Sodium movement in undisturbed, sodic stripmine spoils with emphasis on unsaturated flow
by Mitchell Mitrey Johns

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Soils
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Abstract:
In undisturbed, sodic stripmine spoil and topsoil columns, water, salt, and exchangeable sodium movement with unsaturated flow were measured and expressed as a function of irrigation and chemical treatments. Some saturated flow studies also were carried out. Lithium was applied as a tracer to estimate exchangeable sodium movement.

Water movement through spoil columns, while maintaining a surface moisture tension of 0.08 bars, indicated slow unsaturated water flow with movement being independent of leaching treatment. Water moved faster through topsoil (0.22 cm/day average) than through spoil (0.19 cm/day). Under saturated conditions, distilled water applied to spoil columns resulted in no flow (K=0 cm/day) through the entire length of the columns, while gypsum solution applied to spoil columns resulted in flow through 50% of those columns. Either leaching treatment resulted in saturated flow through topsoil columns.

With unsaturated flow, salt and exchangeable sodium movement in spoil columns were independent of leaching treatment. In 222 days, soluble and exchangeable sodium were significantly removed from the surface 10 cm in spoil with movement passing beyond the 20 cm depth. Lithium movement compared favorably with exchangeable sodium movement and it also was independent of treatment. Topsoil showed greater movement of sodium than spoil.

Significant to highly significant correlations were found, using linear regressions, between unsaturated flow and movement of soluble Na and exchangeable Na and extractable Li. For reclamation purposes, this should be useful in predicting the amount of sodium moved under conditions of a low, unsaturated water flux.

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by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

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ABSTRACT

In undisturbed, sodic stripmine spoil and topsoil columns, water, salt, and exchangeable sodium movement with unsaturated flow were measured and expressed as a function of irrigation and chemical treatments. Some saturated flow studies also were carried out. Lithium was applied as a tracer to estimate exchangeable sodium movement.

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INTRODUCTION

The demands for Western coal will obviously increase in response to the increasing energy needs of the Nation. Almost all of this Western coal is surface-mined which results in substantial amounts of land being disturbed. In order to restore productivity to this mined land, and thus maintain a quality environment, the need for adequate reclamation is apparent.

Current surface-mining methods tend to invert the soil profile that naturally existed above the deepest mined layer. In the northern Great Plains, the spoil material coming from above the deepest mined layer is generally moderately saline and sodic (Sandoval et al. 1973). This situation is typified by the West Decker Coal Company located at Decker, Montana. Here the quality of the 60 cm of topsoil placed over the spoil material is fairly good but the spoil immediately below is often sodic and moderately saline.

This research focuses on soil water and salt movement in spoils and topsoil with saline-sodic conditions under laboratory conditions. The objective is the determination of sodium translocation patterns as a function of irrigation and chemical amendments with emphasis on unsaturated flow. A limited amount of saturated leaching was carried out also. Hopefully, the results presented here will contribute to the formulation of specific recommendations for saline-sodic spoil reclamation.

LITERATURE REVIEW

Reclamation

Sodium can render stripmine spoils extremely unstable, highly impermeable, and erodible to water (Sandoval et al. 1973). Therefore, perhaps the greatest concern with chemical reclamation is permeability. Maintaining a stable permeability while reclaiming a sodic soil generally depends upon three factors: (a) clay type, (b) adsorbed sodium, and (c) electrolyte concentration. Some generalizations can be made (Lutz and Kemper 1959). Smectite clay has the lowest permeability of all the clays especially with clays having adsorbed sodium. Clays with adsorbed sodium are less permeable to both water and electrolytes than clays having either calcium or hydrogen. The greater the electrolyte concentration, the greater the permeability. Increasing the electrolyte concentration apparently suppresses the electric double layer and either destroys the water structure, or reduces its thickness around the clay particles. Concerning soil permeability and aggregate stability, the worst condition would be to have a high proportion of smectite clays associated with a high level of exchangeable sodium (El-Swaify and Henderson 1967). Applying an irrigation water with low salt concentration would create destructive swelling pressure forces which would cause a breakdown of soil aggregates and consequent deterioration of soil structure. These high swelling pressures result in the high water retention capability of a Na-smectite soil.

Quirk and Schofield (1955) showed that the saturated permeability of a given soil decreases with increasing sodium percentage provided that the electrolyte concentration is below a critical level (threshold level). Gardner et al. (1959) measured the effect of electrolyte concentration and exchangeable sodium percentage (ESP) on diffusivity (0 to 15 bar range) in Pachapps sandy loam and Yolo loam soils. They concluded that when the ESP is above about 25, the diffusivity is reduced as much as a thousandfold as the electrolyte concentration is decreased from 300 to 3 milliequivalents per liter. Working with a sodic soil, Reeve and Tammaddoni (1965) found that leaching with an initial electrolyte concentration tended to temporarily "fix" the general level of permeability with the soil with respect to subsequent electrolyte concentrations. Their results indicate that the permeability with subsequent solutions depended upon the degree of flocculation or dispersion that occurred with the application of the initial solution.

Christenson and Ferguson (1966) found that swelling was a factor in water movement in a smectite soil, while it was not a factor in a dickite soil. Using a 0.015N calcium chloride solution eliminated swelling in the smectite soil of ESP 5.5, but only reduced swelling in the 13.6 ESP soil. In their calculations of water diffusivities, use of 0.015N calcium chloride instead of distilled water increased water diffusivity by a factor of 1.8 in all soils except for the 13.6 ESP smectite soil.

Frendel et al. (1978) showed that plugging of soil pores by dispersed clay particles is a major cause of reduced permeability in smectitic, vermiculitic, and kaolinitic soils affected by varying ESP and electrolyte concentrations. The exact levels of ESP and electrolyte concentration at which permeability is reduced varied with mineralogy, clay content, and bulk density.

To measure the effect of mixed Na-Ca solutions on the hydraulic properties of unsaturated soils, Russo and Bresler (1977) developed functional relationships over a wide range of water contents, soil solution concentrations, and Na:Ca ratios. Their results show that diffusivity (D) and hydraulic conductivity (K) are independent of electrolyte concentration in a Ca-saturated system. In mixed Na-Ca systems, K and D functions are highly dependent on the kind and concentration of the electrolyte solution in addition to their dependence on soil water content. Further, they stated that the negative effect of a combination of a high Na:Ca ratio and low electrolyte concentration on K are directly related to the degree of water saturation of the soil. Under unsaturated conditions, low soil water content values can compensate for the negative effect of high Na:Ca ratios and low electrolyte concentrations.

The basic principle of chemical reclamation of a sodic stripmine spoil is the same as for a sodic soil. It requires replacing adsorbed sodium with an acceptable divalent ion, preferably calcium. This released sodium can then be leached downward deeper in the profile. The reaction between a calcium amendment and exchangeable sodium is an equilibrium reaction, and, therefore, does not entirely go to completion. The extent to which this reaction goes to completion is determined by the interaction of several factors, among which are the differences in the replacement energies of calcium and sodium, the exchangeable sodium percentage, and the total cation concentration of the soil solution (U. S. Salinity Laboratory 1954).

Sulfuric acid, calcium chloride, and gypsum were studied for use in sodic soil reclamation by Prather et al. (1978) on two soils high in ESP and cation exchange capacity. Their laboratory results with saturated leaching showed that sulfuric acid was more effective than gypsum and it resulted in a more desirable ESP profile than calcium chloride. However, the calcium chloride treatment removed the greatest amount of sodium per unit volume of leachate.

With field plots and ponding, Reeve and Doering (1966) studied reclaiming a highly sodic soil (ESP = 75) with a high-salt-water dilution method and conventional methods. The high-salt-water dilution method was effective in maintaining high permeability. However, this method is limited since it depends heavily upon having high-salt waters with divalent cation concentrations of 30% or more of the total salt concentration. A saturated gypsum solution (0.038N) and a concentrated calcium chloride solution (0.6N) were two of the conventional methods.

The saturated gypsum solution was not effective in reclaiming this highly sodic soil, even by leaching for a period of 228 days. Reclamation failure was attributed to the adverse physical condition of the highly sodic soil which developed because of the application of a low electrolyte water. The concentrated calcium chloride solution was effective. Comparative reclamation times to a soil depth of 90 cm were 3 days and 7 years for calcium chloride and gypsum, respectively.

From their laboratory experiments, Doering and Willis (1975) concluded that high electrolyte concentrations (greater than 0.5N Ca solutions) are desirable in order to establish and maintain an acceptable saturated hydraulic conductivity with a high ESP stripmine spoil. Therefore, the use of concentrated solutions for reclamation saves time and water. But as the ESP is lowered, use of concentrated solutions becomes increasingly less efficient and uneconomical.

Water Movement

It is generally believed that a significant amount of water movement can occur in soil macropores. Consequently, it has been reported that when much of the water from rainfall or irrigation flows in macropores, the usual occurrence is that of only a partial displacement of soil water (Elrick and French 1966, Ritchie et al. 1972, McMahon and Thomas 1974, Quisenberry and Phillips 1976). In their excellent review, Thomas and Phillips (1979) state that one of the consequences of water flow in macropores is that some of the surface salts will be moved to a much greater depth by a rain or irrigation than predicted by piston displacement. On the other hand, much of the salt will be by-passed and remain near the soil surface. Further, they note that if rain or irrigation water added to the soil moves primarily through macropores, it will interact with solutes to only a limited extent since much of the smaller pores will be by-passed.

Leaching soils during unsaturated conditions brings about the following changes: (1) decreased the relative volume of water passing through larger pore sequences (they are partially empty), (2) increases the mixing between soil pores caused by molecular diffusion associated with the generally smaller flow velocity values, and (3) alters the tortuosity and extent of nearly stagnant pores (Nielsen et al. 1972).

The effectiveness of leaching is usually judged on the basis of redistribution of salt within the profile resulting from a known quantity of surface-applied water. According to Biggar and Nielsen (1967), this efficiency of leaching may be significantly increased by controlling the degree of water saturation and the rate of water movement through the soil profile. In their review, it was shown that for soil water contents less than saturation but greater than one-fifth bar, both laboratory and field data show leaching efficiencies to be greater than for saturated conditions.

Nielsen et al. (1966) attributed better leaching efficiencies under unsaturated flow conditions to greater mixing of the applied treatment solution with the soil solution. This additional mixing is caused principally by ionic diffusion. The contribution of diffusion to mixing depends in part upon the pore-velocity distribution which in turn depends upon the water filled soil-pore structure. In his introduction, Kirda et al. (1974) noted that the apparent diffusion coefficient depends not only on the average pore water velocity but also on the microscopic characteristics of the medium such as pore size, pore sequence channel length, random arrangement of channels within the porous medium, and the molecular diffusion coefficient. It was suggested that for slowly permeable soils, especially those that are sodic, one means of increasing the penetration of water is to allow the soil surface to dry and check between periods of wetting.

Kirda et al. (1974) indicated that a given quantity of water applied by continuous ponding yields relatively large water contents confined initially to the upper portion of the soil profile and thereby displaces salts relatively short distances. By contrast, frequent small quantities of intermittently applied water produced deeper penetration of salt and water on an equal time basis to ponding. Water application methods giving rise to small water contents coupled with small pore water velocities provide the most efficient mode of leaching. Warrick et al. (1971) concluded that the advance of the wetting front is slower and that solute displacement was greater at lower initial soil moisture contents. The cumulative infiltration is greater at lower soil moisture contents and this increases solute displacement.

Although the ultimate goal of water movement studies is to be able to determine water behavior in the soil-plant-atmosphere continuum in the field, the majority of these experiments have been restricted to laboratory models and conditions. In applying the Darcy flow equation or its derivations to unsaturated soil water movement, the use of a homogeneous, porous medium is quite frequent (Bruce and Klute 1956, Gardner and Miklich 1962, Flocker et al. 1968, Watson 1966). This need for homogeneity arises from the fact that quantitative measurements require that the pore size distribution be everywhere geometrically similar. In the natural state, most soils have unequal porosities and are not geometrically similar.

Arnold (1976) measured solute and unsaturated water movement on stripmine spoils in the field. He applied a mathematical model developed by Sisson (1972) for measuring unsaturated water flow. He found that the quantity of soil water movement in native range was approximately 1.5 times greater than in spoils. The lower amount of soil water movement was attributed to bulk density, which was 54% higher than native range, and to higher contents of silt and clay. Due to the short time span of Arnold's study (1 year) no definite trends in solute movement were found.

When a solution moves in the liquid phase in soils under unsaturated conditions, the effect of salt sieving may be of some importance since this solution must flow through thin films which connect the wedge-shaped volumes of solution (Kemper 1960). However, as pointed out by Nielsen et al. (1972), when soil-water pressure differences are small (less than 0.1 bar), the resultant convective flow may be of the same order of magnitude as diffusive flow, and under such conditions salt sieving in soils will be practically negligible. Any appreciable salt sieving may require soil-water pressure differences as large as 10 bars, which probably occurs infrequently in natural systems.

The rate of water movement through undisturbed cores can be strikingly different than the rate it moves in the field. In a swelling clay soil, Ritchie et al. (1972) compared hydraulic conductivities between field basins and undisturbed cores. Their results showed that the saturated conductivity of the undisturbed cores were much less than that of the field. These rate differences were due to the core walls which cut off some large continuous pores associated with the soil structure that exists in the field.

In sodic reclamation, the process of ion exchange is just as important as the leaching process. Rible and Davis (1955) adapted chromatographic theory of DeVault to ion exchange processes in soil columns. It involved the use of a salt-free, homogeneous, homoionic Yolo fine sandy loam soil. Of considerable interest is the exchange of sodium with calcium. Upon leaching a sodium saturated column with a known amount of calcium in solution, theory predicted a sharp boundary where the upper zone should be saturated with calcium while the lower zone remains sodium saturated. It is evident that 100% exchange was assumed. Fair agreement with theory was obtained through experimentation. However, although they found calcium in dilute salt solutions readily replaced most of the sodium in the surface layer, calcium did not adequately penetrate the subsoil.

Tracer, Lithium for Sodium

The tracing of sodium movement with lithium can only be justified through the evidence which shows that both cations react similarly, chemically and physically, in soils. In this regard, the tracer should not change the properties of the leaching fluid or the transmission characteristics of the medium in a manner different from that which it is tracing (Biggar and Nielsen 1962).

The similarity of lithium and sodium with respect to replacement and displacement was noted by Bear (1964). The replaceability (replacing power) from an exchange material grows in the order Li<Na<K<Mg<Ca when these ions function separately as complementary ions. The order of difficulty of displacement is approximately Ca>Mg>Na>Li but the relative position in such a series varies with the concentration in the solution and the nature of the exchange active material.

Shainberg and Kemper (1966a) stated the order of difficulty of displacement as K>Na>Li for these monovalent ions. They consequently showed that the observed relative mobilities (in Stern layer position and relative to their mobilities in bulk solution) of these monovalent ions is the highest for adsorbed lithium, intermediate for adsorbed sodium, and lowest for adsorbed potassium. As would be expected from their relative mobilities in the Stern layer, Shainberg and Kemper (1966b) showed that the fraction of ions in the diffuse layer (completely hydrated) for Li, Na, and K are 0.84, 0.64, and 0.51, respectively.

Husted and Low (1954) studied ion diffusion in bentonite. They indicated that the diffusion rate of potassium depended on the rate of the counterdiffusing ion, and that the diffusion rate of the counterdiffusing ions was in the order NH_4>Na>Li. This is the order of their mobilities in solution. In another experiment, the amount of ions transferred from a cation-bentonite film to a H-bentonite film were in the order Li>Na>K. But the amount of these ions reaching the terminal end of the hydrogen film were in the reverse order. The obvious conclusion is that within the H-bentonite films the diffusion rate of the ions, and hence the diffusion coefficients, was in the order K>Na>Li. This is the order observed for diffusion in bentonite and for diffusion (but of a greater magnitude than clays) in solution.

In terms of swelling, lithium and sodium show similarities. Baver et al. (1972) cited that the swelling of Putman clay (beidellite) varies with nature of the adsorbed cations as follows: Li>Na>Ca. On the other hand, the order of swelling for bentonite (smectite) is Na>Li>K>Ca. In terms of swelling (cm^3 per gram of colloid), Li and Na are 10.77 and 11.08, respectively, for bentonite. In Putman clay, Li and Na are 4.97 and 4.02, respectively.

As pointed out by Norrish (1954), in the initial stages of interlayer swelling for Li- and Na-smectite, their stepwise hydration forms interlayer spacings of 22.5 and 19.0 Angstroms for Li and Na, respectively. Upon osmotic swelling, the interlayer spacings for both Li- and Na-smectite may reach 130 Angstroms (Baver et al. 1972).

A brief summary seems appropriate. In comparison to sodium, lithium has a larger diffuse layer and somewhat less replacing power, but due to a greater hydration, it has, consequently, a lower molecular diffusion rate. Generally speaking, the degree of swelling is quite similar between the two cations.

MATERIALS AND METHODS

Field Site Description

The sampling area is located at the Decker Coal Mine near Decker, Montana (Figure 1). Decker, Montana is located 12 miles (19 km) north of Sheridan, Wyoming at an elevation of 3,530 feet (1076 m). The Decker Coal Mine is adjacent to the Tongue River Reservoir. Montana State Highway 314 separates the West Decker Mine from the East Decker Mine. The Decker area is characterized by rolling dissected hills and broad, nearly flat valley floors. Sparse vegetation cover and impeded soil drainage create severe erosion problems (Sindelar et al. 1973). Saline-sodic soils limit forage productivity and restrict vegetation to tolerant adapted species. Big sagebrush and western wheatgrass dominate the rangeland vegetation. The overburden derives from the Paleocene, Fort Union, Tongue River formation and it is composed of sandstone, stratified sands, siltstone, and clay and silt shales. Also, the overburden generally contains saline and/or sodic materials.

At the West Decker Mine, undisturbed topsoil and spoil cores were collected for laboratory study from sites that had been recontoured. In September 1977, topsoil and spoil cores were collected in sites E and A, respectively (Figure 1).

Sampling

Present reclamation practice involves placing approximately 60 cm of topsoil, which had been stockpiled from the initial stripmining

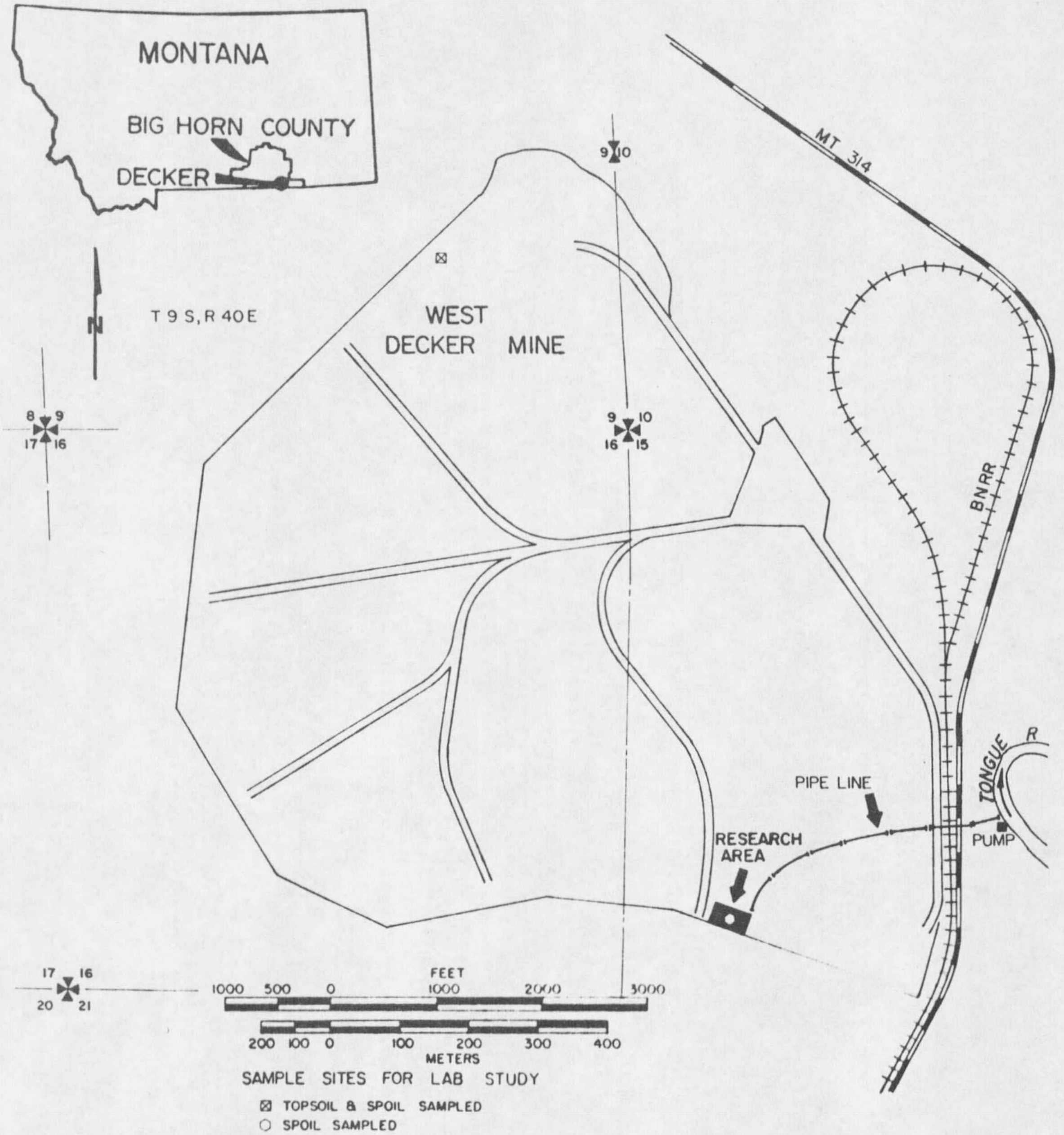


Figure 1. View of the West Decker Mine showing sites E (upper left) and A (lower right) where samples were collected.

process, atop spoil material. It was the intention of the author to gather topsoil and spoil cores from one site. However, the sampler used for collecting undistrubed cores was unable to penetrate into the spoil material at site E (Figure 1). At site A, which had not yet been topsoiled, spoil columns were collected successfully after some unsuccessful attempts.

Topsoil and spoil core columns were gathered by use of a specially designed King tube attached to the Giddings hydraulic soil sampler. The cutting edge of this King tube was bevelled to displace soil to the outside of the tube to reduce compaction when pushed into the soil. Heat shrink tubing 55 cm long (purchased from the Radar Electric Company, Seattle, Washington) was inserted into this King tube. Upon use, the soil sample slipped into this plastic tubing within the King tube. The tubing plus soil core was removed from the King tube and the tubing was shrunk by applying heat to the outside surface of the column. The soil column then fit snugly within the tubing and was held intact. The end result was a relatively undisturbed topsoil or spoil column having a diameter of 4 cm. These columns were collected in 55 cm lengths down to a depth ranging from 110 to 165 cm. All columns were sealed to prevent moisture loss.

Past experience indicated that stripmine spoils had extreme soil chemical variability within very small distances. With this in mind, samples were collected in 1 m^2 stations located within site areas.

Cores were taken as close as possible to each other within these stations. It was hoped that these small distances would reduce as much as possible any variation between columns. Topsoil columns were collected from one station (station E) in site E (Figure 1). Spoil columns were collected from two stations (stations A_1 and A_2) in site A.

Experimental Design

The main emphasis of this study dealt with unsaturated leaching. However, a limited experiment with saturated leaching was included. The design is shown in Table 1. Since spoil cores were collected from two different stations and from two different depths within each station, a randomized complete-block design was used (Steel and Torrie 1960). The leaching treatments studied were distilled water, a saturated gypsum solution (0.03N), a calcium chloride solution (0.06N), and a combination solution containing gypsum (0.026N), ammonium sulfate (0.0015N), and calcium chloride (0.003N). In the unsaturated leaching experiments, all four treatments were tested using four replications per treatment for spoils and no replication for topsoil. Topsoil and spoil columns subjected to saturated flow were leached with only gypsum solution and distilled water using four replications per treatment for spoil and no replication for topsoil.

Table 1. Experimental design.

Station	Column depth	Unsaturated runs[†]				Saturated[†]	
		H_2O	Gyp.	$CaCl_2$	Comb.	H_2O	Gyp.
A_1	0 - 55 cm	S	S	S	S	S	S
(spoil)	55 - 110 cm	S	S	S	S	S	S
A_2	0 - 55 cm	S	S	S	S	S	S
(spoil)	55 - 110 cm	S	S	S	S	S	S
E_1	0 - 55 cm	T	T	T	T	T	T
(topsoil)							

S = Spoil column T = Topsoil column

[†] Treatments: H_2O: Distilled water.

Gyp.: Saturated gypsum solution, 0.03N.

$CaCl_2$: Calcium chloride solution, 0.06N.

Comb.: Combination solution, total conc. = 0.03N
(Gyp. - $(NH_4)_2SO_4$ - $CaCl_2$)
0.026N- 0.0015N - 0.003N

Unsaturated and Saturated Leaching

In all columns lithium was used as a tracer to approximate sodium movement. Eight meq of Li was applied to the top of each column through a 5 ml application of a 1.6 N LiCl solution. It was allowed to soak in for 24 hours.

For use in unsaturated leaching, tensiometers were constructed according to recommendations by Richards (1949). Figure 2 illustrates the column-tensiometer make-up. Mercury was used to measure tension. From the Soil Moisture Equipment Corporation, Santa Barbara, California, ceramic porous cups (2.86 cm L, 0.635 cm O.D.) were purchased. Saran tubing (0.38 cm O.D.) and glass capillary tubing (0.5 mm O.D.) were used with these cups to assemble tensiometers. Snug fitting plastic tubing of various sizes were used to join the ceramic cup, Saran tubing, and glass capillary tubing together. Boiled distilled water was used to fill the tensiometers and checks were made for leaks and trapped air bubbles. In all, 20 tensiometers were assembled.

Planting the tensiometers into the column required drilling a small hole, a little less than halfway through the column, and 2 cm down from the surface of the column material (Figure 2). To make a snug fit, the diameter of the hole was a little less than the diameter of the ceramic cup. Upon installation, the cup extended 2 cm into the column.

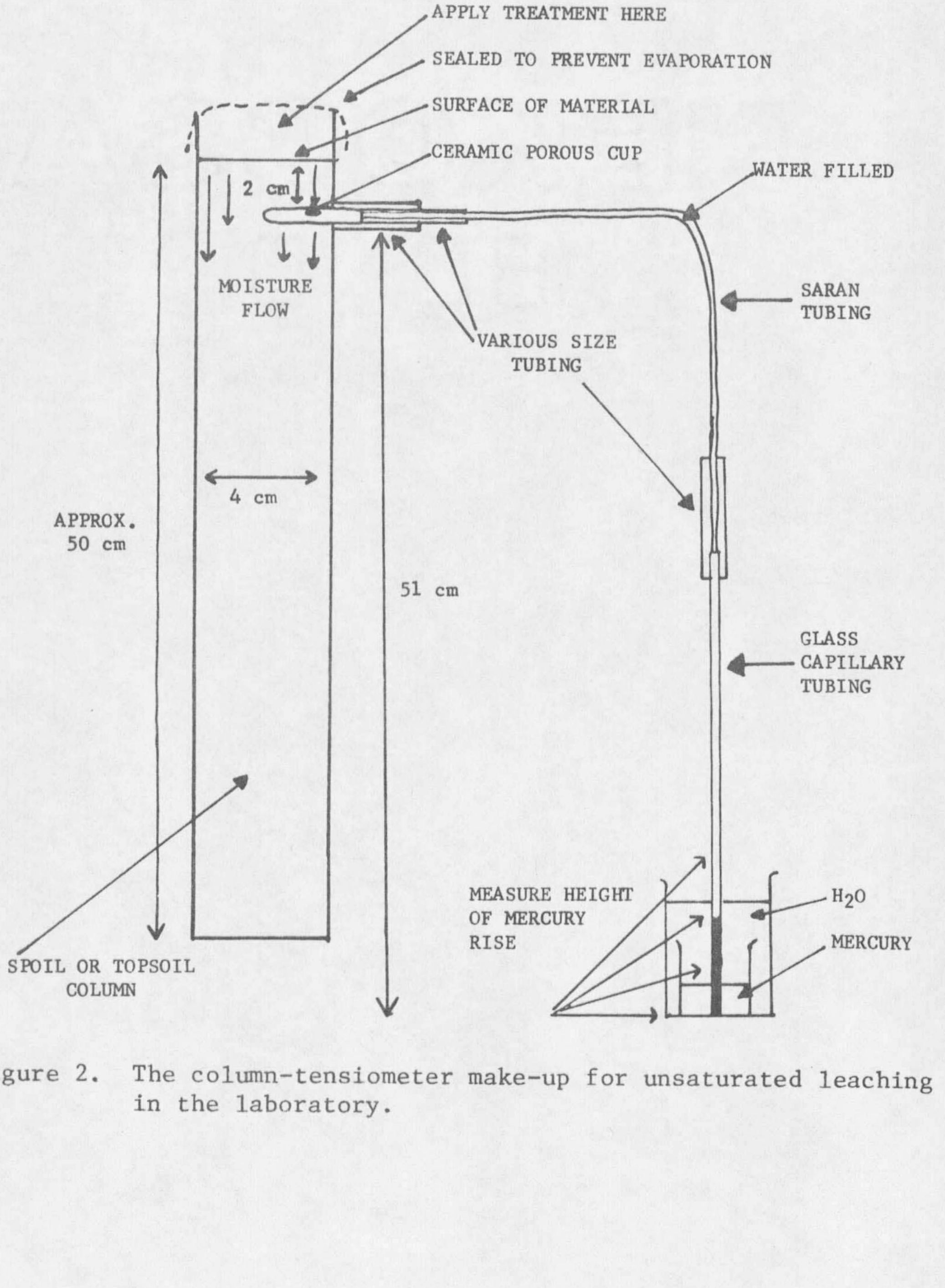


Figure 2. The column-tensiometer make-up for unsaturated leaching in the laboratory.

To collect leachate from unsaturated leaching, a wad (approximately 50 circles) of Whatman 540, hardened-ashless, 3.7-cm diameter filter paper was employed as an absorbent. A fairly flat surface was prepared at the column bottom by removing loose material. The filter paper was then pushed firmly into position and held there with firm backing. Evaporation was prevented through sealing. The filter paper was removed periodically and a new wad was inserted. Immediately after removing, any moisture absorbed was determined gravimetrically. A 48-hour soaking with 20 ml of distilled water was then applied to the wad to remove any salts contained in the leachate.

Unsaturated flow was maintained through applications of, on the average, 1 ml treatments to the tops of the columns. Surface evaporation was prevented through sealing. Soil moisture tension (matric suction) was measured by tensiometers (Figure 2). The gravitational potential of the tensiometer's water column was 51 cm (0.05 bars) and this was accounted for. Treatment was added whenever mercury height reached 2 cm. The mercury height of 2 cm is equivalent to 0.03 bars. Therefore, actual soil moisture tension was the sum of the mercury height plus the gravitational potential of the water column, which equaled 0.08 bars. The elevation of the laboratory is approximately 5,000 feet which gives approximately 750 mm Hg rise for 1 atm. This was accounted for. One bar = 750 mm Hg. The tensiometers allowed the time of application for each column to depend solely upon that particular column's infiltration rate and permeability. Throughout the unsaturated leaching experiments, the temperature of the laboratory remained nearly constant (21.5 ± 0.5 C). Unsaturated leaching was carried out in the manner described for a period of 133 days. The columns were then allowed to drain for a subsequent period of 89 days.

In saturated leaching, a constant head of 8.5 cm was maintained on all columns through the use of specially designed bubblers attached to inverted 1 liter Erlenmeyer flasks. The leachate was collected periodically for analysis. Evaporation was minimized by sealing the top and bottom of each column. Saturated flow was continued for a period of 146 days. Upon reaching a steady-state flow, the saturated hydraulic conductivity (K) was determined through applying the Darcy equation for saturated flow. K (cm/day) was calculated according to the equation

$$K = QL/AT\ \Delta H \tag{3.1}$$

where Q (cm^3) is the leachate volume, A (cm^2) is the cross-sectional area of the column, T (days) is the time required to collect Q, L (cm) is the length of the column, and ΔH (cm) is the hydraulic potential.

Analysis of Leachate

With unsaturated leaching, the salts contained in the leachate were removed from the filter paper through soaking in 20 ml of distilled water as described previously. Since the amount of leachate collected was known, a dilution factor was calculated for the dilution of the leachate with 20 ml of distilled water. Analyses for both saturated and unsaturated leachate were electrical conductivity (Method 4b, U. S. Salinity Laboratory 1954) and soluble lithium, sodium, calcium, and magnesium through atomic adsorption spectrophotometry (Perkin Elmer Model 290). In determining electrical conductivity on the unsaturated leachate, a blank was required to account for the absorbent's (filter paper wad) own level of electrical conductivity. No blank was required for soluble Li, Na, Ca, and Mg since the absorbent did not contain measurable levels. The sodium adsorption ratio (SAR) was calculated according to the equation

$$\mathrm{SAR} = \mathrm{Na}/((\mathrm{Ca} + \mathrm{Mg})/2)^{\frac{1}{2}} \qquad (3.2)$$

with Na, Ca, and Mg in meq/l.

Analysis of Columns

Upon completion of the leaching experiments, all columns were sectioned into successive 5 cm sections. From the columns used for unsaturated leaching, percent moisture was determined for each 5 cm section by taking a subsample from each section. Percent moisture was determined gravimetrically upon completion of oven drying (120 C for 22 hours). Similarly, initial moisture content was determined on five columns not used in the leaching experiments. Percent moisture was not determined on the columns used for saturated leaching. For characterization, soil color, dry consistence, mottling, % coarse fragments, and acid effervescence were determined on many 5 cm samples.

Upon air-drying, bulk density (B.D.) was determined on all sectioned columns used for saturated leaching and on one-half of the columns used for unsaturated leaching. An average B.D. was given to the other half of these unsaturated columns. Clods were coated with Saran resin (Brasher et al. 1966), otherwise the method is identical to Blake (1965a). Three bulk density determinations were made per column; a top (5-10 cm), middle (25-30 cm), and bottom (40-45 cm). The volumetric water percentage (P_v) was found through

$$P_v(\%) = (\%\ \text{moisture by wt.})(\text{B.D.}) \qquad (3.3)$$

for all 5 cm sections from all unsaturated columns. Flux (cm) was calculated as the quantity of soil water that had passed through each 5 cm increment of the unsaturated columns during the total leaching time.

Particle density (P.D.) was determined (Blake 1965b) on the sectioned columns used for saturated leaching. The same 5 cm sections used to determine B.D. were used. An average P.D. value was assigned to all unsaturated columns. Total porosity was calculated as

$$\text{Total Porosity}\ (\%) = 100(1 - (\text{B.D.}/\text{P.D.})) \qquad (3.4)$$

for all sectioned columns.

Particle-size analysis was made on the columns used for saturated leaching using the same 5 cm sections used to determine B.D., P.D., and total porosity. The samples were dispersed with $(NaPO_3)_6$ following the procedure of Day (1965), Method 43-5, except that ultrasound for 2 minutes was used instead of an electric mixer. Particle size determinations were made using the pipette method (Day 1965, Method 43-4) except that the dry sieving was omitted.

Clay mineralogy was determined on selected subsamples from columns used for saturated leaching. X-ray diffraction involved using the treatments and interpretations by Whittig (1965). A semi-quantitative method was employed for estimating percentage content for each specific clay mineral. From X-ray diffraction, it involved taking the peak areas of each clay mineral, dividing by a designated factor, and then calculating its percentage to total clay. Peak areas were divided by 10, 2.5, 1, and 3 for smectite, kaolinite, illite, and chlorite, respectively. Factors were derived experimentally and developed for use by the Montana Agricultural Experiment Station, Bozeman, Montana.

Subsamples from 5 cm sections from sectioned columns were combined to form 10 cm depth samples. The cation exchange capacity (Method 19, U. S. Salinity Laboratory 1954), CEC, was then determined per 10 cm depth. Saturated pastes were made and extracted (Method 2, U. S. Salinity Laboratory 1954) per 10 cm. On the extract, electrical conductivity and soluble Na, Ca, and Mg were determined. The SAR was calculated. Ammonium acetate extractable Li and Na (Method 18, U. S. Salinity Laboratory 1954) were determined on all 5 cm sections. Exchangeable Na per 10 cm depth was determined by difference (Method 18) of extractable (average of two consecutive 5 cm sections) and soluble. The exchangeable sodium percentage (ESP) was calculated by

$$\text{ESP} = (\text{exch. Na/CEC})100 \quad \text{with exch. Na, CEC in meq/100 g} \qquad (3.5)$$

For determining initial base levels, spare columns not used in the leaching experiments underwent the same chemical analyses described above.

Statistical Models

A one-way analysis of variance, a two-factor analysis of variance, and a linear regression analysis were used in this thesis. The actual statistical analyses were performed using computer programs contained in MSUSTAT which is a general purpose interactive statistical analysis package. MSUSTAT was developed for MSU campus use by Dr. Richard E. Lund, MSU Statistical Center, Department of Mathematics. All models presented can be found in Snedecor and Cochran, Statistical Methods.

The model that forms the basis for analysis of variance is:

$$X_{ij} = U + \alpha_i + E_{ij} \ ; \ i = 1 \ldots a, \ j = 1 \ldots n, \ E_{ij} = N(0,\sigma) \qquad (3.6)$$

where X_{ij} = single observation, U = population mean, α_i = treatment effect, E_{ij} = experimental error, and σ = standard deviation. The model implies three assumptions:

1. populations are normally distributed
2. population variances are equal
3. observations are independent.

The model that describes the two-factor (A x B) analysis of variance used is:

$$X_{ijk} = U + \alpha_i + \beta_j + (\alpha\beta)_{ij} + E_{ijk} \; ; \qquad (3.7)$$

$$i = 1 \ldots a,\ j = 1 \ldots b,\ K = 1 \ldots n$$

where X_{ijk} = single observation, U = population mean, α_i and β_j represent main effects for A and B, and $(\alpha\beta)_{ij}$ = two-factor interaction effects, and E_{ijk} = experimental error. This model implies the same assumptions as the one-way analysis of variance applied to two factors and their interaction.

The model for linear regression is specified concisely by the equation

$$Y = \alpha + Bx + E \qquad (3.8)$$

when E is a random variable drawn from N $(0, \sigma y \cdot x)$; it is independent of x and normally distributed. In this model, Y = sum of a random part, E, and a part fixed by x, α = the population mean that corresponds to $x = 0$, and B = the slope of the regression line.

Three assumptions are made about the relation of Y and X in a standard linear regression:

1. For each selected X there is a normal distribution of Y from which the sample value of Y is drawn at random. If desired, more than one Y may be drawn from each distribution.
2. The population of values of Y corresponding to a selected x has a mean U that lies on the straight line $U = a + B(X - \bar{X}) = \alpha + Bx$.
3. In each population the standard deviation of Y about its mean $\alpha + Bx$ has the same value, assumed constant as x varies.

RESULTS AND DISCUSSION

Spoil and Topsoil Characterization

Average values for bulk density, total porosity, and particle size for spoil and topsoil after saturated or unsaturated flow are shown in Table 2. Bulk density after saturated flow on spoil columns was 1.8 g/cc. This is higher than the value of 1.7 g/cc found after unsaturated flow. This higher bulk density found with saturated flow resulted in a lower total porosity (30.7%) over that of unsaturated flow (34.2%). For both saturated and unsaturated flow, bulk density for the topsoil was 1.7 g/cc and total porosity was similar (34.3-35.3%). The average texture for spoil bordered on sandy loam and loam and topsoil averaged on loam.

Results of chemical analyses on unused, unleached spoil and topsoil columns are listed in Table 3. Averages were calculated from totaling all depth measurements taken for all columns (Appendix Tables 18 and 19). Measurements indicated an SAR of 21.0 in spoil and 8.7 in topsoil. Thus, the spoil is sodic (ESP > 15 or SAR > 13) and the topsoil is variable. The standard deviation for ESP indicated considerable variation for among depths and between spoil columns. Electrical conductivity averaged 3.3 mmhos/cm in spoil and 3.3 mmhos/cm in topsoil. This indicated a less than saline (<4 mmhos/cm) condition for both materials, however, some spoil may be saline based on the standard deviation for EC. Initial levels of lithium (Table 3) were only traces making lithium suitable for use as a tracer to approximate exchangeable sodium move-

Table 2. Some physical properties of leached columns (all treatments together).

Measurement	Flow applied	Spoil Average	Spoil Std. Dev.	Topsoil Average	Topsoil Std. Dev.
Bulk Density (g/cc)	Saturated	1.81	0.10	1.72	0.04
	Unsaturated	1.72	0.07	1.72	0.03
Total Porosity (%)	Saturated	30.7	3.8	34.3	1.8
	Unsaturated	34.2	2.7	35.3	1.7
% Sand	n/a	51.9	11.6	41.0	5.5
% Silt	n/a	29.4	10.2	38.4	4.0
% Clay	n/a	18.8	2.2	20.6	1.9
Texture (Avg. %)		Sandy loam-loam		Loam	

Table 3. Some chemical properties of the spoil and topsoil columns used in leaching experiments. (From analyses of unleached columns, Appendix Tables 18 and 19).

	Spoil		Topsoil	
Measurement	Average	Std. Dev.	Average	Std. Dev.
Electrical Conductivity of Saturation Extract (mmhos/cm)	3.3	1.7	3.3	0.5
pH of Saturation Extract	8.3	0.3	7.8	0.1
Soluble Sodium (meq/l)	34.0	14.1	27.0	5.9
Soluble Calcium (meq/l)	4.1	4.7	9.5	1.8
Soluble Magnesium (meq/l)	4.5	4.7	9.6	2.2
SAR	21.0	5.3	8.7	1.8
CEC (meq/100 g)	15.3	3.8	18.3	2.6
ESP (%)	22.4	11.2	18.0	5.1
Dominant Anions (meq/l)†				
SO_4	24.8	18.0	18.5	5.4
HCO_3	3.7	0.7	4.3	0.6
CO_3	0.3	0.1	0.4	0.2
Cl	0.1	0.05	0.1	0.01
Extractable Lithium	Trace	--	Trace	--

† Anion analysis obtained from Reclamation Research Unit, Montana Agricultural Experiment Station, Montana State University, Bozeman, Montana and are not the same samples as the cations.

ment. As a general rule, soils with saturation extracts that have a calcium concentration of more than 20 meq/l should be checked for the presence of gypsum (U. S. Salinity Laboratory 1954). Therefore, the soluble calcium concentrations of 4.1 meq/l in spoil and 9.5 meq/l in topsoil (Table 3) indicated that the concentration of gypsum is low in either the topsoil or the spoil material. The high levels of soluble sodium and sulfate in spoil, 34.0 meq/l Na and 24.8 meq/l SO_4, suggested that much (over one-half) of the soluble salt present is in the form Na_2SO_4. Similarly, the topsoil is dominated by SO_4, but also contained appreciable amounts of HCO_3 (Table 3). Both spoil and topsoil also contained small amounts of CO_3 and Cl.

Additional information was collected on spoil and topsoil columns used in the flow studies (Table 4). The presence of alkaline-earth carbonates in spoil and topsoil was shown by an acid effervescence test which was positive. Soil color (air-dried) was generally similar throughout spoil (10 YR 6/1 to 10 YR 7/2). Topsoil was either 10 YR 5/3 or 10 YR 6/4. Dry consistence for spoil ranged from slightly hard to very hard which would indicate compacted conditions when dry. Topsoil ranged from slightly hard to hard. Coarse fragments were 1-2% for spoil and topsoil. Numerous sizes of sandstones, siltstones, shales, and coal ranging from very small to 4 cm in diameter were found in spoil. Few, fine, and faint mottling found in spoil suggested that there is a

Table 4. Characterization information on spoil and topsoil columns. (USDA-SCS abbreviations).

Column	Soil color	Dry consistence	Mottling Abundance	Mottling Size	Mottling Contrast	% Coarse fragments	Acid (10% HCl) effervescence
A4-1,S[†]	10YR6/1	vh	c	1	f	2	es
A1-1,S	10YR6/1	h	f	1	f	2	es
A8-2,S	10YR6/1	vh	f	1	f	2	es
A6-2,S	10YR6/1	h	f	1	f	1	es
2A4-1,S	10YR6/2	h	f	1	f	1	es
2A7-1,S	10YR7/1	h	f	1	f	1	es
2A6-2,S	10YR6/2	h	f	1	f	1	es
2A3-2,S	10YR6/1	vh	f	1	f	1	es
I1-1,T[†]	10YR5/3	h	f	1	f	2	es
I2-1,T	10YR5/3	h	f	1	f	2	es
A9-1,S	10YR7/1	h	f	1	f	-	e
A6-1,S	10YR6/1	h	f	1	f	-	es
A7-1,S	10YR6/2	h	f	2	f	-	es
A5-1,S	10YR6/2	sh	f	1	f	-	e
A3-2,S	10YR6/2	h	f	1	f	-	e
A4-2,S	10YR7/2	sh	f	1	f	-	es
A5-2,S	10YR7/2	sh	f	1	f	-	e
A7-2,S	10YR7/2	sh	f	1	f	-	e
I7-1,T	10YR6/4	sh	f	1	f	-	es
I5-1,T	10YR6/4	h	f	1	f	-	e

[†] S = Spoil column
T = Topsoil column.

problem with aeration and/or drainage. However, this may be a result of the changed environment following mining, rather than poor aeration and/or drainage.

Measurements taken on selected samples from spoil and topsoil columns used in saturated flow are shown in Table 5. These samples were picked for study because of the variation shown between the measurements and also for the column's ability or inability to conduct saturated flow. The samples were then analyzed for clay mineralogy (Table 6). In Table 6, the sixth sample, A2 0 - 30 cm, was not included in Table 5 but it was analyzed because of its very high saturation (paste) percentage (109%). Clay mineralogy analysis indicated that there is substantial amounts of kaolinite and smectite as well as notable amounts of illite in the spoil material. The presence of sodic condition in spoils containing smectite indicated that there is a potential for swelling (El-Swaify and Henderson 1967).

Water Movement

Unsaturated Flow Using Undisturbed Columns

All leaching treatments (Figure 3) showed similar moisture distributions with the exception of distilled water which showed a higher moisture retention at the surface. This may have been due to swelling which resulted from leaching with distilled water. However, moisture content was independent of treatment (Table 7) based on the lack of

Table 5. Characterization data for various samples.

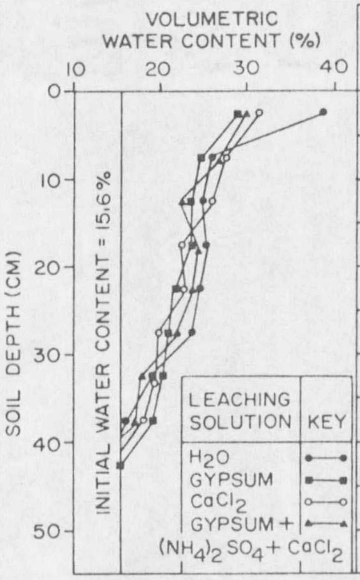
Sample identification	B.D. (g/cc)	Total porosity (%)	% clay	ESP	Permeable to saturated flow
T[†], Composite I1-1 & I2-1	1.7	34.3	20.6	3.8	yes
S[†],A8-2, 0-40	1.7	35.2	18.4	20.9	no
S,A8-2, 40-45	2.1	21.6	23.2	26.7	no
S,2A7-1, 25-50	1.8	31.2	17.6	47.6	yes
S,A6-2, 25-40	1.8	30.6	20.8	23.6	yes

[†]T = Topsoil
S = Spoil

Table 6. Clay mineralogy from X-ray diffraction (approximate values in %).

Sample identification	Clay mineral			
	Smectite	Kaolinite	Illite	Chlorite
T[†], Composite I1-1 & I2-1	41	31	23	5
S[†],A8-2, 0-40	42	44	14	--
S,A8-2, 40-45	7	71	22	--
S,2A7-1, 25-50	32	56	12	--
S,A6-2, 25-40	24	60	17	--
S,A2, 0-30	56	34	10	--

[†]T = Topsoil
S = Spoil



FLUX ↓ (CM)

H_2O	GYP-SUM	$CaCl_2$	GYPSUM + $(NH_4)_2SO_4$ + $CaCl_2$
3.2	4.3	3.6	3.9
2.6	3.4	2.8	3.1
2.0	2.7	2.1	2.3
1.4	2.0	1.5	1.6
0.9	1.5	0.9	1.0
0.4	1.0	0.6	0.5
0.2	0.5	0.3	0.2
0.02	0.2	0.2	0.02
0	0	0	0

Figure 3. Volumetric water content and unsaturated flux (for 222 days) by treatment means for spoil columns.

Table 7. Treatment and depth means for volumetric moisture % and its analysis of variance with multiple comparison.

	Leaching treatments				
Depths (cm)	H_2O	Gypsum	$CaCl_2$	Gyp+$(NH_4)_2SO_4$+$CaCl_2$	Depth means*
0- 5	38.6	29.1	31.5	29.6	32.2 a
5-10	26.1	26.1	26.4	26.2	26.2 b
10-15	25.2	23.8	25.3	25.2	24.9 bc
15-20	25.5	23.9	23.9	24.2	24.4 bcd
20-25	24.9	22.1	22.5	23.0	23.1 cd
25-30	23.8	21.4	20.5	22.1	22.0 d
30-35	19.3	20.5	19.5	18.5	19.4 e
35-40	16.6	19.3	18.1	17.3	17.8 e
40-45	14.5	15.8	14.6	13.6	14.6 f
Treatment means**	23.8 a	22.4 a	22.5 a	22.2 a	

*Any two means followed by the same letter are not significantly different (Newman-Keuls test, .05).

**Any two means followed by the same letter are not significantly different (analysis of variance, .05).

Analysis of Variance

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Treatment	3	59.9	20.0	1.9	no
Depth	8	3374.0	421.7	40.1	yes
Interaction	24	25.9	10.8	1.0	no
Error	108	1136.0	10.5		

Multiple comparison for depth means using Newman-Keuls Test Q values

Depth	Depth means								
means	32.2	26.2	24.9	24.4	23.1	22.0	19.4	17.8	14.6
32.2	--	7.42*	9.02*	9.67*	11.17*	12.63*	15.75*	17.77*	21.69*
26.2		--	1.60	2.26	3.75*	5.22*	8.33*	10.35*	14.27*
24.9			--	0.65	2.14	3.62	6.73*	8.75*	12.67*
24.4				--	1.50	2.96	6.07*	8.09*	12.02*
23.1					--	1.46	4.58*	6.60*	10.52*
22.0						--	3.11*	5.13*	9.06*
19.4							--	2.02	5.94*
17.8								--	3.92*
14.6									--

*Means significantly different (.05).

significant differences between treatment means and for treatment interaction with depth. The column moisture content decreased significantly with depth (Table 7) indicating unsaturated flow conditions prevailed throughout the column and that flux would decrease with depth. Flux (Figure 3) was calculated as the quantity of soil water that had passed through each 5 cm increment of the unsaturated columns during the total flux time (222 days).

The distance to wetting front was estimated for the unsaturated columns by relating moisture levels found after leaching (Appendix Table 20) to the initial volumetric moisture level (P_v = 15.6%) which was averaged from unused, unleached spoil columns (Appendix Table 21). Similarly, initial P_v = 13.0% for topsoil as averaged from unused, unleached topsoil (Appendix Table 21).

For all spoil columns, the wetting front depths are given in Table 8. Treatment means for wetting front were 39.3, 44.7, 43.0, and 40.5 cm for distilled water, gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+ $CaCl_2$, respectively. Treatment means were not significantly different (Table 8) indicating that no leaching treatment was specifically advantageous in increasing wetting front movement. Some of the differences seen between treatment means may possibly be the result of using undisturbed spoil columns which were not initially homogeneous with respect to each other. This variability would affect movement of the wetting front. For comparison only, the distance traveled per treat-

Table 8. Depth (cm) to wetting front with unsaturated leaching.

Treatment	H_2O	Gypsum	$CaCl_2$	Gyp+$(NH_4)_2SO_4$+$CaCl_2$	Overall mean
Replications (spoil columns)					
1	42.5	47.5	54.0	47.5	
2	35.3	50.0	43.0	34.8	
3	41.0	40.3	35.0	38.7	
4	34.0	40.8	39.8	40.8	
Treatment means*	39.3 a	44.7 a	43.0 a	40.5 a	41.8

*Means followed by the same letter are not significantly different (.05).

Analysis of Variance

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Treatments	3	69.54	23.18	.61	no
Error	12	456.8	38.07		
Total	15	526.3			

ment for wetting front (Table 8) divided by the total time allowed for movement (222 days) gave water movement rates of 0.17, 0.20, 0.19, and 0.18 cm/day for distilled water, gypsum, calcium chloride, and gyp+ $(NH_4)_2SO_4$+$CaCl_2$, respectively. All rates were similar and together they indicated slow moisture flow which suggests a low unsaturated permeability in spoil.

The attempt to collect leachate from unsaturated flow was unsuccessful because no leachate was actually collected. In determining the distance to wetting front for each spoil column, it was found that the wetting front had not passed through the entire column (Table 8). The amount of moisture periodically collected per column (Appendix Table 22) was generally less than 1 ml throughout the unsaturated leaching period. This was probably due to absorption of initial moisture either in the vapor or liquid phase.

The amount of leaching solution applied to the spoil columns is listed in Table 9. The tops of the columns were maintained in the unsaturated state at approximately .08 bars by applying leaching solution whenever column tensiometers indicated the soil moisture tension (matric suction) was greater than .08 bars. Cumulative infiltration amounts for the total applying time (133 days) are indicated (Table 9). Treatment means were not significantly different suggesting no measurable infiltration differences as a result of leaching treatment. Based on the quantity and concentration of leaching treatments applied, the

Table 9. Water applied (as ml and cm) to spoil columns receiving various leaching treatments.

	H_2O		Gypsum		$CaCl_2$		Gyp+$(NH_4)_2SO_4$+ $CaCl_2$		Overall means	
Treatment	ml	cm	ml	cm	ml	cm	ml	cm	ml	cm
Replications (Spoil columns)										
1	62.5	5.0	79.0	6.3	48.0	4.6	55.0	4.4		
2	55.0	4.4	58.0	4.6	63.0	5.0	60.0	4.8		
3	65.0	5.2	79.0	6.3	65.0	5.2	75.0	6.0		
4	52.0	4.1	53.0	4.2	60.0	4.8	63.0	5.0		
Treatment means*	58.6a	4.7	67.3a	5.4	61.5a	4.9	63.3a	5.1	62.7	5.0

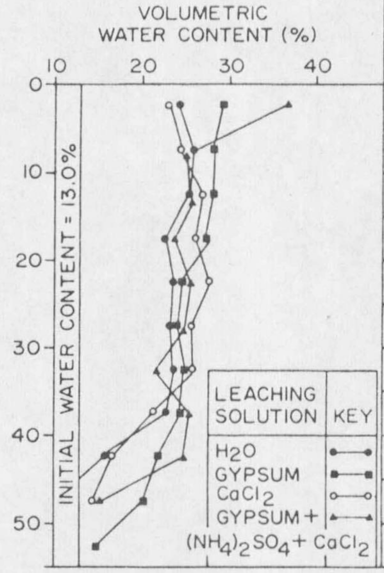
*Means followed by the same letter are not significantly different (.05).

Analysis of Variance

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Treatments	3	156.2	52.06	.68	no
Error	12	923.2	76.93		
Total	15	1079.4			

amounts of Ca added were 0, 2.0, 3.8, and 1.8 meq for distilled water, gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+$CaCl_2$, respectively. An equal amount of exchangeable sodium could be displaced.

Moisture curves after unsaturated leaching and flux for the topsoil columns are shown in Figure 4. The wetting front distance was estimated from these moisture curves as 45.6, 51.5, 47.8, and 47.7 cm for distilled water, gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+$CaCl_2$, respectively. As with the spoil, little or no leachate was collected (Appendix Table 22). Gypsum had the greater wetting front depth, however, there were no replications in topsoil columns to permit statistical analysis. As a group, moisture curves were similar and wetting front movement averaged 48.2 cm. This is greater than the average wetting front distance found with spoil (41.8 cm). Comparative rates (averages) of moisture flow are 0.22 cm/day for topsoil and 0.19 cm/day for spoil. This indicated a slightly greater permeability for topsoil. The leaching treatments added were 5.8, 6.7, 6.9, and 6.8 cm for distilled water, gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+$CaCl_2$, respectively. The average, 6.6 cm, for topsoil indicated a greater cumulative infiltration over spoil (Table 9) which would suggest a greater infiltration for topsoil compared to spoil. This resulted in a greater flux for topsoil than for spoil.



FLUX ↓ (CM)			
H_2O	GYPSUM	$CaCl_2$	GYPSUM+ $(NH_4)_2SO_4$+ $CaCl_2$
5.1	5.8	6.2	5.4
4.2	5.0	5.4	4.7
3.5	4.2	4.5	3.9
2.8	3.5	3.6	3.3
2.2	2.9	2.6	2.6
1.5	2.2	1.7	1.9
0.8	1.6	0.9	1.4
0.2	1.0	0.3	0.7
0	0.5	0.1	0.1
	0.1	0	0
	0		

Figure 4. Volumetric water content and unsaturated flux (for 222 days) for the topsoil columns.

Saturated Flow Using Undisturbed Columns

Only 4 of the 10 columns studied conducted flow through the entire column length resulting in a leachate sample. The saturated hydraulic conductivity, K, was then able to be measured in these columns. The other six columns failed to conduct flow through the entire column length. These four columns were two topsoil columns and two of the four spoil columns treated with gypsum solution. Applying distilled water to spoil columns was not successful in producing flow. Both topsoil columns were permeable to saturated flow.

Figure 5 illustrates K as a function of time for the permeable columns. In the topsoil columns, gypsum increased K (2.9 cm/day average) over that of distilled water (0.2 cm/day average). K values for topsoil ranged from 3.7 cm/day to 0.2 cm/day and were more frequently higher than those for spoil which ranged from 0.3 cm/day to 0.01 cm/day. This would suggest that topsoil was more permeable than spoil.

Permeability may have been influenced by swelling and/or dispersion or through the presence of impermeable rock layers. Swelling was observed in most of the columns. Sodic conditions (Table 3) and medium to high levels of smectite (Table 6) in the spoil indicate that swelling can occur. Though it is harder to observe, the plugging of soil pores by dispersed soil particles was possible. Swelling and/or dispersion

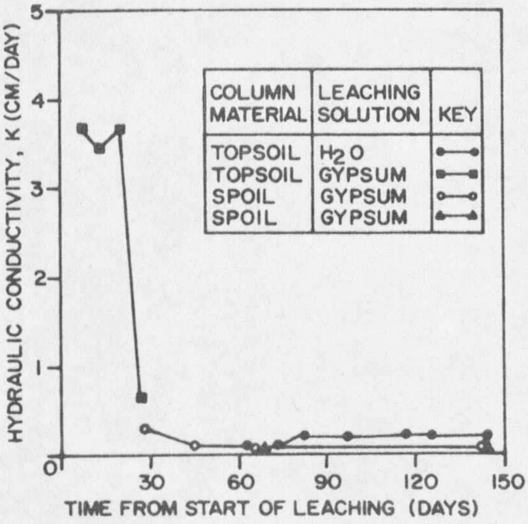


Figure 5. Hydraulic conductivity of soil columns collecting leachate subjected to saturated flow.

can explain why leaching with only distilled water was not successful in spoil. The presence of sandstones, siltstones, shales, and coal fragments in spoil columns also may have had some influence upon permeability since they were found in sizes and in such positions that could plug a column.

Salt Movement with Unsaturated Flow

Very little salt was actually added by the leaching treatments to the spoil. Based on the amount of leaching solution retained in the surface 20 cm and its concentration, distilled water, gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+$CaCl_2$ contributed 0, 2.8, 5.2, and 2.5 percent of the total salt measured in the surface 20 cm of Figure 6 (EC), respectively.

Nothing can be said for general salt movement (Figure 6, EC). Based on the surface 20 cm, no significant effect of treatments for electrical conductivity, or soluble Ca and Mg, were found (Table 10). However, all leaching treatments resulted in significant downward movement of dissolved Na in spoil for the first 10 cm (Table 10) and some movement in the next 10 cm (Figure 6). This movement occurred under slow unsaturated moisture flow. There is no evidence for any upward migration of Na. However, it is possible that there was some diffusion upward since water moved to 40 cm while Na moved only out of the top 20 cm. But it is generally found that the solute front will lag behind

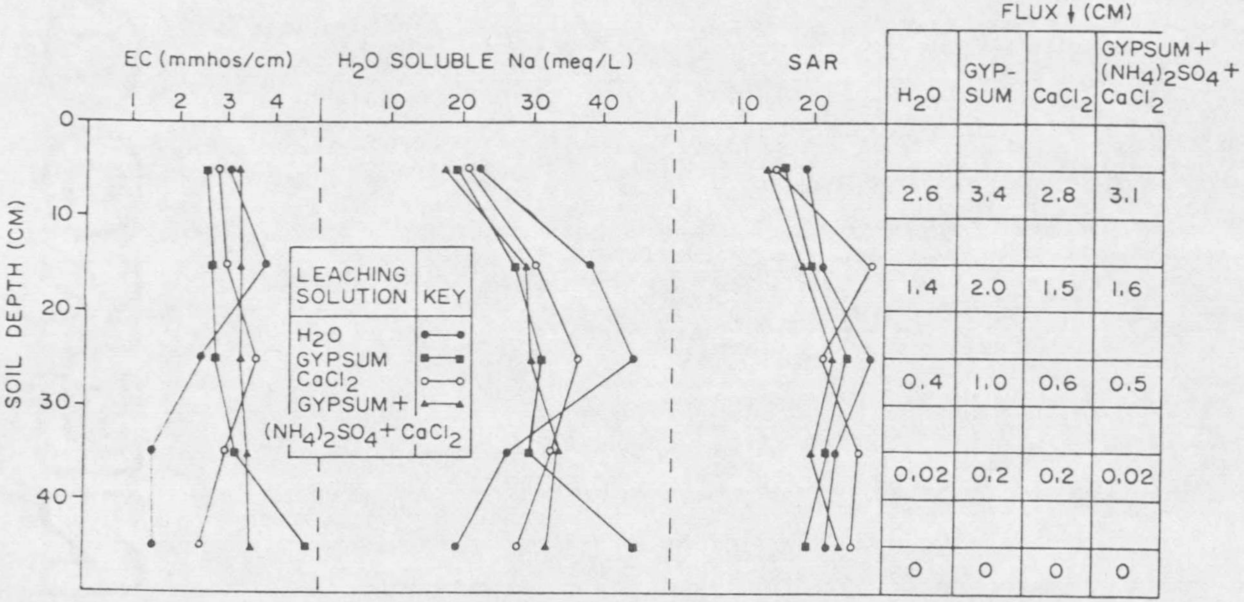


Figure 6. Electrical conductivity (EC), soluble Na, SAR, and unsaturated water flux (for 222 days) by treatment means for spoil columns.

Table 10. Treatment and depth means for indicated parameter for the surface 20 cm in spoil columns after unsaturated leaching.

Soil parameter	Depths (cm)	Leaching treatments				Depth means*
		H_2O	Gypsum	$CaCl_2$	Gyp+$(NH_4)_2SO_4$+ $CaCl_2$	
EC (mmhos/cm)	0-10	3.11	2.90	2.91	3.16	3.02b
	10-20	4.86	2.93	3.13	3.23	3.54b
	Trmt. means*	3.98a	2.91a	3.02a	3.20a	
Soluble Ca (meq/l)	0-10	1.15	1.23	1.09	1.35	1.20b
	10-20	7.22	2.94	0.99	3.39	3.64b
	Trmt. means*	4.19a	2.08a	1.04a	2.37a	
Soluble Mg (meq/l)	0-10	1.70	2.17	3.71	2.36	2.48b
	10-20	7.65	1.49	1.72	2.30	3.30b
	Trmt. means*	4.68a	1.83a	2.72a	2.33a	
Soluble Na (meq/l)	0-10	20.22	19.62	20.76	18.68	19.82b
	10-20	38.75	25.78	31.53	30.46	31.63c
	Trmt. means*	29.48a	22.70a	26.15a	24.57a	
SAR	0-10	18.5	16.1	15.5	14.8	16.2 b
	10-20	21.9	21.8	27.8	21.5	23.2 c
	Trmt. means*	20.2 a	19.0 a	21.6 a	18.1 a	

*Means within each soil parameter followed by the same letter are not significantly different (.05).

Analysis of Variance

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
EC: Treatment	3	5.64	1.88	1.88	no
Depth	1	2.13	2.13	2.13	no
Trmt. x Depth	3	4.13	1.38	1.38	no
Error	24	23.90	1.00		
Ca: Treatment	3	41.06	13.69	0.69	no
Depth	1	47.00	47.36	2.39	no
Trmt. x Depth	3	40.00	13.55	0.68	no
Error	24	475.9	19.83		
Mg: Treatment	3	37.27	12.42	0.90	no
Depth	1	5.18	5.18	0.37	no
Trmt. x Depth	3	74.47	24.82	1.79	no
Error	24	332.9	13.87		
Na: Treatment	3	198.2	66.08	1.84	no
Depth	1	1116.00	1116.00	31.1	yes
Trmt. x Depth	3	156.3	52.11	1.45	no
Error	24	861.3	35.89		
SAR: Treatment	3	56.14	18.71	0.51	no
Depth	1	391.7	391.7	10.65	yes
Trmt. x Depth	3	85.19	28.40	0.77	no
Error	24	882.9	36.79		

the wetting front (Warrick et al. 1971, Kirda et al. 1974). Downward Na movement resulted in a significant reduction in SAR for the top 10 cm (SAR = 16.2) as compared to the 10-20 cm depth (SAR = 23.2). Some reductions in SAR also occurred in the 10-20 cm depth (Figure 6). No significant differences due to treatment were found for either soluble Na or SAR (Table 10).

Topsoil (Figure 7, EC) shows higher levels and greater movement of salt than spoil (Figure 6). Movement is seen to the 20-30 cm depth. A greater water flux is seen in topsoil (Figure 7) than in spoil (Figure 6). This greater flux in topsoil resulted in greater surface removal of soluble Na (Figure 7) and perhaps deeper movement than spoil with good reductions in SAR (Figure 7). As in spoil columns, no evidence was found for any upward movement of Na. Higher salt levels in topsoil were due to higher concentrations of dissolved Ca and Mg than in spoil. Some downward movement is seen for these two cations. Depth means show levels of 7.7 meq/l Ca and 3.2 meq/l Mg in the 0-10 cm depth. This increased to 13.8 meq/l Ca and 12.8 meq/l Mg in the next 10-20 cm zone. Again, it increased to 16.8 meq/l Ca and 17.3 meq/l Mg in the 20-30 cm depth. Statistical significance of leaching treatments was not determined since the lack of treatment replication with topsoil made this impossible.

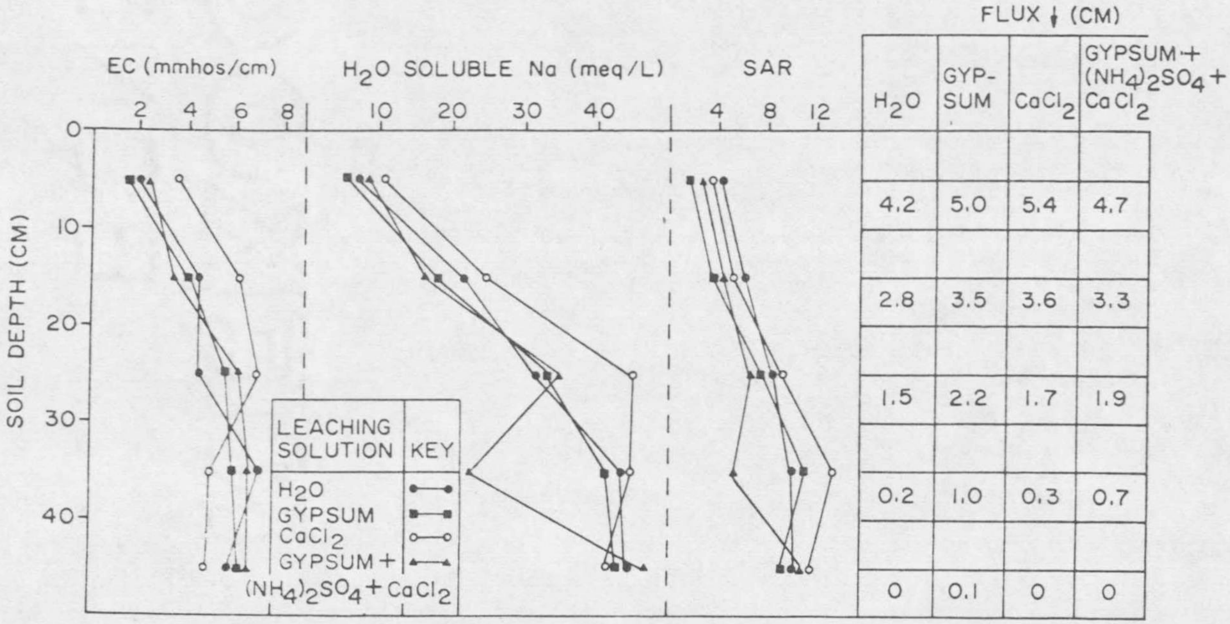


Figure 7. Electrical conductivity (EC), soluble Na, SAR, and unsaturated water flux (for 222 days) for topsoil columns.

Soluble Sodium Movement as a Function of Unsaturated Water Flux

Soluble Na displaced from the top 20 cm as shown in Figures 6 and 7 was calculated by use of averages shown in Table 3 for spoil and topsoil. Soluble Na movement per 10 cm (to 20 cm depth) was then correlated to water flux with linear regression analyses (Table 11). Since no significant differences were found between leaching treatments for soluble Na movement in spoil (Table 10), all treatments were grouped together. Similarly, treatments were grouped together in topsoil.

A highly significant correlation ($r = .67$, $P < .01$) was found between Na displaced in spoil and water flux (Table 11). In topsoil columns, a significant correlation ($r = .79$, $P < .05$) was found for the same comparison (Table 11). Figure 8 shows that the regression line describing Na movement in spoil almost intercepts at the origin which is what would be expected, whereas the line for topsoil indicates that approximately 2 cm of water flux was required before any Na salt moved passed the first 10 cm depth. These two regression equations may be useful in predicting the amount of soluble Na that would be removed from a topsoil-spoil profile by an amount of unsaturated water flux. However, the usefulness of these two equations is limited to the range of water flux actually measured, which is denoted by the solid lines in Figure 8. This linear relationship between soluble Na and moisture flow was developed from only a small water flux range, 1.1 to 4.2 cm in spoil

Table 11. Linear regression analyses for movement of soluble Na in spoil and in topsoil as a function of water flux.

	x-value Flux (cm)	y-value Soluble Na displaced (meq/l)

Spoil:

	x-value	y-value
Mean (28) =	2.42	10.71
Std. Dev. =	0.84	4.97

Fit for Flux:	r	B	SE(B)	T	P-value
	0.668	3.948	0.864	4.571	.0001

Intercept = 1.157

r^2 = 0.446

Analysis of Variance:

Source	D.F.	S.S.	M.S.	F-value	P-value
Regression	1	296.8	296.8	20.90	.0001
Error	26	369.3	14.2		
Total	27	666.2			

	x-value Flux (cm)	y-value Soluble Na displaced (meq/l)

Topsoil:

	x-value	y-value
Mean (8) =	4.06	13.00
Std. Dev. =	0.91	7.49

Fit for Flux:	r	B	SE(B)	T	P-value
	0.794	6.518	2.036	3.201	.02

Intercept = -13.47

r^2 = 0.631

Analysis of Variance:

Source	D.F.	S.S.	M.S.	F-value	P-value
Regression	1	247.5	247.5	10.25	.02
Error	6	144.9	24.15		
Total	7	392.4			

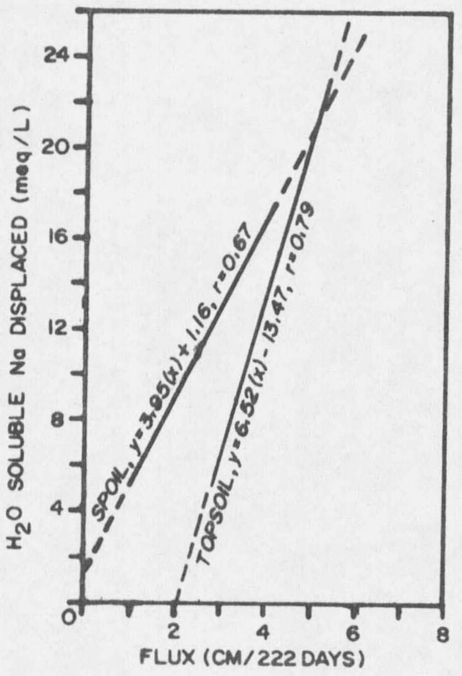


Figure 8. Linear regressions of soluble Na displaced and unsaturated water flux.

and 2.8 to 5.4 cm in topsoil. An erroneous conclusion about the amount of Na salt moved would result with usage of greater water fluxes which can occur through irrigation. This is because Na removal and water flux is not a linear relationship as water flux increases. Rather, Na removed per unit flux will decrease and then level off indicating that little soluble Na remains to be removed. The equations might be especially useful in estimating Na movement in small water flux ranges such as due to natural precipitation. Of considerable importance also, is that these equations were derived from the redistribution of Na under slow, unsaturated flow conditions. Biggar and Nielsen (1967) reported that the efficiency of salt leaching is greater for unsaturated conditions than for saturated conditions. Therefore, the equations should not be applied to saturated flow conditions. Saturated flow conditions seldom occur naturally under normal precipitation in the field.

Exchangeable Sodium Movement with Unsaturated Flow

There was significant removal of exchangeable Na from the surface 10 cm (Table 12). Some additional removal occurred in the 10-20 cm depth (Figure 9). Only 2.0, 3.8, and 1.8 meq Ca were added with gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+$CaCl_2$, respectively. A low amount of NH_4 (0.09 meq) was also added, in addition to Ca, with the gyp+$(NH_4)_2SO_4$+$CaCl_2$ treatment. Distilled water was effective because of native soluble salts. Based on the analysis of variance, treatment

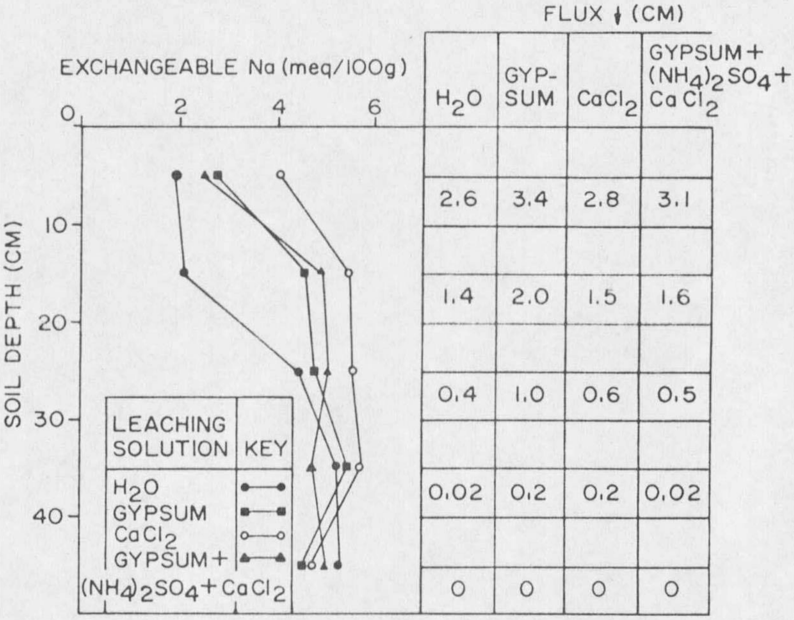
Table 12. Treatment and depth means for exchangeable Na and ESP for the surface 20 cm in spoil after unsaturated leaching.

Soil parameter	Depths (cm)	Leaching treatments: H_2O	Gypsum	$CaCl_2$	Gyp+$(NH_4)_2SO_4$+ $CaCl_2$	Depth means*
Exch. Na (meq/100 g)	0-10	2.07	2.80	4.29	2.60	2.94b
	10-20	2.62	4.59	5.80	4.82	4.45c
	Trmt. means*	2.34a	3.69a	5.02a	3.71a	
ESP	0-10	14.0	18.9	23.5	17.8	18.5 b
	10-20	21.1	30.5	37.4	31.2	30.0 c
	Trmt. means*	17.5 a	24.7 a	30.5 a	24.5 a	

*Means within each soil parameter followed by the same letter are not significantly different (.05).

Analysis of Variance

	Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Exch. Na:	Treatment	3	28.81	9.61	2.80	no
	Depth	1	18.17	18.17	5.29	yes
	Trmt. x Depth	3	3.03	1.01	0.29	no
	Error	24	82.43	3.44		
ESP:	Treatment	3	674.0	224.7	2.9	no
	Depth	1	1057.00	1057.00	13.9	yes
	Trmt. x Depth	3	58.1	19.4	0.25	no
	Error	24	1831.00	76.3		



H_2O	GYP-SUM	$CaCl_2$	GYPSUM + $(NH_4)_2SO_4$ + $CaCl_2$
2.6	3.4	2.8	3.1
1.4	2.0	1.5	1.6
0.4	1.0	0.6	0.5
0.02	0.2	0.2	0.02
0	0	0	0

Figure 9. Exchangeable Na and unsaturated water flux (for 222 days) as a function of different leaching treatments.

means for exchangeable Na in the top 20 cm (Table 12) were found to be not significantly different. This indicates that exchangeable Na differences were not due to leaching treatments. It is likely that differences seen at the surface (Figure 9) can be due to inherent variability in spoil columns. As with soluble Na, no evidence is seen for any upward migration of Na.

ESP levels in stripmine spoil after unsaturated leaching indicated that sodic conditions persisted in all treatment columns, but there was a significant reduction in ESP for the surface 10 cm (Table 12). Treatment means for the top 20 cm of the columns were 17.5, 24.7, 30.5, and 24.5 for distilled water, gypsum, calcium chloride, and gyp+$(NH_4)_2SO_4$+ $CaCl_2$, respectively. Means were not significantly different (Table 12) indicating that ESP was independent of leaching treatment. As with exchangeable Na, ESP differences were likely due to inherent variability. Since sodic conditions remained in spoil, much more time and treatment is needed.

Less treatment and time will be needed for reclamation of topsoil as compared to spoil. ESP levels in topsoil (Figure 10) were less than those found for spoil with sodic conditions rare above 30 cm in topsoil. Topsoil showed deeper exchangeable Na movement at depths below 20 cm than spoil. A similar interpretation can be made from SAR (Figure 7). Deeper exchangeable Na movement in topsoil than spoil was most likely attributable to the greater flux for topsoil.

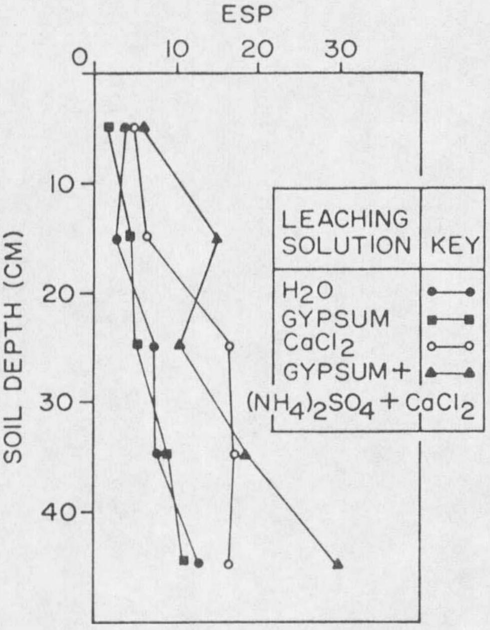


Figure 10. ESP for topsoil after unsaturated flow.

Exchangeable Sodium Movement as a Function of Unsaturated Water Flux

Using an identical approach as for soluble Na, exchangeable Na displaced from the top 20 cm in spoil columns and from the top 30 cm in topsoil columns was calculated. Exchangeable Na movement per 10 cm (to 20 cm or 30 cm depth) was then correlated to water flux with linear regression analyses (Table 13). All treatments were grouped together for the analysis in spoil and in topsoil columns.

A significant correlation ($r = .57$, $P < .05$) was found in spoil between exchangeable Na movement and water flux. In topsoil, a significant correlation ($r = .65$, $P < .05$) also was found between exchangeable Na movement and water flux. Figure 11 shows that spoil and topsoil displaced similar amounts of exchangeable Na per unit flux and that both regression lines almost intercept at the origin, which is what would be expected. As with soluble Na, the usefulness of these two equations is limited to the range of water flux actually measured, which is denoted by the solid lines in Figure 11. The range was small, 1.1 to 4.2 cm in spoil and 1.5 to 5.4 cm in topsoil. Therefore, it can probably apply to fluxes associated with normal precipitation and not to greater fluxes associated with irrigation. Also, these equations deal with slow, unsaturated water flow and not saturated flow.

Table 13. Linear regression analyses between exchangeable Na movement and unsaturated water flux for spoil and topsoil.

	x-value	y-value
	Flux (cm)	Exch. Na displaced (meq/100 g)
Spoil:		
Mean (13) =	2.52	1.71
Std. Dev. =	0.92	0.87

Fit for Flux:	r	B	SE(B)	T	P-value
	0.568	0.537	0.235	7.74	.04

Intercept = 0.357

r^2 = 0.322

Analysis of Variance:

Source	D.F.	S.S.	M.S.	F-value	P-value
Regression	1	2.901	2.901	5.229	.04
Error	11	6.103	0.555		
Total	12	9.004			

	x-value	y-value
	Flux (cm)	Exch. Na displaced (meq/100 g)
Topsoil:		
Mean (12) =	3.32	1.99
Std. Dev. =	1.33	0.86

Fit for Flux:	r	B	SE(B)	T	P-value
	0.654	0.426	0.156	2.73	.02

Intercept = 0.576

r^2 = 0.428

Analysis of Variance:

Source	D.F.	S.S.	M.S.	F-value	P-value
Regression	1	3.511	3.511	7.474	.02
Error	10	4.698	0.470		
Total	11	8.209			

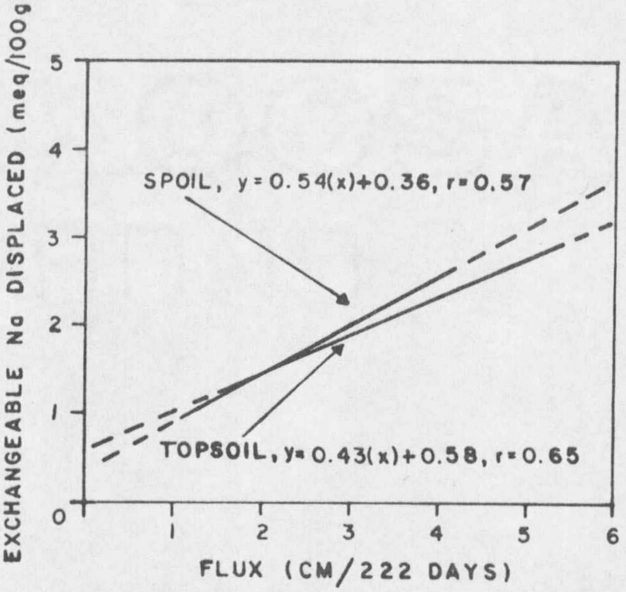


Figure 11. Linear regressions of exchangeable Na displaced and unsaturated water flux.

Exchangeable Lithium Movement

The purpose of Li was to act as a tracer to approximate exchangeable Na movement. The same amount of Li (8 meq) was applied to the top of each column and prior to this, there were only traces of Li present in the spoil material (Table 3). The amount of Li added was small in relation to the total cation exchange capacity of the spoil column (approximately 4%). Because of this low concentration, accurately measuring both exchangeable and soluble Li was analytically impossible due to the limitations of the atomic adsorption spectrophotometer employed. Because of this, extractable Li (NH_4OAc) was used to describe exchangeable Na.

For all leaching treatments, Li advanced about 25 to 30 cm (Figure 12) in spoil columns. However, statistical analysis does not show any significant amount of Li below the 15-20 cm depth (Table 14). Therefore, this distance compared favorably with distance of about 20 cm estimated for exchangeable Na movement. As with exchangeable Na, no significant differences were found regarding Li distribution in columns as a function of leaching treatments based on either treatment means or treatment and depth interaction (Table 14). This suggested that Li movement was independent of treatment.

In topsoil, Li advanced to about 20-25 cm with only trace levels below 25 cm (Figure 12). This is about 5 cm greater than in spoil and

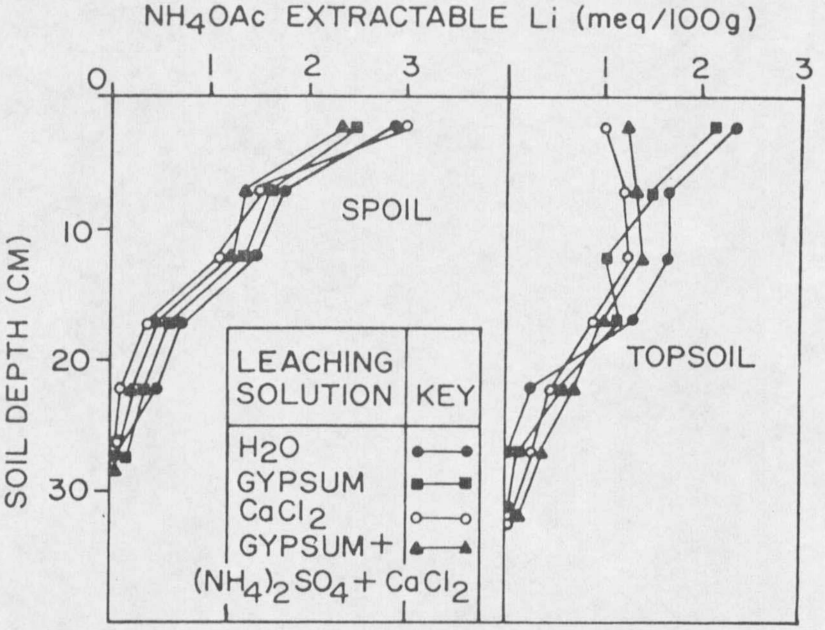


Figure 12. Lithium in spoil and topsoil after unsaturated flow.

Table 14. Treatment and depth means for extractable Li (meq/100 g) in spoil columns after unsaturated leaching.

	Leaching treatments				
Depths (cm)	H_2O	Gypsum	$CaCl_2$	Gyp+$(NH_4)_2SO_4$+$CaCl_2$	Depth means*
0- 5	2.98	2.53	3.11	2.52	2.78 a
5-10	1.90	1.86	1.85	1.68	1.82 b
10-15	1.38	1.36	1.21	1.25	1.30 c
15-20	0.66	0.59	0.42	0.53	0.55 d
20-25	0.24	0.19	0.07	0.19	0.17 e
25-30	0.04	0.07	0.03	0.05	0.05 e
30-35	0.02	0.01	0.03	0.02	0.02 e
Treatment means**	1.03 a	0.94 a	0.96 a	0.89 a	

*Any two means followed by the same letter are not significantly different (Newman-Keuls test, .05).

**Any two means followed by the same letter are not significantly different (analysis of variance, .05).

Analysis of Variance

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Treatment	3	0.29	0.094	0.44	no
Depth	6	107.00	17.83	82.35	yes
Trmt. x Depth	18	1.23	0.068	0.32	no
Error	84	18.19	0.22		

Multiple Comparison for Depth Means using Newman-Keuls Test Q Values

Depth	Depth means						
means	2.78	1.82	1.30	0.55	0.17	0.05	0.02
2.78	--	8.29*	12.77*	19.20*	22.45*	23.53*	23.76
1.82		--	4.48*	10.91*	14.15*	15.24*	15.47*
1.30			--	6.43*	9.67*	10.76*	10.99*
0.55				--	3.24*	4.33*	4.56*
0.17					--	1.09	1.31
0.05						--	0.23
0.02							--

*Means significantly different (.05)

would suggest a slightly greater movement for exchangeable Na in topsoil than in spoil. This was actually the case seen for exchangeable Na in topsoil.

Exchangeable Lithium Movement as a Function of Unsaturated Water Flux

Extractable Li movement per 10 cm depth was correlated to water flux to a depth of 20 cm with linear regression analyses (Table 15). In both spoil and topsoil, treatments were grouped together. A highly significant correlation ($r = .80$, $P < .01$) was found in spoil and also in topsoil ($r = .93$, $P < .01$). In Figure 13, the solid lines denote the water flux range actually measured, which was 1.1 to 4.2 cm for spoil and 2.8 to 5.4 for topsoil. Like the equations developed to describe movement of soluble and exchangeable Na (Figures 8 and 11), movement of Li occurred under slow, unsaturated water flow and not under saturated flow.

It can be seen that the regression lines describing the movement of exchangeable Na and Li are not similar (Figures 11 and 13). Unlike exchangeable Na, regression lines for Li show negative intercepts. This can be explained by the fact that Li was surface-applied while Na was initially dispersed throughout the spoil and topsoil columns. Figure 13 showed that it required water fluxes of approximately 1 cm in spoil and 2.8 cm in topsoil before any Li, moving initially from the surface, moved passed the first 10 cm depth. Because of this, close

Table 15. Linear regression analyses between extractable lithium movement and unsaturated water flux for spoil and topsoil.

	x-value Flux (cm)	y-value Extr. Li displaced (meq/100 g)
Spoil:		
Mean (32) =	2.30	1.21
Std. Dev. =	0.85	0.99

Fit for Flux:	r	B	SE(B)	T	P-value
	0.803	0.935	0.127	7.37	.0001

Intercept = -0.939

r^2 = $-.644$

Analysis of Variance:

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Regression	1	19.74	19.74	54.32	.0001
Error	30	10.90	0.363		
Total	31	30.64			

- -

	x-value Flux (cm)	y-value Extr. Li displaced (meq/100 g)
Topsoil:		
Mean (8) =	4.06	1.85
Std. Dev. =	0.91	1.38

Fit for Flux:	r	B	SE(B)	T	P-value
	0.931	1.404	0.226	6.22	.0001

Intercept = -3.851

r^2 = 0.866

Analysis of Variance:

Source	D.F.	S.S.	M.S.	F-value	Significant at 5%?
Regression	1	11.48	11.48	38.74	.0001
Error	6	1.78	0.296		
Total	7	13.26			

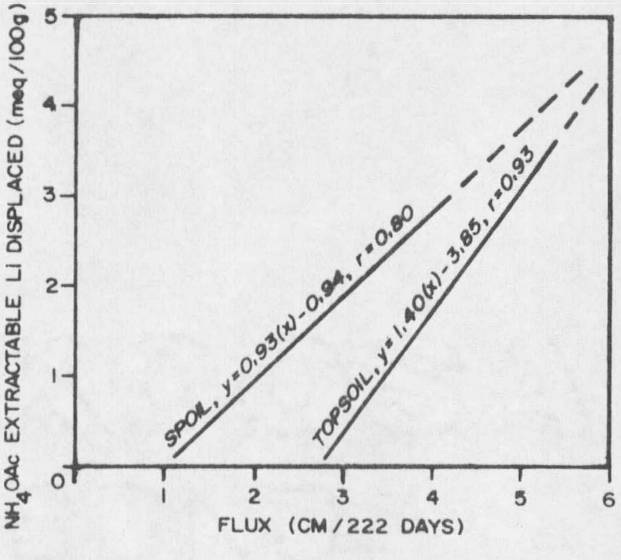


Figure 13. Linear regressions of extractable Li displaced and unsaturated water flux.

examination of the regression lines in Figures 11 and 13 indicated that the movement of Li would not describe the movement of exchangeable Na. Calculations showed that below 3.3 cm (intercept between Li and Na regression lines) water flux in spoil, the use of the Li regression line would underestimate the amount of exchangeable Na moved. Similarly, this is the same situation below 4.6 cm (intercept between Li and Na regression lines) water flux in topsoil.

Saturated Flow Experiments

Salt, Li, and Na Content of Leachate from Saturated Flow

Electrical conductivity (Figure 14) of the leachate indicated that salt was removed from both topsoil columns, with the column leached with gypsum solution being leached relatively free in 30 days. This was due to the greater hydraulic conductivity for gypsum-leached topsoil (2.9 cm/day average) compared to distilled water (0.2 cm/day average) which resulted in more leachate washing through in a shorter time period. With the gypsum solution, 695 ml of leachate was collected in 30 days while only 266 ml of leachate was collected using distilled water in 146 days. More Li was removed from the gypsum-leached topsoil column than with distilled water and in this shorter time period (Figure 14). Similarly, Na was removed more quickly and efficiently from topsoil leached with gypsum solution. Leachate SAR levels decreased from 18 to 2 in 30 days when topsoil was leached with

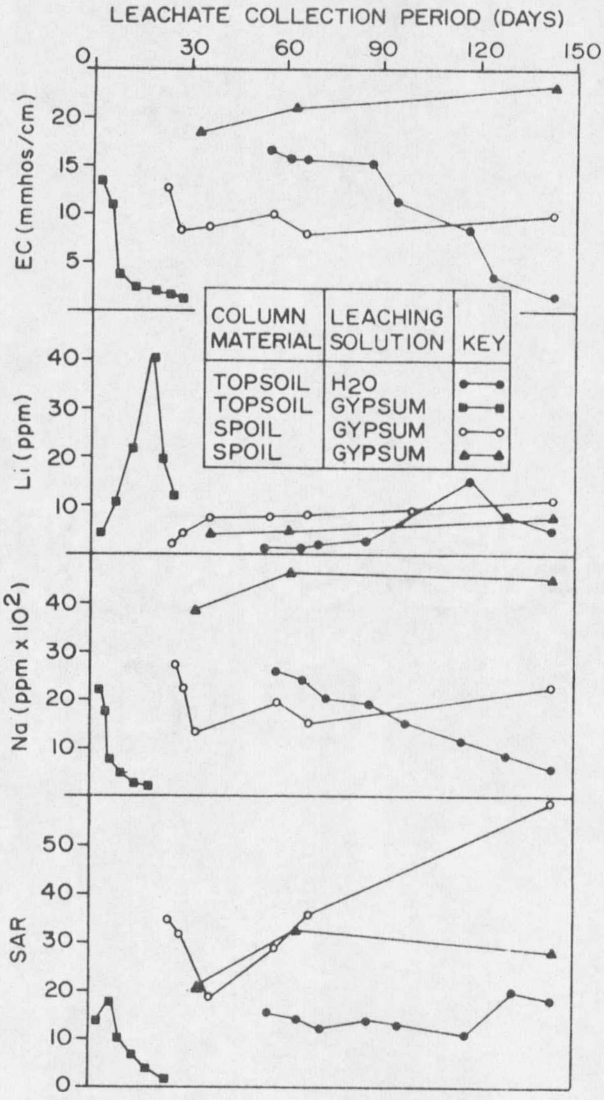


Figure 14. Leachate EC, Li, Na, and SAR periodically collected from soil columns subjected to saturated flow conditions.

gypsum solution while SAR levels remained between 10 and 20 when topsoil was leached with only distilled water. This suggests that gypsum would be effective in reducing sodic conditions in topsoil while leaching alone would not.

Unlike topsoil, leachate EC remained consistently high for both spoil columns leached with gypsum solution (Figure 14). Very little leachate was collected throughout the leaching period as compared to topsoil. In 146 days, 126.5 ml of leachate was collected from one spoil column and only 32.0 ml of leachate from the other column. Similar to leachate EC, Li and Na levels in the leachate (Figure 14) showed no decrease with time. Leachate SAR levels remained high (30-60) after 146 days of saturated leaching indicating that sodic conditions still persisted in both spoil columns.

Exchangeable Li and Na Movement

Only trace levels of exchangeable Li remained after leaching with gypsum solution in topsoil, whereas exchangeable Li levels after distilled water leaching remained high (Figure 15). Similarly, ESP levels within topsoil were very low (<1) after leaching with a gypsum solution and were higher after water leaching averaging 7.5. This would indicate that exchangeable Li and Na were effectively leached from the column with gypsum but not with distilled water only.

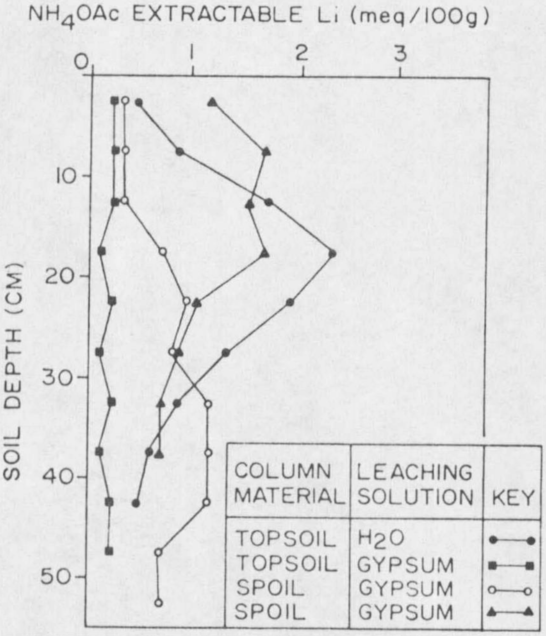


Figure 15. Lithium, distribution after saturated leaching.

After saturated leaching with gypsum solution, both spoil columns showed that much exchangeable Li remained within these columns (Figure 15) and that the ESP remained mostly at sodic levels (30.2 average). Therefore, exchangeable Li and Na were not effectively leached from the spoil columns.

SUMMARY AND CONCLUSIONS

A laboratory study was initiated in October 1977, using undisturbed stripmine spoil and topsoil columns taken from the West Decker Coal Mine at Decker, Montana. The stripmine spoils are characterized as somewhat saline and moderately sodic. Exchangeable Na, and water and salt movement with unsaturated flow, were observed as a function of irrigation and chemical treatments. Distilled water, a saturated gypsum solution (0.03N), a calcium chloride solution (0.06N), and a combination solution (gypsum, 0.026N; ammonium sulfate, 0.0015N; calcium chloride, 0.003N) were applied. A limited study with saturated flow also was carried out using only distilled water and gypsum. Prior to leaching, Li (LiCl) was applied to all column tops for use as a tracer to approximate exchangeable Na movement.

Clay mineralogy analysis indicated the presence of substantial amounts of kaolinite and smectite as well as notable amounts of illite in the spoil materials. Bulk density in spoil averaged 1.7 g/cc after unsaturated flow and 1.8 g/cc after saturated flow. Bulk density in topsoil averaged 1.7 g/cc after either saturated or unsaturated flow. Sodium sulfate was the dominant salt present in both spoil and topsoil and some alkaline-earth carbonates also were present.

While maintaining a surface moisture tension of 0.08 bars for unsaturated flow, 4.7, 5.4, 4.9, and 5.1 cm (averages) of distilled water, gypsum solution, $CaCl_2$ solution, and combination solution, respectively, were applied to the spoil columns during 133 days. No significant effect of leaching treatments was found. Together, they indicated a low cumulative infiltration in spoil. Leaching treatments added averaged 6.6 cm in topsoil and this would suggest a greater infiltration for topsoil than for spoil. This resulted in a greater water flux for topsoil than for spoil.

After unsaturated leaching, all treatments showed similar moisture distributions in spoil. The wetting front advanced an average of 41.9 cm in spoil. Wetting front movement was independent of leaching treatment. Together, all treatments indicated slow moisture movement in spoil (0.19 cm/day) suggesting a low unsaturated permeability. Wetting front distance averaged 48.2 cm for topsoil showing that moisture moved faster through topsoil (0.22 cm/day). Because the wetting fronts had not passed through either spoil or topsoil columns, no leachate was actually collected.

With saturating conditions, applying distilled water to spoil columns resulted in no flow through the entire column legnth, while gypsum solution applied to spoil columns caused flow through 50% of those columns. Gypsum-treated topsoil increased the hydraulic conductivity, K, (2.9 cm/day average) over that of water-treated topsoil (0.2 cm/day average). K values for gypsum-treated spoil columns ranged from 0.3 cm/day to 0.01 cm/day. This would indicate that topsoil is more permeable than spoil. Spoil columns which did not conduct saturated flow through the entire column length may have been affected by swelling and/or dispersion or impermeable rock layers.

With spoil columns and unsaturated flow, no significant effects of leaching treatments were found on electrical conductivity and soluble Ca and Mg. Only dissolved Na moved significantly down from the surface. Movement passed the 20 cm depth. This resulted in a significant reduction in SAR at the surface. Sodium movement and SAR were independent of leaching treatment. In topsoil, salt levels exceeded those found for spoil due to higher concentrations of soluble Ca and Mg. Greater salt movement occurred in topsoil with some dissolved Na moving to 30 cm and some dissolved Ca and Mg moving down from the surface. Greater salt movement can be attributed to topsoil's greater water flux. Good reductions in SAR were found for the top 20 cm. Though 89 days were allowed for draining after 133 days of treatment application, there was no indication of any upward migration of Na in either spoil or topsoil. With linear regression analysis, a highly significant correlation was found in spoil ($r = .67$, $P < .01$) and a significant correlation was found in topsoil ($r = .79$, $P < .05$) between the amount of soluble Na displaced per depth increment and unsaturated water flux.

Significant movement of exchangeable Na from the surface 10 cm occurred in the spoil columns under unsaturated flow. This resulted in a significant reduction in ESP at the surface. However, all depths remained sodic. Movement passed the 20 cm depth. Exchangeable Na movement and ESP were independent of leaching treatment. Distilled water's ability to dissolve native soluble salts made it effective in displacing exchangeable Na. Little Na remained above 30 cm in topsoil. Deeper exchangeable Na movement is evidenced to have occurred in topsoil than spoil. This was due to a greater flux for topsoil. No evidence was found for any upward migration of Na in either spoil or topsoil. Significant correlations were found in spoil ($r = .57$, $P < .05$) and in topsoil ($r = .65$, $P < .05$) between exchangeable Na displaced per depth increment and unsaturated water flux.

Lithium movement with unsaturated flow advanced to about 15-20 cm in spoil and 20-25 cm in topsoil. Movement was independent of leaching treatment in spoil. Through the comparing of Li and Na distribution profiles with depth, Li movement compared favorably to the estimated distance for exchangeable Na movement. Highly significant correlations were found in spoil ($r = .80$, $P < .01$) and in topsoil ($r = .93$, $P < .01$) between extractable Li displaced per depth increment and unsaturated water flux. Because Li was initially surfaced-applied while Na was initially dispersed throughout the spoil and topsoil columns, regression lines for Li were found not to be applicable in describing exchangeable Na movement.

Applying gypsum solution on topsoil subjected to saturated flow resulted in removal of exchangeable Na and Li more quickly and efficiently than applying distilled water only. In 30 days, leaching with gypsum solution resulted in almost complete removal of exchangeable Na while after 146 days, leaching with distilled water did not. This suggested that using gypsum may be advantageous for removing Na from topsoil. Little exchangeable Na and Li were removed in spoil columns leached with gypsum solution subjected to saturated flow. After 146 days, sodic conditions persisted in the spoil columns indicating the difficulty in reclaiming this spoil material.

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APPENDIX

Table 16. Bulk density, particle density, and total porosity on spoil and topsoil columns.

Column	Leaching applied[†]	Sample depth	Bulk density	Particle density	Total porosity
		(cm)	(g/cc)	(g/cc)	(%)
A4-1, Spoil	S	5-10	1.8	2.63	31.6
		20-25	1.8	2.64	31.8
		40-45	1.8	2.61	31.0
A1-1, Spoil	S	5-10	1.9	2.59	26.6
		25-30	1.8	2.64	31.8
		45-50	1.7	2.69	36.8
A8-2, Spoil	S	5-10	1.7	2.61	34.9
		25-30	1.7	2.65	35.8
		40-45	2.1	2.68	21.6
A6-2, Spoil	S	5-10	1.8	2.63	31.6
		20-25	1.7	2.53	32.8
		30-35	1.8	2.51	28.3
2A4-1, Spoil	S	5-10	1.9	2.55	25.5
		25-30	1.8	2.52	28.6
		40-45	1.8	2.60	30.8
2A7-1, Spoil	S	5-10	1.8	2.64	31.8
		25-30	1.8	2.62	31.3
		40-45	1.8	--	31.0
2A6-2, Spoil	S	5-10	1.8	2.65	32.1
		20-25	1.7	2.63	35.4
		40-45	2.0	2.71	26.2
2A3-2, Spoil	S	5-10	2.0	2.59	22.8
		25-30	1.8	2.61	31.0
		45-42	1.7	2.50	32.0

(table continued)

Table 16. continued.

Column	Leaching applied[†]	Sample depth	Bulk density	Particle density	Total porosity
		(cm)	(g/cc)	(g/cc)	(%)
I1-1, Topsoil	S	5-10	1.8	2.64	31.8
		20-25	1.7	2.63	35.4
		35-40	1.7	2.65	35.8
I2-1, Topsoil	S	5-10	1.8	2.64	31.8
		20-25	1.7	2.65	35.8
		40-45	1.7	2.63	35.4
A9-1, Spoil	US	10-15	1.8	--	31.6[‡]
		20-25	1.8	--	31.0
		30-35	1.7	--	34.9
A6-1, Spoil	US	5-10	1.8	--	31.0
		25-30	1.7	--	34.9
		40-45	1.7	--	34.9
A7-1, Spoil	US	5-10	1.8	--	31.0
		25-30	1.7	--	34.9
		35-40	1.7	--	34.9
A5-1, Spoil	US	5-10	1.8	--	31.0
		25-30	1.7	--	34.9
		40-45	1.6	--	38.7
A3-2, Spoil	US	5-10	1.7	--	34.9
		15-20	1.6	--	38.7
A4-2, Spoil	US	5-10	1.7	--	34.9
		20-25	1.7	--	36.8
		30-35	1.8	--	31.0
A5-2, Spoil	US	5-10	1.7	--	36.4
		20-25	1.6	--	38.7

(table continued)

Table 16. continued.

Column	Leaching applied[†]	Sample depth	Bulk density	Particle density	Total porosity
		(cm)	(g/cc)	(g/cc)	(%)
A7-2, Spoil	US	5-10	1.8	--	31.0
		20-25	1.8	--	31.0
		35-40	1.7	--	34.9
I7-1, Topsoil	US	5-10	1.7	--	35.6[‡]
		25-30	1.7	--	35.6
		35-40	1.7	--	35.6
I5-1, Topsoil	US	10-15	1.8	--	31.8
		25-30	1.7	--	35.6
		40-45	1.7	--	37.5

[†] S = saturated leaching on column, US = unsaturated leaching.

[‡] Averaged value for particle density used; spoil = 2.61, topsoil = 2.64.

Table 17. Particle size analysis on spoil and topsoil columns.

Column	Sample depth	Percent Sand	Percent Silt	Percent Clay	Texture
	(cm)				
A4-1, Spoil	5-10	43.4	37.7	18.9	l
	20-25	44.5	36.5	19.0	l
	40-45	60.5	21.5	18.0	l
A1-1, Spoil	5-10	57.2	23.7	19.0	sl
	25-30	48.0	31.2	20.8	l
	45-50	54.2	23.1	22.7	scl
A8-2, Spoil	5-10	47.0	34.6	18.4	l
	25-30	45.6	37.0	18.4	l
	35-40	55.8	25.7	18.5	sl
A6-2, Spoil	5-10	58.6	22.1	19.3	sl
	20-25	66.7	25.1	18.2	sl
	30-35	48.6	28.1	23.3	scl
2A4-1, Spoil	5-10	54.3	27.0	18.7	sl
	25-30	73.8	9.1	17.1	sl
	40-45	56.1	25.5	18.4	sl
2A7-1, Spoil	5-10	38.0	44.3	17.7	l
	25-30	42.2	41.4	16.4	l
	40-45	56.8	24.5	18.7	sl
2A6-2, Spoil	5-10	61.0	21.8	17.2	sl
	20-25	57.9	22.4	19.7	sl
	40-45	34.8	41.5	23.7	l
2A3-2, Spoil	5-10	72.4	13.0	14.6	sl
	25-30	53.1	27.7	19.2	sl
	45-52	49.1	31.3	19.6	l
I1-1, Topsoil	5-10	39.4	40.3	20.3	l
	20-25	45.5	33.6	20.9	l
	35-40	30.9	45.3	23.8	l

(table continued)

Table 17. continued.

Column	Sample depth	Percent Sand	Percent Silt	Percent Clay	Texture
	(cm)				
I2-1, Topsoil	5-10	41.8	38.9	19.3	1
	20-25	48.3	34.0	17.7	1
	40-45	39.9	38.4	21.7	1

Table 18. Results of saturation paste and extract for unused, unleached spoil and topsoil columns.

Column	Sample depth	Saturation	pH		EC	Soluble			SAR
			Paste	Extract		Ca	Mg	Na	
	(cm)	(%)			(mmhos/cm)	---(meq/1)---			
A2-1, Spoil	0-10	85	7.9	8.4	2.7	1.3	1.5	33.0	27.9
	10-20	73	8.1	8.5	2.1	0.7	1.0	23.5	25.9
	20-30	66	7.7	8.3	3.0	2.0	2.7	33.0	21.6
	30-40	74	7.8	8.4	3.7	3.6	3.6	37.4	19.7
	40-50	79	7.2	8.0	5.0	8.9	8.0	47.9	16.5
A2-2, Spoil	0-10	81	6.9	7.9	6.5	15.8	13.2	55.7	14.6
	10-20	66	7.7	8.4	3.8	2.7	3.2	43.0	25.0
	20-30	49	7.8	8.3	3.5	1.7	3.0	43.0	28.1
	30-40	34	8.0	8.1	3.2	1.9	4.2	32.6	18.7
2A2-1, Spoil	0-10	50	8.1	8.3	4.3	1.9	3.4	41.3	25.4
	10-20	57	8.2	8.6	1.5	0.5	6.5	18.3	9.8
	20-30	72	8.2	8.7	1.2	0.2	0.4	15.2	27.8
	30-40	76	8.3	8.7	1.2	0.2	0.3	13.5	19.1
	40-50	93	8.2	8.6	1.4	0.3	0.6	16.5	25.0
2A1-2, Spoil	0-10	65	7.9	8.5	3.3	1.8	3.0	37.0	23.9
	10-20	63	7.9	8.6	2.0	0.8	1.3	21.9	21.2
	20-30	60	7.8	8.5	2.2	1.1	1.8	24.0	20.0
	30-40	65	7.1	7.9	4.6	10.3	10.0	41.0	12.9
	40-50	76	7.1	8.0	7.7	21.5	18.9	67.7	15.1

(table continued)

Table 18. continued.

Column	Sample depth	Saturation	pH		EC	Soluble			SAR
			Paste	Extract		Ca	Mg	Na	
	(cm)	(%)			(mmhos/cm)	---(meq/l)---			
I6-1, Topsoil	0-10	43	7.6	7.8	2.4	11.0	6.4	16.1	5.5
	10-20	50	7.6	7.7	3.6	9.8	10.6	28.7	9.0
	20-30	53	7.7	7.9	3.2	7.1	8.0	26.1	9.5
	30-40	53	7.7	7.7	3.9	11.8	12.7	31.3	8.9
	40-50	55	7.7	7.8	3.5	7.8	10.4	32.6	10.8

Table 19. Extractable Li^+ and Na^+, exchangeable Na, CEC, and ESP for unused, unleached spoil and topsoil columns.

Column	Sample depth	Extractable Li	Extractable Na	Exch. Na[†]	CEC[†]	ESP
	(cm)	----------------(meq/100 g)----------				
A2-1, Spoil	0- 5	Trace[‡]	7.5	3.6	13.6	26.2
	5-10	Trace	5.2			
	10-15	Trace	6.1	2.3	15.4	15.1
	15-20	Trace	1.9			
	20-25	Trace	6.7	4.6	16.2	28.5
	25-30	Trace	6.9			
	30-35	Trace	6.9	4.2	18.2	23.0
	35-40	Trace	6.9			
	40-45	Trace	9.1	5.0	16.3	30.7
	45-50	Trace	8.5			
A2-2, Spoil	0- 5	Trace	4.2	0.0	17.4	0.0
	5-10	Trace	4.8			
	10-15	Trace	4.0	0.4	17.4	2.5
	15-20	Trace	2.5			
	20-25	Trace	6.7	3.5	18.0	19.4
	25-30	Trace	4.6			
	30-35	Trace	1.9	1.2	6.1	20.2
	35-40	Trace	2.7			
	40-45	Trace	4.8			
2A2-1, Spoil	0- 5	Trace	6.7	2.8	10.1	28.1
	5-10	Trace	3.1			
	10-15	Trace	3.1	3.1	9.5	32.4
	15-20	Trace	5.1			
	20-25	Trace	5.1	4.0	12.0	33.4
	25-30	Trace	5.1			
	30-35	Trace	5.1	4.3	13.9	31.1
	35-40	Trace	5.6			
	40-45	Trace	5.9	5.4	17.2	31.5
	45-50	Trace	8.0			
2A1-2, Spoil	0- 5	Trace	10.7	6.6	15.4	42.5
	5-10	Trace	7.2			
	10-15	Trace	5.6	4.0	15.4	25.7
	15-20	Trace	5.1			

(table continued)

Table 19. continued.

Column	Sample depth	Extractable Li	Extractable Na	Exch. Na [†]	CEC[†]	ESP
	(cm)	---------------(meq/1)--------------				
	20-25	Trace	4.8	3.4	17.4	19.4
	25-30	Trace	4.8			
	30-35	Trace	5.6	2.4	17.7	13.5
	35-40	Trace	4.6			
	40-45	Trace	--	0.7	23.5	3.0
	45-50	Trace	5.9			
I6-1, Topsoil	0- 5	Trace	1.7	1.9	18.0	10.6
	5-10	Trace	3.5			
	10-15	Trace	4.0	3.7	18.0	20.2
	15-20	Trace	6.1			
	20-25	Trace	4.2	2.8	18.3	15.4
	25-30	Trace	4.2			
	30-35	Trace	5.6	3.8	14.6	25.9
	35-40	Trace	5.2			
	40-45	Trace	5.1	4.1	22.7	18.1
	45-50	Trace	6.7			
	50-55	Trace	5.2			

[†] Measurements determined using 10 cm sample depths (i.e., 0-10 cm).

[‡] Trace is less than 0.04 meq/100 g.

Table 20. Gravimetric and volumetric moisture percentage (P_v) for columns after unsaturated leaching.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_v
			(cm)	------(%)-----	
A9-1, Spoil	1	H_2O	0- 5	24.3	43.8
			5-10	14.8	26.7
			10-15	15.2	27.3
			15-20	17.5	31.5
			20-25	14.2	25.5
			25-30	13.3	23.9
			30-35	12.2	20.7
			35-40	12.0	20.4
			40-47	10.0	17.1
A3-2, Spoil	2	H_2O	0- 5	20.4	34.7
			5-10	16.9	28.7
			10-15	15.9	27.1
			15-20	15.9	25.5
			20-25	19.2	30.7
			25-30	18.3	29.3
			30-35	12.0	19.2
			35-40	8.3	13.3
			40-46	8.8	14.0
2A9-1, Spoil	3	H_2O	0- 5	25.6	43.5
			5-10	12.8	21.8
			10-15	12.5	21.3
			15-20	11.3	19.2
			20-25	11.0	18.6
			25-30	11.5	19.6
			30-35	11.8	20.0
			35-40	11.2	19.1
			40-45	8.8	14.9
			45-50	7.6	12.9
			50-55	7.3	12.4

(table continued)

Table 20. continued.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_v
			(cm)	--------(%)----	
2A2-2, Spoil	4	H_2O	0- 5	19.0	32.3
			5-10	16.0	27.1
			10-15	14.8	25.2
			15-20	15.2	25.8
			20-25	14.6	24.8
			25-30	13.2	22.4
			30-35	10.2	17.3
			35-40	7.9	13.4
			40-46	7.0	11.9
A6-1, Spoil	1	Gypsum	0- 5	15.3	27.6
			5-10	14.6	26.2
			10-15	14.0	25.1
			15-20	13.2	23.7
			20-25	11.9	20.2
			25-30	11.6	19.7
			30-35	12.1	20.5
			35-40	10.9	18.5
			40-45	11.0	18.7
			45-50	9.1	15.5
			50-54	9.3	15.7
A4-2, Spoil	2	Gypsum	0- 5	20.6	35.0
			5-10	17.8	30.1
			10-15	16.8	28.5
			15-20	16.9	28.8
			20-25	15.2	25.8
			25-30	13.4	22.7
			30-35	12.1	21.9
			35-40	11.6	20.9
			40-45	10.1	18.2
			45-50	12.9	23.2
2A8-1, Spoil	3	Gypsum	0- 5	14.2	24.2
			5-10	12.9	22.0
			10-15	11.1	18.9

(table continued)

Table 20. continued.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_V
			(cm)	------(%)----	
			15-20	12.4	21.0
			20-25	12.8	21.8
			25-30	13.1	22.2
			30-35	12.0	20.4
			35-40	10.6	18.0
			40-45	7.8	13.2
			45-50	7.4	12.6
			50-55	7.0	11.9
2A4-2, Spoil	4	Gypsum	0- 5	17.4	29.5
			5-10	15.2	25.9
			10-15	13.4	22.8
			15-20	13.0	22.1
			20-25	12.2	20.7
			25-30	12.4	21.0
			30-35	11.2	19.0
			35-40	11.6	19.7
			40-45	7.6	12.9
			45-50	7.7	13.2
A7-1, Spoil	1	$CaCl_2$	0- 5	16.9	30.4
			5-10	14.5	26.2
			10-15	15.3	27.5
			15-20	14.8	25.2
			20-25	13.8	23.5
			25-30	12.1	20.6
			30-35	11.6	19.7
			35-40	12.0	20.3
			40-45	11.2	19.0
			45-50	10.3	17.5
			50-54	10.7	18.3
A5-2, Spoil	2	$CaCl_2$	0- 5	19.5	33.2
			5-10	17.1	29.1

(table continued)

Table 20. continued.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_v
			(cm)	------(%)----	
			10-15	16.7	28.3
			15-20	16.7	26.7
			20-25	15.0	24.0
			25-30	13.4	21.4
			30-35	13.2	21.0
			35-40	10.6	16.9
			40-43	10.9	17.5
2A6-1, Spoil	3	$CaCl_2$	0- 5	15.6	26.5
			5-10	12.7	21.6
			10-15	12.4	21.1
			15-20	11.5	19.6
			20-25	11.6	19.8
			25-30	10.3	17.6
			30-35	9.5	16.1
			35-40	9.0	15.3
			40-45	6.4	10.9
			45-52	7.0	24.5
2A8-2, Spoil	4	$CaCl_2$	0- 5	21.1	35.9
			5-10	17.0	28.8
			10-15	14.3	24.2
			15-20	14.1	23.9
			20-25	13.4	22.7
			25-30	13.2	22.5
			30-35	12.5	21.2
			35-40	11.7	19.8
			40-45	6.6	11.1
A5-1, Spoil	1	Comb.	0- 5	18.1	32.6
			5-10	15.3	27.5
			10-15	15.2	27.3
			15-20	15.3	27.5
			20-25	13.3	22.7
			25-30	12.3	21.0

(table continued)

Table 20. continued.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_v
			(cm)	(%)	(%)
			30-35	11.2	19.0
			35-40	11.1	17.7
			40-45	10.5	16.8
			45-50	9.8	15.7
			50-52	9.0	14.3
A7-2, Spoil	2	Comb.	0- 5	17.1	31.9
			5-10	17.8	32.1
			10-15	15.4	27.7
			15-20	13.6	24.5
			20-25	14.6	26.2
			25-30	12.4	22.4
			30-35	10.4	17.6
			35-40	7.9	13.3
			40-47	7.7	13.0
2A1-1, Spoil	3	Comb.	0- 5	14.4	24.5
			5-10	13.4	22.8
			10-15	12.9	21.8
			15-20	13.6	23.2
			20-25	13.3	22.6
			25-30	11.9	20.2
			30-35	11.0	18.6
			35-40	10.0	17.1
			40-45	6.9	11.7
			45-51	5.2	8.8
2A5-2, Spoil	4	Comb.	0- 5	17.4	29.5
			5-10	13.1	22.3
			10-15	14.1	24.0
			15-20	12.6	21.4
			20-25	12.1	20.6
			25-30	14.5	24.7
			30-35	10.9	18.6
			35-40	12.3	20.9
			40-45	7.5	12.8

(table continued)

Table 20. continued.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_v
			(cm)	------(%)----	
I7-1, Topsoil	--	H_2O	0- 5	14.5	24.6
			5-10	15.5	26.4
			10-15	15.1	25.7
			15-20	13.4	22.8
			20-25	14.1	23.9
			25-30	14.0	23.7
			30-35	14.1	23.9
			35-40	13.4	22.8
			40-45	9.5	16.2
			45-50	6.1	10.4
I5-1, Topsoil	--	Gypsum	0- 5	16.3	29.4
			5-10	15.8	28.4
			10-15	15.7	28.2
			15-20	16.2	27.6
			20-25	14.4	24.4
			25-30	14.8	24.6
			30-35	14.7	25.0
			35-40	14.5	24.7
			40-45	13.0	22.1
			45-50	12.1	20.5
			50-53	8.9	15.0
I8-1, Topsoil	--	$CaCl_2$	0- 5	13.6	23.2
			5-10	14.8	25.2
			10-15	15.6	26.6
			15-20	15.4	26.2
			20-25	16.3	27.8
			25-30	15.2	25.8
			30-35	15.1	25.6
			35-40	12.6	21.4
			40-45	9.4	15.9
			45-51	8.5	14.4

(table continued)

Table 20. continued.

Column	Rep. no.	Treatment	Sample depth	Moisture Gravimetric	Moisture P_v
			(cm)	------(%)----	
I4-1, Topsoil	--	Comb.	0- 5	21.9	37.1
			5-10	15.1	25.7
			10-15	15.3	26.0
			15-20	14.1	24.0
			20-25	14.8	25.1
			25-30	14.2	24.1
			30-35	12.7	21.7
			35-40	14.6	24.8
			40-45	14.5	24.6
			45-50	8.4	14.3

Table 21. Gravimetric and volumetric moisture for unused, unleached spoil and topsoil columns.

Column	Sample depth	Moisture	
		Gravimetric	P_v
	(cm)	---------(%)-------	
A8-1, Spoil	0- 5	8.0	13.6
	5-10	9.7	16.5
	10-15	9.5	16.1
	15-20	10.3	17.5
	20-25	10.7	18.2
	25-30	11.0	18.7
	30-35	10.9	18.5
	35-40	10.7	18.2
	40-45	10.0	17.0
	45-50	10.2	17.3
	50-55	11.0	18.7
A9-2, Spoil	0- 5	6.8	11.6
	5-10	8.0	13.6
	10-15	8.0	13.6
	15-20	9.2	15.6
	20-25	8.9	15.1
	25-30	9.4	16.0
	30-35	9.0	15.3
	35-40	8.8	15.0
	40-45	9.0	15.3
	45-50	8.5	14.4
	50-55	9.0	15.3
2A5-1, Spoil	0- 5	7.0	11.9
	5-10	8.3	14.1
	10-15	8.6	14.6
	15-20	8.6	14.6
	20-25	8.6	14.6
	25-30	8.6	14.6
	30-35	8.1	13.8
	35-40	8.7	14.8
	40-45	7.2	12.2
	45-50	10.4	17.7
	50-55	9.3	15.8

(table continued)

Table 21. continued.

Column	Sample depth	Moisture Gravimetric	Moisture P_v
	(cm)	----------(%)	------
2A7-2, Spoil	0- 5	9.9	16.8
	5-10	9.8	16.7
	10-15	9.6	16.3
	15-20	10.3	17.5
	20-25	11.0	18.7
	25-30	10.3	17.5
	30-35	10.4	17.7
	40-45	9.9	16.8
	45-50	7.3	12.4
	50-55	5.7	9.7
I9-1, Topsoil	0- 5	5.3	9.0
	5-10	4.9	8.3
	10-15	6.8	11.6
	15-20	9.5	16.1
	20-25	9.2	15.6
	25-30	9.1	15.5
	30-35	9.1	15.5
	35-40	8.1	13.8
	40-45	8.0	13.6
	45-50	7.5	12.7
	50-55	7.3	12.4
	55-60	6.9	11.7

Table 22. Analysis of the leachate periodically collected from the columns used in unsaturated leaching.

Column	Rep. no.	Treatment	Collection No.	Collection Period	Moisture collected	EC	Li	Ca	Mg	Na	SAR
				(days)	(ml)	(mmhos/cm)	(ppm)	---(meq/1)--			
A9-1, Spoil	1	H_2O	1	10	1.0	2.8	0	7.8	8.4	27.3	9.6
			2	19	0.9	3.1	Trace	3.8	3.2	25.3	13.5
			3	50	1.0	1.4	0	3.5	4.2	38.5	19.6
A3-2, Spoil	2	H_2O	1	10	0.9	0.3	0	4.6	5.3	14.5	6.5
			2	19	0.9	2.4	0	4.1	4.8	22.4	10.6
			3	50	1.0	3.6	0	2.5	7.6	26.2	11.7
2A9-1, Spoil	3	H_2O	1	75	0.8	--	0	4.7	7.0	26.4	10.9
			2	53	0.8	--	0	0.6	6.5	11.6	6.2
			3	59	1.0	1.1	Trace	2.6	4.4	17.0	9.1
			4	36	1.0	--	0	1.4	1.9	23.0	17.7
2A2-2, Spoil	4	H_2O	1	75	0.7	3.9	Trace	3.5	7.3	15.2	6.5
			2	53	0.7	--	0	2.0	8.1	15.0	6.7
			3	59	0.7	0.2	Trace	0.6	2.7	12.0	9.3
			4	36	0.7	--	2.8	0.6	0.0	9.6	17.1
A6-1, Spoil	1	Gypsum	1	10	1.0	2.4	12.1	7.8	8.4	27.3	9.6
			2	19	1.1	4.9	32.7	19.0	9.0	26.5	7.1
			3	50	1.1	4.6	Trace	8.7	9.4	61.9	20.6
A4-2, Spoil	2	Gypsum	1	10	1.0	1.8	0	4.0	10.4	22.6	8.5
			2	19	0.9	3.7	Trace	11.2	7.4	25.7	8.4
			3	50	0.9	3.1	0	10.7	7.1	16.3	5.4

(table continued)

Table 22. continued.

Column	Rep. no.	Treatment	Collection		Moisture collected	EC	Li	Ca	Mg	Na	SAR
			No.	Period							
				(days)	(ml)	(mmhos/cm)	(ppm)	---(meq/l)--			
2A8-1, Spoil	3	Gypsum	1	75	0.7	--	0	6.3	7.4	17.3	6.6
			2	53	0.6	0.2	0	23.9	6.7	14.1	3.6
			3	59	1.0	7.1	89.9	21.8	8.3	38.0	9.8
			4	36	1.0	--	8.0	2.4	1.9	16.9	11.5
2A4-2, Spoil	4	Gypsum	1	75	0.9	7.7	0	13.0	11.1	32.6	9.4
			2	53	1.0	4.9	0	12.2	10.3	42.6	12.7
			3	59	1.1	8.6	Trace	11.8	12.7	84.7	24.2
			4	36	1.2	7.0	2.6	10.0	8.5	61.2	20.1
A7-1, Spoil	1	$CaCl_2$	1	10	1.2	1.7	Trace	3.4	7.7	18.8	8.0
			2	19	1.1	3.1	0	8.9	7.0	30.7	10.9
			3	50	1.2	3.9	Trace	12.8	9.7	29.6	8.8
A5-2, Spoil	2	$CaCl_2$	1	10	1.1	4.3	Trace	7.4	9.1	11.2	3.9
			2	19	0.7	1.3	Trace	7.9	5.9	20.9	7.9
			3	50	0.9	2.2	0	6.5	8.9	35.2	12.7
2A6-1, Spoil	3	$CaCl_2$	1	75	0.6	2.4	0	4.3	7.2	10.1	4.2
			2	53	0.7	--	0	2.2	6.3	7.8	3.8
			3	59	0.7	--	17.3	0.6	2.7	8.0	6.2
			4	36	0.7	--	6.8	2.0	1.3	9.2	7.3
2A8-2, Spoil	4	$CaCl_2$	1	75	0.4	7.7	0	1.2	10.5	11.0	4.6
			2	53	0.4	--	0	0.0	9.8	6.9	3.1
			3	59	0.5	--	Trace	0.0	3.9	4.3	3.1
			4	36	0.5	--	2.1	0.5	0.0	7.9	16.4
A5-1, Spoil	1	Comb.	1	10	1.2	2.3	Trace	13.9	9.7	16.6	4.8
			2	19	1.0	0.9	0	5.7	4.2	12.7	5.7
			3	50	1.1	3.1	Trace	7.9	8.0	27.5	9.8

(table continued)

Table 22. continued.

Column	Rep. no.	Treat-ment	Collection No.	Collection Period	Moisture collected	EC	Li	Ca	Mg	Na	SAR
				(days)	(ml)	(mmhos/cm)	(ppm)	---(meq/l)--			
A7-2, Spoil	2	Comb.	1	10	0.7	4.0	Trace	11.3	12.1	10.1	2.9
			2	19	0.5	0.04	0	16.6	9.6	15.8	4.4
			3	50	0.6	--	0	8.7	8.3	14.9	5.1
2A1-1, Spoil	3	Comb.	1	75	0.4	5.3	0	1.2	10.6	14.9	6.1
			2	53	0.4	--	0	1.2	10.6	9.3	3.8
			3	59	0.6	--	Trace	0.7	3.2	9.4	6.7
			4	36	0.5	--	3.9	0.9	0.0	9.9	15.0
2A5-2, Spoil	4	Comb.	1	75	0.8	7.4	0	4.6	8.3	27.8	11.0
			2	53	0.8	5.9	18.3	8.2	10.9	40.4	13.1
			3	59	1.1	3.4	38.4	3.2	6.9	46.6	20.7
			4	36	1.1	4.9	22.5	6.8	4.0	35.1	15.1
I7-1, Topsoil		H_2O	1	10	0.6	--	0	20.1	9.6	5.9	1.5
			2	19	0.5	--	10.5	7.4	6.4	6.1	2.3
			3	50	0.6	0.5	Trace	4.9	4.9	5.9	2.7
I5-1, Topsoil		Gypsum	1	10	0.7	--	0	11.7	11.1	7.2	2.1
			2	19	0.7	--	Trace	19.9	6.2	8.7	2.4
			3	50	1.0	0.6	0	9.0	6.7	9.9	3.5
I8-1, Topsoil		$CaCl_2$	1	75	0.6	6.2	0	30.3	11.5	13.1	2.9
			2	53	0.7	4.3	Trace	42.6	14.0	12.3	2.3
			3	59	1.3	14.0	12.9	140.2	15.5	44.3	5.0
			4	36	1.0	0.8	3.0	21.6	4.1	23.8	6.6
I4-1, Topsoil		Comb.	1	75	0.6	4.8	14.0	36.7	13.9	13.9	2.8
			2	53	0.6	0.7	0	20.0	11.9	9.1	2.3
			3	59	0.8	--	10.2	6.8	3.7	10.6	4.7
			4	36	1.0	--	Trace	5.5	2.0	16.8	8.7

Table 23. Analysis of leachate from the four columns under saturated leaching successful in collecting leachate.

Column	Treatment	Collection No.	Collection Date	Moisture collected	K	EC	Li	Ca	Mg	Na	SAR
					(cm/day)	(mmhos/cm)	(ppm)	--(meq/l)--			
I1-1, Topsoil	H_2O	1	3-19-78	12.0	--	16.5	0	27.6	72.4	108.3	15.3
		2	4-01-78	21.5	0.1	16.0	0	29.5	75.3	106.1	14.7
		3	4-07-78	9.0	0.1	16.1	Trace	31.4	79.2	93.5	12.6
		4	4-17-78	26.8	0.2	15.0	Trace	21.8	56.7	87.4	14.0
		5	5-01-78	46.0	0.2	11.8	8.6	37.1	22.0	69.7	12.8
		6	5-17-78	51.0	0.2	8.9	15.2	9.5	31.5	45.1	10.0
		7	5-31-78	42.5	0.2	3.1	8.8	0.6	4.8	32.6	19.8
		8	6-18-78	57.0	0.2	2.2	9.4	0.3	2.7	23.0	18.9
I2-1, Topsoil	Gypsum	1	1-27-78	32.5	--	14.0	0	25.6	56.7	91.4	14.3
		2	1-30-78	--	--	11.2	4.6	11.9	22.0	77.4	18.8
		3	2-2-78	165.0	3.7	4.5	10.4	6.5	6.9	26.1	10.1
		4	2-6-78	208.0	3.5	3.1	24.9	4.8	6.3	17.4	7.4
		5	2-10-78	--	--	2.8	40.0	5.0	6.3	12.1	5.1
		6	2-14-78	219.0	3.7	2.4	20.0	13.2	15.3	3.4	0.9
		7	2-21-78	70.5	0.7	2.0	12.1	17.2	20.5	--	--
2A7-1, Spoil	Gypsum	1	2-14-78	24.0	--	13.0	1.5	11.8	11.7	119.3	34.8
		2	2-21-78	32.5	0.3	8.7	3.0	4.5	13.9	99.7	32.9
		3	3-2-78	16.0	--	9.0	5.4	8.4	12.5	64.0	19.8
		4	3-19-78	26.5	0.1	10.5	7.0	3.3	15.3	91.4	29.9
		5	4-01-78	11.0	0.06	9.5	8.7	1.6	7.7	75.5	35.0
		6	6-18-78	16.5	0.01	10.5	11.5	0.2	5.0	98.4	60.8
A6-2, Spoil	Gypsum	1	3-02-78	13.0	--	18.7	2.7	15.6	125.3	173.5	20.7
		2	4-01-78	8.5	0.02	21.0	3.0	19.3	60.3	208.0	33.0
		3	6-18-78	10.5	0.01	23.5	8.0	19.9	69.1	195.2	29.3

Table 24. Results of saturation paste and extract for columns after unsaturated leaching.

Column	Rep. no.	Treatment	Sample depth	Saturation	pH		EC	Soluble			SAR
					Paste	Extract		Ca	Mg	Na	
			(cm)	(%)			(mmhos/cm)	---(meq/l)--			
A9-1, Spoil	1	H_2O	0-10	91	8.2	7.9	2.2	0.3	1.0	17.4	21.7
			10-20	89	8.2	7.9	2.3	0.3	0.8	23.1	30.9
			20-30	96	8.3	8.3	2.1	0.4	0.7	25.3	34.3
			30-40	90	8.2	8.5	1.8	0.2	0.4	20.0	36.2
			40-50	106	8.2	8.5	1.4	0.2	0.4	18.3	33.1
A3-2, Spoil	2	H_2O	0-10	85	7.8	7.4	3.5	1.4	1.6	21.7	17.6
			10-20	56	7.3	7.9	8.3	23.5	21.6	57.7	12.2
			20-30	55	6.5	7.8	11.0	26.3	41.9	88.9	15.2
			30-40	66	7.1	7.2	6.0	24.0	25.2	55.7	11.2
2A9-1, Spoil	3	H_2O	0-10	46	8.4	7.7	3.0	0.5	1.0	17.0	19.9
			10-20	46	8.2	7.8	4.0	0.9	2.1	31.7	25.8
			20-30	56	8.1	7.8	3.4	1.0	2.2	36.4	28.6
			30-40	91	8.4	8.1	1.7	0.4	5.7	21.5	12.4
			40-50	77	8.4	8.3	1.4	0.3	4.9	19.9	12.4
2A2-2, Spoil	4	H_2O	0-10	74	7.8	7.9	3.7	2.4	3.2	24.8	14.8
			10-20	60	7.8	8.1	4.9	4.2	6.2	42.6	18.7
			20-30	116	8.4	8.4	2.0	0.4	0.5	21.5	32.8
			30-40	147	8.7	8.4	0.9	0.1	0.1	10.6	35.2
A6-1, Spoil	1	Gypsum	0-10	106	8.2	8.0	2.1	0.5	0.8	18.3	22.6
			10-20	93	8.1	8.4	2.7	0.6	1.2	28.4	29.7
			20-30	63	8.0	8.5	3.0	0.8	1.6	31.9	29.5
			30-40	70	8.2	8.3	1.9	0.4	0.8	20.4	26.3
			40-50	64	7.9	8.3	2.4	0.8	1.6	24.9	22.8
A4-2, Spoil	2	Gypsum	0-10	83	7.8	7.6	3.5	1.5	3.4	23.8	15.2
			10-20	89	8.2	8.0	2.8	0.7	1.3	25.2	25.5
			20-30	96	8.4	8.0	2.2	0.5	5.7	24.8	14.2

(table continued)

Table 24. continued.

Column	Rep. no.	Treatment	Sample depth	Saturation	pH		EC	Soluble			SAR
					Paste	Extract		Ca	Mg	Na	
			(cm)	(%)			(mmhos/cm)	--(meq/l)--			
			30-40	69	7.9	8.2	3.0	1.5	1.6	33.0	21.0
			40-50	71	6.5	7.8	8.1	24.6	22.4	70.7	14.6
2A8-1, Spoil	3	Gypsum	0-10	46	8.1	7.5	3.2	1.5	2.5	19.4	13.8
			10-20	52	8.2	7.7	3.2	9.4	1.9	24.8	10.4
			20-30	69	8.2	7.8	2.8	0.7	1.9	41.5	36.7
			30-40	92	8.4	7.9	1.8	0.4	0.6	19.9	29.0
			40-50	63	8.2	8.2	1.8	0.5	0.8	23.1	28.6
2A4-2, Spoil	4	Gypsum	0-10	63	7.9	8.3	2.8	1.4	2.0	17.0	13.0
			10-20	69	8.1	8.2	3.1	1.1	1.6	24.8	21.5
			20-30	59	7.9	8.3	3.8	2.1	3.2	34.8	21.3
			30-40	59	7.4	7.9	6.0	10.6	9.5	53.2	16.8
			40-50	57	7.0	8.0	7.5	22.5	20.9	62.2	13.4
A7-1, Spoil	1	$CaCl_2$	0-10	88	8.0	8.2	3.0	1.0	1.7	21.7	18.7
			10-20	94	8.2	8.3	2.6	0.6	1.2	25.8	27.0
			20-30	66	8.0	8.3	3.3	1.1	2.1	36.0	28.6
			30-40	63	8.0	8.0	2.7	0.9	1.5	24.9	22.8
			40-50	62	8.1	8.2	2.3	0.9	1.6	25.8	23.3
A5-2, Spoil	2	$CaCl_2$	0-10	78	7.8	8.1	3.3	1.9	2.4	21.1	14.4
			10-20	81	8.0	7.9	3.5	1.1	2.0	35.9	28.8
			20-30	90	8.3	8.0	2.8	7.0	1.0	33.4	16.6
			30-40	81	8.0	7.8	2.8	1.1	1.5	35.2	30.9
2A6-1, Spoil	3	$CaCl_2$	0-10	79	8.2	7.9	2.9	0.8	1.3	20.3	20.1
			10-20	85	8.3	7.9	2.7	0.7	1.2	29.1	30.5
			20-30	59	7.9	7.9	4.5	2.8	4.1	45.5	24.6
			30-40	55	7.9	8.2	3.7	2.4	3.1	43.0	26.1

(table continued)

Table 24. continued.

Column	Rep. no.	Treat- ment	Sample depth	Satur- ation	pH		EC	Soluble			SAR
					Paste	Extract		Ca	Mg	Na	
			(cm)	(%)			(mmhos/cm)	--(meq/1)--			
			40-50	64	8.0	8.4	2.8	1.1	1.6	30.9	26.4
2A8-2, Spoil	4	$CaCl_2$	0-10	98	8.1	8.0	2.5	0.7	9.5	19.9	8.8
			10-20	66	7.9	8.1	3.7	1.6	2.5	35.4	24.7
			20-30	63	7.9	8.2	3.4	1.6	2.7	34.2	23.4
			30-40	79	7.8	8.4	3.0	1.7	2.2	35.4	25.5
A5-1, Spoil	1	Comb.	0-10	100	8.3	8.2	2.6	0.5	0.9	16.5	19.8
			10-20	91	8.1	8.2	2.9	0.7	1.2	32.4	32.7
			20-30	74	8.0	7.9	3.0	0.9	1.5	33.3	30.7
			30-40	71	8.0	7.7	2.7	0.9	1.4	27.9	26.1
			40-50	67	8.1	8.1	2.2	0.5	1.1	27.0	30.6
A7-2, Spoil	2	Comb.	0-10	78	7.8	8.2	3.2	1.4	2.4	21.1	15.3
			10-20	81	8.0	8.3	3.2	9.7	1.8	28.3	11.8
			20-30	89	8.2	8.4	2.8	6.5	1.0	30.0	15.6
			30-40	77	7.9	8.3	3.0	1.3	1.6	35.2	29.4
			40-50	74	7.3	7.8	6.9	18.4	14.8	57.4	14.1
2A1-1, Spoil	3	Comb.	0-10	46	8.0	8.2	3.9	1.8	3.6	20.7	12.6
			10-20	62	8.2	8.2	3.5	1.1	2.6	33.4	24.6
			20-30	92	9.2	9.2	2.6	0.5	1.1	28.7	32.2
			30-40	75	8.2	7.8	1.9	0.6	8.6	22.3	10.4
			40-50	93	8.4	8.3	1.6	0.4	0.4	18.3	29.4
2A5-2, Spoil	4	Comb.	0-10	64	7.9	8.4	3.0	1.7	2.6	16.5	11.3
			10-20	61	7.9	8.2	3.3	2.0	3.6	27.8	16.7
			20-30	59	7.3	8.2	4.5	6.9	5.9	40.7	76.1
			30-40	58	7.1	8.1	6.3	11.8	10.6	53.2	15.9

(table continued)

Table 24. continued.

Column	Rep. no.	Treat-ment	Sample depth	Satur-ation	pH		EC	Soluble			SAR
					Paste	Extract		Ca	Mg	Na	
			(cm)	(%)			(mmhos/cm)	--(meq/l)--			
I7-1, Topsoil		H_2O	0-10	58	7.5	8.0	2.1	3.5	1.4	6.5	4.1
			10-20	55	7.5	7.8	4.3	13.2	12.3	22.0	6.1
			20-30	59	7.5	7.8	4.6	13.2	13.7	32.1	8.8
			30-40	53	7.6	7.7	6.5	18.0	20.4	43.0	9.8
			40-50	63	7.7	7.8	5.9	14.5	18.9	43.9	10.8
I5-1, Topsoil		Gypsum	0-10	52	7.5	7.8	2.0	6.8	2.4	4.8	2.2
			10-20	57	7.5	7.8	4.1	16.4	13.6	18.3	4.7
			20-30	52	7.5	7.7	5.8	17.4	16.7	33.4	8.1
			30-40	52	7.6	7.8	6.0	15.8	19.3	41.3	9.9
			40-50	56	7.7	7.8	6.0	16.4	19.3	42.6	10.1
I8-1, Topsoil		$CaCl_2$	0-10	43	7.3	7.9	3.9	12.5	5.2	10.9	3.7
			10-20	53	7.4	8.0	6.1	16.8	16.0	24.4	6.0
			20-30	55	7.4	7.9	6.6	18.3	20.0	43.5	9.9
			30-40	57	7.6	8.1	4.8	9.8	12.7	43.5	13.0
			40-50	55	7.6	8.0	4.6	11.3	14.4	41.5	11.6
I4-1, Topsoil		Comb.	0-10	46	7.4	8.3	2.4	8.2	3.8	7.7	3.1
			10-20	58	7.5	7.9	3.7	8.8	9.1	17.4	5.8
			20-30	53	7.4	8.2	6.2	18.3	18.9	33.4	7.7
			30-40	53	7.4	8.2	6.4	19.1	17.8	22.7	5.3
			40-50	54	7.5	8.1	6.2	17.0	16.0	46.2	11.4

Table 25. Extractable Li^+ and Na^+, exchangeable Na^+, CEC, and ESP for columns after unsaturated leaching.

Column	Rep. no.	Treatment	Sample depth	Extractable		Exch. Na†	CEC†	ESP
				Li	Na			
			(cm)	--------(meq/100 g)----				
A9-1, Spoil	1	H_2O	0- 5	2.9	2.5	0.9	11.5	7.6
			5-10	1.8	2.5			
			10-15	1.2	3.5	2.5	14.7	16.7
			15-20	0.8	4.8			
			20-25	0.2	5.9	3.8	17.0	22.7
			25-30	Trace‡	6.7			
			30-35	Trace	8.2	6.5	16.5	39.4
			35-40	Trace	8.4			
			40-47	Trace	9.5	7.5	17.4	43.3
A3-2, Spoil	2	H_2O	0- 5	4.8	6.1	4.2	19.4	21.9
			5-10	2.4	6.0			
			10-15	1.8	6.4	4.0	15.0	26.7
			15-20	0.5	8.0			
			20-25	0.4	10.2	5.6	26.1	21.3
			25-30	Trace	10.6			
			30-35	Trace	8.9	3.2	12.5	25.7
			35-40	Trace	6.0			
			40-46	Trace	8.4			
2A9-1, Spoil	3	H_2O	0- 5	1.8	1.6	0.9	7.2	13.1
			5-10	1.6	1.9			
			10-15	1.4	2.4	1.2	6.0	20.2
			15-20	0.8	3.0			
			20-25	0.4	4.0	2.4	8.8	27.1
			25-30	0.1	4.8			
			30-35	Trace	6.7	5.0	17.1	29.2
			35-40	Trace	7.2			
			40-45	Trace	5.1	3.8	12.6	30.4
			45-50	Trace	5.6			
			50-55	Trace	6.4			
2A2-2, Spoil	4	H_2O	0- 5	2.5	4.0	2.2	16.5	13.4
			5-10	1.8	4.0			
			10-15	1.2	4.8	2.8	13.5	20.7
			15-20	0.5	5.9			
			20-25	0.1	8.8	7.5	19.3	39.0

(table continued)

Table 25. continued.

Column	Rep. no.	Treatment	Sample depth	Extractable		Exch. Na†	CEC†	ESP
				Li	Na			
			(cm)	--------(meq/100 g)-----				
			25-30	Trace	11.2			
			30-35	Trace	10.4	7.8	20.7	37.6
			35-40	Trace	8.3			
			40-46	Trace	7.2			
A6-1, Spoil	1	Gypsum	0- 5	3.1	6.1	4.3	17.4	24.9
			5-10	2.0	6.4			
			10-15	1.0	9.5	6.7	15.8	42.6
			15-20	0.3	9.2			
			20-25	Trace	7.6	5.2	12.5	41.9
			25-30	Trace	6.6			
			30-35	Trace	7.0	5.8	12.7	45.2
			35-40	Trace	7.4			
			40-45	Trace	7.4	5.6	14.1	39.6
			45-50	Trace	7.1			
			50-54	Trace	9.5			
A4-2, Spoil	2	Gypsum	0- 5	3.7	5.3	3.6	16.3	22.2
			5-10	2.1	6.1			
			10-15	1.6	7.0	6.3	16.9	37.6
			15-20	0.6	10.2			
			20-25	0.1	10.4	7.3	18.5	39.5
			25-30	Trace	9.2			
			30-35	Trace	8.4	6.0	16.3	36.7
			35-40	Trace	8.2			
			40-45	Trace	11.4	6.8	19.9	34.4
			45-50	Trace	12.8			
2A8-1, Spoil	3	Gypsum	0- 5	1.3	1.5	0.7	6.0	11.1
			5-10	1.3	1.7			
			10-15	1.1	1.8	0.9	6.0	14.4
			15-20	0.9	2.5			
			20-25	0.5	3.8	2.5	12.3	20.2
			25-30	0.2	6.9			
			30-35	Trace	9.1	5.9	17.1	34.6
			35-40	Trace	6.4			
			40-45	Trace	5.9	3.8	13.5	28.0
			45-50	Trace	4.6			
			50-55	Trace	5.6			

(table continued)

Table 25. continued.

Column	Rep. no.	Treat- ment	Sample depth	Extractable Li	Extractable Na	Exch. Na†	CEC†	ESP
			(cm)	--------(meq/100 g)----				
2A4-2, Spoil	4	Gypsum	0- 5	2.1	2.7	2.6	14.9	17.3
			5-10	2.0	4.6			
			10-15	1.7	5.1	4.4	16.3	27.2
			15-20	0.6	7.2			
			20-25	0.1	7.7	5.9	15.4	38.5
			25-30	Trace	8.3			
			30-35	Trace	6.9	4.9	18.7	25.9
			35-40	Trace	9.1			
			40-45	Trace	7.5	3.6	14.6	24.6
			45-50	Trace	6.7			
A7-1, Spoil	1	$CaCl_2$	0- 5	4.6	8.4	6.6	15.8	42.0
			5-10	1.4	8.9			
			10-15	1.1	10.6	8.5	17.2	49.2
			15-20	0.3	11.1			
			20-25	0.1	10.4	6.9	15.4	44.8
			25-30	Trace	8.2			
			30-35	Trace	6.4	5.2	12.7	40.7
			35-40	Trace	7.1			
			40-45	Trace	6.4	4.8	12.5	38.6
			45-50	Trace	6.4			
			50-54	Trace	6.6			
A5-2, Spoil	2	$CaCl_2$	0- 5	3.4	4.8	3.6	19.9	18.1
			5-10	2.0	6.6			
			10-15	1.7	7.4	5.5	16.3	33.9
			15-20	0.6	9.5			
			20-25	0.1	9.2	6.4	16.1	39.7
			25-30	Trace	9.5			
			30-35	Trace	11.4	8.2	17.2	47.6
			35-40	Trace	10.6			
			40-43	Trace	10.6			
2A6-1, Spoil	3	$CaCl_2$	0- 5	1.9	3.8	3.1	18.3	16.9
			5-10	2.0	5.6			
			10-15	1.3	7.2	4.7	15.4	30.7
			15-20	0.5	7.2			

(table continued)

Table 25. continued.

Column	Rep. no.	Treatment	Sample depth	Extractable		Exch. Na†	CEC†	ESP
				Li	Na			
			(cm)	--------(meq/100 g)----				
			20-25	Trace	7.7	4.9	15.2	32.3
			25-30	Trace	7.5			
			30-35	Trace	5.2	3.3	13.0	25.6
			35-40	Trace	6.1			
			40-45	Trace	6.9	5.1	14.9	34.3
			45-52	Trace	7.2			
2A8-2, Spoil	4	$CaCl_2$	0- 5	2.6	5.2	3.9	22.6	17.2
			5-10	2.0	6.4			
			10-15	0.8	5.2	4.3	12.0	36.0
			15-20	0.3	8.0			
			20-25	Trace	8.5	6.2	17.1	36.6
			25-30	Trace	8.3			
			30-35	Trace	10.9	8.0	26.7	29.9
			35-40	Trace	10.7			
			40-45	Trace	7.7			
A5-1, Spoil	1	Comb.	0- 5	3.8	6.4	5.0	16.1	30.9
			5-10	1.4	7.0			
			10-15	1.0	10.4	7.4	17.7	41.5
			15-20	0.3	10.2			
			20-25	0.1	10.2	6.6	14.4	45.9
			25-30	Trace	7.4			
			30-35	Trace	8.7	5.9	12.5	46.8
			35-40	Trace	7.0			
			40-45	Trace	7.6	3.2	17.4	18.4
			45-50	Trace	8.9			
			50-52	Trace	6.4			
A7-2, Spoil	2	Comb.	0- 5	2.7	4.2	3.0	16.5	17.9
			5-10	2.0	5.9			
			10-15	1.4	5.2	4.2	15.4	27.2
			15-20	0.5	7.7			
			20-25	Trace	9.3	6.7	16.3	40.9
			25-30	Trace	9.3			
			30-35	Trace	7.7	4.7	17.0	27.6
			35-40	Trace	6.9			
			40-47	Trace	10.7	8.0	18.3	43.6

(table continued)

Table 25. continued.

Column	Rep. no.	Treatment	Sample depth	Extractable Li	Extractable Na	Exch. Na†	CEC†	ESP
			(cm)	--------(meq/100 g)----				
2A1-1, Spoil	3	Comb.	0- 5	1.5	1.5	0.7	6.3	10.5
			5-10	1.4	1.7			
			10-15	1.5	3.5	2.2	9.6	23.3
			15-20	0.8	5.1			
			20-25	0.4	7.2	4.6	16.1	28.3
			25-30	Trace	7.2			
			30-35	Trace	6.4	4.6	16.1	28.7
			35-40	Trace	6.1			
			40-45	Trace	5.9	5.2	19.0	27.6
			45-51	Trace	8.0			
2A5-2, Spoil	4	Comb.	0- 5	2.1	3.0	1.8	15.3	11.8
			5-10	1.9	2.7			
			10-15	1.1	5.1	5.5	16.9	32.7
			15-20	0.5	9.3			
			20-25	0.2	5.9	4.3	17.9	23.8
			25-30	0.1	7.5			
			30-35	Trace	9.9	4.9	17.1	28.7
			35-40	Trace	6.1			
			40-45	Trace	10.7			
I7-1, Topsoil		H_2O	0- 5	2.4	0.8	0.5	15.4	3.3
			5-10	1.6	1.1			
			10-15	1.6	1.7	0.6	18.1	3.1
			15-20	1.0	1.8			
			20-25	0.3	3.1	1.4	17.4	7.8
			25-30	Trace	3.5			
			30-35	Trace	3.8	1.8	19.4	9.2
			35-40	Trace	4.5			
			40-45	Trace	5.6	2.3	20.6	11.3
			45-50	Trace	4.6			
I5-1, Topsoil		Gypsum	0- 5	2.2	3.5	0.3	19.9	1.5
			5-10	1.5	7.5			
			10-15	1.1	1.4	0.9	17.4	4.9
			15-20	1.1	2.2			
			20-25	0.5	3.1	1.6	24.1	6.6
			25-30	0.1	3.8			

(table continued)

Table 25. continued.

Column	Rep. no.	Treat- ment	Sample depth	Extractable Li	Extractable Na	Exch. Na†	CEC†	ESP
			(cm)	--------(meq/100 g)-----				
			30-35	Trace	4.2	2.5	24.8	10.1
			35-40	Trace	5.1			
			40-45	Trace	4.2	2.3	20.4	11.2
			45-50	Trace	4.8			
			50-53	Trace	5.1			
I8-1, Topsoil		$CaCl_2$	0- 5	1.1	0.8	0.8	23.9	3.4
			5-10	1.6	1.7			
			10-15	1.7	1.9	1.2	19.3	6.1
			15-20	1.1	3.0			
			20-25	0.4	5.2	2.8	18.7	15.1
			25-30	0.1	5.2			
			30-35	Trace	6.9	3.9	21.2	18.4
			35-40	Trace	5.9			
			40-45	Trace	5.9	3.1	17.9	17.2
			45-51	Trace	4.8			
I4-1, Topsoil		Comb.	0- 5	1.3	0.6	0.7	15.8	4.3
			5-10	1.5	1.4			
			10-15	1.6	3.0	2.7	17.9	14.9
			15-20	1.0	4.2			
			20-25	0.5	4.0	2.3	19.6	11.6
			25-30	0.1	4.0			
			30-35	Trace	5.1	4.1	22.3	18.5
			35-40	Trace	6.7			
			40-45	Trace	10.1	6.1	20.1	30.1
			45-50	Trace	6.9			

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†Measurements determined using 10 cm sample depths (i.e., 0-10 cm).

‡Trace is less than 0.04 meq/100 g.

Table 26. Results of saturation paste and extract for columns after saturated leaching.

Column	Rep. no.	Treatment	Sample depth	Saturation	pH		EC	Soluble			SAR
					Paste	Extract		Ca	Mg	Na	
			(cm)	(%)			(mmhos/cm)	--(meq/l)--			
A4-1, Spoil	1	H_2O	0-10	51	8.1	8.5	0.9	0.5	0.7	5.1	6.8
			10-20	75	8.5	7.9	1.3	0.2	0.3	10.3	21.6
			20-30	92	8.4	7.7	2.0	0.3	0.5	19.2	30.5
			30-40	103	8.5	8.2	2.0	0.5	0.8	21.3	26.3
			40-50	117	8.5	7.8	2.1	0.4	0.6	21.7	31.2
A8-2, Spoil	2	H_2O	0-10	74	8.0	8.4	1.1	0.3	0.5	7.4	11.7
			10-20	64	8.1	8.4	2.2	0.4	1.1	21.3	25.0
			20-30	69	8.2	8.0	1.7	0.4	0.6	17.4	25.5
			30-40	91	8.2	7.6	2.5	0.6	1.6	27.9	26.2
			40-50	88	8.3	7.8	2.8	0.8	1.6	27.0	24.6
2A4-1, Spoil	3	H_2O	0-10	85	8.1	8.4	1.0	0.3	0.2	8.5	18.7
			10-20	84	8.3	7.8	1.6	0.3	0.5	15.7	25.7
			20-30	119	8.3	8.1	2.0	0.4	0.6	20.4	30.0
			30-40	101	8.2	7.6	1.9	0.3	0.7	21.7	31.4
			40-50	67	8.0	8.0	3.4	2.1	2.9	34.1	21.6
2A6-2, Spoil	4	H_2O	0-10	61	7.9	8.3	0.9	0.4	0.4	5.6	8.8
			10-20	110	8.5	8.0	1.1	0.3	0.3	9.5	18.1
			20-30	86	7.6	8.1	3.0	1.5	1.6	26.6	21.2
			30-40	48	6.8	7.7	7.0	19.2	19.4	54.1	12.3
			40-50	45	7.6	7.8	5.0	7.9	8.8	47.0	16.2
A1-1, Spoil	1	Gypsum	0-10	66	7.6	8.4	1.6	1.6	1.5	11.3	9.9
			10-20	93	8.2	7.5	2.1	0.5	0.9	19.1	23.0
			20-30	97	8.1	8.3	2.3	1.0	1.2	26.2	24.7
			30-40	90	7.6	7.9	3.7	2.9	3.3	40.0	22.8
			40-50	87	8.0	7.9	3.3	1.8	2.6	36.0	24.3

(table continued)

Table 26. continued.

Column	Rep. no.	Treatment	Sample depth	Saturation	pH		EC	Soluble			SAR
					Paste	Extract		Ca	Mg	Na	
			(cm)	(%)			(mmhos/cm)	--(meq/l)--			
A6-2, Spoil	2	Gypsum	0-10	57	7.3	7.7	3.5	9.1	9.0	12.2	4.1
			10-20	74	6.6	8.0	3.5	5.2	4.8	28.4	12.7
			20-30	87	7.4	8.4	3.0	1.9	1.6	31.4	24.1
			30-40	80	6.8	7.6	7.5	21.6	20.6	54.1	11.8
2A7-1, Spoil	3	Gypsum	0-10	50	7.5	7.7	1.8	6.6	5.4	1.3	0.5
			10-20	43	7.7	8.3	1.4	0.9	1.6	7.9	7.2
			20-30	43	8.1	7.8	1.3	4.4	5.2	4.5	2.1
			30-40	63	8.3	8.0	1.1	0.4	0.3	9.8	16.8
			40-50	101	8.6	8.3	1.2	0.2	0.2	13.0	33.1
2A3-2, Spoil	4	Gypsum	0-10	60	8.0	8.1	1.8	2.7	1.8	13.9	9.3
			10-20	84	8.0	7.7	1.7	0.4	0.7	16.5	22.3
			20-30	92	8.2	8.0	1.8	0.4	0.7	17.4	24.0
			30-40	66	7.5	8.1	4.1	4.0	4.6	38.7	18.7
			40-50	55	6.9	7.8	7.7	21.0	0.6	68.2	20.8
I1-1, Topsoil		H_2O	0-10	39	7.7	7.1	0.6	2.9	1.6	0.8	0.5
			10-20	42	8.0	7.7	0.6	0.7	0.6	2.0	2.5
			20-30	43	8.2	8.2	0.7	0.5	0.4	3.7	5.4
			30-40	36	8.2	7.8	0.7	0.5	0.6	5.7	7.8
I2-1, Topsoil		Gypsum	0-10	44	7.5	7.1	2.2	24.2	2.6	0.4	0.1
			10-20	47	7.7	7.5	1.3	11.6	5.5	0.4	0.2
			20-30	51	7.8	7.5	1.2	7.2	7.6	0.5	0.2
			30-40	50	7.8	7.5	1.2	6.1	7.5	0.5	0.4
			40-50	48	7.7	7.9	1.3	9.6	12.8	0.9	0.3

Table 27. Extractable Li^+ and Na^+, exchangeable Na, CEC, and ESP for columns after saturated leaching.

Column	Rep. no.	Treatment	Sample depth	Extractable Li	Extractable Na	Exch. Na†	CEC†	ESP
			(cm)	--------(meq/100 g)----				
A4-1, Spoil	1	H_2O	0- 5	0.9	0.9	0.6	12.0	5.2
			5-10	0.5	1.0			
			10-15	1.4	1.4	2.0	10.6	18.5
			15-20	1.0	4.0			
			20-25	0.4	3.0	2.4	12.8	18.4
			25-30	0.3	4.2			
			30-35	0.3	2.1	0.7	16.9	4.1
			35-40	0.1	3.7			
			40-45	0.3	6.8	2.5	17.4	14.1
			45-50	0.3	4.7			
			50-55	0.3	6.9			
A8-2, Spoil	2	H_2O	0- 5	1.8	2.2	1.7	14.1	11.7
			5-10	1.1	2.2			
			10-15	1.1	4.0	2.0	12.0	16.4
			15-20	0.7	2.5			
			20-25	0.7	3.8	4.1	11.3	35.9
			25-30	0.5	5.4			
			30-35	0.7	4.8	2.7	13.9	19.5
			35-40	0.7	7.5			
			40-45	0.5	5.4	4.1	15.4	26.7
			45-50	0.5	6.7			
			50-56	0.5	7.5			
2A4-1, Spoil	3	H_2O	0- 5	1.5	2.7	2.7	14.6	18.7
			5-10	1.8	4.8			
			10-15	1.4	4.2	2.7	9.5	28.9
			15-20	0.9	3.8			
			20-25	0.7	7.5	5.5	15.2	36.3
			25-30	0.5	9.3			
			30-35	0.4	7.7	5.1	15.2	33.2
			35-40	0.5	6.9			
			40-45	0.5	9.1	4.1	15.8	26.1
			45-51	0.5	6.1			
2A6-2, Spoil	4	H_2O	0- 5	0.8	10.0	8.1	13.3	60.8
			5-10	0.9	2.2			
			10-15	0.8	1.4	0.8	17.2	4.7

(table continued)

Table 27. continued.

Column	Rep. no.	Treat- ment	Sample depth	Extractable Li	Extractable Na	Exch. Na†	CEC†	ESP
			(cm)	-------(meq/100 g)----				
			15-20	0.4	2.3			
			20-25	0.4	3.8	1.2	19.0	6.2
			25-30	0.3	3.4			
			30-35	0.3	0.8	--	13.1	--
			35-40	0.3	1.8			
			40-45	0.3	2.3	0.6	7.8	7.3
			45-50	0.3	3.0			
			50-55	0.3	1.6			
A1-1, Spoil	1	Gypsum	0- 5	1.4	2.7	2.8	20.1	13.7
			5-10	1.6	4.8			
			10-15	1.5	7.2	5.9	13.9	43.0
			15-20	1.1	8.3			
			20-25	0.7	7.5	4.9	14.6	33.7
			25-30	0.7	7.5			
			30-35	0.5	9.3	6.6	19.4	34.0
			35-40	0.5	11.2			
			40-45	0.5	7.7	4.7	15.4	30.7
			45-50	0.7	8.5			
			50-55	0.7	9.3			
A6-2, Spoil	2	Gypsum	0- 5	1.2	2.2	1.8	19.0	9.5
			5-10	1.8	4.6			
			10-15	1.6	3.5	3.3	23.8	14.0
			15-20	1.8	7.2			
			20-25	1.1	10.1	5.5	22.0	25.2
			25-30	0.9	7.2			
			30-35	0.7	6.9	4.4	20.1	22.0
			35-40	0.7	9.3			
2A7-1, Spoil	3	Gypsum	0- 5	0.3	0.2	0.1	5.5	0.02
			5-10	0.3	0.2			
			10-15	0.3	0.4	4.8	6.3	75.6
			15-20	0.7	8.9			
			20-25	1.0	8.9	--	5.8	--
			25-30	0.9	2.2			
			30-35	1.2	4.0	3.4	9.1	37.4
			35-40	1.2	4.0			

(table continued)

Table 27. continued.

Column	Rep. no.	Treat-ment	Sample depth	Extractable Li	Extractable Na	Exch. Na†	CEC†	ESP
			(cm)	-------(meq/100 g)----				
			40-45	1.2	9.3	7.8	13.5	57.8
			45-50	0.7	9.1			
			50-56	0.7	12.8			
2A3-2, Spoil	4	Gypsum	0- 5	1.0	1.9	2.1	16.6	12.9
			5-10	1.4	5.1			
			10-15	1.1	5.1	4.1	14.3	29.0
			15-20	0.9	6.7			
			20-25	0.7	6.9	5.4	14.4	37.8
			25-30	0.7	7.2			
			30-35	0.5	7.2	4.8	12.5	38.4
			35-40	0.7	7.5			
			40-45	0.7	8.0	4.1	14.1	29.0
			45-52	0.7	7.7			
I1-1, Topsoil		H_2O	0- 5	0.5	0.2	0.2	16.3	1.3
			5-10	0.9	0.4			
			10-15	1.8	0.5	0.7	18.5	3.8
			15-20	2.5	1.1			
			20-25	2.1	2.3	1.4	17.4	8.3
			25-30	1.4	1.5			
			30-35	0.9	3.1	2.8	16.9	16.7
			35-40	0.7	2.8			
			40-45	0.5	3.2			
I2-1, Topsoil		Gypsum	0- 5	0.3	0.2	0.2	17.7	0.9
			5-10	0.3	0.2			
			10-15	0.3	0.2	0.1	14.9	0.9
			15-20	0.1	0.2			
			20-25	0.3	0.2	0.2	18.5	0.8
			25-30	0.1	0.2			
			30-35	0.3	0.2	0.2	17.9	0.8
			35-40	0.1	0.2			
			40-45	0.3	0.3	0.2	17.7	0.9
			45-50	0.3	0.2			

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†Measurements determined using 10 cm sample depths (i.e., 0-10 cm).

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Johns, Mitchell M
Sodium movement in undisturbed, sodic stripmine spoils ...

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