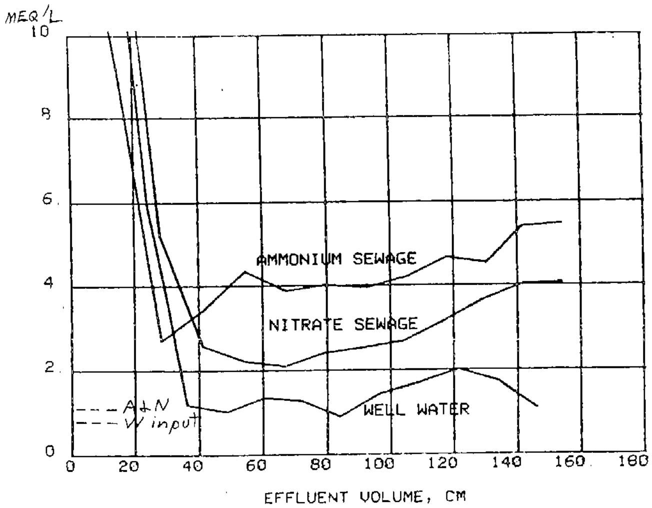


Fig. 36. Calcium concentrations in effluents from Panoche clay loam treated with sewages or well water.

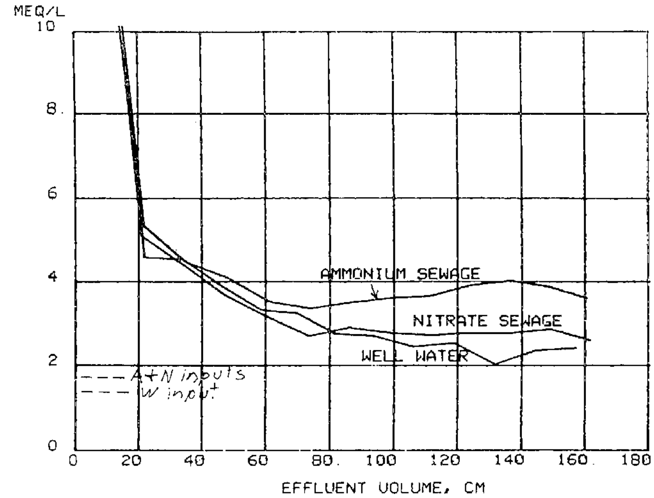


Fig. 39. Magnesium concentrations in effluents from Panoche sandy loam treated with sewages or well water.

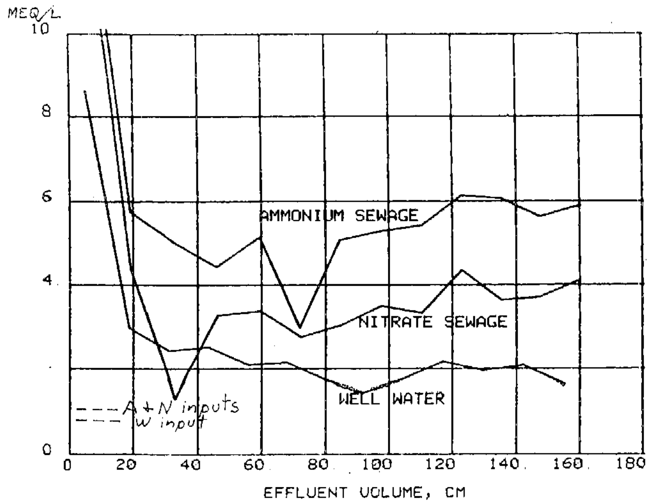


Fig. 37. Calcium concentrations in effluents from Columbia fine sandy loam treated with sewages or well water.

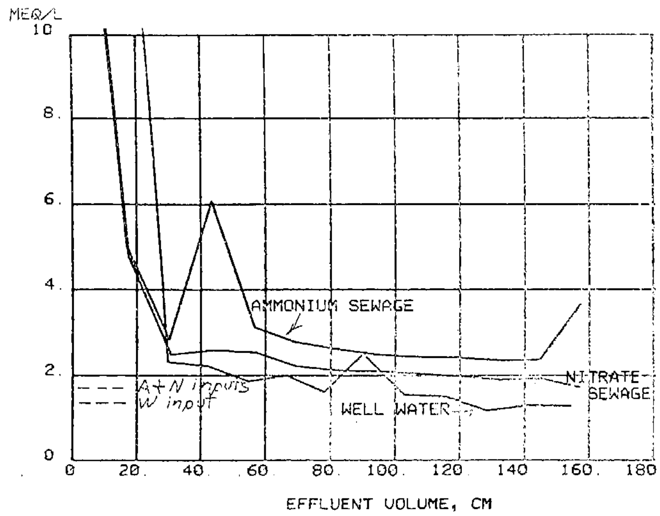
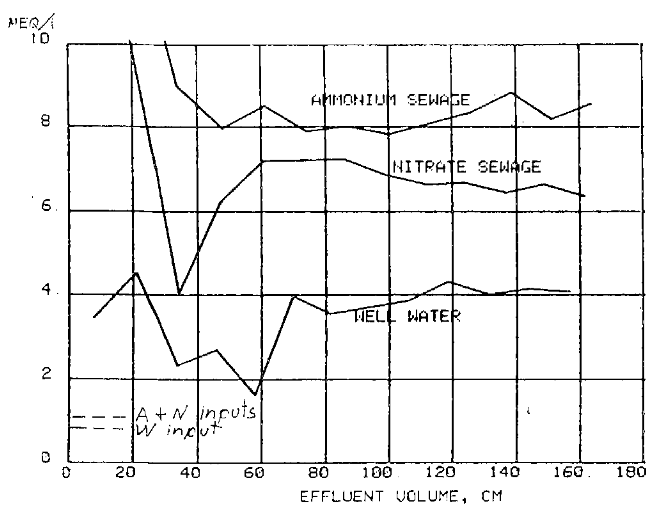


Fig. 40. Magnesium concentrations in effluents from Panoche loam treated with sewages or well water.



.g. 38. Calcium concentrations in effluents from .on-calcareous Panoche loam treated with sewages or well water.

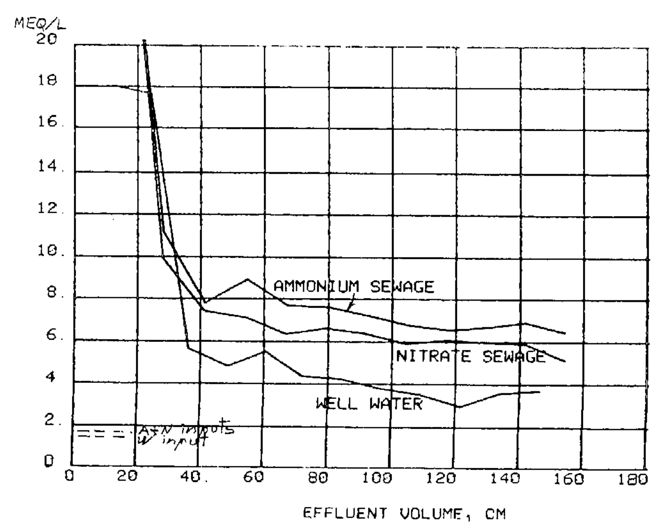


Fig. 41. Magnesium concentrations in effluents from Panoche clay loam treated with sewages or well water.

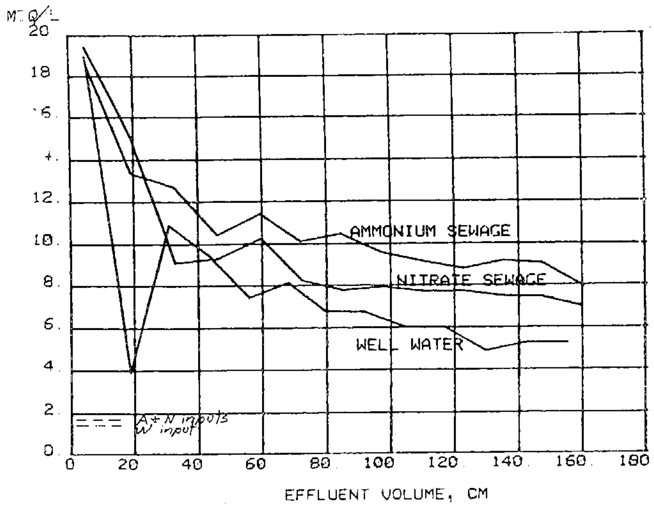


Fig. 42. Magnesium concentrations in effluents from Columbia fine sandy loam treated with sewages or well water.

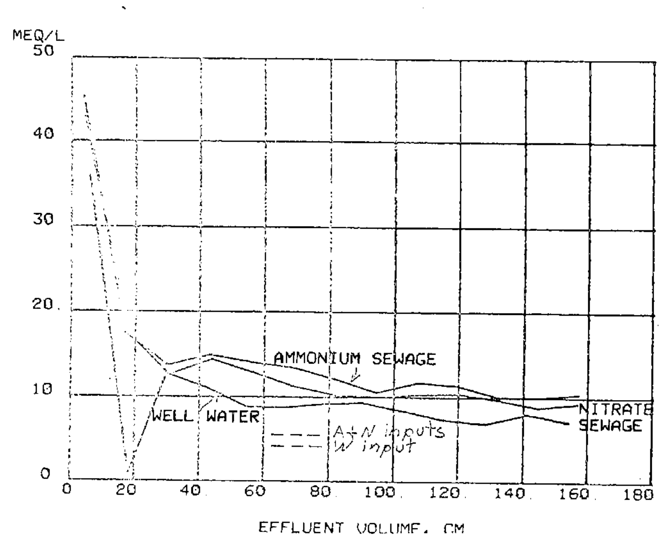


Fig. 45. Sodium concentrations of effluents from Panoche loam treated with sewages or well water.

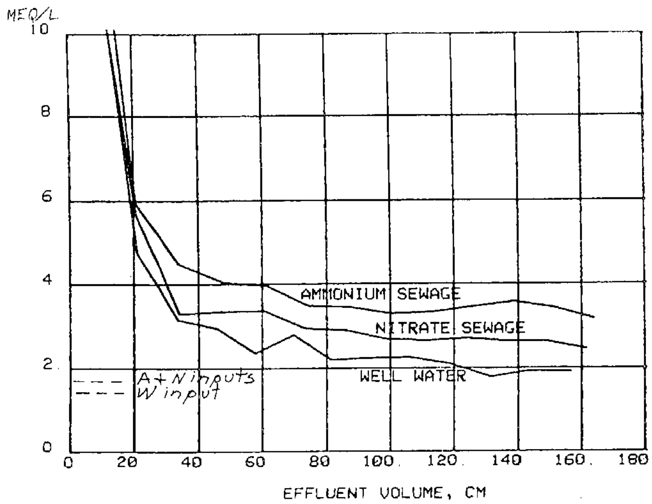


Fig. 43. Magnesium concentrations in effluents from non-calcareous Panoche loam treated with sewages or well water.

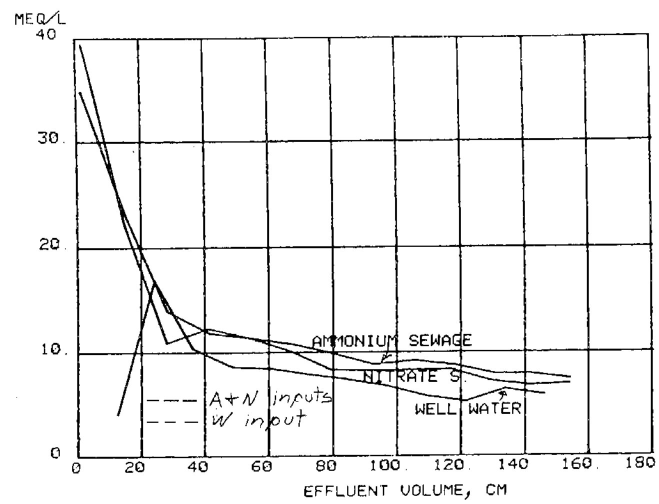
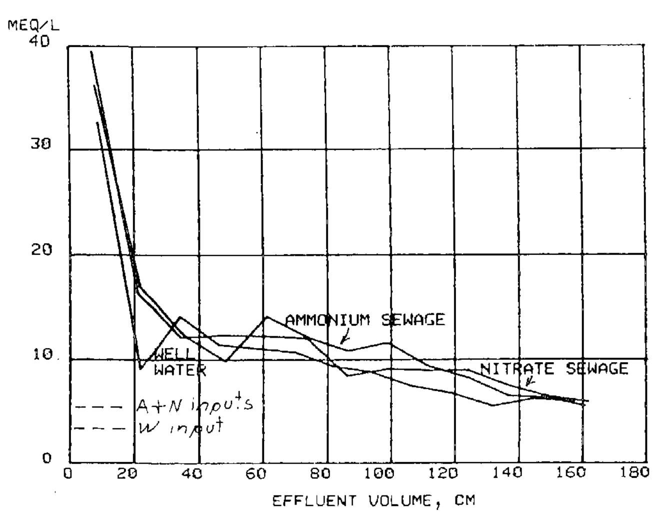


Fig. 46. Sodium concentrations in effluents from Panoche clay loam treated with sewages or well water.



ig. 44. Sodium concentrations in effluents from Panoche sandy loam treated with sewages or well water.

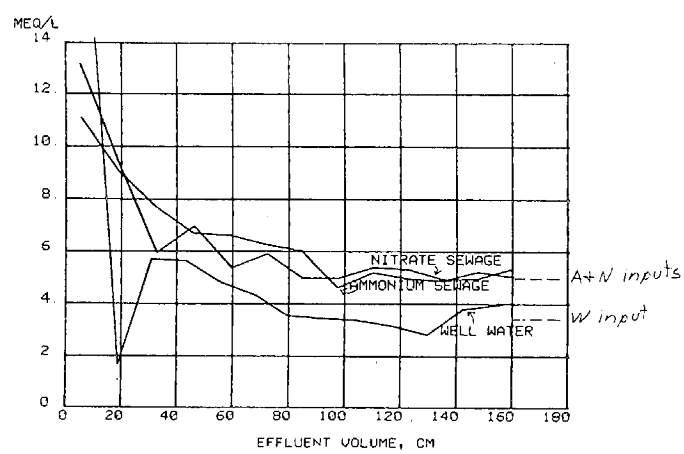


Fig. 47. Sodium concentrations in effluents from Columbia fine sandy loam treated with sewages or well water.

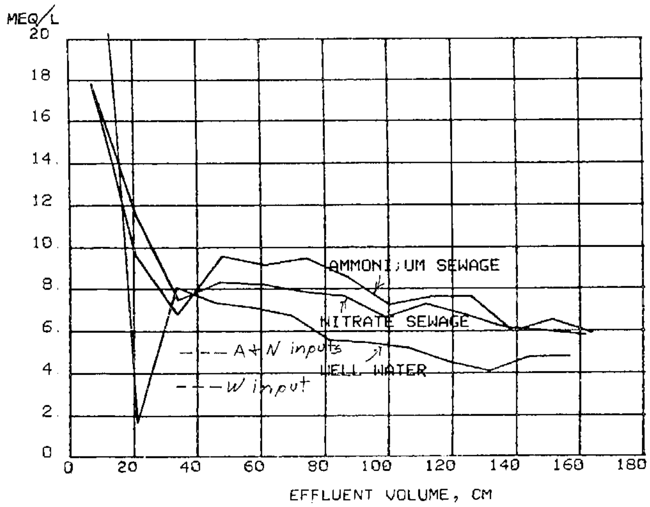


Fig. 48. Sodium concentrations in effluents from noncalcareous Panoche loam treated with sewages or well-water.

effluents from well water columns much lower than in those receiving sewage. Bicarbonate concentrations shown in Figures 49-53 show that in general effluents from nitrate sewage columns had the highest concentrations, ammonium sewage columns had the lowest, with well water columns intermediate between the two. This suggests that acid generated by nitrification in the ammonium sewage columns was neutralized by reaction with bicarbonate, which reduced the concentration of this constituent in the effluent. The fact that the pH values of the effluents remained alkaline throughout the leaching period indicates that the ammonium sewage was self-buffering as a result of its content of bicarbonate and possibly other ions such as phosphate. Table 13 gives the pH values calculated for the total effluents from the five soils and three treatments. If all the leachate collected over the 24-week period were mixed together and the pH measured, it theoretically would have the value indicated in the table.

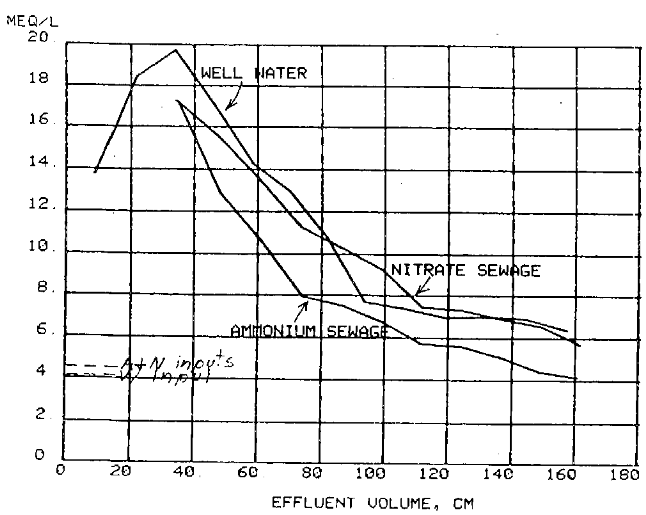


Fig. 49. Bicarbonate concentrations in effluents from Panoche sandy loam treated with sewages or well water.

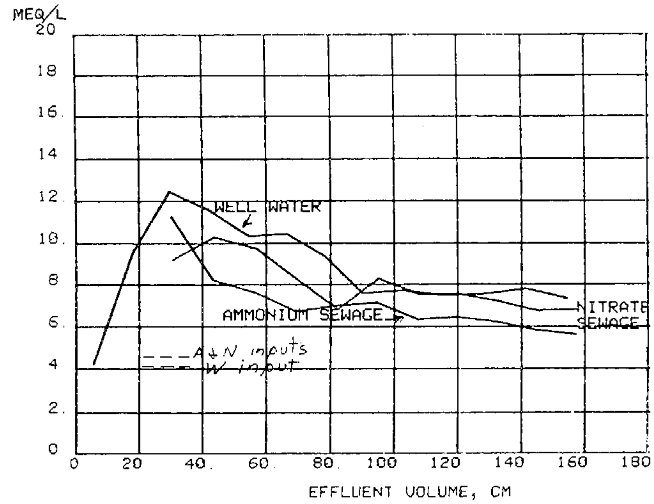


Fig. 50. Bicarbonate concentrations in effluents from Panoche loam treated with sewages or well water.

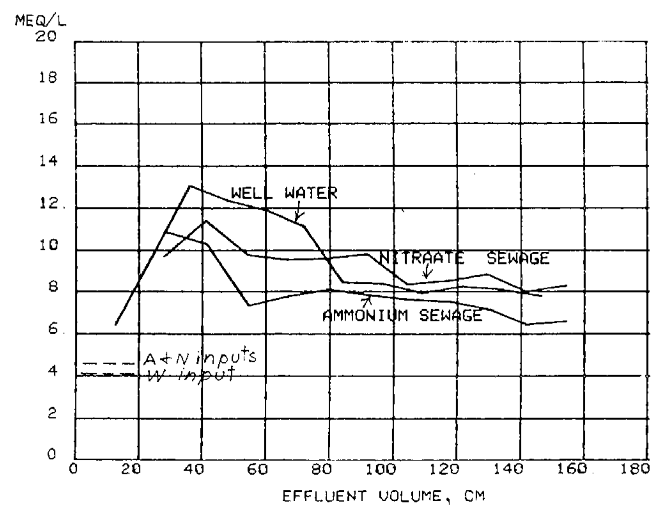


Fig. 51. Bicarbonate concentrations in effluents from Panoche clay loam treated with sewages or well water.

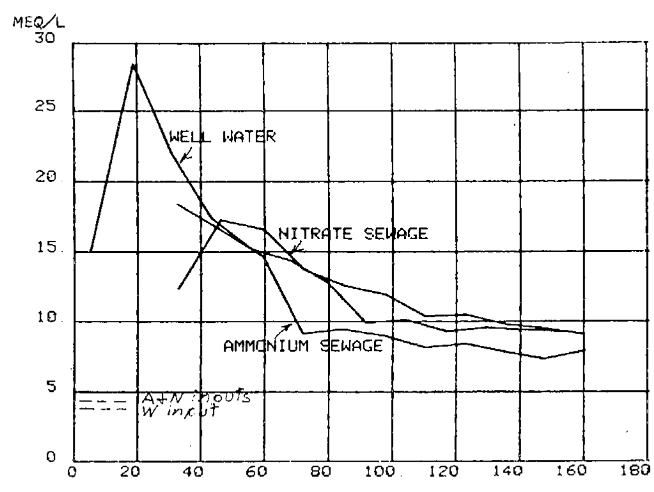


Fig. 52. Bicarbonate concentrations in effluents from Columiba fine sandy loam treated with sewages or well water.

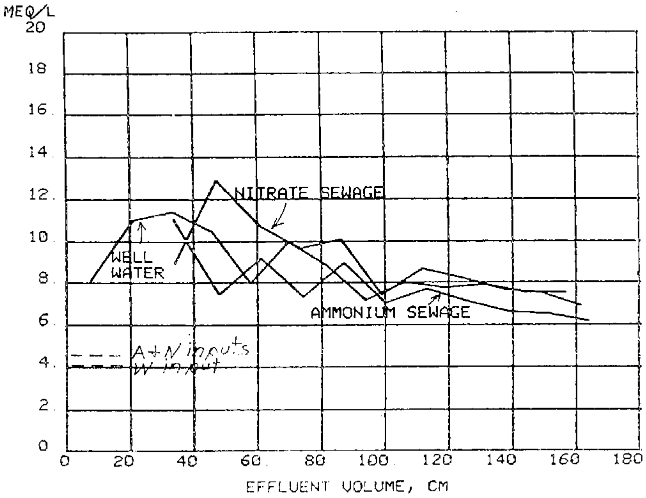


Fig. 53. Bicarbonate concentrations in effluents from non-calcareous Panoche loam after treatment with sewages or well water.

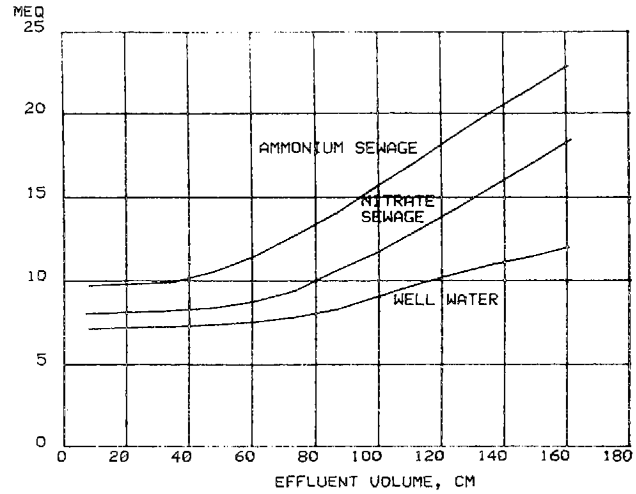


Fig. 54. Inorganic nitrogen in effluents from Panoche sandy loam treated with sewages or well water.

Table 13. pH values of total effluent from columns of 5 soils leached with NH_4-sewage, NO_3-sewage, or well water.

Soil	NH_4 Sewage	NO_3 Sewage	Well Water
Panoche sandy loam	7.67	7.83	7.68
Panoche loam	8.05	8.13	7.98
Panoche clay loam	8.08	8.13	8.05
Columbia fine sandy loam	8.01	8.12	8.00
Panoche loam (non-calc.)	8.19	8.19	7.94

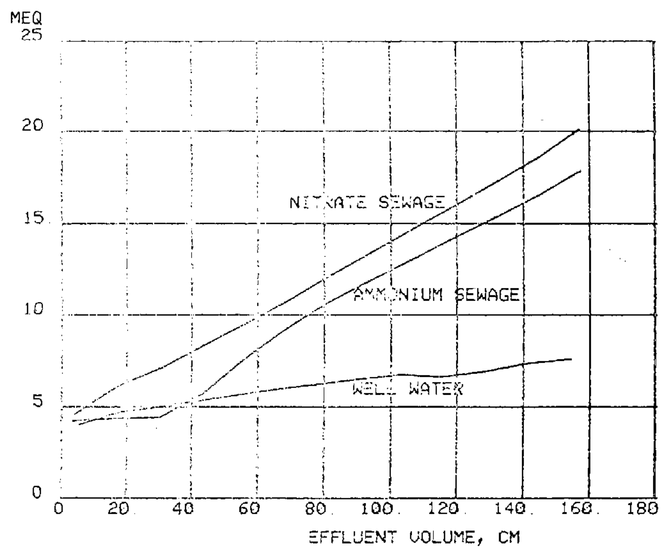


Fig. 55. Inorganic N in effluents from Panoche loam treated with sewages or well water.

It is interesting to note that the pH values of effluents from well water columns are slightly lower than those for ammonium sewage columns. Clearly the ammonium content of the input sewage did not have a dominant effect on the pH of the effluent.

Cumulative inorganic nitrogen in effluents, shown in Figures 54-58, followed patterns similar to those seen in previous experiments. Because labeled nitrogen was not used, precise balance sheet accounting of nitrogen was not attempted. Cumulative balances for these five soils are given in Table 14. Referring to net losses of calcium, the differences between ammonium and nitrate sewage columns were only 3-4 meq in the three calcareous soils, but 7-8 meq in the two non-calcareous ones. Differences between treatments with respect to net losses of magnesium were likewise small. The large net losses of total bases from ammonium sewage columns as compared to the others are somewhat misleading and require explanation. These are due primarily to the accumulation of potassium in columns of soil receiving nitrate sewage, where the input potassium was increased by addition of potassium nitrate. It is well known that potassium is fixed in many soils, and this input without a corresponding output is reflected in the smaller net losses

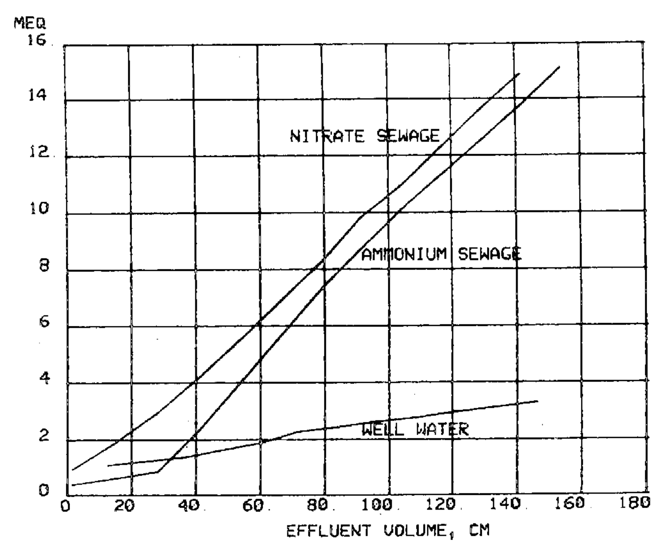


Fig. 56. Inorganic N in effluents from Panoche clay loam treated with sewages or well water.

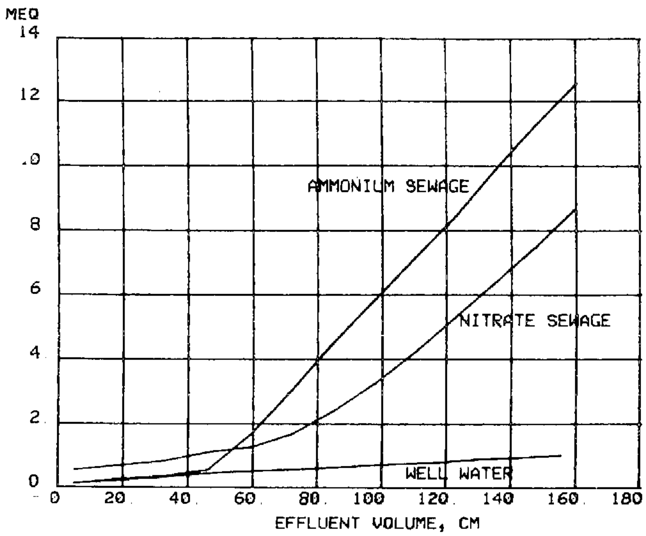


Fig. 57. Inorganic N in effluents from Columbia fine sandy loam treated with sewages or well water.

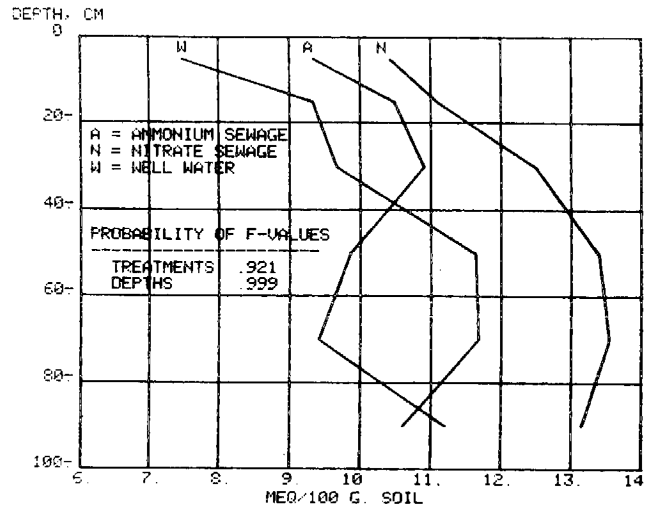


Fig. 59. Exchangeable calcium in Panoche sandy loam after treatment with sewages or well water.

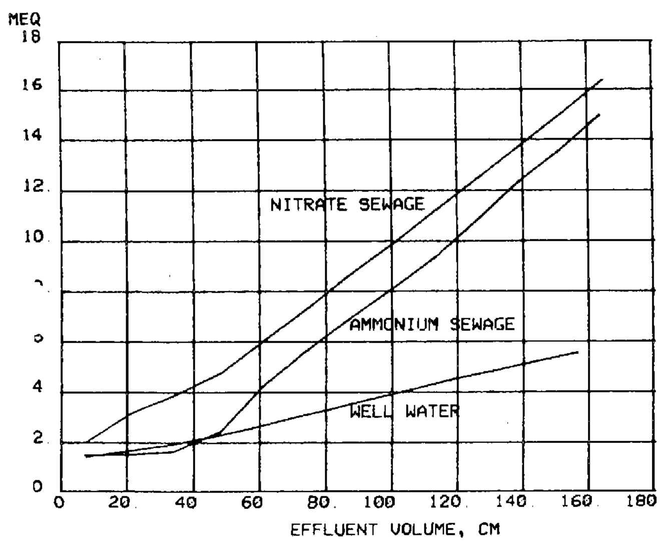


Fig. 58. Inorganic N in effluents from non-calcareous Panoche loam treated with sewages or well water.

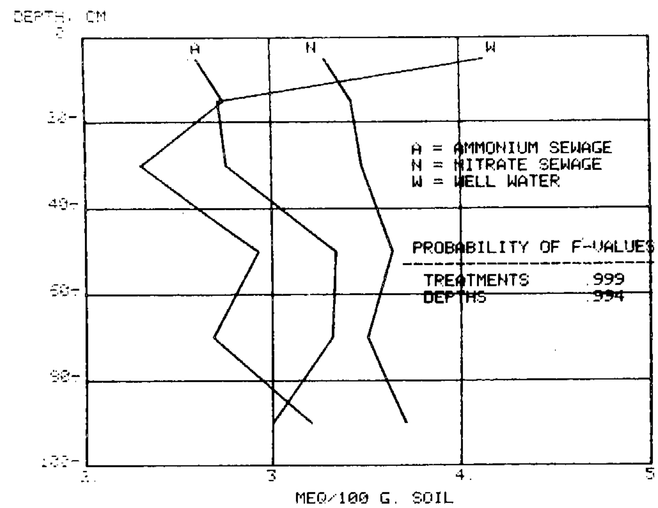


Fig. 60. Exchangeable magnesium in Panoche sandy loam after treatment with sewages or well water.

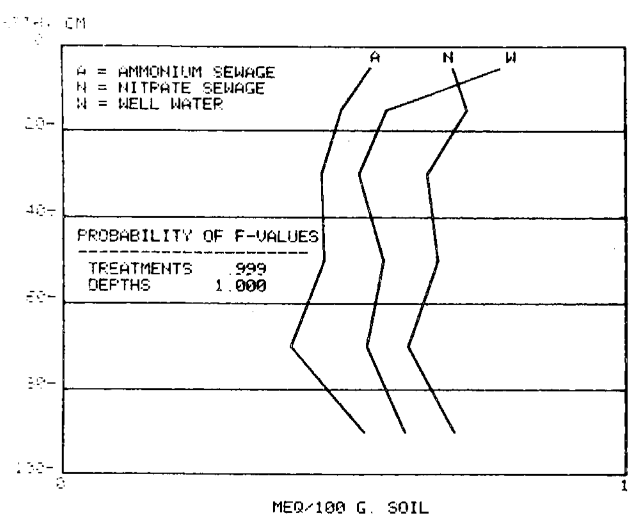


Fig. 61. Exchangeable sodium in Panoche sandy loam after treatment with sewages or well water.

of total bases from these columns. It will be noted that net loss of total bases from columns treated with well water were higher than from those receiving nitrate sewage in four out of the five soils.

An indication of the total salt content of effluents fromthe five soils is given in Table 15 which records electrical conductivities. As expected, values for effluents from ammonium sewage columns are a little higher than those for other treatments, but all values are in a relatively low range in spite of the artificially increased level of nitrogen in the input sewage.

Exchangeable calcium, magnesium, and sodium in columns of Panoche sandy loam after the experiment was concluded were distributed as shown in Figures 9, 60 and 61. In general, these exchangeable bases ended to be highest in columns receiving nitrate

Table 14. Cumulative balance for columns of 5 soils treated with 222 cm of wastewater containing NH_4^+ or NO_3^- or with well water.

	Ca^{++}	Mg^{++}	K^+	Na^+	Σ bases	NH_4^+	NO_3^-	ΣN	Cl^-	HCO_3^-	$CO_3^=$
					Input, meq						
NH_4^+-sewage	4.48	8.06	0.77	22.97	36.28	17.60	1.94	19.54	28.83	20.31	0
NO_3^--sewage	4.53	8.39	18.05	22.14	53.11	.028	18.26	18.29	10.54	20.07	0
Well Water	3.17	5.99	0.19	14.38	23.73	.045	.088	.13	5.10	16.92	0
					Panoche sandy loam (calcareous)						
					Output, meq						
NH_4^+-sewage	25.48	15.80	3.06	38.90	83.24	1.20	21.72	22.92	26.84	23.27	0
NO_3^--sewage	21.04	13.61	2.03	38.06	74.74	1.39	17.06	18.45	10.91	29.67	0.065
Well Water	2.04	12.46	1.15	31.06	46.71	0.98	11.02	12.00	7.89	37.11	0
					Net Change, meq						
NH_4^+-sewage	-21.90	-7.74	-2.29	-15.93	-47.86	16.40	-19.78	-3.38	1.99	-2.96	0
NO_3^--sewage	-17.18	-5.22	16.02	-15.92	-22.33	-1.36	1.20	-0.16	-0.37	-9.60	-0.065
Well Water	1.13	-6.47	-0.96	-16.68	-22.98	-0.93	-10.93	-11.86	-2.79	-20.19	0
					Panoche loam						
					Output meq						
NH_4^+-sewage	20.67	12.23	0.867	43.10	76.87	0.06	17.81	17.87	26.54	20.81	0.097
NO_3^--sewage	17.53	9.48	0.82	39.90	67.73	0.14	20.03	20.17	11.04	23.31	0.24
Well Water	9.99	10.71	1.07	29.12	50.89	0.10	7.47	7.57	7.68	28.44	0
					Net Change, meq						
NH_4^+-sewage	-16.19	-4.17	-0.10	-20.13	-40.59	17.54	-15.87	1.67	2.29	-0.50	-0.10
NO_3^--sewage	-13.00	-1.09	17.23	-17.76	-14.62	-0.11	-1.77	-1.88	-0.50	-3.24	-0.24
Well Water	-7.17	-4.72	-0.88	-14.74	-27.51	-0.06	-7.38	-7.44	-2.58	-11.52	0
					Panoche clay loam						
					Output, meq						
NH_4^+-sewage	20.37	33.11	1.51	35.80	90.79	0.06	15.08	15.14	26.13	23.07	0.24
NO_3^--sewage	17.16	29.98	1.47	33.25	81.86	0.08	16.09	16.17	12.42	26.77	0.13
Well Water	12.06	19.52	1.31	15.17	48.06	0.03	3.04	3.07	9.12	28.60	0
					Net Change, meq						
NH_4^+-sewage	-15.89	-25.05	-0.74	-12.83	-54.51	17.54	-13.14	4.40	2.70	-2.76	-0.24
NO_3^--sewage	-12.63	-21.59	16.58	-11.11	-28.75	-0.05	2.17	2.12	-1.88	-6.70	-0.13
Well Water	-8.89	-13.53	-1.12	-0.79	-24.33	0.01	-2.95	-2.94	4.02	-11.68	0
					Columbia fine sandy loam						
					Output, meq						
NH_4^+-sewage	18.41	34.81	4.67	20.68	78.57	0.53	12.06	12.59	24.91	31.29	0.06
NO_3^--sewage	12.24	30.24	4.20	20.03	66.71	0.68	7.98	8.66	9.94	35.57	1.22
Well Water	7.37	22.64	3.18	14.59	47.78	0.48	0.53	1.01	6.61	45.25	0
					Net Change, meq						
NH_4^+-sewage	-14.83	-26.75	-3.90	2.29	-43.19	17.07	-10.12	6.95	3.92	-10.98	-0.06
NO_3^--sewage	-7.71	-21.85	13.85	2.11	-13.60	-0.65	10.28	9.63	0.60	-15.50	-1.22
Well Water	-4.20	-16.65	-2.99	-0.21	-24.05	-0.43	-0.44	-0.87	-1.51	-28.33	0
					Panoche loam (non-calcareous)						
					Output, meq						
NH_4^+-sewage	34.48	14.66	2.84	28.12	80.10	0.36	14.61	14.97	25.70	23.03	1.05
NO_3^--sewage	27.02	11.93	2.43	26.69	68.07	0.13	16.29	16.42	9.94	26.26	0.40
Well Water	11.57	9.89	3.02	22.24	46.72	0.07	5.44	5.51	6.36	28.44	0
					Net Change, meq						
NH_4^+-sewage	-30.00	-6.60	-2.07	-5.15	-43.82	17.24	-12.67	4.57	3.13	-2.72	-1.05
NO_3^--sewage	-22.49	-3.54	15.62	-4.55	-14.96	-0.10	1.97	1.87	0.60	-6.19	-0.40
Well Water	-8.40	-3.90	-2.83	-7.86	-22.99	-0.02	-5.35	-5.37	-1.26	-11.52	0

sewage, next highest in those treated with well water, and lowest in those treated with ammonium sewage, although treatment differences with respect to calcium were not statistically significant. Exchangeable bases in Panoche loam shown in Figures 62, 63, and 64 were significantly affected by sewage treatment only in the case of magnesium (Figure 63), and in that case only in the surface 10 cm of soil. Less movement of cations would be expected in this soil of finer texture than the sandy loam in which treatment differences were significant. This trend is evident in the data for Panoche clay loam (Figures 65, 66 and 67) where no significant treatment differences were observed. For purposes of this discussion statistical significance is attributed to F-values with a probability greater than .95 or stated another way, the odds are less than 1 in 20 that the observed difference is due to chance variation. Treatment differences in exchangeable calcium in Columbia fine sandy loam, although apparently largely due to the scale of the graph (Figure 68) are not statistically significant. Magnesium (Figure 69) and sodium (Figure 70) exhibited significant differences

Table 15. Electrical conductivity of total effluent from columns of 5 soils leached with 222 cm of NH_4- sewage, NO_3- sewage or well water.

Soil	NH_4 Sewage	NO_3 Sewage	Well Water
		mmhos/cm	
Panoche sandy loam	2.09	1.90	1.60
Panoche loam	2.02	1.78	1.33
Panoche clay loam	2.27	2.10	1.64
Columbia fine sandy loam	1.96	1.64	1.29
Panoche loam (non-calc.)	2.00	1.71	1.29

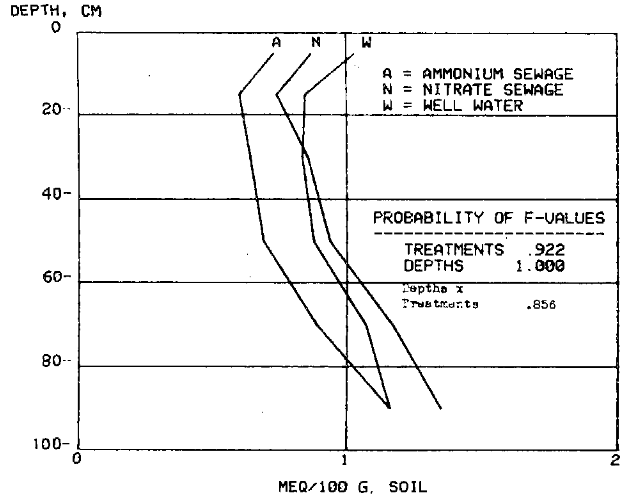


Fig. 64. Exchangeable sodium in Panoche loam after treatment with sewages or well water.

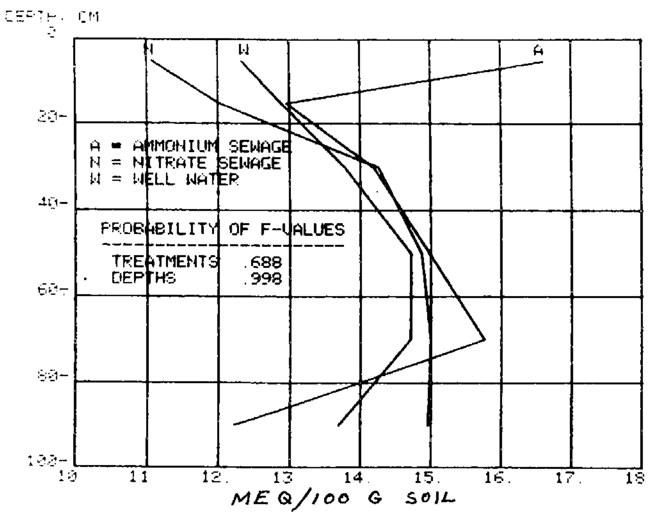


Fig. 62. Exchangeable calcium in Panoche loam after treatment with sewages or well water.

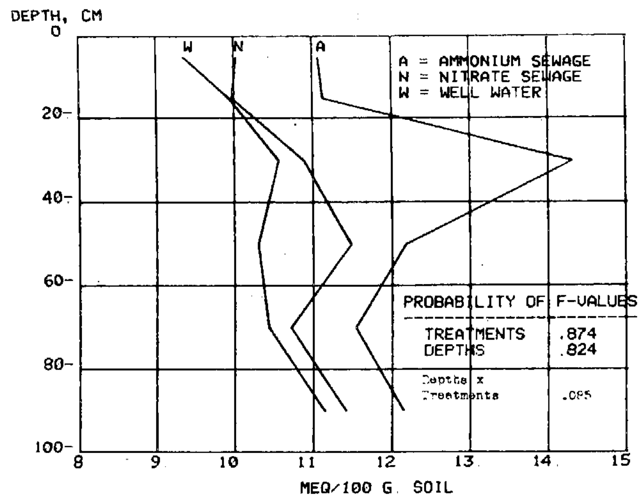


Fig. 65. Exchangeable calcium in Panoche clay loam after treatment with sewages or well water.

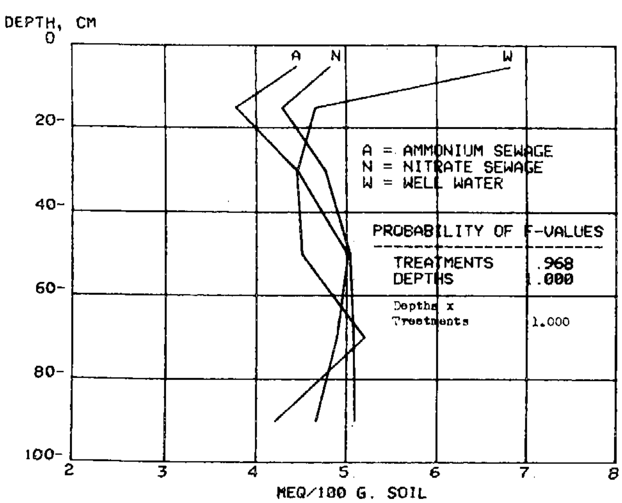


Fig. 63. Exchangeable magnesium in Panoche loam after treatment with sewages or well water.

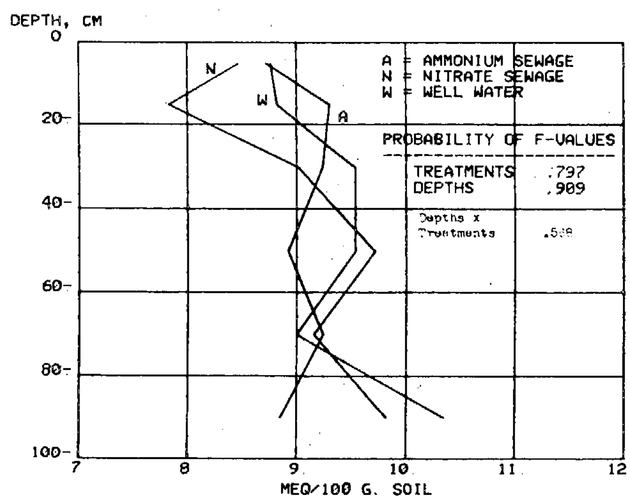


Fig. 66. Exchangeable magnesium in Panoche clay loam after treatment with sewages or well water.

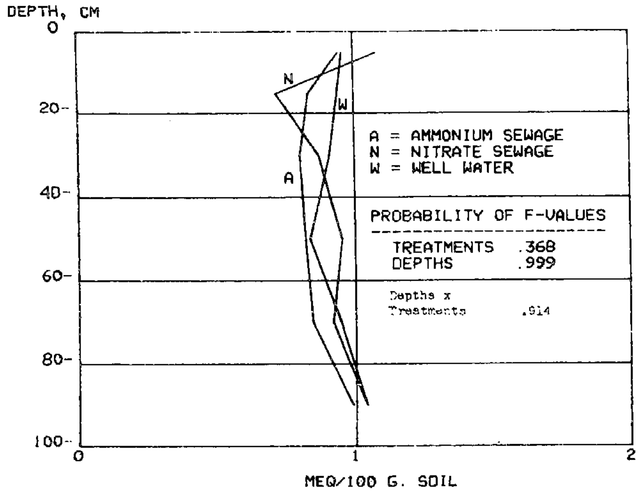


Fig. 67. Exchangeable sodium in Panoche clay loam after treatment with sewages or well water.

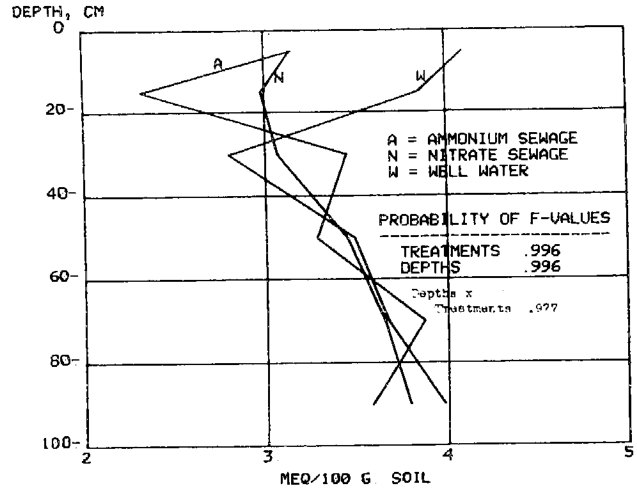


Fig. 69. Exchangeable magnesium in Columbia fine sandy loam after treatment with sewages or well water.

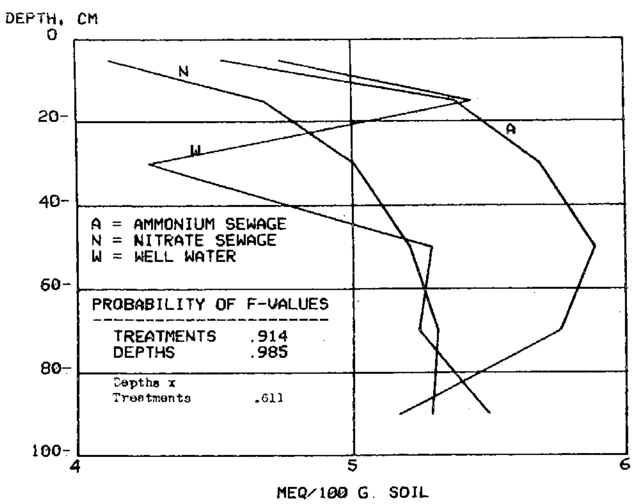


Fig. 68. Exchangeable calcium in Columbia fine sandy loam after treatment with sewages or well water.

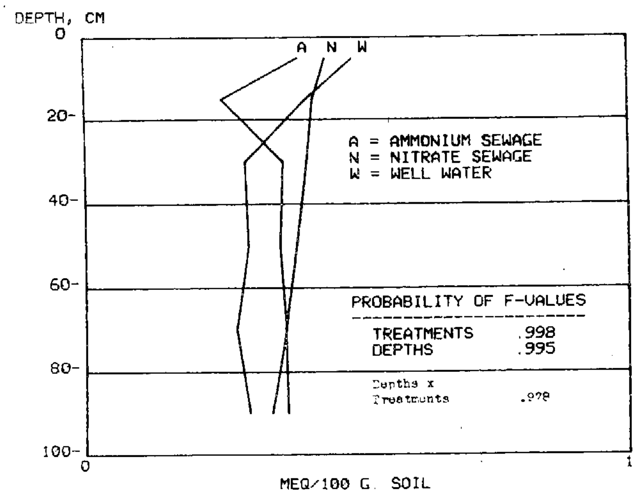


Fig. 70. Exchangeable sodium in Columbia fine sandy loam after treatment with sewages or well water.

although the differences in magnesium were confined to the surface 20 cm of soil. Exchangeable cations in the non-calcareous Panoche loam soil (Figures 71, 72 and 73) exhibited no treatment differences.

d. Experiments with nitrified and non-nitrified sewages at natural levels of nitrogen.

Calcium concentrations shown in Figures 74 and 75 displayed no differences of statistical significance as a result of type of input sewage. In Panoche clay loam application of nitrate sewage resulted in higher effluent concentrations of magnesium (Figure 76), but no differences were found with Columbia fine sandy loam (Figure 77). Data for potassium and sodium (Figures 78-81) show no differences between types of sewage. Bicarbonate concentrations (Figures 82 and 83) were likewise very similar, in spite of higher input levels in the ammonium sewage. Inorganic nitrogen concentrations shown in Figures 84 and 85 show no differences in Panoche clay loam and relatively small differences in Columbia fine sandy loam following the initial lag period when nitrifiers were building up.

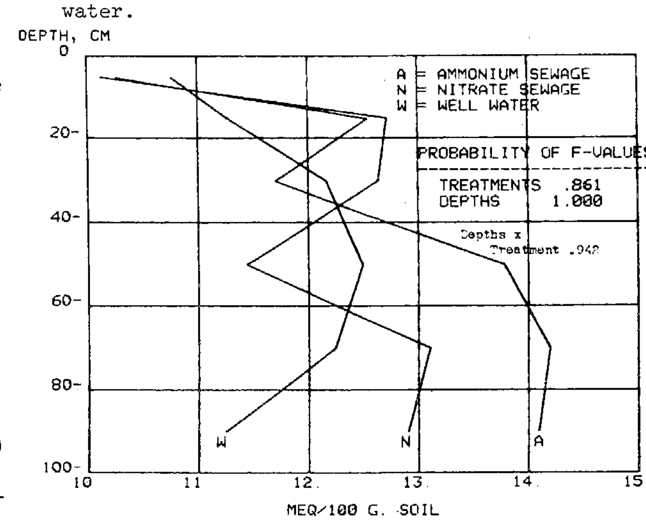


Fig. 71. Exchangeable calcium in non-calcareous Panoche loam after treatment with sewages or well water.

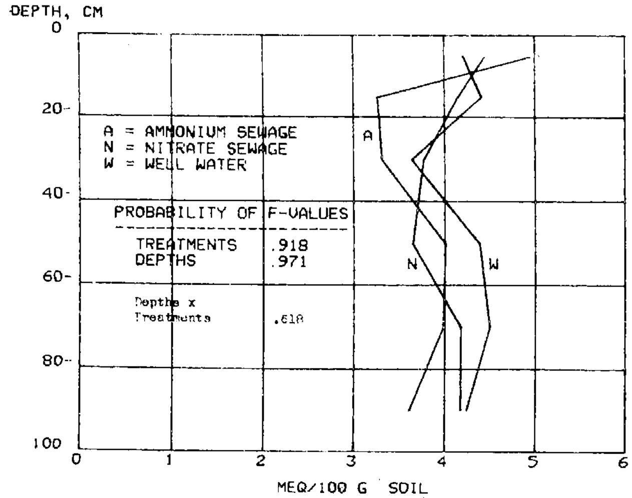


Fig. 72. Exchangeable magnesium in non-calcareous Panoche loam after treatment with sewages or well water.

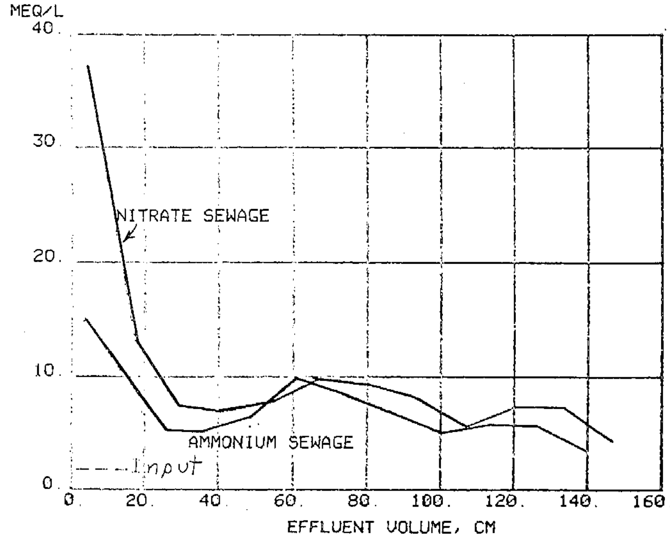


Fig. 75. Calcium concentrations in effluents of Columbia fine sandy loam treated with unamended sewage.

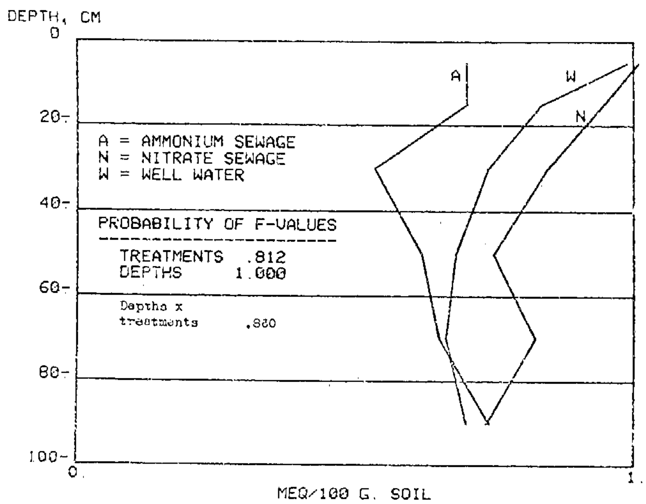


Fig. 73. Exchangeable sodium in non-calcareous Panoche loam after treatment with sewages or well water.

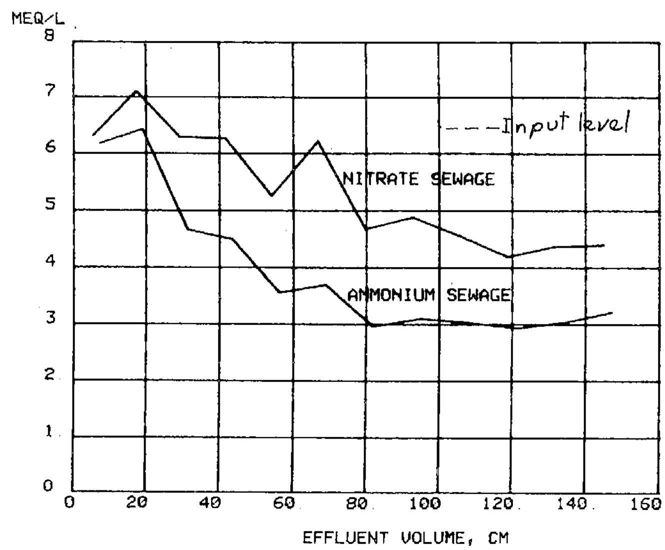


Fig. 76. Magnesium concentrations in effluents from Panoche clay loam treated with unamended sewage.

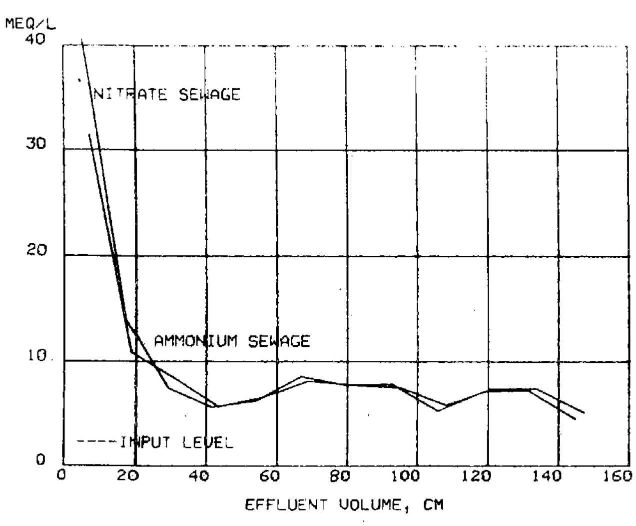


Fig. 74. Calcium concentrations in effluents of Panoche clay loam treated with unamended sewage.

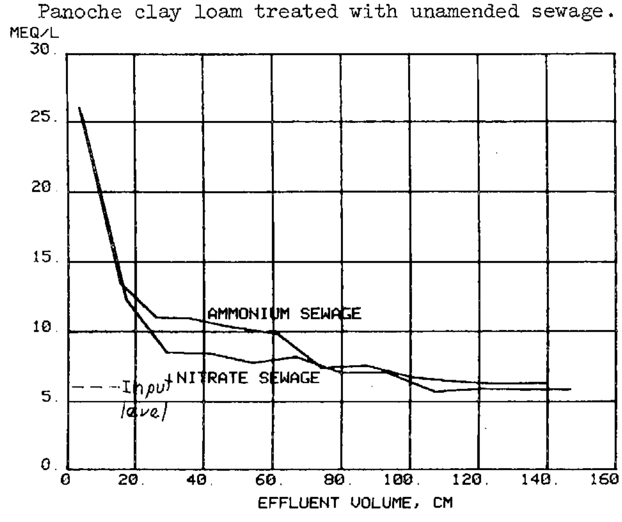


Fig. 77. Magnesium concentrations in effluents from Columbia fine sandy loam treated with unamended sewage.

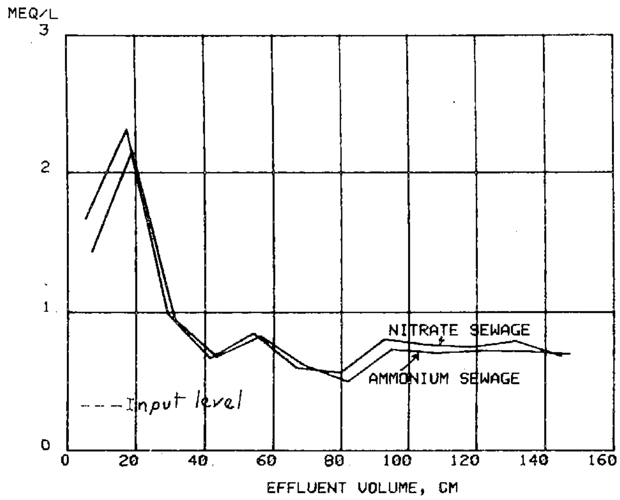


Fig. 78. Potassium concentrations in effluents from Panoche clay loam treated with unamended sewage.

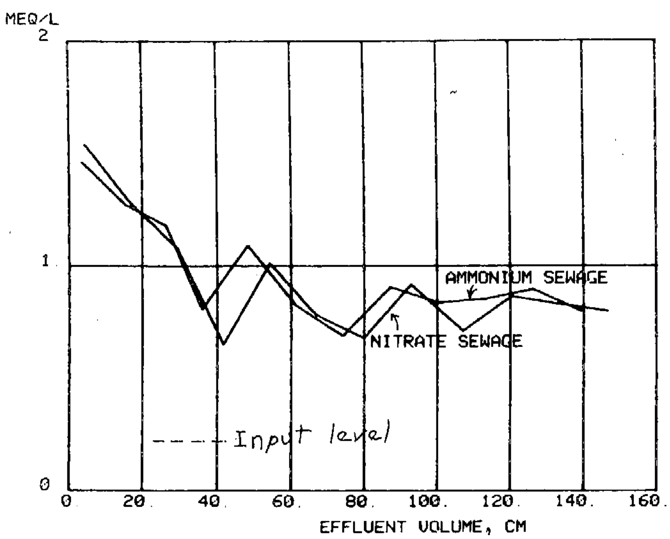


Fig. 79. Potassium concentrations in effluents from Columbia fine sandy loam treated with unamended sewage.

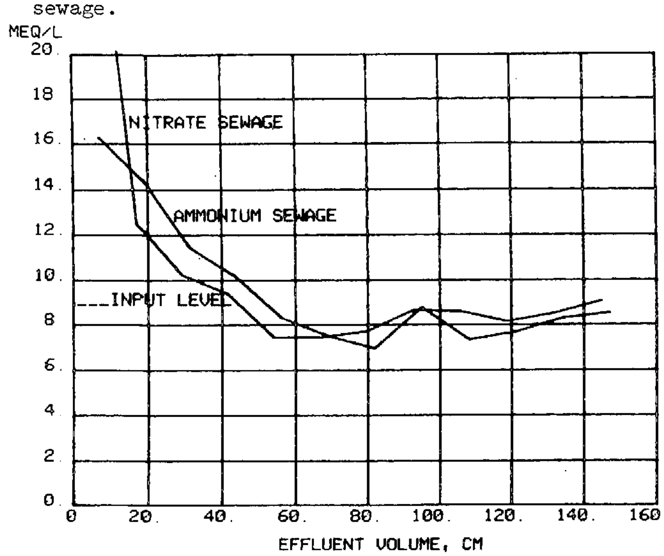


Fig. 80. Sodium concentrations in effluents from Panoche clay loam treated with unamended sewage.

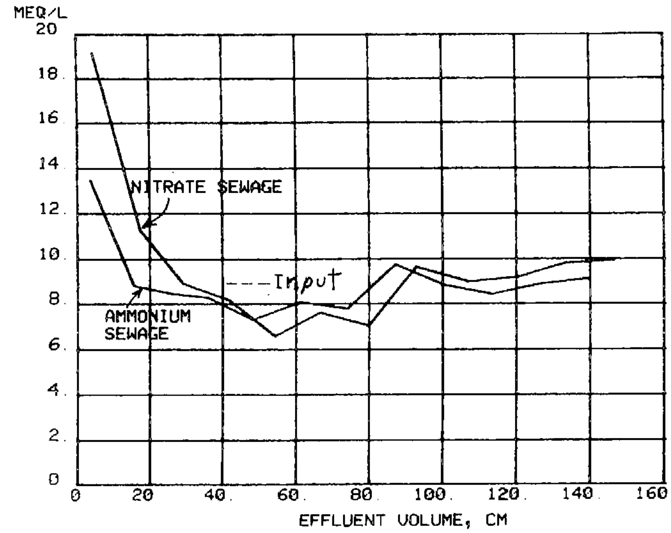


Fig. 81. Sodium concentrations in effluents from Columbia fine sandy loam treated with unamended sewage.

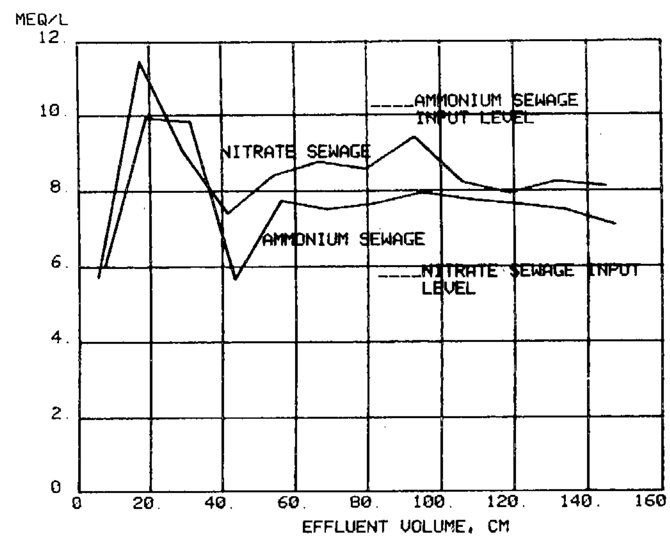


Fig. 82. Bicarbonate concentrations in effluents from Panoche clay loam treated with unamended sewage.

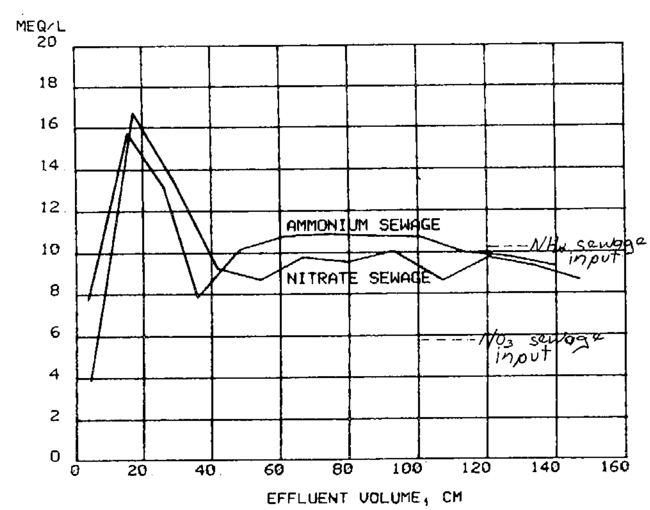


Fig. 83. Bicarbonate concentrations in effluents from Columbia fine sandy loam treated with unamended sewage.

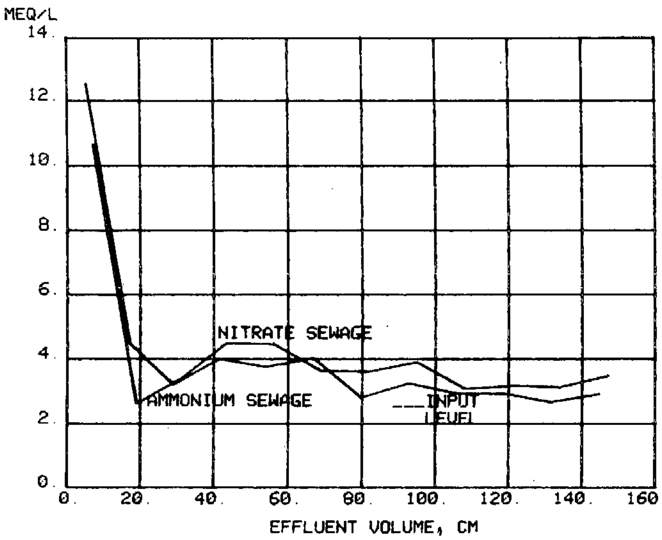


Fig. 84. Inorganic N concentrations in effluents from Panoche clay loam treated with unamended sewage.

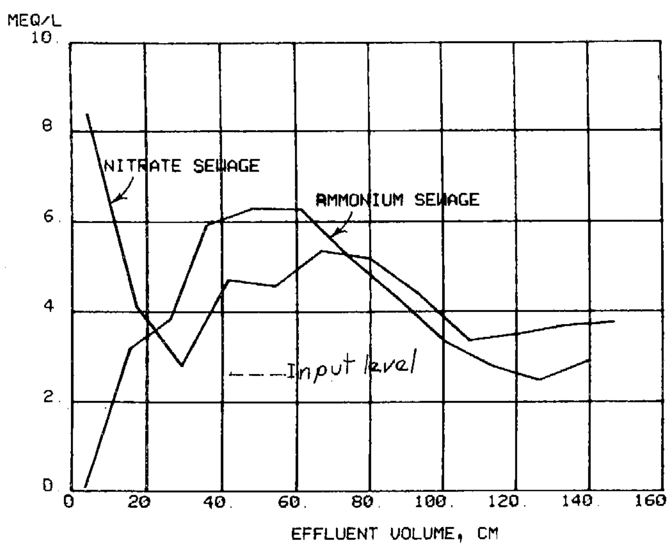


Fig. 85. Inorganic N concentrations in effluents from Columbia fine sandy loam treated with unamended sewage.

Cumulative balances of constituents eluted from these two soils are presented in Table 16. Columbia fine sandy loam receiving nitrate sewage sustained greater net loss of bases than did the same soil treated with ammonium sewage. In general, treatment differences were small in both soils. Equivalent conductance values indicate a slightly higher salt content of effluents from the Columbia soil with nitrate sewage than with ammonium sewage. In Panoche clay loam the equivalent conductances were almost identical with the two sewages.

Exchangeable calcium, magnesium and sodium in Panoche clay loam after sewage treatment were distributed as shown in Figures 86, 87 and 88. Similarly, data for Columbia fine sandy loam are presented in Figures 89, 90, and 91. Differences in any of the three cations due to sewage treatment were not found in either of these soils.

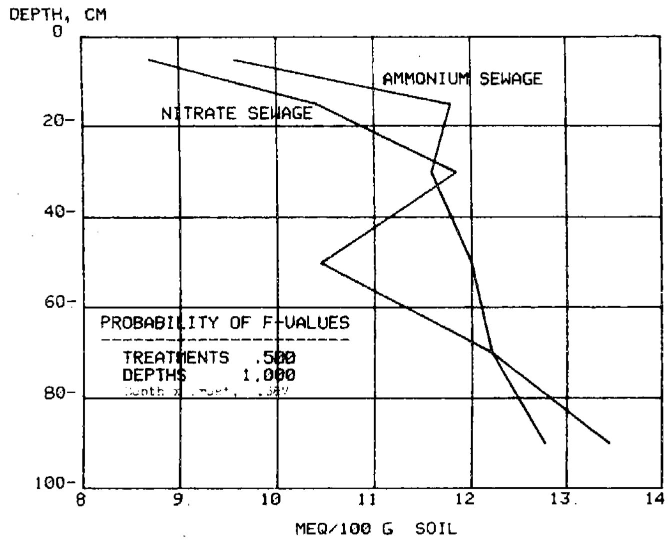


Fig. 86. Exchangeable calcium in Panoche clay loam after treatment with unamended sewage.

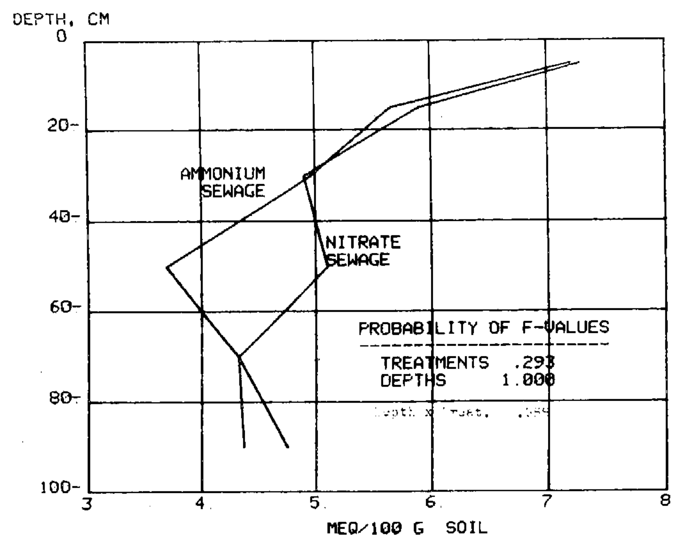


Fig. 87. Exchangeable magnesium in Panoche clay loam after treatment with unamended sewage.

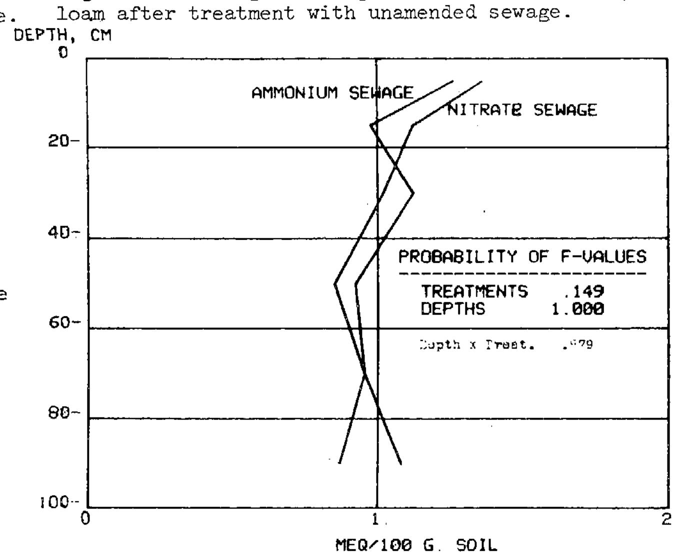


Fig. 88. Exchangeable sodium in Panoche clay loam after treatment with unamended sewage.

Table 16. Cumulative balances for two soils treated with 203 cm of ammonium or nitrate sewage at natural N content.

Ion	NH_4 - Sewage			NO_3 - Sewage		
	Input meq	Output meq	Net Change meq	Input meq	Output meq	Net Change meq
			Columbia fine sandy loam			
Ca^{++}	6.97	19.44	12.47	8.12	26.60	18.48
Mg^{++}	27.49	26.10	1.39	26.60	24.20	2.40
K^+	0.97	2.69	- 1.72	1.02	2.70	- 1.68
Na^+	36.41	25.03	11.38	37.83	27.81	10.02
Σ bases	71.84	73.26	- 1.42	73.57	81.31	- 7.74
NH_4^+	10.13	0.09	10.04	0.17	0.11	0.05
NO_3^-	1.25	11.70	-10.45	9.60	12.79	- 3.19
Σ N	11.38	11.79	- 0.45	9.77	12.90	- 3.13
Cl^-	39.65	30.03	9.62	45.49	33.08	12.44
HCO_3^-	42.88	31.08	11.80	24.59	30.79	- 6.20
E.C.	1.70	2.16		1.66	2.28	
			Panoche Clay Loam			
Ca^{++}	6.97	25.65	-18.68	8.12	25.56	-17.44
Mg^{++}	27.49	11.64	15.85	26.60	15.90	10.70
K^+	0.97	2.63	- 1.66	1.02	2.71	- 1.69
Na^+	36.44	28.45	7.96	37.83	30.25	7.58
Σ bases	71.87	68.37	3.50	73.57	74.42	- 0.85
NH_4^+	10.13	0.06	10.07	0.16	0.08	0.08
NO_3^-	1.25	11.62	-10.37	9.60	10.89	- 1.29
Σ N	11.38	11.88	- 0.47	9.76	11.97	- 1.21
Cl^-	39.65	35.47	4.18	45.49	35.92	9.57
HCO_3^-	42.88	23.63	19.25	24.59	25.69	- 1.10
E.C.	1.70	2.05		1.66	2.07	

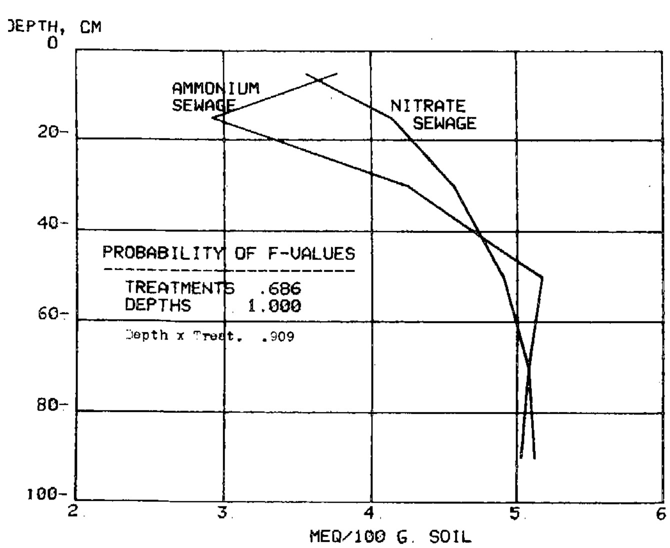


Fig. 89. Exchangeable calcium in Columbia fine sandy loam after treatment with unamended sewage.

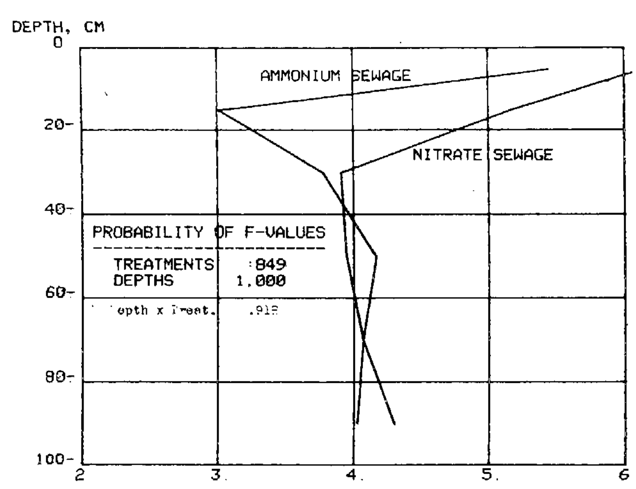


Fig. 90. Exchangeable magnesium in Columbia fine sandy loam after treatment with unamended sewage.

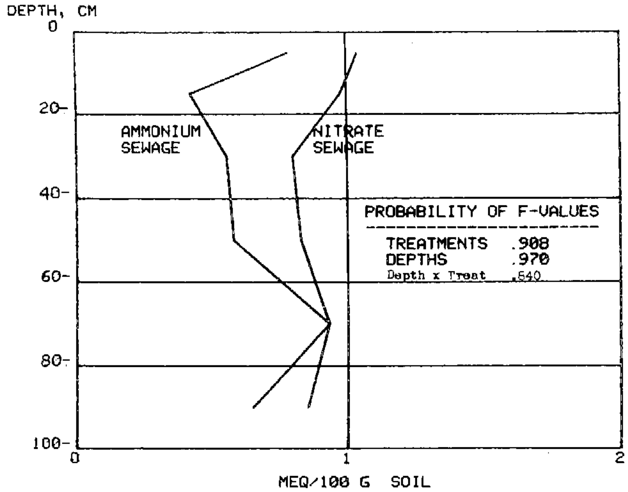
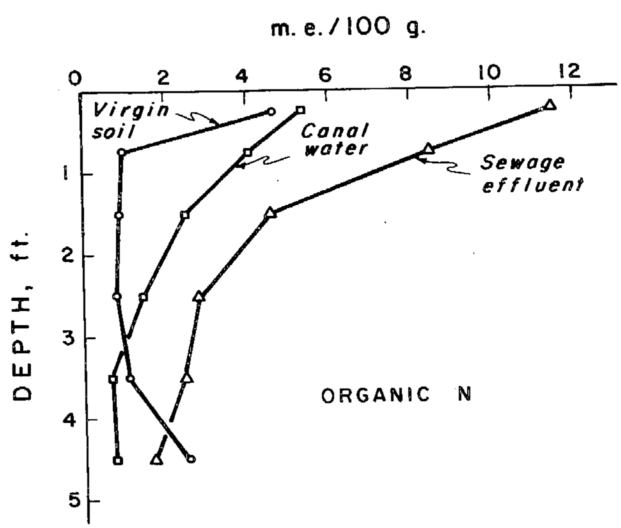


Fig. 91. Exchangeable sodium in Columbia fine sandy loam after treatment with unamended sewage.

B. Analyses of field sites

1. Bakersfield site

Soil samples taken from an area treated with wastewater since 1938, a virgin area never cropped, and a nearby area cropped to cotton and irrigated with canal water were compared with respect to several properties. Distribution of organic nitrogen as a function of depth is shown in Figure 92. Clearly there was a significant buildup of organic nitrogen as a result of application of sewage effluent. Figure 93 shows a substantial increase in exchangeable calcium as a result of wastewater application, and similar improvement in the magnesium status is shown in Figure 94. Removal of excess sodium originally present in the soil by many years of wastewater application (Figure 95) confirms the fact that this saline alkali soil was to a considerable extent reclaimed by wastewater treatment. Unfortunately the composition of the applied wastewater is unknown, but the conversion of a soil profile dominated by sodium into one dominated by calcium by application of



.g. 92. Distribution of organic N in Kimberlina soil as affected by 36 years of sewage application.

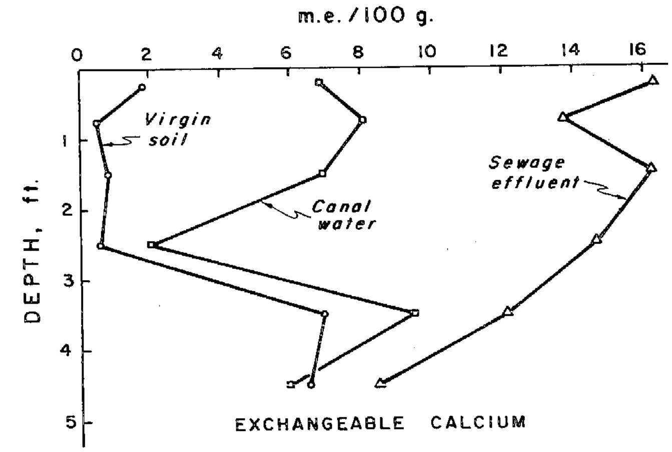


Fig. 93. Exchangeable calcium in Kimberlina soil as affected by 36 years of sewage application.

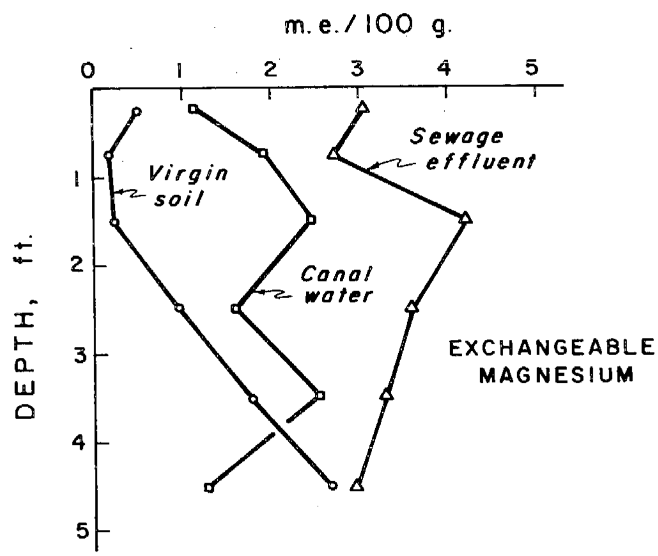


Fig. 94. Exchangeable magnesium in Kimberlina soil as affected by 36 years sewage application.

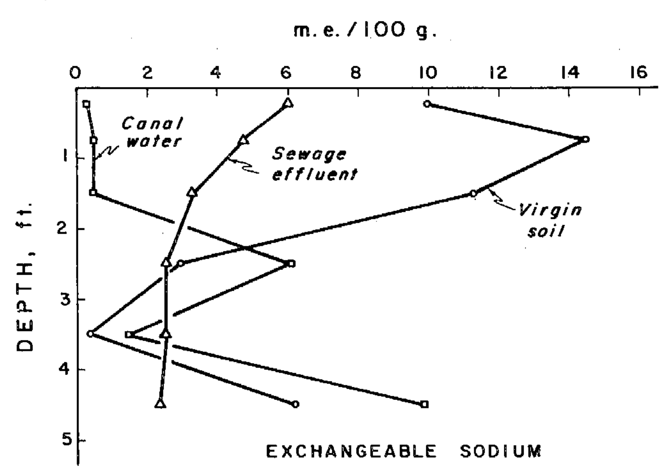


Fig. 95. Exchangeable sodium in Kimberlina soil as affected by 36 years of sewage application.

Table 17. Composition of saturation extracts from samples of Kimberlina soil near Bakersfield.

Depth, inches	0-6	6-12	12-24	24-36	36-48	48-60
			Equivalent conductance, mmhos/cm			
Uncultivated soil	7.63	23.81	10.10	3.70	8.55	4.52
Irrigated with canal water	1.09	1.39	0.93	0.76	0.86	0.73
Irrigated with sewage effluent	3.70	2.14	2.14	1.87	1.48	1.25
			Chloride, mg/l			
Uncultivated soil	1807	--	2462	953	2362	1121
Irrigated with canal water	85	103	102	99	145	99
Irrigated with sewage effluent	408	320	369	364	270	157

wastewater strongly suggests that depletion of soil calcium through wastewater treatment is not likely to be a problem. The improvment in the condition of the Kimberlina soil at the Bakersfield site is further detailed in the composition of saturation extracts from the soil (Table 17).

2. Ontario sludge disposal site

Analyses of soil cores from the sludge pit area, a wastewater treated area, and an untreated area were very informative in spite of a lack of data on the composition of the applied sludge or wastewater.

A very high input of ammonium in the sludge pit area is shown in Figure 96, with concentrations from 300 to 530 ppm (soil basis) depending on depth. In the other two areas ammonium concentrations were below 6 ppm. In spite of the high ammonium levels, nitrification in the sludge pit soil occurred, evidence of which is provided in Figure 97 showing higher nitrate concentrations in the sludge pit than in the wastewater and untreated areas. These data also suggest denitrification near the surface because of the accumulation of organic matter there.

Exchangeable calcium and magnesium in the Ontario samples are shown in Figures 98 and 99. Except for a significant increase of these two bases near the surface of the sludge pit, there was no significant effect of sludge application on distribution of calcium and magensium in the soil profile. There was, however, an increase in exchangeable sodium as a result of many years sludge application, as shown in Figure 100. Application of sludge increased the soil pH (Figure (101), whereas wastewater application made the soil slightly more acid.

V. PRACTICAL IMPLICATIONS

In the application of wastewaters from municipal sewage treatment plants to soils conversion of input ammonium to nitrate can be expected to occur at and near the soil surface owing to the presence of nitrifying bacteria. A lag in initiation of nitrification may occur in subsoils where the native population of nitrifying bacteria is fairly low. When ammonium is supplied, the population of nitrifiers will build up within a

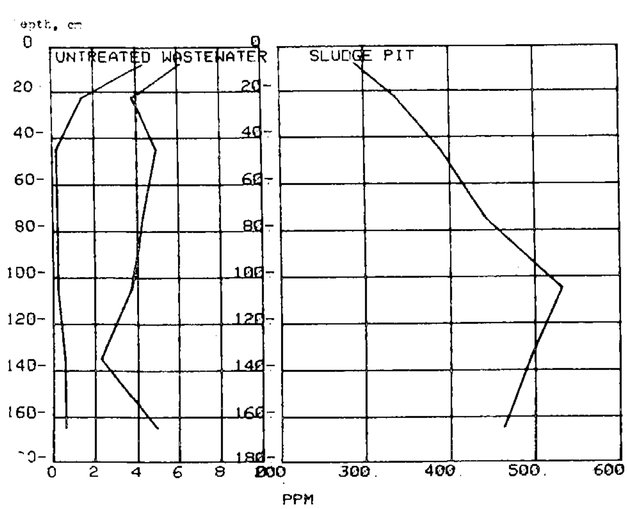


Fig. 96. Ammonium nitrogen in soil at Ontario site.

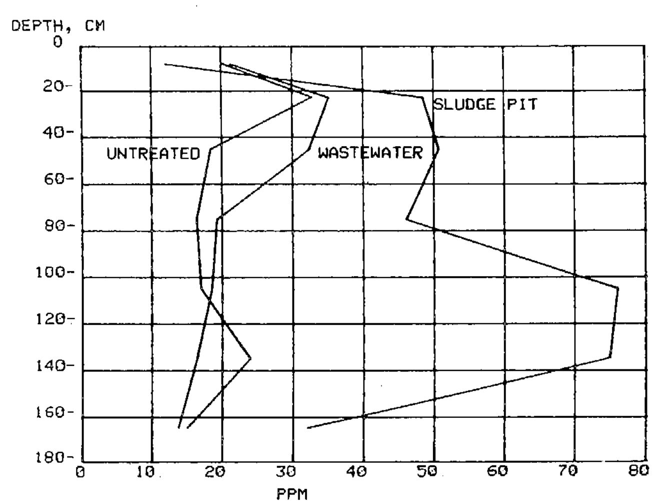


Fig. 97. Nitrate nitrogen in soil at Ontario site.

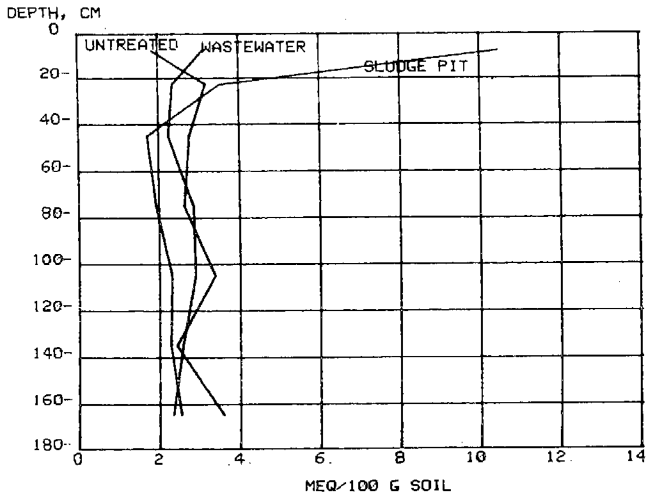


Fig. 98. Exchangeable calcium in soil at Ontario site.

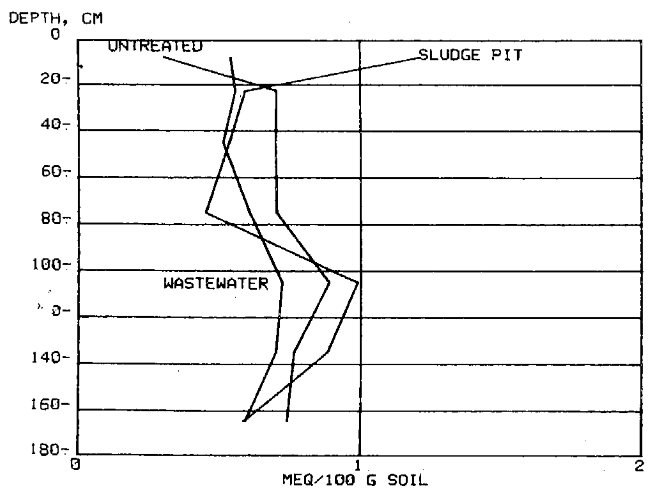
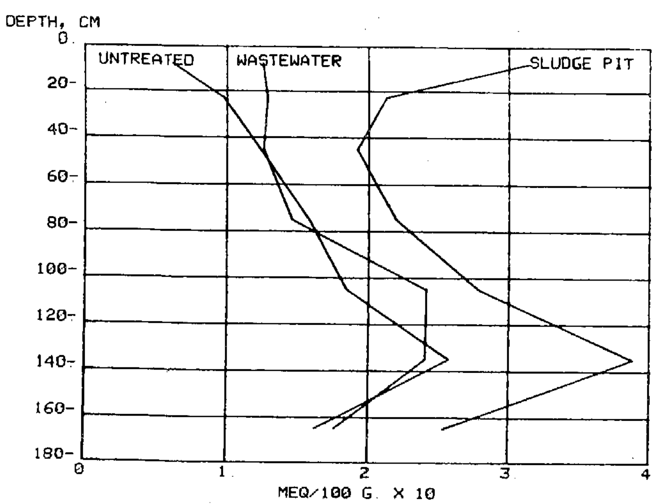


Fig. 99. Exchangeable magnesium in soil at Ontario site.



-g. 100. Exchangeable sodium in soil at Ontario site.

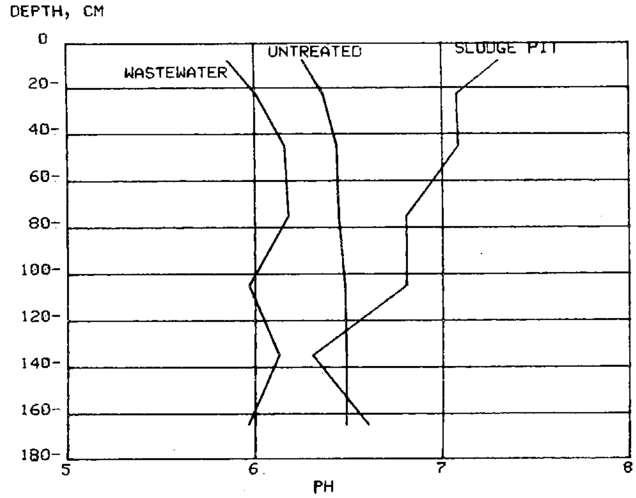


Fig. 101. Soil pH at Ontario site.

few weeks even in such a subsoil. Some loss of nitrogen from the soil is very probable during passage of wastewater down through the soil. The amount of loss ranges from slight to almost complete, depending upon such factors as soil texture, length of the period the soil is saturated, level of organic matter in the soil and quantity of input nitrogen. It seems probable that sewage applications can be managed to promote denitrification in order to minimize the possibility of nitrate contamination of groundwater.

Wastewater containing high input levels of ammonium are likely to increase concentrations of calcium, magnesium and other cations more than would the corresponding sewage if nitrified prior to application. However, nitrified sewage applied to soil also results in substantial concentrations of these cations in soil effluents, and the differences between nitrified and unnitrified sewage are not great. In our experiments nitrification of previously unmodified sewage had no effect on composition of soil effluents. It seems clear that the acid generated in the nitrification process is not the dominant factor in controlling pH of wastewaters or of soils to which they are applied, and soils to which wastewaters containing ammonium are applied are unlikely to become acid. It is worthy of note that Kardos and Sopper (1973) observed a significant increase in the pH of an initially acid soil as a result of adding 1 inch of wastewater per week, and an even greater increase where 2 inches per week were applied.

In these experiments the concentrations of calcium, magnesium, and other ions in soil column effluents were in general somewhat higher than input values. After a long period of wastewater application equilibrium would of course be achieved, but this might require several years for ions such as calcium of which the soil has large reserves. Attention is directed to the degree of leaching of ions which was brought about by well water compared to sewages (Table 14).

The field studies indicate that application of sewage to soil over a long period of time did not adversely affect soil pH or result in depletion of calcium or magnesium; in fact wastewater may have value in reclaiming soils containing insufficient amounts of these cations. High input levels of ammonium in sludge similarly did not adversely effect soil properties exceptfor the presence of rather high levels of nitrate. Problems associated with sludge application to land are unlikely to arise from its ammonium content.

.I. CONCLUSIONS

A. Soil column studies.

1. Effluents from soil columns treated with wastewater containing ammonium nitrogen in concentrations of 3-5 meq/l as a result of natural levels being augmented by artificial additions had higher concentrations of calcium, magnesium, and total bases than did effluents from columns treated with wastewater containing nitrogen only in the nitrate form. These differences were on the order of 10-20% of input levels in the sewage, but were very small compared to total exchangeable bases in the soil.

   Total input of nitrogen in experiments with artificial or N-fortified sewages ranged from 938 to 1425 kg/ha (838 to 1272 lbs/A), and rates of input ranged from 22.8 to 61.9 kg N/ha/week (20.4 to 55.3 lbs/A/week) in soils where differences due to treatment were observed. Input rate was 20 kg/ha/week (17.9 lbs/A/week) in one soil where treatment differences were not observed.

2. Effluents from soil columns treated with nitrified vs. non-nitrified wastewater with no additional nitrogen were essentially identical in composition of cations. Total input was 787 kg N/ha (703 lbs/A) or 32.8 kg N/ha/week (29.3 lbs N/A/week) for two soils showing no differences in output of calcium and magnesium.

   Nitrified sewage contained less bicarbonate than did ammonium sewage.

3. Secondary sewage undergoing nitrification of contained ammonium is self buffering in that the acid produced is neutralized by reaction with bicarbonate. Thus, nitrification does not exert a dominant effect on the pH of wastewater, and the pH may increase during nitrification. In none of the column experiments was an effluent found which was not alkaline in reaction.

4. The total salt burden in soil effluents, as reflected by equivalent conductance measurements, was about the same in soils receiving nitrified and unnitrified sewages where there was no artificial elevation of input ammonium levels.

B. Field studies

1. Long term application of wastewater to a saline alkali soil near Bakersfield increased the exchangeable calcium and magnesium and decreased exchangeable sodium, thereby greatly improving the soil from the standpoint of agricultural production potential.

2. Long term applicaton of sewage sludge of high ammonium content to a sandy soil near Ontario has not resulted in significant removal of calcium and magnesium from the soil. Some increase in sodium content resulted from sludge application.

VII. REFERENCES

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