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Predicting Optimum Depth of Profile Modification by Deep Plowing for Improving Saline-Sodic Soils

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Predicting Optimum Depth of Profile Modification by Deep Plowing for Improving Saline-Sodic Soils[1]

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ABSTRACT

A previously developed procedure for predicting the effect of mixed-salt solutions on soil hydraulic conductivity (HC) was used to predict the relative hydraulic conductivity (RHC) of separate soil horizons from saline-sodic soils, using a standard low-salt solution following a standard high-salt solution at a fixed exchangeable-sodium level. These values were then used to predict the RHC of mixtures of the same horizons simulating profiles modified to various depths by deep plowing. Weighting RHC values for individual horizons by the depth fraction of each horizon in the soil mixture provided RHC values of proper magnitude, except when large proportions of calcareous subsolum material were incorporated into the mixture. Results were improved by multiplying calculated RHC values for each soil mixture by the initial HC of the mixture. This corrected for the filling of conducting pores in more permeable horizons by smaller particles from less permeable horizons during the mixing process (analogous to particle dispersion and pore sealing during the leaching of saline-sodic soils). Soil constants determined for the mixed soils permit the prediction of the response of these soils to any other exchangeable sodium levels or soil solution concentrations of interest. Results were consistent with lysimeter and field plot observations on the same soils, including deep plowing trials.

Additional Index Words: hydraulic conductivity, dispersion, mixed-salt solutions, reclamation, gypsum, lime, soil mixing.

SOIL PROFILE modification has been proposed as a means of improving saline-sodic soils and soils with hardpans, claypans, or dense clay subsoil layers (1, 2, 3, 7, 8, 9, 12). Various means have been suggested and devised for mechanical mixing to radically alter soil profile conditions. At the present time, deep plowing is the most practical means of significantly and economically modifying adverse soil profile conditions on a large scale.

On the lower Snake River Plain and in the adjacent river valleys of southwestern Idaho and southeastern Oregon, more than 100,000 ha (250,000 acres) of irrigated and potentially irrigable lands are affected by inclusions of saline-sodic (slick spot) soils. The occurrence of such soils in these lands seriously complicates soil and water management and greatly decreases land value and productivity. Several studies have shown that the soils can be improved by adequate deep plowing or mechanical mixing (8, 9). An estimated 6,000 to 8,000 ha (15,000 to 20,000 acres) of such soils in the area have been deep plowed with 1.0- or 1.3-m (3- or 4-foot) moldboard plows.

The success of deep plowing depends on the mixing of low-clay calcareous or gypsiferous subsoil material with high-clay, B-horizon material to provide a more favorable physical matrix for soil water movement (physical reclamation) and to provide a source of calcium for replacement of exchangeable sodium in the profile (chemical reclamation). If the soluble salt concentration of the leaching solution is not maintained sufficiently high during the chemical reclamation process or the exchangeable sodium percentage (ESP) of the soil is not reduced sufficiently by mixing, the soil will disperse due to the presence of excess exchangeable sodium. Also, the hydraulic conductivity (HC) of the soil will decrease substantially. Increasing the depth of deep plowing on those soils that are most responsive to this treatment generally results in a more coarse textured and more calcareous mixed soil, that is more resistant to the effects of high soil ESP and low salt concentration of the leaching water. The initial mixing tends to lower the overall ESP of the mixed soil and to modify the average salt concentration of the soil solution as well. However, the depth of plowing is limited to about 107 cm (42 inches) by available equipment, and plowing to the maximum possible depth costs considerably more than more shallow plowing because of the increased power requirements. Thus, it is economically advantageous to mix the soil to the minimum depth required for adequate reclamation.

The conditions that affect soil improvement by deep plowing are not fully understood. There are few precedent studies on methods for evaluating mixed soil systems or for predicting the possible beneficial effects of soil profile modification. The general method for evaluating soil conditions which may be improved by deep plowing has been to plow the affected soils and to evaluate soil improvement through detailed chemical and physical analyses over a 3-to-5 year period. Such large scale tests are costly, time consuming, and often yield little fundamental information of use in extending the results to other soils. Consequently, there is a need for adequate methods to predict the types of response to be expected from deep plowing operations.

This study determines the applicability of a procedure (4) for using predicted changes in relative hydraulic conductivity (RHC) of separate soil horizons from saline-sodic soils (determined first by using a standard high-salt solution followed by a standard low-salt solution, at a fixed exchangeable-sodium level) for predicting the relative HC of mixtures of the same horizons simulating profiles modified to various depths by deep plowing. The ultimate objective was to develop a procedure for predicting the depth of deep plowing necessary to insure the maintenance of adequate permeability during the reclamation process. This aspect of the problem, coupled with the question of the average particle-size distribution to be sought in the mixed

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Table 1—Physical and chemical characteristics of soils used in the hydraulic conductivity and plowing depth studies

Location	Horizon	Depth	Clay (<0.002 mm)	Silt (0.50–0.002 mm)	Sand (2–0.05 mm)	Saturation percentage	EC_e*	ESP	$CaCO_3$	CEC	Gypsum	pH
		cm	%				mmho/cm	%		meq/100 g		
Site A	A2	0–1	15	59	27†	31.0	1.4	7.6	0.0	15.4	0.0	6.7
	B21t	1–23	44	40	16†	55.9	5.4	28.3	0.0	38.9	0.0	7.8
	B22tsa	23–33	27	52	19	59.1	16.7	41.6	0.0	35.4	0.0	7.8
	B3tsaca	33–48	39	30	28	61.8	16.7	25.7	12.7	32.4	0.0	7.8
	B3saca	48–69	26	38	36	58.7	16.7	38.1	13.2	34.4	0.0	7.9
	C1sacacs	69–>99	16	25	59‡§	47.1	13.9	30.2	12.8	31.4	9.3	7.9
Site B	A2	0–1	12	63	25	33.0	1.6	19.9	0.0	14.0	0.0	7.5
	B21t	1–13	40	42	18	51.3	7.5	29.7	0.0	30.5	0.0	7.5
	B22tsa	13–36	42	42	16	42.9	17.2	37.5	0.0	25.5	0.0	7.7
	B3sa	36–46	28	48	24	43.6	15.9	22.0	2.7	26.3	1.6	7.8
	C1sa	46–51	24	35	41‡§	50.7	13.5	26.9	2.7	22.5	1.6	7.8
	C1cacs	51–>61	22	29	49‡§	49.9	6.2	22.7	26.2	18.7	9.5	7.9
Site C	A2	0–4	9	39	52	17.6	1.5	5.6	0.0	14.3	0.0	7.8
	B2t	4–20	43	32	25	47.2	3.6	28.5	0.0	33.8	0.0	7.2
	B3t	20–36	33	29	39†	39.8	8.1	33.8	2.4	29.8	0.0	7.8
	C1saca	36–56	23	40	37†	34.9	14.7	37.5	11.2	25.6	0.0	7.9
	C2sasica	56–69	14	36	50‡§	34.1	10.0	30.4	9.8	28.0	0.0	8.0
	C3sica	69–>102	8	32	60†	28.9	8.5	32.3	7.6	18.2	0.0	8.1
Site A	Mixture	0–89	35	46	19	54.4	16.1	42.0	12.1	36.5	0.8	7.8
Site B	Mixture	0–61	36	47	17	45.7	18.2	42.5	9.6	28.7	2.8	7.6
Site C	Mixture	0–86	25	38	37	32.1	9.2	44.6	7.2	26.3	0.0	7.9

* EC_e = electrical conductivity of saturation extract at 25C; ESP = exchangeable-sodium percentage; CEC = Cation-exchange capacity.
† Horizon also contains 3 to 10% gravel.
‡ Horizon also contains 20 to 30% gravel.
§ Sands consist mostly of caliche.

profile in order to provide adequate initial permeability (a question which is beyond the scope of the current paper), constitutes one of the major considerations in establishing the optimum depth of deep plowing on saline-sodic soils.

MATERIALS AND METHODS

The study samples were representative saline-sodic soils from three sites (designated A, B, and C), typical of the soil inclusions (slick spots) occurring in three major complex soil associations in the proposed Initial Butte Irrigation Unit near Boise, Idaho. The individual soils in the complexes are unnamed but the saline-sodic and normal associated soils within each complex usually have similar morphological characteristics. The strongly salt-affected soils of the "slick spot" areas merge gradually to the predominant nonsaline, nonsodic soils in the areas surrounding the spots. Generally, the soils have developed over or in mixed silty alluvium or alluvium and loess with the surface horizons influenced by variable depositions of loess. The soils at Sites A and C are deep soils, underlain by coarse textured alluvium to depths greater than 3 m (10 feet). The saline-sodic soil inclusions at these sites would be classified as natrargids, whereas the surrounding soils would be classed as calcic haplargids. The soils at Site B have moderately shallow profiles formed in thin layers of loess over poorly consolidated alluvium or basalt at depths of 60 to 75 cm (24 to 30 inches). The saline-sodic soils at Site B have an indurated or strongly cemented silica—calcium carbonate duripan at depths of 40 to 100 cm (16 to 40 inches) and would be classed as nadurargids. They are similar to the Sebree soils described previously (8), whereas the surrounding nonsaline, nonsodic soils would be classified as calcic durargids and are similar to the Chilcott series. The associations containing the slick spots comprise approximately 50% of the irrigable land area in the irrigation unit. Each soil association contains from 25 to 35% of slick spots on an areal basis. The soils occur on nearly level alluvial terraces and have favorable topographic characteristics. Except for the presence of the slick spots, they appear to be well suited for irrigation.

Soil characterization included particle-size distribution, pH, and electrical conductivity of the saturation extract, exchangeable sodium percentage, cation-exchange capacity, and gypsum and lime contents. Procedures used were those outlined by the US Salinity Laboratory Staff (14). Some initial analyses were performed by personnel at the Snake River Development Office of the US Bureau of Reclamation, Boise, Idaho (Vernon C. Bushnell and Everett V. Williams, unpublished data). Samples from individual horizons of each of the soils, as well as samples mixed to simulate the same soils deep plowed to various depths, were analyzed. As the field bulk density on the major horizons were comparable, each horizon was included in the mixture as a weight fraction equal proportionally to the depth of the horizon relative to the overall depth of the mixture. This is equivalent to assuming a uniform bulk density for the profile.

Hydraulic conductivity was determined by the method outlined by McNeal and Coleman (5), except for the substitution of 25-g samples and 3.2-cm I.D. permeameters. (6). Determinations were made at a high-salt concentration (500 meq/liter) and then at a low-salt concentration (50 meq/liter) as discussed by McNeal (4). All solutions had an SAR of 100 [SAR = sodium-adsorption-ratio = $Na/((Ca + Mg)/2)^{1/2}$ where all concentrations are in meq/liter]. These solutions would produce an equilibrium ESP of approximately 60 for many arid-land soils (14). These salt concentrations and this exchangeable sodium level were selected to provide a significant reduction in HC from which to calculate reductions in HC at other salt concentration and exchangeable sodium levels. A total of 250 ml of each solution was passed through the soil to insure equilibration of soil and solution and to produce nearly constant HC values.

RESULTS

Physical and chemical characteristics of the soils are summarized in Table 1. Each soil had both a high clay content and a high ESP level in the B horizon which enhanced the probability of HC reductions as soluble salts were leached during reclamation. Initial soluble salt concentrations were high in all but the surface layers. Mineralogical data for the soils indicated that montmorillonite was the dominant clay-sized mineral throughout the soil profiles at Sites A and B and in the lower B horizon at Site C (unpublished data, Vernon C. Bushnell).

All three soils contained calcium carbonate at the lower depths. The soils at Sites A and B contained measurable quantities of gypsum in the lowest horizon as well (1.0 meq of gypsum per 100 g ≅ 0.1% gypsum, or approximately 2.0 tons of gypsum per acre-foot of material). The gypsum present in the lowest horizon would be sufficient to replace 11% of the exchangeable sodium in a sample of the soil from Site A mixed to a depth of 80 cm or 27% in a sample mixed to 100 cm. Comparable figures for the shallow soil at Site B would be 24% and 55% of the exchangeable

Table 2—Hydraulic conductivity data for soils used in the hydraulic conductivity and plowing depth studies

Location	Horizon	Depth	High-salt HC*	Low-salt HC	Relative HC	Weighted† relative HC
		cm	cm/hour			
Site A	A2	0–1	0.27	0.15	0.57	0.01
	B21	1–23	1.05	0.04	0.04	0.01
	B22	23–33	0.99	0.03	0.03	0.00
	B3	33–48	1.69	0.06	0.04	0.01
	B3	48–69	1.41	0.14	0.10	0.03
	C1	69–>99	0.49	0.43	0.88	0.13
						0.19†
Site B	A2	0–1	0.19	0.08	0.45	0.01
	B21	1–13	0.18	0.05	0.30	0.04
	B22	13–36	0.14	0.11	0.80	0.23
	B3	36–46	0.28	0.25	0.91	0.11
	C1	46–51	0.28	0.26	0.94	0.06
	C1	51–>61	0.25	0.22	0.88	0.33
						0.78†
Site C	A2	0–4	0.39	0.34	0.87	0.04
	B2	4–20	0.43	0.07	0.16	0.03
	B3	20–36	0.32	0.08	0.24	0.05
	C1	36–56	0.29	0.23	0.81	0.20
	C2	56–69	0.46	0.41	0.88	0.14
	C3	69–>102	0.39	0.35	0.89	0.13
						0.59†

* HC = Hydraulic conductivity.
† Assuming an 81-cm (32-inch) depth of mixing.

sodium replaced for samples mixed to depths of 60 cm and 80 cm, respectively. However, many of the soils from the same geographical area have been reclaimed satisfactorily with deep plowing and irrigation alone when $CaCO_3$ is the only detectable source of calcium in the soil profile (9). Visual observation of field tests suggests that the native gypsum is imperfectly mixed under these conditions and hence would be less effective as a chemical amendment. The quantity of gypsum present would dissolve in the first 25 to 50 ml of high-salt solution that passed through the mixed soils during the laboratory HC determinations. Sufficient high-salt solution was passed through the soils subsequently to ensure equilibration of the soil and solution. Thus, the gypsum was not a factor in most conclusions from the laboratory portion of this study although it would be an important asset in the reclamation of the field soils.

Properties of the soil mixtures such as EC_e and clay content were in general agreement with those anticipated from determinations on individual soil horizons. The most disconcerting deviation was the occurrence of the ESP levels which were 10 to 13% higher for the soil mixtures than predicted from the ESP and CEC values of the component horizons. No suitable explanation for this result has been developed to date. Minor variations in predicted properties probably reflect the variations in bulk density among the different layers so that weight proportions and depth proportions are not strictly comparable. Determination of field bulk densities and mixing in proportion to weight fractions of the mixture instead of in proportion to depth fractions would constitute an improvement in future studies.

HC data for individual soil horizons at each site are given in Table 2. These values are the means of three to nine separate determinations on each sample. Average coefficients of variation for the low-salt HC values were 5.0, 7.7, and 4.3% at Sites A, B, and C, respectively, expressed as a percentage of the respective high-salt values. Such a basis of expression is reasonable for it is the maintenance of the inherent (high-salt) HC that is of most concern to the reclamation process. For the deep soils from Sites A and C, samples from the upper and lower parts of the profile were relatively stable under high-sodium, low-salt conditions, but samples from intermediate depths were unstable under these same conditions. This unstable material was present from the 1- to-69-cm depths at Site A, so reclamation by deep plowing would require mixing to depths as great as 90 cm or deeper. For soils from both Site A and Site C, a mixture containing less than 25% clay appeared to be required to insure a relatively stable HC during the reclamation process. However, samples from Site A were more unstable than those from Site C at comparable clay contents.

Table 3—Hydraulic conductivity data for soils mixed to simulate deep plowing

Location	Depth of Mixing	Relative HC (1) Measured	Relative HC (2) Predicted	High-salt HC (3) Measured	High-salt HC (4) Predicted	Low-salt HC (5) Measured	Low-salt HC (6) Predicted
	cm	cm/hour					
Site A	0–81	0.23	0.19	0.55	1.16	0.12	0.10
	0–89	0.22	0.25	0.41	1.10	0.09	0.10
	0–99	0.44	0.32	0.37	1.04	0.16	0.12
	0–107	0.66	0.36	0.45	1.00	0.29	0.16
Site B	0–61	0.92	0.74	0.16	0.20	0.15	0.12
	0–69	0.80	0.76	0.19	0.21	0.15	0.14
	0–76	0.77	0.77	0.25	0.21	0.19	0.19
Site C	0–81	0.79	0.60	0.13	0.37	0.11	0.08
	0–99	0.74	0.65	0.12	0.37	0.08	0.08
	0–107	0.87	0.67	0.22	0.38	0.19	0.15

Although clay contents and ESP levels were as high as those observed at the other sites, samples from the shallow, gypsiferous site (Site B) maintained considerably higher RHC values under high-sodium, low-salt conditions. However, such apparent "stability" may be partially due to the low values for high-salt HC observed for these samples, resulting in less opportunity for drastic changes in soil HC under low-salt conditions. The rapid reclamation of soils at this site following mixing in lysimeters and in the field probably arises more from the presence of substantial quantities of gypsum in the profile than from an unusually high stability under high-sodium, low-salt conditions.

Sample calculations in the final column of Table 2 illustrate the relative contributions of the individual horizons to the predicted RHC of typical soil mixtures. An 81-cm (32-inch) depth of mixing was assumed for the calculations. The weighted RHC of the mixed soil (RHC_m) is calculated from the relation

$$RHC_m = \sum_{i=1}^{n} (RHC_i \times D_i) / D_m \qquad [1]$$

where D refers to the appropriate horizon thickness (in cm), i is an interger serving as an index for the horizon under consideration, and D_m is the total thickness of the mixed profile. For the deep soils (Sites A and C), the predicted RHC of the mixture would depend largely upon the quantity of C horizon material incorporated, with ⅔ to ¾ of the RHC attributable to C horizon material. For the more shallow soil (Site B), however, nearly half of the RHC of the mixture was associated with material from the B horizons. In all cases, the thin A2 layer at the soil surface had essentially no effect on the overall HC of the mixture.

Columns 1 and 2 of Table 3 compare measured and

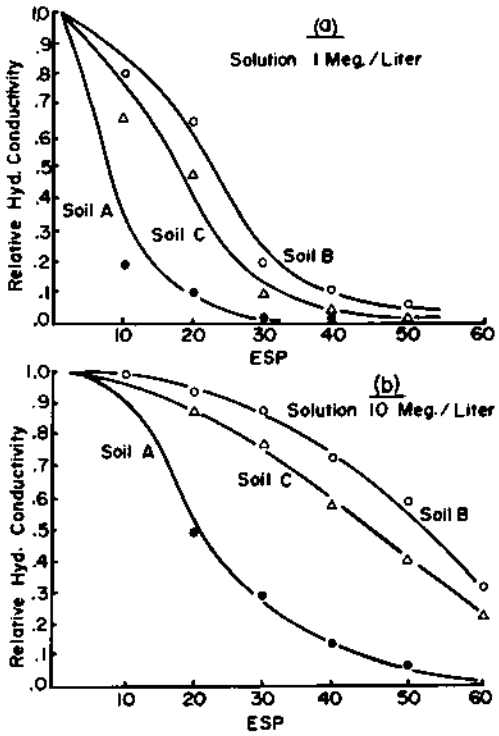

Fig. 1—Predicted relative hydraulic conductivity as a function of soil ESP and soil solution concentration. Hypothetical depth of mixing = 86 cm for soils, Site A and C, 61 cm for soil, Site B.

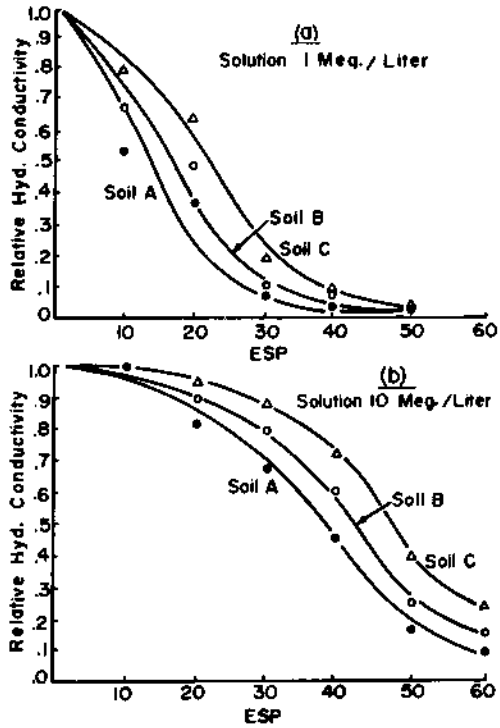

Fig. 2—Predicted relative hydraulic conductivity as a function of soil ESP and soil solution concentration. Hypothetical depth of mixing = 107 cm for soils, Site A and C, 76 cm for soil, Site B.

predicted RHC values for soil mixtures. Predicted RHC values were of the same magnitude as measured values but generally somewhat smaller. For samples from Sites A and C, measured RHC values did not increase commensurably with the increasing amounts of C horizon material incorporated into the mixture by mixing to greater soil depths.

The values in columns 3 and 4 of Table 3 represent measured and predicted HC (rather than RHC) values for the high-salt solution. Predicted values were two- to threefold greater in all cases than measured values for mixtures from the deep soils (Sites A and C). This probably arises from small particles from other horizons being packed into interaggregate pores of a given horizon in the mixed samples. As a result, the HC of the mixture was lower than would be predicted from the HC of the component horizons. However, high-sodium, low-salt conditions also tend to decrease the HC by decreasing the size and number of conducting pores (5, 11, 13). If some of the conducting pores were already partially clogged during the soil mixing process, opportunity for additional decreases in HC would be less because of swelling and dispersion, and the RHC of the mixture to the low-salt solution would be higher than anticipated. This effect should be lessened under field conditions where soil aggregates would be less completely disrupted and less intimately mixed than in the laboratory.

The last two columns of Table 3 show the measured and predicted values of the low-salt HC for various soil mixtures. Predicted values were weighted as indicated in equation [1], except that the low-salt HC was obtained by multiplying the measured high-salt HC by the predicted RHC of the mixture. In this manner, differences in HC arising from the mixing and packing operations were compensated. Although it had been hoped initially that even this degree of curve-fitting would not be necessary, fitting at this single point permits the generation of an entire family of curves describing response of the soil to any other salt concentrations and exchangeable sodium levels. This is also the suggested manner for using predicted HC values in the field (4). The procedure thus can be coupled with models of the salt concentrations and ESP during the reclamation process to predict in advance the success or failure of various deep plowing and leaching combinations.

The agreement between measured and predicted low-salt HC values was acceptable in all cases and was excellent in the case of all but the greatest depth of mixing at the deep, gypsiferous site (Site A). The situation at Site A represents the maximum possible depth for current deep-plowing equipment and should not be considered a serious discrepancy in evaluating the recommended approach.

Once the RHC of a soil mixture has been predicted at a given salt concentration and exchangeable sodium level, the RHC at any other salt concentration and exchangeable sodium level can be predicted subsequently. The predictions can be used in conjunction with models of the chemical reclamation process to estimate changes in soil permeability at selected depths in the soil profile during various stages of the leaching process. Typical predictions are presented in Fig. 1, where the predicted RHC of samples from Sites A, B, and C mixed to depths of 86, 61, and 86 cm, respectively, are given as a function of ESP at total salt concentrations of 1 and 10 meq/liter. Similar predictions are given in Fig. 2 for mixing depths of 107, 76, and 107

cm, respectively. Plotted points represent the results of calculations at predetermined ESP levels with smooth curves then fitted through these points. The procedure described by McNeal (4) involves fitting a function of specified form to the experimental values and then using the resultant empirical constants to predict RHC for any other salt concentration or exchangeable sodium levels of interest. A nomograph simplifying the calculations is given in the cited article. Once generated, soil curves can be used to predict the response of a mixed soil to a wide variety of chemical conditions which may be anticipated during the reclamation process.

The total salt concentration of the river waters to be used for the proposed irrigation project is approximately 1 meq/liter. The average initial ESP level for all mixing depths represented by the figures was approximately 40%. The most dispersive chemical conditions which could be encountered during the leaching process would occur if soil solutions having the approximate salt concentration of the irrigation water were to coexist with soil particles having the approximate ESP of the mixed soil. This is not unreasonable because salt is removed more readily than exchangeable sodium during the leaching process. Soil from the deep, gypsiferous site (Site A) would be stable (i.e. RHC $\lesseqgtr$ 0.50) only to an ESP of approximately 5 to 10 at a total salt concentration of 1 meq/liter if mixing were carried out to a depth of 86 cm. In comparison, soil from Site A mixed to a depth of 107 cm would be stable to an ESP of 15 to 20. Reclamation following deep plowing would be unlikely with the first depth of plowing but quite probable when the deeper plowing depth was employed. Soils from Sites B and C exhibited approximately the same stability at either mixing depth with respective stabilities to 20 and 25% ESP at a salt concentration of 1 meq/liter.

Due to mineral dissolution, a total salt concentration of 10 meq/liter is more reasonable for the lower limit of salt concentration in the soil solution during the initial stages of the reclamation process when the highest levels of exchangeable sodium are present on the soil (10). At this salt concentration, soil from Site A is particularly responsive to depth of mixing with stability to ESP levels of 25 and 40, respectively, for the shallow and deep mixing depths. Therefore, deep plowing at Site A should be more successful by mixing to the greatest possible depth, so more effort should be made to increase the depth of deep plowing at this site. At a total salt concentration of 10 meq/liter, soils from Sites B and C would be stable at either depth of deep plowing so increasing the depth of deep plowing would be of little benefit at these locations. Data such as given in Fig. 1 and 2 would also indicate situations where deep plowing would be impractical for sodic soil reclamation because of insufficient soil depth of or insufficient stability of the mixed soil under anticipated chemical conditions.

DISCUSSION

Verification of RHC predictions under field conditions is difficult because of variations in soil properties, difficulties in predicting soil chemical conditions during reclamation, and limitations on the degree of mixing obtained during field operations. Infiltration rates determined during application at 15 to 20 cm (6 to 8 inches) of water by basin irrigation for the deep plowed field plots were in the ranges of 0.5 to 2, 5 to 10, and 2 to 4 cm/hour at Sites A, B, and C, respectively. This compares with infiltration rates of 0.05 to 0.10 cm/hour for untreated slick-spot soils at the same sites. Soils at the shallow, gypsiferous site (Site B) and the deep, nongypsiferous site (Site C) were reclaimed readily by deep plowing to the 61- and 86-cm depths, respectively. Such responses were predictable from RHC vs. ESP relationships shown in Fig. 1 and 2. However, soils from the deep, gypsiferous site (Site A), which was deep plowed to a depth of approximately 81 cm in the field, were not reclaimed after 4 years of cropping. Furthermore, this site demonstrated only limited reductions in ESP on two of four field plots after 4 years of cropping, despite the significant amounts of gypsum that were present in the lower portion of the profile at this site before plowing. This is probably a consequence of the relatively high clay content persisting in the upper soil layers following mixing and the dispersion and sealing of this soil during the initial increments of leaching which restricted water penetration, gypsum dissolution, and replacement of exchangeable sodium. The rate of reduction of ESP in the field was greatest at the shallow, gypsiferous site (Site B) as predicted from Fig. 1 and 2 and from the presence of considerable natural gypsum within the profile at this site.

In lysimeter studies where the soils were thoroughly mixed to 86 cm reclamation had occurred in all cases within 3 to 4 years after mixing. Thus, the critical depth of mixing for the deep, gypsiferous site (Site A) was somewhat greater than 81 cm for imperfectly mixed sites and somewhat less than 86 cm for well mixed sites. In the lysimeter experiments, the rate of reduction in ESP was lowest for mixed soil from the deep, nongypsiferous site (Site C). This is undoubtedly so because gypsum was lacking in this profile with resultant dependence only on lime from the calcareous layer and of the irrigation water as sources of soluble calcium to replace exchangeable sodium. However, the relative stability of this soil when plowed to the 86-cm depth sustains adequate water percolation and permits reclamation even in the absence of a more readily-soluble source of calcium. Since the soil would be quite unstable at the average ESP of the mixture (ESP = 44.6, Table 1) and the salt concentration of the irrigation water (1 meq/liter), the average salt concentration of the soil solution must have been closer to 10 meq/liter or higher during the initial stages of the field leaching process. Salt concentrations of saturation extracts from various depths of this soil during the field reclamation process ranged between 10 and 100 meq/liter, bearing out this prediction (W. W. Rasmussen, unpublished data). At salt concentrations of this magnitude, the soil has a relatively high RHC even at ESP values of 40 or greater.

In time, more precise criteria for mixing probably will be established. In the past, average clay and lime contents of the mixed profiles have been the main criteria used. However, a priori prediction of the effects of these parame-

ters on soil hydraulic conductivity is still in the embryonic stages. So, direct consideration of the degree to which the mixed soil can be expected to resist HC changes under the most adverse chemical conditions (lowest salt concentrations and highest exchangeable sodium levels) anticipated for the reclamation process is a substantial improvement in the selection criteria. The approach may eventually be extended to the selection of actual infiltration rates or HC values below which the values for the mixed soils should not decrease for "safe" chemical and physical reclamation. Such values are difficult to predict in advance, whereas RHC can be predicted in advance following a few simple measurements using the approach outlined above.

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