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ABSTRACT

Sodium leaching efficiencies (moles of Na removed per unit leachate volume) were measured and compared from four noncropped and four cropped treatments applied in duplicate to 1.0 m deep sodic calcareous silt loam in lysimeters. Treatments included a check, gypsum, chopped alfalfa (*Medicago sativa* L.), fresh manure, alfalfa, sorghum (*Sorghum bicolor*), sudan grass (*Sorghum sudanese*) hybrid (which will be called sorghum hybrid for simplicity), sorghum hybrid + leaching, and cotton (*Gossypium hirsutum* L.). The sorghum hybrid + leaching treatment soil was leached with tap water until 0.5 pore volume of leachate was collected from lysimeter bottoms, and then sorghum hybrid was planted. Sorghum hybrid was the most efficient treatment in reclaiming Na-affected soil. All four noncropped soils eventually became dispersed in the lower part of the profile and hydraulic conductivity became very low. Cropped treatments continued to conduct water at a satisfactory rate for reclamation; however, due to low water use, cotton treatment produced a low total Na removal. Sorghum hybrid shows promise as a crop that could be used to speed reclamation of sodic calcareous soils. The treatments producing the highest sodium removal efficiencies also produced the highest soil atmosphere CO_2 concentrations. By selecting crops, amendments, and water application rates and timing, calcareous sodic soil reclamation can very likely be accomplished faster and more economically than in the past.

Additional index words: **Salinity, Sodicity, Exchangeable sodium percentage, Sodium adsorption ratio, Lime, Calcium carbonate.**

WELL DEFINED theoretical descriptions of the $CaCO_3$-H_2O-CO_2 system in soils and its control of pH and Ca, HCO_3, and CO_3 ion concentrations (Nakayama 1970, Ponnamperuma 1967, Robbins 1985, and Tanji and Doneen 1966) and their interactions with other soluble and exchangeable ions, are present in the literature (Pratt and Bair 1969). Carbonate reactions affect sulfate-gypsum reactions in aqueous and soil systems and are also well defined (Nakayama 1969). Laboratory studies have shown that under controlled conditions these theoretical descriptions are quite accurate. However, when other ions, exchange materials, or organic molecules are introduced into calcium carbonate reactions, the carbonate mineral solubilities are often affected (Levy 1981, Robbins 1985, Suarez and Rhoades 1982). These reactions and interactions have been used in various combinations of develop deterministic salinity models for predicting salinization and reclamation of salt affected soils (Robbins, et al. 1980, Suarez 1982, and Tanji and Doneen 1966).

These descriptions and models require CO_2 partial pressure values. Usually, the CO_2 concentrations have been controlled in the laboratory studies. For field or lysimeter studies, CO_2 values are assumed or back calculated from HCO_3 and CO_3 data. Very few root zone CO_2 data are available, especially from studies where different crops were grown under similar conditions. A previous paper reporting soil atmosphere CO_2 data from four noncropped and six cropped treatments in greenhouse lysimeters, showed a wide range of CO_2 concentrations between the treatments (Robbins 1986). The differences in CO_2 concentration levels under the different treatments coincided with the Na ion removal efficiencies from the differently treated soils, as would be expected from theoretical models. Consequently, differences in the final physical characteristics in the soil were oberved. These chemical and physical differences, due to different soil atmosphere CO_2 levels, and their implications in sodic soil reclamation are reported and discussed here.

MATERIALS AND METHODS

Freedom silt loam (fine-silty, mixed, mesic Xerollic Calciorthids) surface soil (0.15 m) was used in this lysimeter study. The sodic soil had not previously been irrigated or cultivated. Initial exchangeable Na percentage (ESP) was 33, cation exchange capacity (CEC) was 210 mmoles of charge kg^{-1} of soil, saturation paste pH was 8.6, and saturation paste extract electrical conductivity was 2.4 dS m^{-1}. A 0.05 m layer of coarse sand was used to cover drain tubes in the bottom of each lysimeter. Soil was added and vibrated until a 1.0-m soil depth at a bulk density of 1.35 Mg m^{-3} was obtained. Lysimeters had a surface area of 0.073 m^2 and a total pore volume of 37 L or 506 mm of water. Lysimeters were on a hydraulic weighing system that allowed measuring weight changes due to evapotranspiration, irrigation, and drainage (Robbins and Willardson 1980), and were located in a semi-temperature controlled greenhouse (minimum of 15°C and maximum of 35°C) with supplemental lighting from 1 October to 1 April for 14 h each day.

Four non-crop treatments included an untreated check, 5.0 kg gypsum m^{-2}, 5.0 kg chopped alfalfa (*Medicago sativa, L.) m*$^{-2}$, and 5.0 kg fresh manure m^{-2}. Gypsum application was equivalent to 1.25 times the exchangeable Na^+ in the surface 0.5 m of soil; chopped alfalfa and manure were applied on an air-dry basis (24 h at 55°C), and these three treatments were mixed in the surface 0.20 m of soil. All noncropped treatments were irrigated every 7 days with 70 mm (5.0 L) of tap water (EC = 0.7 dS m^{-1} and SAR = 1.7) until infiltration rate decreased to below 70 mm in 5 days (0.6 mm h^{-1}).

The four cropped treatments discussed here are alfalfa, a sorghum (*Sorghum bicolor*), sudan grass (*Sorghum sudanese*) hybrid (which will be referred to as the sorghum hybrid for simplicity), sorghum hybrid + leaching, and cotton (*Gossypium hirsutum* L.). The CO_2 study (Robbins 1986) also contained barley (*Hordeum vulgare*) and tall wheatgrass [*Elytrigia pontica* (Podp.) *Holub*] treatments, but will not be discussed here because tall wheatgrass followed barley in the same soil and consequently Na data cannot be compared. Two lysimeters were initially irrigated the same as the two check lysimeters and when infiltration began to decrease (0.5 pore volume of drainage), sorghum hybrid was planted (leached + sorghum hybrid treatment). The other three crops were planted three days after a 140 mm (10.0 L) tap water irrigation and then covered with aluminum foil until each crop emerged. All crops were then irrigated at 1.25 times consumptive use (0.20 leaching fraction) since the last irrigation. Treatments were duplicated in a randomized design. Leachate volumes were measured and used in calculating evapotranspiration.

Four alfalfa crops were grown and harvested at full bloom. The sorghum hybrid was cut four times when seed heads

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were at hard dough stage and was fertilized with 2.1 g of ammonium nitrate (100 kg N ha^{-1}) after each cutting. Cotton was allowed to grow until all cotton bolls matured and leaves started to drop and new leaf buds started to form.

Lysimeter leachates were collected and volume, pH, and electrical conductivity (EC) were measured. Soluble Na was measured by flame emission spectrophotometry. Infiltration rates were determined on alternate irrigations by applying 70 mm of water and then recording the time required for the first 50 mm to enter the soil. Soil atmosphere samples were collected from septum covered glass sample ports at 0.25, 0.50, and 0.75 m below the soil surface and analyzed for CO_2. Initially, CO_2 samples were taken daily from all lysimeters. After two months, samples were not taken from cropped lysimeters on weekends. Daily O_2 samples were taken from all cropped treatments for a 2-week period while the crops were growing vigorously and analyzed to determine the relationship between O_2 and CO_2 concentrations.

Initially, the CO_2 samples were collected with a 20 mL syringe and needle through the septum covered ports and a 15 mL sample was stored in 10 mL evacuated vials. The vial septums had been coated with hot paraffin to reduce sample leakage. These samples were analyzed with a Hewlett Packard 5730A Gas Chromatograph.[3] Later, 5 mL samples were collected and analyzed directly from the glass sampling ports with a Microtechnology 500[3] portable gas microchromatography unit. Both CO_2 and O_2 samples were analyzed with this instrument.

At the end of the greenhouse study, soil profiles were sectioned into 0.05-m increments down to 0.60 m, and the lower portion was sampled from 0.60 to 0.80 m and 0.80 to 1.00 m. Root volumes for each depth were measured in the soil samples by wet sieving two core samples of known volume (3.53×10^4 mm^3) from each section, gently removing excess water with a paper towel, weighing the washed roots, and assuming a root density equal to that of water. Each section was then thoroughly mixed and subsampled for chemical analysis. Saturation paste pH, saturation paste extract EC, and soluble Na concentration were measured. Extractable Na was measured using 1.0 *M* ammonium acetate adjusted to pH 7.0 as the extractant. Exchangeable Na was calculated as extractable Na minus soluble Na. Cation exchange capacity was measured by saturating soil samples with Na using 1.0 *M* sodium acetate, washing excess sodium acetate from the soil with ethanol, and then replacing the exchanged Na with NH_4 in 1.0 *M* ammonium acetate solutions. Sodium concentrations were measured by flame emission.

RESULTS

Accumulated Na in the leachate for noncropped and cropped lysimeters was plotted as a function of leachate water volume (Fig. 1A and 1B, respectively). One pore volume is 37.0 L (506-mm depth). If Na-removal efficiency is defined as moles of Na removed per unit volume of leachate, then Na-removal efficiency is shown as the slope of the curves at any given point in Fig. 1A and 1B. The check was the least efficient treatment and the gypsum the most efficient treatment in terms of Na removal for noncropped treatments. Chopped alfalfa was slightly less efficient than gypsum, and manure was between the check and chopped alfalfa. The end of each line represents the volume of leachate recovered before soils sealed and would no longer conduct water due to dispersion.

Sodium-removal efficiency for the cropped treat-

[3] The use of brand names is for the reader's convenience and does not imply endorsement of these instruments over any others by the author or sponsoring institution.

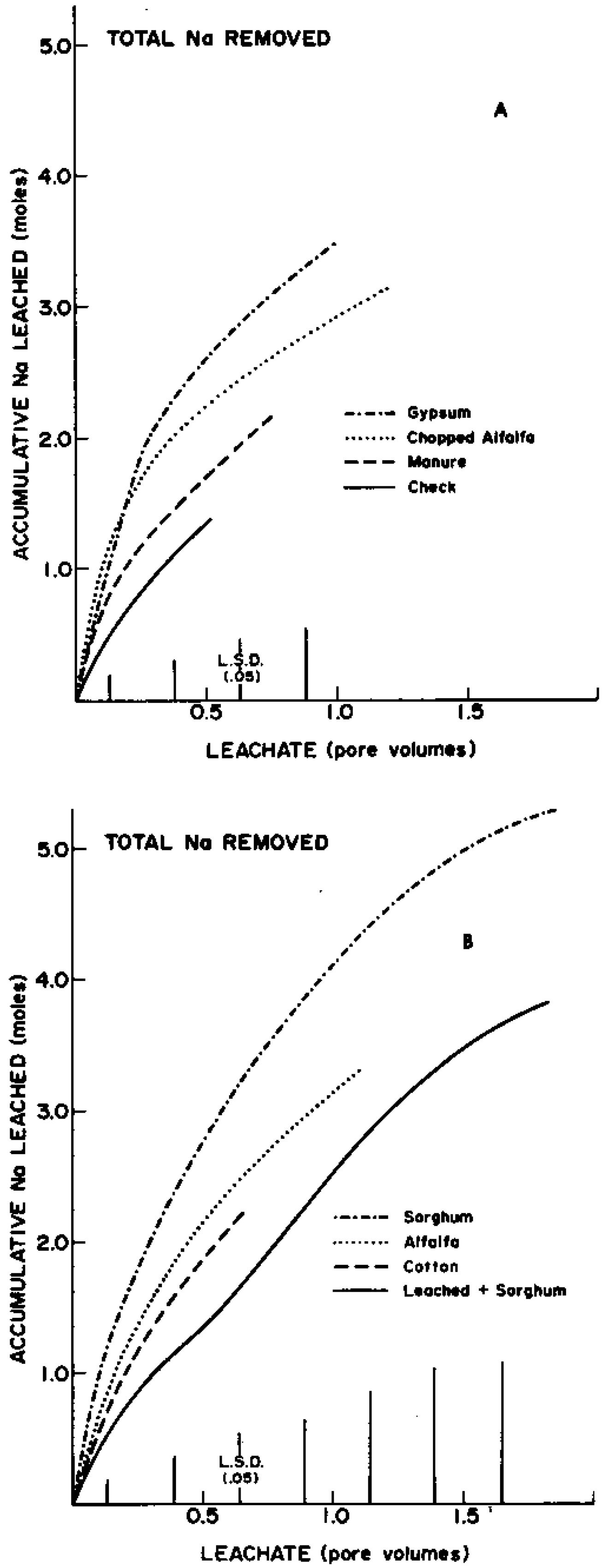

Fig. 1. Accumulative Na collected in drainage water as a function of leachate volume and reclamation treatments for noncropped (A) and cropped (B) treatments.

Table 1. Net Na removed from lysimeters and time required for 50 mm of a 70 mm irrigation to infiltrate into the soil at time of 0.5, 1.0, and 1.5 pore volumes of leachate.†

	Pore volumes						
	0.5	1.0	1.5	0.5	1.0	1.5	Last irrigation
	Moles Na			h			
Check	1.0 ± 0.1			192 ± 26			192 ± 26
Gypsum	2.3 ± 0.3	3.3 ± 0.3		21 ± 3	132 ± 16		132 ± 16
Manure	1.6 ± 0.2			18 ± 2			162 ± 19
Chopped alfalfa	2.1 ± 0.2	2.6 ± 0.3		2.4 ± 0.2	6.2 ± 0.7		146 ± 20
Cotton	1.4 ± 0.1			4.8 ± 0.3			4.2 ± 0.5
Alfalfa	1.7 ± 0.2	2.6 ± 0.2		5.0 ± 0.4	2.3 ± 0.3		3.1 ± 0.4
Leached + sorghum hybrid	1.0 ± 0.1	2.1 ± 0.2	2.6 ± 0.2	28 ± 4	4.2 ± 0.5	3.1 ± 0.4	2.7 ± 0.3
Sorghum hybrid	2.4 ± 0.3	3.7 ± 0.3	4.0 ± 0.3	4.6 ± 0.6	2.2 ± 0.2	2.6 ± 0.3	2.8 ± 0.2

† Initially, there were 7.5 moles of Na (soluble and exchangeable) in the soil added to each lysimeter.

Table 2. Mean soil atmosphere CO_2 partial pressures for the non-cropped treatments for the period prior to the first drainage event and the period following the first drainage event.†

	Sample depths (m)					
	0.25	0.50	0.75	0.25	0.50	0.75
	CO_2 partial pressure (kPa)					
	Before first drainage event			After first drainage event		
Check	4.3	3.9	2.8	3.4	2.0	0.9
Gypsum	2.4	2.1	1.3	0.9	0.9	1.4
Chopped alfalfa	9.1	10.3	9.5	4.0	4.6	4.9
Manure	6.0	5.5	5.5	3.1	3.4	4.1

† See Robbins (1985) for daily values and fluctuation.

ments was greatest for sorghum hybrid and lowest for cotton when the crops were planted following the first irrigation. The sorghum hybrid treatment had very nearly the same efficiency as gypsum until approximately 0.5 (253 mm) pore volume of water had leached out. Beyond that point, sorghum hybrid gradually became more efficient than gypsum. Alfalfa and cotton were not as efficient as sorghum hybrid or gypsum. Leached + sorghum hybrid was the same as the check up to approximately 0.5 pore volume of leachate since they were treated in the same way up to that point. When sorghum hybrid started vigorous growth and water use, Na-removal efficiency increased (indicated by steeper slope) and became as efficient as the sorghum hybrid treatment beyond 0.7 (354 mm) pore volume. The line ends represent the total leachate volume recovered from each of the respective cropping treatments.

Net Na removal, the amount measured in the leachate minus that added in the irrigation water, for each treatment also differed among treatments (Table 1). Sorghum hybrid and gypsum were equally effective up to 0.5 pore volume, but sorghum hybrid was more effective than gypsum at 1.0 pore volume. The gypsum treated soil sealed after that point, while the sorghum hybrid treatment continued to be effective in net Na removal. All cropped treatments, except the leached + sorghum hybrid, were more effective than the check in removing Na from the soil for the first 0.5 pore volume.

Infiltration times for the first 50 mm of a 70 mm water application was less than the check for all treatments until 0.5 pore volume had been collected. By 1.0 pore volume the check, manure, and gypsum treated soils had sealed, and the chopped-alfalfa treated soil sealed shortly after that. Alfalfa, sorghum hybrid, and leached + sorghum hybrid cropped soils were still conducting water at a satisfactory rate. Water use by cotton was not great enough to produce 1.0 pore volume of drainage water during the growth period (Fig. 1B). Final infiltration rates for all treatments (Table 1) are a reflection of the amount of Na removed by the respective treatments.

Soil atmosphere CO_2 concentration means for various time periods at 0.25, 0.50, and 0.75 m depths are shown (Table 2). The first set of three values for the check, gypsum, chopped alfalfa, and manure treatments are means for the time from first irrigation until the first leachate was collected. The second set of three values are CO_2 concentration means for the remainder of the irrigation period for each treatment. Cotton CO_2 values are time weighted means for the entire growing period (Table 3). Sorghum hybrid, alfalfa, and leached + sorghum hybrid values are time weighted means

Table 3. Soil atmosphere CO_2 partial pressures for the cropped treatments. The cotton values are means for the entire growing period and remaining values are for each of four cuttings.†

	Sample depths (m)											
	0.25	0.50	0.75	0.25	0.50	0.75	0.25	0.50	0.75	0.25	0.50	0.75
	CO_2 partial pressure (kPa)											
	Cutting											
	1st			2nd			3rd			4th		
Sorghum hybrid	6.6	6.4	5.8	10.1	10.3	9.6	11.7	14.1	14.1	9.4	11.1	9.9
Alfalfa	6.8	6.6	4.8	7.1	7.2	6.3	6.3	6.0	5.3	6.9	6.7	6.1
Leached + sorghum hybrid	4.0	4.6	3.4	9.4	8.8	6.9	8.9	8.9	6.0	8.2	8.8	7.1
Cotton	3.0	3.3	3.6									

† See Robbins (1985) for daily values and fluctuations.

for the first, second, third, and fourth cutting periods. Individual daily CO_2 values and trends were reported earlier (Robbins 1986).

Final exchangeable-Na profiles for noncropped soils had the same general shape and ranked (Fig. 2A) as would be predicted from Na removal data (Fig. 1A). Cotton and alfalfa exchangeable-Na profiles were similar in shape to the noncropped profiles, while the two sorghum hybrid profiles tended to be more uniform with depth (Fig. 2B). Cotton and alfalfa roots were concentrated in the upper soil profile while the sorghum hybrid roots extended throughout the profile (Fig. 3). Low O_2 (CO_2+O_2 partial pressures totaled nearly 20 kP at all times measured) levels appeared to inhibit cotton and alfalfa root growth but did not seem to inhibit sorghum hybrid root growth.

DISCUSSION

Except for the gypsum treatment, the order of Na-removal efficiency within cropped and noncropped treatment groups was the same as the CO_2 concentration order in the previous study (Robbins 1986); i.e., the Na-removal efficiency of chopped alfalfa was > manure was > check, for noncropped treatments; and sorghum hybrid was > alfalfa was > cotton was > leached + sorghum hybrid, up to 0.5 pore volume. After 1.0 pore volume of leachate, the leached + sorghum treatment became more effective at removing Na than were cotton or alfalfa. In both cases, the higher the daily and overall average CO_2 concentrations, the greater the total quantity of Na leached from the soil profile per unit leachate volume. Care must be taken in comparing data from the cropped group with data from the noncropped treatments since water application rates and water removal methods were different. Leaching fractions, water removal patterns, soil water contents, and water profiles were different.

With both the cropped and noncropped treatments, three different reaction mechanisms could be acting individually or in combination to produce increased soil atmosphere CO_2 concentrations and increased Na-reclamation efficiency. In the first mechanism, respiring crop roots and decomposing organic matter (applied or indigenous) could produce CO_2, which dissolves in water to produce carbonic acid. This acid would increase the solubility of calcium carbonate minerals by lowering the pH and dissolving the lime minerals and forming a host of complex calcium ion pairs, thus increasing soil solution Ca concentration (Nakayama 1970, Robbins 1985). A second mechanism could act as a source of CO_2 in soil solution by producing CO_2 from the oxidation of plant root exudates (Vancura and Hanzlikova 1972). Soil organisms oxidizing these polysaccharides, proteins, and peptides could produce CO_2 as a by-product and likewise, carbonic acid would be produced to dissolve soil lime minerals. By means of a third mechanism, soil organisms could produce organic acids (Chandrasekaran 1969) which in turn would dissolve calcareous soil minerals, releasing CO_2 as the $CaCO_3$ dissolves, and Ca salts of the organic acids would be produced.

Regardless of the CO_2 source, whether it be from respiring roots, decomposing organic matter and root exudates, or organic acid dissolution of calcareous

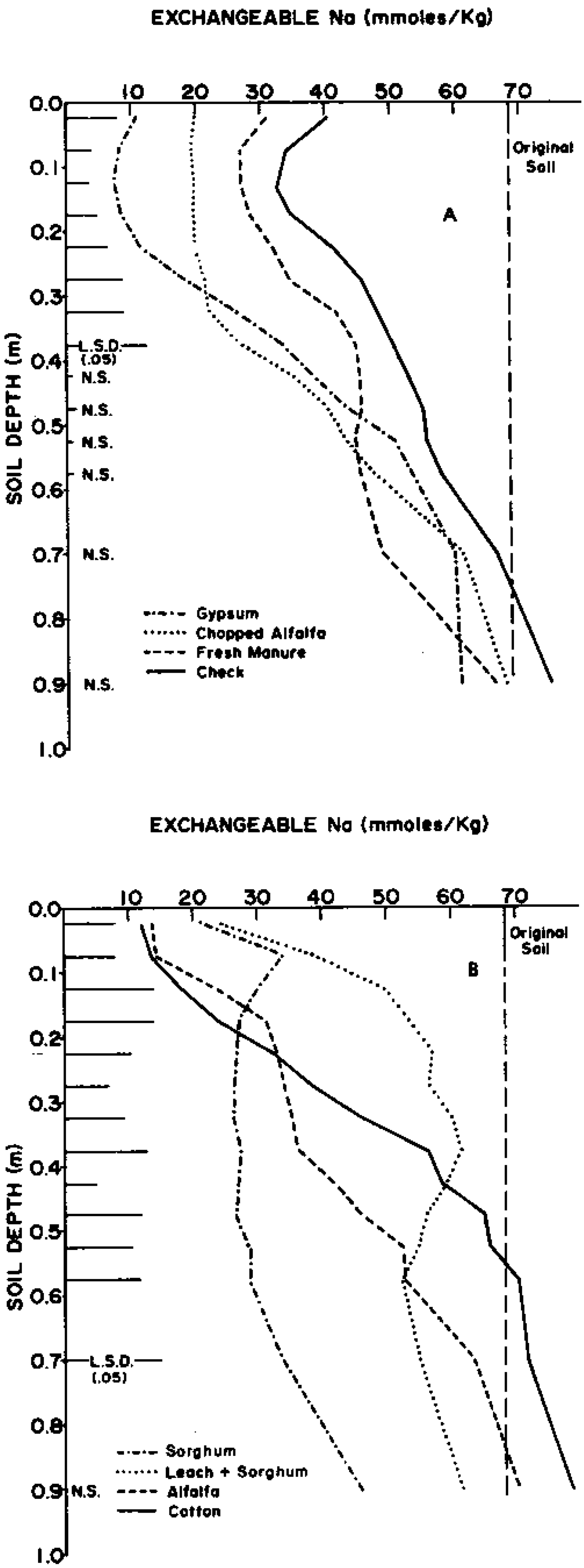

Fig. 2. Final exchangeable Na concentration with depth of soil as a function of reclamation treatments for noncropped (A) and cropped (B) treatments.

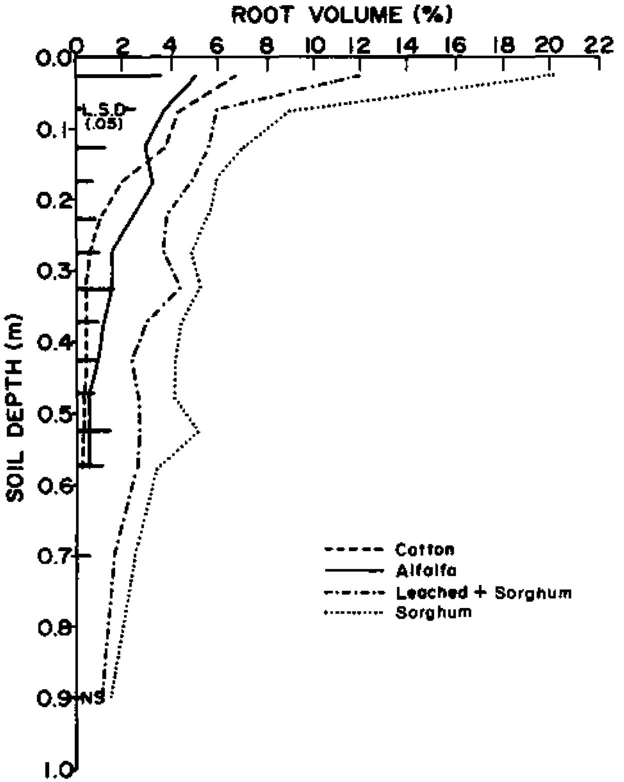

Fig. 3. Final root volume in the lysimeter soils as a function of crop treatments.

minerals, the end result is the same; i.e., soil atmosphere CO_2 concentrations are elevated, calcareous minerals are dissolved, Ca concentrations in solution are increased, the soil solution pH is lowered (Whitney and Gardner 1943), Ca and Na exchange occurs, and Na goes into solution where it is leached from the soil at a much higher rate than can be explained by the simple hydrolysis of calcareous minerals.

For a given soil and a given leachate flow volume, the only mechanism that allows a greater Na-removal efficiency than that allowed by Ca ions supplied by lime hydrolysis is the existence of an additional Ca-ion supply such as applied gypsum or the dissolution of soil lime by an acid of some kind.

Details of the mechanisms involved are not completely understood. For instance, why did one crop have a greater influence on the Na-leaching rate than did another? However, the fact that treatments with the highest CO_2 concentrations were also the ones with the greatest Na-removal efficiency gives valuable clues as to the types of mechanisms that should be investigated further.

The fact that the sorghum hybrid was more effective in reclaiming a sodic soil with very poor physical properties than was a gypsum application in excess of what would normally be economically feasible indicates reclamation techniques may be developed that are both effective and economically practical for reclaiming certain lands whose reclamation is not considered practical.

Further study is needed to determine the source of the measured CO_2 and the mechanism which dissolved the Ca that exchanged with the Na.

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