Soil Salinity—Four-electrode Conductivity Relationships for Soils of the Northern Great Plains[1]

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ABSTRACT

Influence of soil texture, soil geographic location and parent material, and calibration method on the linear EC_e-EC_a relationship was investigated. Linear regression relationships between saturation extract electrical conductivity (EC_e) and bulk soil electrical conductivity (EC_a) as measured by the four-electrode technique were developed for northern Great Plains soils. Most correlation coefficients *(r)* exceeded 0.95 and all were significant at the 0.01 probability level. Geographic location had little effect on the EC_e vs. EC_a relationship; therefore, an EC_e vs. EC_a calibration made for a soil textural class at one location will apply to another location having a similar range in soil water, clay content, and salinity. Clay content affected linear regression line slopes more than did other factors investigated. Regression slopes varied from 3.06 for a clay to 12.99 for a loamy sand over the clay concentration range of 63.0 to 6.5%, respectively.

To minimize adverse effects caused by natural variation in soil texture, water content, and salinity when making field EC_e vs. EC_a calibrations, we suggest artificial salinization of columns of the soil type in question, which will permit subsequent analysis of the soil by either the cell or *EC*-probe calibration method.

Additional Index Words: **Bulk soil electrical conductivity, saline seep, EC_e vs. EC_a salinity calibration, dryland salinity, soil texture, in situ field salinity.**

THE FOUR-ELECTRODE resistivity technique for measuring bulk soil electrical conductivity (EC_a) has been used by Rhoades and Ingvalson (7) on irrigated soils and Halvorson and Rhoades (4, 5) on dryland, saline-seep areas to estimate soil salinity in the field without soil sampling and subsequent laboratory analyses. Rhoades and Ingvalson (7) reported a linear relationship, $EC_e = 9.095(EC_a) - 0.274$ with a correlation coefficient *(r)* of 0.997, between saturation extract electrical conductivity (EC_e) and EC_a, as measured by the four-electrode technique for a Pachappa fine sandy loam. Halvorson and Rhoades (4) reported a linear relationship between EC_e and EC_a, for a combination of sandy loam (sl) and clay loam (cl) soils, of $EC_e = 6.71(EC_a) - 1.31$ with an r value of 0.98. The EC_e vs. EC_a calibration has been reported to change with soil type and saturation percentage (6, 9). These relatively large differences in regression line slopes suggest that differences in texture, field soil water content, and/or soil geographic location or parent material may affect the components of the linear EC_e vs. EC_a relationship.

Our objective was to determine if the relationship between EC_e and EC_a changed: (i) when using different methods of calibration; (ii) for soils of different geographic locations and parent material; and (iii) for different textural classes of soils found in the northern Great Plains. Each geographic location examined was affected by the dryland saline-seep problem (3).

MATERIALS AND METHODS

One predominant soil texture was selected for study by local Soil Conservation Service personnel in each geographic location examined. The following dryland locations in the glaciated plains of Montana and North Dakota were selected: (i) sites A, B, C, N, and O in north-central Montana; (ii) sites D, E, F, F1, F2, G, and G1 in northeast Montana; and (iii) site H in northwest North Dakota. Three dryland areas were selected in the sedimentary plains of Montana: (i) site I in south-central Montana; and (ii) sites J and K in southeast Montana. Two irrigated sites, L and M, in the Lower Yellowstone Valley of northeast Montana were also examined.

To minimize the influence of soil water content on the EC_e vs. EC_a relationship (4), nearly all data were collected from summer-fallowed fields associated with a saline seep (3) or in the spring when soil water content was near field capacity. Some data were collected in August 1973 under drier field conditions at sites C, F, and G. Those samples and EC_a readings collected where soil water content was less than 80% of the gravimetric soil water content found in fallow soil were disregarded in the linear regression analyses. The data were collected during May and August 1973 and June 1974 through August 1976.

EC_a was determined by three different methods during the study, but not all were used at each geographic location. The "conventional method," whereby four electrodes were equally spaced in a straight line (referred to as the Wenner-electrode configuration), was used at most dryland locations. Details of this procedure have been described (4, 7). Apparent EC_a, values in

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Table 1—Linear regression results of conventional field EC_e vs. EC_a calibration method and mean soil water content, saturation percentage, and clay and sand content for several study sites examined in the northern Great Plains (a = 30.5 cm).

Site	Linear regression									Texture
	n†	m ± SE†	b ± SE†	r†	$SE_{y.x}$†	H_2O ± SD†	SP ± SD	Clay ± SD	Sand ± SD	
						%				
I	7	3.50 ± 0.60	−0.12 ± 4.35	0.93	5.82	24.5 ± 4.1	62.8 ± 11.0	48.3 ± 8.5	32.2 ± 11.5	c
E	6	4.68 ± 0.55	−2.21 ± 1.06	0.97	1.32	24.3 ± 3.2	54.6 ± 4.2	43.0 ± 8.2	21.2 ± 6.9	c
B	7	5.50 ± 0.47	0.46 ± 1.05	0.98	1.38	19.2 ± 2.9	42.4 ± 3.8	35.4 ± 3.7	40.1 ± 2.7	cl
C	8	5.29 ± 0.77	0.62 ± 2.08	0.94	4.39	22.1 ± 6.4	41.9 ± 6.3	32.0 ± 3.1	28.4 ± 2.2	cl
G	36	5.85 ± 0.24	−0.93 ± 0.44	0.97	1.74	20.6 ± 3.5	46.8 ± 4.7	39.0‡	26.0‡	cl
H	6	4.59 ± 0.31	−0.23 ± 0.62	0.99	0.94	26.6 ± 5.0	50.3 ± 4.7	32.6 ± 3.7	37.2 ± 7.2	cl
A	6	6.35 ± 1.06	−2.40 ± 3.34	0.95	4.86	21.1 ± 2.5	51.2 ± 8.2	35.6 ± 1.7	13.0 ± 1.4	sicl
D	7	5.61 ± 0.79	0.05 ± 1.28	0.95	2.32	20.0 ± 2.0	40.0 ± 4.6	24.4 ± 3.1	54.2 ± 4.7	scl
D	5	5.58 ± 0.68	−0.10 ± 1.51	0.98	1.81	24.9 ± 3.3	42.6 ± 3.7	26.2 ± 0.6	34.3 ± 1.0	l
F	8	7.25 ± 1.23	−0.62 ± 1.20	0.92	1.72	16.6 ± 4.1	--	16.0‡	59.0‡	sl
Combined sites										
	8	3.05 ± 0.34	0.86 ± 1.72	0.96	3.68	25.8 ± 3.6	77.2 ± 10.9	58.8 ± 1.0	8.2 ± 7.5	c
	16	4.22 ± 0.27	−0.02 ± 0.97	0.97	3.03	22.0 ± 4.3	53.3 ± 8.1	43.1 ± 2.7	26.6 ± 7.5	c
	47	5.65 ± 0.25	−0.80 ± 0.46	0.96	2.22	19.8 ± 2.6	46.6 ± 4.0	36.0 ± 3.0	29.2 ± 6.1	cl
	12	5.96 ± 0.88	−1.34 ± 1.32	0.91	2.70	20.0 ± 2.7	43.0 ± 7.3	26.8 ± 4.5	51.7 ± 3.7	scl
	11	6.02 ± 0.35	−1.18 ± 0.70	0.99	1.24	26.5 ± 3.8	41.9 ± 4.1	23.8 ± 3.8	39.0 ± 7.7	l
	13	7.36 ± 0.94	−0.85 ± 0.74	0.92	1.60	17.3 ± 4.2	33.2 ± 2.5	17.7 ± 2.4	60.8 ± 8.7	sl

† n = number of samples; m = slope and b = intercept of linear regression equation $EC_e = m(EC_a) + b$; SE = standard error; r = correlation coefficient; $SE_{y.x}$ = standard error of estimate y on x; SD = standard deviation.
‡ Estimates from previous work (3).

mmhos/cm were calculated as follows:

$$EC_a = 1{,}000 f_t / 2\pi a R_t \qquad [1]$$

where a is the inter-electrode spacing (cm), R_t is the measured soil resistance (ohms) at field temperature, and f_t (12) is the correction factor for converting EC_a to 25°C. Inter-electrode spacings *(a)* of 30.5, 61, 91.5, and 122 cm were used at the site of each EC_a determination when using this method. One soil core to a depth of 122 cm was collected at the center point of the straight line of electrodes and sectioned into 30.5-cm sections for separate laboratory analyses.

The cell calibration method (8) was used at many of the locations to determine EC_a values of undisturbed soil cores, which were subsequently used for laboratory analyses. In this method, undisturbed soil cores having a range in EC_a and EC_e values were collected in plastic cells (7.5-cm diameter, 7-cm deep) from the field. An average EC_a value was calculated from eight resistance readings made on each core in the field using the following equation to calculate EC_a in mmhos/cm:

$$EC_a = k f_t \, 1{,}000 / R_t \qquad [2]$$

where k is a predetermined cell constant (cm^{-1}), R_t is measured soil resistance (ohms), and f_t (12) is a temperature correction factor for converting EC_a to 25°C.

The EC-probe calibration method (9) was used at several dryland locations and at all irrigated locations. Using this method, each of four plastic cylinders (25.4-cm diameter by 50-cm long) placed on the soil surface was filled with a different salt solution (EC = 4, 20, 40, and 60 mmhos/cm) having a sodium-adsorption ratio (SAR) of approximately 8. A total of 18 liters of salt solution was passed through the surface soil (0- to 30-cm soil depth) located below each cylinder. After a minimum 24-hour equilibration period, EC_a readings were taken from the 8- to 23-cm soil depth and a corresponding soil sample was collected for laboratory analyses from approximately the same soil volume. Sodium and calcium chloride salts were used to prepare the salt solutions.

Each soil sample collected was analyzed for EC_e (12) and gravimetric soil water content. Most samples were analyzed for saturation percentage (SP) and sand, silt, and clay percentages by the hydrometer method (1). Corresponding textural class was determined as defined in the Soil Survey Manual (11). The following symbols will be used to identify textural classes: c–clay; sic–silty clay; sicl–silty clay loam; scl–sandy clay loam; cl–clay loam; l–loam; sl–sandy loam; and ls–loamy sand.

The least squares linear regression method was used to determine the relationship between EC_e and EC_a (2).

Only data from sites having adequate ranges and distributions of EC_e and EC_a values are reported. At many sites, soil texture varied considerably with profile depth. Therefore, we analyzed the data for each site in terms of EC_a values for a = 30.5 cm and corresponding EC_e values for the 0- to 30.5-cm soil depth. Data were further grouped at each site for samples of similar texture, enabling us to compare calibration methods.

RESULTS AND DISCUSSION

Comparison of Calibration Methods

Conventional Method

Results of EC_e vs. EC_a regression analyses for the conventional EC_a method are summarized in Table 1 for those samples at a site and a combination of sites having similar textures for the 0- to 30.5-cm soil depth. In general, as clay content increased, the slope *(m)* of the regression line decreased. Comparing clay loam sites B, C, G and H shows that the regression line slope was less for site H than for site B, both similar in clay and sand content. Less slope for site H probably resulted from higher field soil water content. Rhoades, Raats, and Prather (10) found that as soil water content increased, the slope of the regression line for plots of EC_e vs. EC_a decreased. They further reported that the regression line of EC_e vs. EC_a plots should have negative intercepts because of natural surface soil conductance associated with exchangeable ions at the solid/liquid interface. Positive intercepts reported in Table 1 are probably due to conditions under which the EC_e vs. EC_a correlation was made. Soil samples collected from high salinity areas generally contained more water than did samples from low salinity areas. Higher soil water content at higher salinity levels tended to increase the EC_a value measured or to lessen the slope of the regression line, resulting in a positive intercept. Saline-seep soils tend to have higher water contents than surrounding soils because the salt source is a shallow perched water table. Soils in the seep also tend to be higher in clay content than surrounding soils. Therefore,

Table 2—Linear regression results of the cell EC_e vs. EC_a calibration method and mean soil water content, saturation percentage, and clay and sand content for several study sites examined in the northern Great Plains.

Site	Linear regression									
	n†	$m \pm$ SE†	$b \pm$ SE†	r†	$SE_{y.x}$†	$H_2O \pm$ SD†	SP ± SD	Clay ± SD	Sand ± SD	Texture
						%				
I	6	3.48 ± 0.13	-1.07 ± 0.57	0.99	0.84	23.2 ± 1.3	66.5 ± 7.7	48.2 ± 3.2	36.0 ± 4.3	c
B	8	4.02 ± 0.33	0.14 ± 0.95	0.98	1.29	21.1 ± 3.0	52.8 ± 4.4	41.5 ± 1.9	26.8 ± 2.2	c
A	5	4.85 ± 0.14	-0.69 ± 0.54	0.99	0.76	22.3 ± 1.1	57.9 ± 6.4	40.9 ± 1.1	9.0 ± 7.7	sic
H	5	4.83 ± 0.06	-1.54 ± 0.22	0.99	0.33	27.5 ± 3.9	51.2 ± 3.5	31.3 ± 2.6	33.0 ± 5.7	cl
D	4	4.35 ± 0.28	0.41 ± 0.83	0.99	0.81	26.3 ± 3.2	47.7 ± 3.8	26.2 ± 0.6	32.9 ± 1.8	l
H	3	4.81 ± 0.07	-1.72 ± 0.14	0.99	0.12	27.2 ± 5.1	53.0 ± 2.5	25.1 ± 2.0	40.1 ± 0.7	l
D	5	4.22 ± 0.34	0.08 ± 1.19	0.99	1.71	21.4 ± 2.2	40.7 ± 6.8	23.9 ± 4.1	54.0 ± 2.4	scl
D‡	7	5.44 ± 0.49	-0.37 ± 0.25	0.98	0.40	17.1 ± 3.4	28.6 ± 4.3	14.7 ± 3.8	62.7 ± 6.5	sl
Combined sites										
	5	3.06 ± 0.20	-2.42 ± 1.02	0.99	1.48	28.2 ± 2.8	79.3 ± 5.0	63.0 ± 2.6	5.7 ± 7.8	c
	14	3.47 ± 0.24	0.42 ± 0.84	0.97	1.82	22.0 ± 2.6	58.7 ± 9.1	44.4 ± 4.2	30.7 ± 5.7	c
	3‡	6.19 ± 0.66	-2.03 ± 0.53	0.99	0.44	21.1 ± 0.8	47.7 ± 2.1	37.3 ± 2.2	13.5 ± 5.0	sicl
	12	5.17 ± 0.36	-0.48 ± 1.11	0.98	2.51	23.9 ± 5.7	49.6 ± 7.2	31.8 ± 4.0	34.5 ± 6.0	cl
	8	4.23 ± 0.26	-0.04 ± 0.82	0.99	1.44	22.2 ± 4.5	37.9 ± 6.0	21.6 ± 1.8	56.2 ± 5.0	scl
	7	4.74 ± 0.29	-1.37 ± 0.89	0.99	0.89	29.1 ± 4.5	50.8 ± 4.7	24.0 ± 2.9	37.7 ± 6.1	l
	4	6.53 ± 1.03	-1.63 ± 0.87	0.98	0.96	20.3 ± 1.7	42.5 ± 7.3	24.8 ± 1.8	38.3 ± 5.4	l

† n = number of samples; m = slope and b = intercept of linear regression equation $EC_e = m(EC_a) + b$; SE = standard error; r = correlation coefficient; $SE_{y.x}$ = standard error of estimate y on x; SD = standard deviation.
‡ Very low salinity (EC_e) level <6 mmhos/cm.

conditions for a true linear EC_e vs. EC_a calibration are not always met when using existing field salinity conditions to establish an EC_e vs. EC_a calibration curve. However, as the data in Table 1 indicate, errors involved for all practical purposes are insignificant, and such EC_e vs. EC_a calibrations may be used. Multiple regression techniques were examined to evaluate the independent effects of soil clay and water content, but were found to be of little value in interpreting the data.

A summary of the $EC_e = m(EC_a) + b$ relationships for a combination of samples from all sites having similar soil textures or clay contents is also presented in Table 1. Decreasing clay content resulted in an increase in the slope of the regression line.

Cell Calibration Method

Some of the same errors in calibration were encountered with this technique as with the conventional method. The cell calibration data collected at each site were separated into textural classes before linear regression analysis. In addition, samples of similar clay and soil water content were combined for several sites and subjected to regression analysis (Table 2). Higher correlation coefficients, r, and lower SE y.x were obtained with the cell calibration technique than with the conventional calibration method. Where field soil water content, clay content, and textural class were similar, slopes of regression lines for cell EC_e vs. EC_a calibration data compare very closely to slopes of linear regression lines obtained from conventional field method data (i.e., compare sites H and I of Tables 1 and 2).

Clay loam, silty clay loam, loam, and clay textural classes for combined cell data of Table 2 compare very favorably with the same textural classes in Table 1. As shown previously (8), the cell calibration method, which requires fewer samples and less work, can be used to establish EC_e vs. EC_a calibration curves for use with the con-

Table 3—Linear regression results of the EC-probe EC_e vs. EC_a calibration method and mean soil water content, saturation percentage, and clay and sand content for several study sites examined in the northern Great Plains.

Site	Linear regression									
	n†	$m \pm$ SE†	$b \pm$ SE†	r†	$SE_{y.x}$†	$H_2O \pm$ SD†	SP ± SD	Clay ± SD	Sand ± SD	Texture
						%				
L	13	3.26 ± 0.12	-4.02 ± 0.40	0.99	0.61	26.5 ± 2.0	74.2 ± 2.1	58.5 ± 1.5	6.8 ± 1.4	c
M	3	3.51 ± 0.13	-1.79 ± 0.45	0.99	0.36	26.6 ± 1.0	60.4 ± 0.8	46.2 ± 0.1	11.9 ± 1.3	sic
G	4	5.95 ± 0.18	-2.17 ± 0.72	0.99	0.71	23.1 ± 1.0	47.3 ± 2.6	37.2 ± 3.6	19.0 ± 3.4	sicl
C	3	5.27 ± 0.20	-2.13 ± 0.76	0.99	0.75	19.6 ± 2.2	45.7 ± 5.7	35.5 ± 5.8	22.5 ± 5.3	cl
A	4	5.73 ± 0.12	-4.14 ± 0.53	0.99	0.54	25.0 ± 0.5	49.9 ± 1.8	32.4 ± 2.0	26.4 ± 3.2	cl
N	4	5.93 ± 0.66	0.78 ± 2.25	0.99	2.64	18.0 ± 0.5	37.5 ± 1.2	27.2 ± 2.0	52.5 ± 2.9	scl
J	4	6.16 ± 0.49	-5.16 ± 2.24	0.99	2.06	19.3 ± 0.2	38.2 ± 2.6	23.5 ± 2.3	63.5 ± 2.5	scl
G1	9	5.44 ± 0.14	-2.19 ± 0.47	0.99	0.86	19.5 ± 1.6	39.3 ± 1.4	24.0 ± 1.5	37.7 ± 1.5	l
F2	6	6.75 ± 0.48	-1.48 ± 0.87	0.99	1.26	15.6 ± 1.2	26.7 ± 1.2	13.9 ± 1.6	63.4 ± 2.9	sl
F	6	9.75 ± 0.33	-2.51 ± 0.79	0.99	1.31	12.9 ± 2.0	23.8 ± 0.9	14.2 ± 0.9	72.9 ± 1.4	sl
K	4	8.87 ± 0.10	-1.49 ± 0.29	0.99	0.33	14.9 ± 1.7	27.7 ± 1.4	11.0 ± 0.6	79.2 ± 1.6	sl
F1	6	8.51 ± 0.22	-0.47 ± 0.64	0.99	1.12	15.9 ± 1.8	23.1 ± 1.2	9.3 ± 0.7	73.4 ± 2.8	sl
O	4	9.99 ± 0.52	0.71 ± 1.56	0.99	1.88	11.8 ± 0.7	26.8 ± 4.4	7.6 ± 1.3	81.1 ± 1.3	ls
F3	6	12.99 ± 0.48	-1.89 ± 0.73	0.99	1.25	11.0 ± 1.2	22.4 ± 2.0	6.5 ± 1.5	82.5 ± 2.5	ls
Combined sites										
	4	3.31 ± 0.22	-0.93 ± 0.68	0.99	0.76	26.1 ± 1.4	58.0 ± 5.1	44.8 ± 2.8	13.0 ± 2.4	sic
	10	5.73 ± 0.20	-3.21 ± 0.85	0.99	1.52	22.1 ± 2.9	46.0 ± 4.1	32.6 ± 3.3	26.4 ± 5.0	cl
	8	5.69 ± 0.56	-0.91 ± 2.28	0.97	3.44	18.6 ± 0.8	37.8 ± 1.9	25.4 ± 2.9	58.0 ± 6.4	scl
	22	8.84 ± 0.31	-2.04 ± 0.76	0.99	2.39	14.8 ± 2.0	25.1 ± 2.2	12.2 ± 2.4	71.6 ± 6.0	sl
	10	10.74 ± 0.57	-0.10 ± 1.27	0.99	2.78	11.3 ± 1.1	24.2 ± 3.7	7.0 ± 1.4	82.0 ± 2.1	ls

† n = number of samples; m = slope and b = intercept of linear regression equation $EC_e = m(EC_a) + b$; SE = standard error; r = correlation coefficient; $SE_{y.x}$ = standard error of estimate y on x; SD = standard deviation.

Table 4—Comparison of EC_e vs. EC_a calibration methods for textural groups having similar clay and water contents.

Calibration method	Texture	Linear regression n†	m†	b†	r†	$SE_{y.x}$†	H_2O	SP	Clay	Sand
									—%—	
Conventional	c	7	3.05	0.86	0.96	3.68	25.8	77.2	58.8	8.2
Cell	c	5	3.06	−2.42	0.99	1.48	28.2	79.3	63.0	5.7
EC-probe	c	13	3.26	−4.02	0.99	0.61	26.5	74.2	58.5	6.8
Conventional	c	8	4.22	−0.02	0.97	3.03	22.0	53.3	43.1	26.6
Cell	c	14	3.47	0.42	0.97	1.82	22.0	58.7	44.4	30.7
EC-probe	c	--	--	--	--	--	--	--	--	--
Conventional	sic	--	--	--	--	--	--	--	--	--
Cell	sic	5	4.85	−0.69	0.99	0.76	22.3	57.9	40.9	9.0
EC-probe	sic	4	3.31	−0.93	0.99	0.76	26.1	58.0	44.8	13.0
Conventional	cl	47	5.65	−0.80	0.96	2.22	19.8	46.6	36.0	29.2
Cell	cl	12	5.17	−0.48	0.98	2.51	23.9	49.6	31.8	34.5
EC-probe	cl	10	5.73	−3.21	0.99	1.52	22.1	46.0	32.6	26.4
Conventional	sicl	6	6.35	−2.40	0.95	4.86	21.1	51.2	35.6	13.0
Cell‡	sicl	3	6.19	−2.03	0.99	0.44	21.1	47.7	37.3	13.5
EC-probe	sicl	4	5.95	−2.17	0.99	0.71	23.1	47.3	37.2	19.0
Conventional	scl	12	5.96	−1.34	0.91	2.70	20.0	43.0	26.8	51.7
Cell	scl	8	4.23	−0.04	0.99	1.44	22.2	37.9	21.6	56.2
EC-probe	scl	8	5.69	−0.91	0.97	3.44	18.6	37.8	25.4	58.0
Conventional	l	11	6.02	−1.18	0.99	1.24	26.5	41.9	23.8	39.0
Cell	l	4	6.53	−1.63	0.98	0.89	20.3	42.5	24.8	38.3
EC-probe	l	9	5.44	−2.19	0.99	0.86	19.5	39.3	24.0	37.7
Conventional	sl	13	7.36	−0.85	0.92	1.60	17.3	33.2	17.7	60.8
Cell‡	sl	7	5.44	−0.37	0.98	0.40	17.1	28.6	14.7	62.7
EC-probe	sl	22	8.84	−2.04	0.99	2.39	14.8	25.1	12.2	71.6

† n = number of samples; m = slope and b = intercept of linear regression equation equation $EC_e = m(EC_a) + b$; r = correlation coefficient; $SE_{y.x}$ = standard error of estimate y on x.
‡ Very low salinity (EC_e) level <6 mmhos/cm.

ventional field method. Combined site data in Table 2 for the loam group demonstrate the influence soil water can have on the slope of the regression line. One of the combined loam samples had a mean water content of 29.1% and a slope of 4.74; the other had a mean water content of 20.3% and a slope of 6.53.

EC-Probe Method

At all locations where the EC-probe was used, a good range in EC_e values was obtained. Because of the small area sampled at a site, soil texture and water content variations were minimized. EC-probe calibration data are summarized in Table 3. All correlation coefficients were 0.99 and significant at the 0.01 probability level for all individual sites. Combining data from several sites lowered the r value for the sandy loam clay group and increased the SE y.x values slightly. The excellent correlation, however, indicated that geographic location had little influence on the EC_e vs. EC_a relationship. The combined site data in Tables 1, 2, and 3 demonstrate that soils of similar texture, clay content, and water content, from different geographic locations in the northern Great Plains, give similar EC_a readings for a given EC_e soil salinity level.

Table 4 summarizes data from all three calibration methods for soils of similar clay, sand, and water content. With few exceptions, regression slopes for a given texture were very similar for all three methods. Data in both Table 3 and 4 clearly indicate that the slope of the regression line increases as clay content decreases. The data in Table 4 indicate that EC_e vs. EC_a calibrations, made with the EC-probe method, can be used for appraising salinity in the field with the conventional four-electrode technique. The EC-probe calibration method gave a better linear relationship between EC_e and EC_a than the conventional method because of minimal fluctuation in soil water content and texture for a given soil type. The EC–probe calibration method was the easiest and simplest to use of the three methods examined in this study for establishing EC_e vs. EC_a relationships for a given soil type. Furthermore, this method gave the same accuracy and predicability as the other calibration methods.

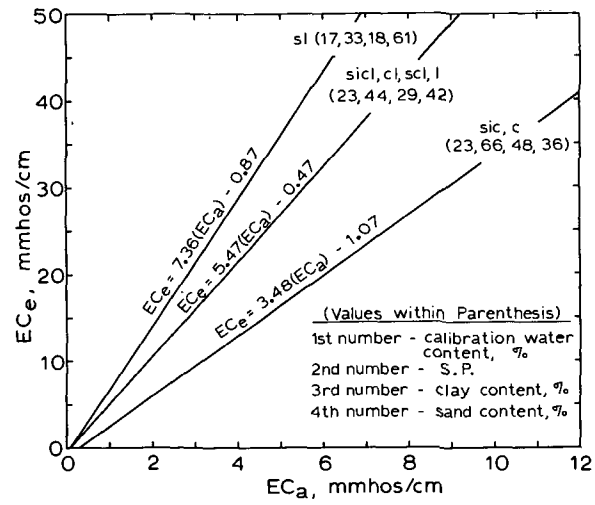

Fig. 1—EC_e vs. EC_a calibration by textural groupings for representative soil types of the northern Great Plains.

Generalized EC_e vs EC_a Calibrations

Because soil water content increases with increasing soil salinity in saline-seep areas and the similarity of regression line slopes for several soil textural classes, we combined several textural classes into one regression line (Fig. 1). These calibrations may be used for northern Great Plains soils of similar textures or clay content to diagnose soil salinity when soil water content is near field capacity, such as in the spring or in summer-fallowed fields in dryland areas, or after irrigations in irrigated areas. If soil texture or clay content, water-holding capacity, and surface conductivity differ markedly from calibration soils reported here, an appropriate calibration should be established for that soil.

Estimating Root Zone Salinity

As has been reported (4, 7), the conventional four-electrode technique for meausring EC_a can be used to estimate root zone (0- to 122-cm soil depth) salinity, EC_e, in the field without soil sampling, once an EC_e vs. EC_a calibration curve has been established for the soil in question. Table 5 summarizes the combined average EC_e vs. EC_a relationships for the 0- to 30.5-, 0- to 61-, 0- to 91.5-, and 0- to 122-cm soil depths, established for electrode spacings of a = 30.5, 61.0, 91.5, and 122-cm, irrespective of texture, for several sites used in this study. With the conventional four-electrode method, soil depth to which EC_a is measured is approximately equal to the inter-electrode spacing, a (4, 7, 9). As shown in Fig. 2 for site H, the plot of EC_a values (a = 30.5, 61, 91.5, and 122 cm) vs. average EC_e values (0- to 30.5-, 0- to 61-, 0- to 91.5-, and 0- to 122-cm

Table 5—Combined average EC_e (0- to 30.5-, 0- to 61-, 0- to 91.5, and 0- to 122-cm soil depth) vs. Ec_a calibration data for several electrode spacings (a = 30.5, 61, 91.5, and 122 cm), irrespective of soil texture, for several study sites in the northern Great Plains when using the conventional field method.

Site	Linear regression								
	n†	$m \pm$ SE†	$b \pm$ SE†	r†	$SE_{y \cdot x}$†	$H_2O \pm$ SD†	SP ± SD	Clay ± SD	Sand ± SD
						%			
I	30	3.45 ± 0.22	0.90 ± 1.23	0.95	3.50	24.0 ± 5.0	63.7 ± 14.3	47.4 ± 11.1	32.1 ± 12.4
E	32	4.15 ± 0.26	-1.03 ± 0.33	0.94	1.10	22.1 ± 4.9	59.0 ± 14.3	46.8 ± 12.4	19.5 ± 10.4
A	40	5.27 ± 0.17	0.05 ± 0.73	0.98	2.50	22.2 ± 3.5	53.5 ± 7.9	40.0 ± 5.5	15.4 ± 8.4
B	52	5.59 ± 0.22	-0.67 ± 0.38	0.96	1.35	17.4 ± 3.3	47.3 ± 5.5	40.1 ± 6.3	33.9 ± 9.5
C	51	5.93 ± 0.26	-1.01 ± 0.51	0.96	2.62	20.7 ± 3.3	49.5 ± 7.0	39.6 ± 7.3	22.9 ± 4.1
G	143	5.79 ± 0.14	-0.86 ± 0.21	0.96	1.56	20.1 ± 2.9	48.2 ± 4.6	39.0‡	26.0‡
H	36	4.59 ± 0.24	-0.34 ± 0.52	0.96	1.58	26.1 ± 5.0	54.5 ± 7.4	34.2 ± 5.0	36.5 ± 5.1
D	56	4.34 ± 0.25	1.42 ± 0.48	0.92	2.30	19.2 ± 5.1	48.4 ± 22.1	28.1 ± 6.5	53.1 ± 11.6
F	47	7.17 ± 0.49	-0.40 ± 0.35	0.91	1.43	14.1 ± 6.2	--	16.0‡	59.0‡

† n = number of samples; m = slope and b = intercept of linear regression equation $EC_e = m(EC_a) + b$; SE = standard error; r = correlation coefficient; $SE_{y \cdot x}$ = standard error of estimate y on x; SD = standard deviation.
‡ Estimates from previous work (3).

soil depths, respectively) fall very close to the corresponding linear regression line. Therefore, average soil salinity of the root zone can be estimated quite accurately by the conventional four-electrode method for this particular dryland, glacial till site. Soil texture was predominantly clay loam.

The correlation data in Table 5 combined EC_a values for all four inter-electrode spacings and corresponding average EC_e values. Correlation coefficients, r, exceeded 0.90 at all locations and were significant at the 0.01 probability level. However, not all plots of average EC_e vs. EC_a data fit as well as that shown in Fig. 2. A plot of average EC_e vs. EC_a data from site D is presented in Fig. 3. Site D was a glacial till site, however, soil texture ranged from clay to sandy loam among locations of EC_a readings and with profile depth. Soil textures encountered were clays, clay loams, sandy clay loams, sandy clays, loams, and sandy loams. Although scatter of the data about the regression line is greater in Fig. 3 than in Fig. 2, the EC_e vs. EC_a relationship of Fig. 3 could be used to ascertain the development of an encroaching saline-seep condition and to estimate the existing level of soil salinity. For highly stratified soil situations, which may cause inaccuracies in salinity appraisals with the conventional method, the EC-probe technique may be more useful and accurate.

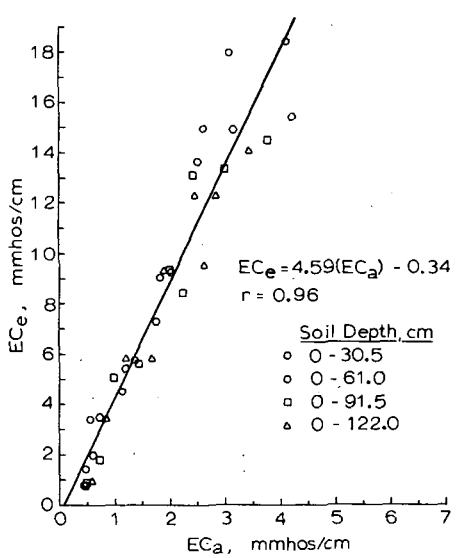

Fig. 2—Relationship between bulk soil conductivity, EC_a, (interelectrode spacings of 30.5, 61, 91.5, and 122 cm) and average soil salinity, EC_e, for soil depths of 0 to 30.5, 0 to 61, 0 to 91.5, and 0 to 122 cm, respectively, at location H using the conventional field method.

Measured vs. Calculated EC_e

Using linear regression relationships given in Fig. 1 and EC_a data from the conventional calibration method, we calculated an EC_e value for 0- to 30.5-cm soil samples from all sites. Linear regression analysis established the following relationship: Measured EC_e = Calculated $EC_e(1.04)$ + 0.32 with an r value of 0.95 (139 data points). These data indicate that surface soil salinity can be estimated accurately with the conventional four-electrode technique. We further calculated EC_e values corresponding to EC_a values for inter-electrode spacings, a = 30.5, 61, 91.5, and 122 cm, for each site examined by the conventional four-electrode technique. The resulting relationship between average measured EC_e (0- to 30.5-, 0- to 61-, 0- to 91.5-, and 0- to 122-cm soil depths) and corresponding calculated EC_e was: measured EC_e = calculated $EC_e(1.01)$ + 0.75 with an r

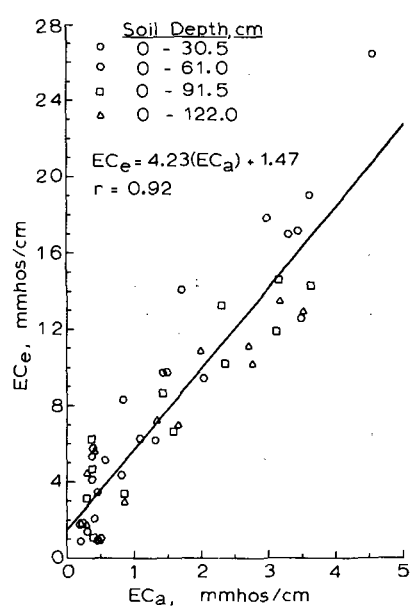

Fig. 3—Relationship between bulk soil conductivity, EC_a, (interelectrode spacings of 30.5, 61, 91.5, and 122 cm) and average salinity, EC_e, for soil depths of 0 to 30.5, 0 to 61, 0 to 91.5, and 0 to 122 cm, respectively, at location D using the conventional field method.

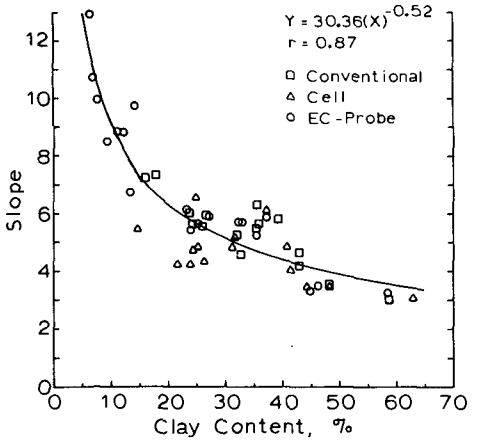

Fig. 4—A plot of slopes from the linear regression equations in Tables 1, 2, and 3 as a function of the average clay content of the samples used in the EC_e vs. EC_a calibration.

value of 0.92 (554 data points). These data further indicate that root-zone salinity can be accurately estimated by using the conventional four-electrode technique and EC_e vs. EC_a calibration curves established for surface soils.

Based on analyses of soil samples used in cell and EC-probe calibrations, a linear relationship was established between clay content and saturation percentage (SP): % Clay = SP (0.90) − 11.12 with an r value of 0.95 (157 samples). For the same samples, the linear relationship between sand content and SP was: % Sand = SP (-1.28) + 99.42 with an r value of −0.88. This information can be used to estimate either clay or sand content or SP for northern Great Plains soils if just one of these factors is known.

Slopes from the linear regression equations of the EC_e vs. EC_a calibrations in Table 1, 2, and 3 were plotted as a function of clay content (Fig. 4). As clay content increased, the slopes of the linear EC_e vs. EC_a relationship decreased curvilinearly (r=0.87).

SUMMARY AND RECOMMENDATIONS

The EC_e vs. EC_a calibration data indicate that the slope of the linear regression line will increase as clay content decreases. They also indicate that field soil water content can change the slope of the regression line slightly (i.e., increasing soil water content decreases slope). Compared with conventional field calibrations methods, cell and EC-probe calibration methods for establishing EC_e vs. EC_a calibrations required less work and fewer samples, were easier to use, and resulted in very similar calibration curves. In fact, these methods were more accurate because the EC_e values were obtained from nearly the same soil volume as EC_a values.

Textural and field soil water content differences were encountered among samples at a site when using naturally occurring field salinity for EC_e vs. EC_a calibrations. Generally, soil samples collected from highly saline areas (saline seep) were finer-textured and had higher water contents than those collected from less saline areas. To minimize the effects of texture and soil water content differences during EC_e vs EC_a calibration procedures, we recommend leaching the desired soil type with salt solutions and using either the cell or EC-probe calibration method to obtain needed EC_a data to correlate with corresponding EC_e values from collected soil samples. This would minimize the number of samples needed for calibration purposes and result in reliable information.

For general salinity estimates, Fig. 1 gives typical EC_e vs. EC_a correlation data for several textural groupings in the northern Great Plains. Slopes and intercepts of the linear regression equations reported in Fig. 1 may change slightly with clay and soil water content and should be used with this information in mind. Geographic location or soil parent material had little influence on the EC_e vs. EC_a correlation. It was affected predominantly by soil texture or clay content; therefore, a calibration made for a soil textural class at one geographic location in the northern Great Plains will apply to another location having a similar range in soil water and salinity. If soils within a textural class vary greatly in clay content, water-holding capacity and surface conductivity (9, 10), we would advise establishing an appropriate calibration for that soil, if not already available and if a high degree of accuracy is important.

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