DETERMINING FIELD SOIL SALINITY WITH FOUR-ELECTRODE CONDUCTIVITY MEASUREMENTS

by

Hadi Samir Tabbara

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SIGNED: Hadi Tabbara

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Hinrich Bohn — 14 Dec 79

H. L. BOHN — Date

Professor of Soils, Water and Engineering

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ABSTRACT

Field soil salinity can be inferred from four-electrode soil electrical conductivity (ECa) if the water content and the soil type are known. A laboratory experiment was established, using four-electrode conductivity cells, to study EC as a function of volumetric water content (θv) and *in situ* soil water conductivity (ECw). Linear regression relationships between ECa and ECw were developed. Results indicated that the equation that best fit the data has the form ECa = $\theta_v x$ ECw. All correlation coefficients (r^2) exceeded 0.94.

This model was then tested on three Arizona soils. The salinity probe was used to measure the bulk soil electrical conductivity (ECp) of artificially salinized field plots. The functional relationship between ECp and the saturated extract salinity (ECse) was also in the form ECp = $\theta_v s$ ECse. Correlation coefficients (r^2) exceeded 0.86. Effects of water content and clay content on the linear regression equation was investigated. In general, the higher the clay and water contents of a given soil, the lower the slope of the ECse vs. ECa linear regression line.

INTRODUCTION

The 11th International Soil Science Society Congress considered soil salinity as a major problem in the national economy of many countries. In order to develop a proper management program, an accurate method of predicting salinization periodically is required.

To date, the diagnosis of salinity has required tests on a large number of soil samples that are brought into the laboratory where much time and effort are needed especially when salinity is to be monitored with depth in the soil. Even with a portable field kit (Reeve and Doering, 1965) these limitations are not eliminated.

A salt balance evaluation provides important information relative to the changes in river-water quality that occurs with its diversion, use, and return downstream. It is, however, not a suitable criterion upon which to base the adequacy of leaching and salinity control of large irrigation basins, much less of individual fields or part of them (Rhoades, 1974).

The salinity sensor developed by Richards (1966) can monitor the salinity of the soil solution and its change with time provided suction does not exceed 2 bars. It is also useful for measuring the electrical conductivity of drainage water which is needed for application of leaching requirement theory. But the sensor responds to only the salinity in the small volume of soil measured whereas the plant responds to the bulk soil salinity in which the roots proliferate. Thus a number of sensors must be used in profile especially when salinity distribution is non-uniform with depth.

Rhoades and his co-workers at the United States Salinity Laboratory have adopted a technique that is suitable for field use, that does not require soil sampling (once calibration is made) and that is rapid, simple and inexpensive to use. In addition, no buried in situ devices are required. This method involves the measurement of resistance between an array of four electrodes that are placed in the immediate surface of the soil.

Rhoades and Ingvalson (1971) showed the usefulness of the four electrode conductivity technique for measuring soil salinity of irrigated soils. Halvorson and Rhoades (1974) extended its use to dry land salinity for saline seep investigations. Rhoades, Raats, and Prather (1976) in their column study discussed the influence of soil water, surface conductivity, and salt content on the ECa (4-electrode) vs. saturated-extract electrical conductivity (ECe) relationship, but did not apply it to field situations. Rhoades and van Schilfgaarde (1976) used a single probe to monitor salinity with depth under field capacity water contents. Halvorson, Rhoades, and Reule (1977) discussed the influence of soil texture and presented calibration curves under field capacity water contents also.

The purpose of this study is to:

1. Evaluate the effect of soil texture and water content on bulk soil electrical conductivity over the entire field moisture range.
2. Measure soil salinity by use of the four electrode cell (laboratory study), and the salinity probe (field study).

LITERATURE REVIEW

Theory

The use of electrical resistance for soil investigations started at the turn of this century when Whitney, Gardner, and Briggs (1897) employed a two electrode method for measuring the moisture, temperature and soluble salt content of soils.

The two electrode method however, measures the sum of both the soil resistance and the contact resistance between the electrode and the soil. The latter is erratic and irreproducible for any expansion or contraction of the soil around the electrode will lower or raise that contact resistance (Edlefsen and Anderson, 1941). The standard method of eliminating the contact resistance between the electrodes and the material is to use four electrodes. Wenner (1916) devised a four electrode resistance network to measure soil resistivity by placing four metal electrodes in the soil surface in a straight line with equal distances between them (Fig. 1). A constant alternating current is passed between terminals C_1 and C_2. Alternating rather than direct current was used to avoid polarization of ions around the electrodes. An ammeter measured the current supplied by a suitable voltage while the resulting potential difference across the inner electrodes is measured

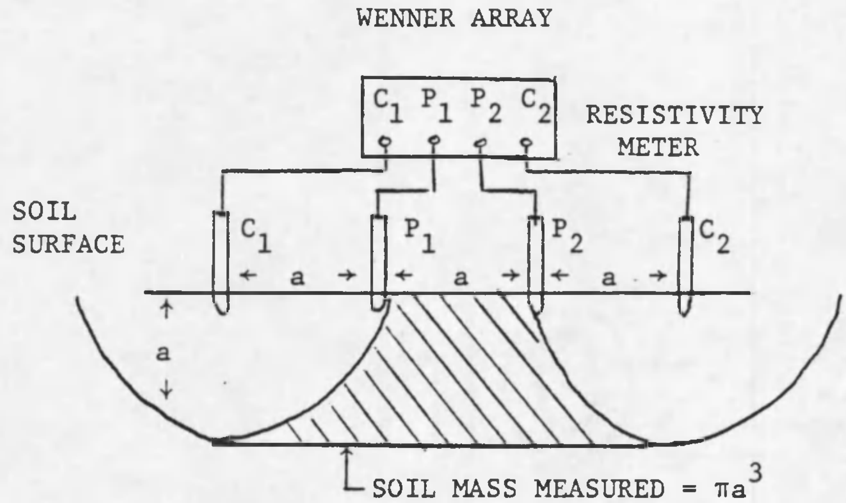

Fig. 1. The Wenner Array method used to measure soil electrical resistance where a represents the interelectrode spacing; C_1 and C_2 the current electrodes; P_1 and P_2 the potential electrodes.

(After Rhoades and Halvorson, 1977.)

by a voltmeter. Ohm's Law is then used to calculate the resistance between the center electrodes. We are concerned with the volume resistivity, which is the resistance of a portion of a conductor having unit length and unit cross section. The equation given by Wenner for the resistivity ρ:

$$\rho = 2\pi aR \tag{1}$$

where R is the measured resistance, a is the inter-electrode spacing, and $2\pi a$ is the geometry factor. Rho (ρ) represents the resistivity of earth between the inner electrodes whose cross section equals the square of half the distance between the outer pair. This is the case when the electrode depth is small compared to the inter-electrode distance.

The four electrode method was successfully used by Kirkham and Taylor (1950) to determine the soil moisture. They measured the current with a resistance of known value connected in series with one of the outer electrodes, and the potential drop with a vacuum tube voltmeter. According to their results, deviation of the electrodes from their theoretical position may cause significant error. The displacement of the middle two electrodes 0.05a inward from their normal position irrespective of electrode depth caused an 11.2% error. The magnitude of this error diminishes as the electrode spacing increases. Shea and Luthin

(1961) employed a similar four electrode set-up to measure soil salinity except they buried a series of in situ electrode sets at various depths within a soil profile. They suggested that closely arranged electrodes should be avoided and that the optimum spacing would depend on the depth of the electrodes as well as the uniformity of the soil profile. However, their experiment is similar in concept to methods employing in situ salinity sensors and suffers from the same limitations (numerous units of electrodes must be buried at several depths).

Rhoades and Ingvalson (1971) measured soil resistance by the Wenner array utilizing the electronic equipment that are available nowadays. They found that at equal inter-electrode distance a, the depth of current penetration, is equal to a. They used this hypothesis to measure apparent soil conductivity (ECa is apparent rather than absolute, because of the heterogeneity of most soil profiles) of saline soils at different depths by moving the electrodes between measurements. They gave this equation for calculating ECa:

$$ECa = \frac{1000 \times f_t}{2\pi a \ R_t} \tag{2}$$

where a is the inner-electrode separation in centimeters, R is the resistance in ohms at field temperature t, and the apparent soil conductivity in mmho/cm at 25°C.

Conversion to 25°C is done by multiplying by the factor f_t obtained from appropriate tables (U. S. Salinity Laboratory Staff, 1954).

Rhoades and Ingvalson's studies showed that electrode depth was critical only at small inner electrode spacings in saline soils and that electrode size ranging in diameter from 0.3 to 1.3 cm had no appreciable effect on resistance values.

The resistance measurement is made with a geophysical earth resistivity tester. This instrument provides a low frequency (10 to 20 cps) alternating current that passes across terminal C_1 and C_2 (Fig. 1). The consequent potential across terminal P_1 and P_2 is balanced by an equal and opposite potential produced across an adjustable resistance so that, at balance, no current flows in the potential circuit.

Converting resistance to conductivity was seen to make the soil electrical conductivity values nearly constant for a given level of soil salinity irrespective of inner-electrode spacing; this was not true for the resistance values. This is the reason for using EC_a, rather than resistance itself for assessing soil salinity with depth (Rhoades and Ingvalson, 1971).

The Wenner array measures the average salinity of a relatively large soil volume, about $\frac{5\pi a^3}{6}$. To estimate salinity within discrete soil depth intervals, Halvorson and Rhoades (1974) measured soil conductivity at depth intervals by assuming that depth of measurement is equal to a and that soil layers can be accurately described as resistors in parallel. Later Rhoades and van Schilfgaarde (1976) pointed out that these two assumptions are not exact especially when salinity is not uniform with depth. As an alternative they used a single probe in which four electrodes are mounted as annular rings (referred to as the Salinity Probe) with 2.6 cm spacing between the electrodes. This measures EC_a soil salinity within about 15 cm depth increment and a soil volume of about 90 cm^3 ($5\pi a^3/3$). The probe is slightly tapered (1°) toward the tip so that all four electrodes firmly contract the soil upon insertion into a hole made by a soil sampler. The soil EC_x at each depth interval (X) is calculated by:

$$EC_x = \frac{K\ f_t}{R_t} \tag{3}$$

where K is a geometry constant determined by submerging the probe in a large fiberglas barrel filled with solution of known EC. Although the probe does have some of the same sensors (i.e., soil must be removed with a soil sampling tube), it can more accurately determine soil salinity of a discrete depth interval in the soil than can the surface-positioned four electrode equipment. The probe is also useful for establishing calibrations between bulk soil EC (ECa) and EC of the saturated extract (ECe) which is the standard indicator of soil salinity.

An equally accurate method of establishing such calibration was established by Gupta and Hanks (1972) with the use of special conductivity cups made of acrylic tubing with small stainless steel bolts equally spaced in the sides of the cup serving as the electrodes. Equation (3) is also used here to calculate ECa after the cell constant of the cup is determined.

Both the salinity probe and the four-electrode cell gave better calibration curves than the conventional Wenner array because the ECe values were obtained from nearly the same volume as the ECa values (Halvorson et al., 1977).

Application: Salinity Appraisal

In measurement of soil electrical conductivity, the soil with its salts, organic matter, and water is considered as an electrolyte. The conductivity of electrolyte is shown by Krauss (1922) to be a function of the temperature, the viscosity of the solution, the dissociation of the salt and the kind of salts. Most soil minerals are insulators and conduction therefore occurs through the interstitial water which contains, in saline soils, appreciable amounts of dissolved electrolytes (effect of water content is discussed later). Surface conductance via the exchangeable cations may be appreciable in soils with high clay content which contain little soluble salts but appreciable exchangeable sodium (Rhoades and Ingvalson, 1971).

Hence the conductivity of a saline soil should depend primarily on the electrical conductivity of the soil solution, on the effective soil porosity, and on the degree of water saturation. Soil salinity, therefore, can be correlated with soil conductivity if a knowledge of the soil type and water content are available.

Salinity Variations with Water Content

A major obstacle for the use of the two electrode method to measure variations in moisture content is the effect that variations in salt content have on the electrical resistance of the soil. Edlefson and Anderson (1941), using the four-electrode method, studied the variation of electrical resistance with moisture content at different soil-moisture cycles (beginning with a complete irrigation of the soil, then passing through the drying stage and ending with a complete irrigation). They observed that very small changes in soil water content near the permanent wilting point caused comparatively large changes in electrical resistance and concluded that the variation in resistance due to variation in salt content are not highly important in the top of the soil. Kirkham and Taylor (1950) compared measured soil EC with gravimetric water content and obtained a correlation coefficient of 0.83 but with a high variability caused by salinity.

Shea and Luthin (1961) in their tank study tried to evaluate the effect of soil water content and salinity on bulk soil conductivity. They adjusted their soil to various levels of salinity and water content by leaching with waters of different salinities and imposing different suctions at ceramic base of the tank. The suction they studied (0-125 cm of water) corresponds to saturation to field capacity, i.e., "wet" conditions. When the water content is decreased by drainage, salt is removed with the water and the salinity of the soil water remains constant. In the field situation, the soil will generally be at field capacity or lower, and water losses by evapotranspiration will increase the soil water salinity.

Gupta and Hanks (1972) adjusted two soils to various water and salt contents and packed the material into special conductivity cups to determine ECa. They used suctions up to one bar by use of "Tempe" cells. The soil salinity was measured either in saturated extracts, ECe, or in 1:5 soil water extracts, EC (1:5), rather than the water contents at which the four-electrode conductivities were determined (Rhoades, Raats, and Prather, 1976). Their

ECa increased markedly as the water content (θ) or the salinity increased. Their data fit the equation:

$$\frac{ECa}{ECe} = a\theta + b \tag{4}$$

Regression coefficients ranged from 0.75 to 0.95. Rhoades and Ingvalson (1971) successfully used the four-electrode technique to estimate soil salinity in artifically salinized plots. They recommended that ECa measurements be made two to three days after irrigation in irrigated lands when the soil reaches its field capacity. Normal deviations from field capacity water content did not interfere with salinity diagnosis because the salt concentration of the soil water would increase as the volume of soil water decreased by evapotranspiration, hence, the increasing salt concentration would tend to compensate for the relatively small variations in water content.

Halvorson and Rhoades (1974) extended the use of this method to dry land salinity investigations. Their results indicated that soil conductivity measurements can be used to identify potential saline-seep areas. They ran regression analyses to examine the relations between ECa, ECe and water content and showed that ECa was more related to salt content when soil water content was high and was more related to water content when the soil was dry. They recommended ECa determination be restricted to fallow land or in cropped land in the spring of the year or after rainfall when the soil profile is near field capacity.

Rhoades, Raats, and Prather (1976) extended the use of this method to arbitrary water contents. They studied ECa as a function of water content (θ) and in situ water conductivity (EC_w). Undisturbed cores of four soil types were collected using Lucite column inserts which were tapped for later insertion of electrodes. These cells were equilibrated with waters of a desired EC_w and, using a pressure membrane apparatus, adjusted to a desired θ. The ECa is a product of ECw and θ, i.e., total solute per unit volume of soil:

$$ECa = T(ECw \cdot \theta) + EC_s \qquad (5)$$

where T accounts for the tortuosity of the current, EC_s is the surface conductance, as discussed in the next section.

When drainage ceases after irrigation, crop water uptake decreases θ but most of the salts are left behind in the soil solution. Except for the effect of salt precipitation, the product $(ECw)_i \cdot (\theta)_i$ where i is the initial condition (after irrigation), would be unchanged at some later time, t_2, i.e.:

$$(ECw)_i \cdot (\theta)_i = (ECw)_{t_2} \cdot (\theta)_{t_2} \qquad (6)$$

Hence ECw · (θ) should be reasonably constant for the first few days after irrigation and changes in ECa over this time should be primarily related to the tortuosity T (Rhoades, 1975).

Rhoades estimated that a 5 percent variation in θ from the reference "field capacity" water will produce a 6 percent change in ECa (1975). It was also shown that increasing water content will decrease the slope of the ECe vs. ECa regression line (Halvorson et al., 1977).

Salinity Variations with Soil Type

Shea and Luthin (1961) reported the effect of soil type on the value of the "specific" conductance (conductivity being due only to current transfer by the ions absorbed on the colloid particles in the soil). This value will vary between soil types depending on the cation-exchange capacity. They also indicated the effect of soil type on the relationship between soil salinity and electrical conductivity and later suggested that the physical characteristics of the soil must be considered if the relationship is to be linear.

Rhoades and Ingvalson (1971) modified Eq. (2) to correct for the conductivity due to ions at the double layer and found it to have little effect on the linearity of ECa vs. ECe.

The same conclusion was drawn by Gupta and Hanks (1972). They observed, however, a lower correlation coefficient of $\frac{ECa}{ECe}$ vs. water content when soils were considered together than for a single soil suggesting that calibration is needed for each type of soil.

Rhoades and his co-worker's empirical Eq. (5) defined tortuosity T and surface conductance ECs as properties of the soil solid phase. T accounts for the tortuous current lines and any decreases in mobility of the ions near the solid-liquid and liquid-gas interfaces. T is therefore, a function of θ.

$$T = a\theta + b \tag{7}$$

with constants a and b determined by linear regression. These values are related to texture, and where θ is known or measured, actual _in situ_ soil water electrical conductivity ECw can be determined from four electrode soil conductivity measurements using Eq. (5).

Halvorson, Rhoades, and Reule (1977) studied the effect of soil texture and geographic location on the linear ECe-ECa relationship. The slope of the regression line increased as the clay content decreased. Geographic location or soil parent material had little influence on the relationship.

Dutt and Anderson (1964) derived an expression similar to Eq. (5) with the use of a special two-electrode conductivity cell. Although the experiment was aimed at studying the ionic composition of the soil solution in the field-moisture range, their results demonstrate the effect of moisture content and soil type on the specific conductivity.

MATERIAL AND METHOD

Laboratory Experiment

Technique and Equipment

Special conductivity cells were used to evaluate the relationship between four-electrode conductivity and soil salinity at different water contents. The cells [similar to those used by Gupta and Hanks (1972)] were made of acrylic tubing 4 cm long and 8.2 cm diameter. Eight holes were threaded in the sides of the cell at 45-degree intervals. Eight brass bolts of 4 mm diameter were inserted into the cell to a depth of 1 cm and held fixed at this depth by a locking nut. The bolts served as electrodes. Any four neighboring ones can be regarded as a Wenner array --the outer two are used as current electrodes, the inner two as potential electrodes. The resistance is determined using a model 63241, Biddle Null balance earth tester. This unit measures from 0.01 to 10,000 ohms. By rotating the connections, eight independent measurements can be taken on any sample which are then averaged to obtain EC. Cell constant K was determined for each cell by filling it with 0.01 N KCl solution that has an electrical conductivity at 25°C (EC_{25}) of 1.4118 mmho/cm. Resistance Rt is measured at temperature t and K is calculated as:

$$K = EC_{25} \cdot R_t \cdot \frac{1}{f_t} \tag{8}$$

K was 0.01 cm^{-1} for all cells.

When the four-electrode cell is filled with soil, the soil EC_a is then calculated from the measured resistance, soil temperature and established cell constant using Eq. (3).

Experimental Procedure

Three different Arizona soils were used in this study: Comoro loamy sand, Laveen loam and White House clay loam. Table 1 lists their properties. Specific amounts of these soils were uniformly packed in the EC cells and leached with NaCl + $CaCl_2$ solution of a desired ECw and an SAR of 4. Five salinity levels 2, 4, 8, 16, and 31 mmho cm^{-1} were used. Approximately two pore volumes of leaching solution were needed to adjust each soil to the desired ECw (soil water conductivity). Three replicates of the leached soils were made. After the soils drained freely, resistance was measured and ECa obtained. This corresponds to measurement at zero bar suction. The cells were then randomly placed on moisture-retention pressure plates and adjusted to a specific suction for 24 hours. The suctions used correspond to matric potentials of 0.1, 0.5, 1, 5, and 15 bars.

After equilibrium had reached, i.e., no more water outflow, the plates were removed and the resistance of the soil R_t and temperature t were measured. Gravimetric water

Table 1. Properties of soils used in the laboratory study.

Soil Type	CEC*	Particle Size** sand	silt	clay
	meq/100 g		%	
Comoro loamy sand (1)	4.9	87.1	10.2	2.5
Laveen loam (2)	12.1	46.0	36.1	17.8
White House clay loam (3)	19.3	44.2	19.3	36.4

* By Na acetate method of USSL Staff, 1954
** By Hydrometer method
(1) Coarse-loamy, mixed (calcareous), Thermic Typic Torrifluvent
(2) Coarse-loamy, mixed, Hyperthermic Typic Calciorthid
(3) Fine, mixed, Thermic Ustollic Haplargids

content was then determined by ovendrying a sample of the soil from the cell at 105°C for 24 hours. Volumetric water content θ_v can then be calculated after the bulk density of the soil in the cell is determined. Thus ECa is determined for soil samples under conditions of known ECw and θ values.

Field Experiment

Equipment

The Salinity probe described by Rhoades and Van Schilfgaarde (1976) (Micron Engineering, Riverside, California) was used to measure ECa along with the resistivity meter described previously. The probe's cell constant was

21.6 cm^{-1}. A four-electrode surface network was also used in this experiment, but results and comparison among methods are reported elsewhere (M. Marwan, University of Arizona, M. S. thesis in preparation).

Experimental Procedure

The experiment was carried out at 3 sites located around the Tucson area. Table 2 lists the properties of the top soil found on each site. Five plots (1.2 x 0.3 m) were levelled and surrounded by a dike. To adjust salinity, four of the plots were leached with waters of 4 different salinities (EC = 4, 10, 20, 40 mmho/cm; SAR = 8; NaCl + $CaCl_2$ solution).

The fifth plot was left as control and leached with tap water (EC = 0.4 mmho/cm).

By rough calculation, 75 liters of saline water were needed to bring the soil to a depth of 30 cm to the desired level of salinity. When the soil had freely drained a soil sample was removed from the 30 cm depth with an Oakfield soil sampler. (This sample can be used to determine the gravimetric water content.) The salinity probe was centered in the sample hole, and the resistance value measured. Soil temperature at 30 cm depth was recorded using a field thermometer. ECa value corresponding to this depth is then determined using Eq. (3). After the probe is

Table 2. Properties of soils used in the field study.

Soil Type	CEC*	Bulk Density**	Particle Size*** sand	silt	clay
	meq/100 g	g/cc		%	
Vinton loamy sand[1]	2.5	1.5	80.3	10.5	9.1
Gila loam[2]	3.4	1.8	51.0	35.9	13.0
Pima clay loam[3]	5.3	1.5	44.2	30.9	26.8

* By Na acetate method of USSL Staff, 1954
** By the core method
*** By Hydrometer method
(1) Sandy, mixed, Thermic Typic Torrifluvent
(2) Coarse-loamy, mixed (Calcarceous), Thermic Typic Torrifluvent
(3) Fine-silty, mixed (Calcareous), Thermic Typic Torrifluvent

removed, a soil sample (0 to 30 cm) is then taken using a soil auger. The ECe (electrical conductivity of saturated extract) of this soil sample was then determined using the U. S. Salinity Laboratory Staff (1954) method.

This procedure was repeated for each soil. Measurements were taken during the months of June and July on the last day of flooding and after approximately 1, 7, 20, 30, and 45 days after the end of irrigation.

RESULTS

Laboratory Experiment

Bulk soil electrical conductivity as measured by the four-electrode conductivity cell (ECa), volumetric water content (θv) and *in situ* soil water conductivity (ECw) as measured by the EC of solution added are given in Table 3 for the three soils under study. The water content ranged from 6 to 49 percent and the imposed salinity from 2 to 31 mmho cm^{-1}, giving a suitable range for calibration purposes. Data in this table represents average values of the three replicates of each soil used.

Table 3a gives the results at zero bar suction level, that is, at saturation. ECa increased markedly as the salinity, the measured conductivities were higher for the fine textured soils due to their higher relative moisture contents and partly due to the effect of soil type. Table 3b presents the data when 0.1 bar suction was applied to the soils. Bulk soil electrical conductivity decreased due to the decrease in the moisture content for each soil. Measured ECa decreased more with decreasing water content in the case of sandy soil than in the other two soils. Higher salinity levels magnified this decrease.

Tables 3c and 3d show the results when 0.5 bar and 1 bar suction were applied to the soils. The clay loam

Table 3. Bulk soil electrical conductivity (ECa) corresponding to different salinity levels (ECw) for the three soils and measured at different applied matric potentials Ψm (bars).

Volumetric water content (θv) corresponding to this suction is also shown.

a. $\Psi m=0$	ECa mmho cm^{-1}		
	Sand $\theta v=0.3$	Loam $\theta v=0.41$	Clay Loam $\theta v=0.49$
EC_w mmho cm^{-1}			
2	0.55	0.96	1.42
4	1.00	1.75	2.11
8	1.80	2.88	3.00
16	3.23	5.68	5.49
31	6.66	9.47	9.00

b. $\Psi m=0.1$	ECa mmho cm^{-1}		
	Sand $\theta v-0.13$	Loam $\theta v=0.26$	Clay Loam $\theta v=0.34$
EC_w mmho cm^{-1}			
2	0.17	0.58	1.14
4	0.32	0.70	1.89
8	0.57	1.37	2.58
16	0.85	2.61	4.05
31	1.87	4.18	7.12

Table 3, Continued.

c.

$\Psi m=0.5$	ECa mmho cm^{-1}		
	Sand $\theta v=0.8$	Loam $\theta v=0.15$	Clay Loam $\theta v=0.24$
EC_w mmho cm^{-1}			
2	0.05	0.29	0.87
4	0.12	0.37	0.84
8	0.16	0.58	1.48
16	0.26	0.72	1.69
31	0.54	1.08	2.82

d.

$\Psi m=1$	ECa mmho cm^{-1}		
	Sand $\theta v=0.07$	Loam $\theta v=0.14$	Clay Loam $\theta v-0.23$
ECw mmho cm^{-1}			
2	0.07	0.23	0.77
4	0.09	0.33	0.96
8	0.12	0.69	1.14
16	0.20	0.55	1.43
31	0.37	0.66	2.35

e.

$\Psi m=5$	ECa mmho cm^{-1}		
	Sand $\theta v=0.06$	Loam $\theta v=0.13$	Clay Loam $\theta v=0.22$
ECw mmho cm^{-1}			
2	0.05	0.19	0.65
4	0.07	0.20	0.81
8	0.13	0.27	1.00
16	0.17	0.50	1.47
31	0.31	0.83	2.28

Table 3, Continued.

f. $\Psi m=15$	ECa mmho cm^{-1}		
	Sand $\theta v=0.06$	Loam $\theta v=0.12$	Clay Loam $\theta v=0.22$
ECw mmho cm^{-1}			
2	0.06	0.10	0.56
4	0.06	0.22	1.41
8	0.10	0.32	1.04
16	0.18	0.54	2.25
31	0.19	0.85	2.79

soil lost most of its moisture between 0.1 and 0.5 bar, hence a larger decrease in ECa values occurred when the soil water content was decreased from $\theta v = 0.34$ to $\theta v = 0.24$ than when it decreased from $\theta v = 0.49$ to $\theta v = 0.34$.

In Table 3d, the moisture content decreased by one percent in each soil. Comparing Tables 3c and 3d show that a one percent decrease of moisture content for each soil type decreases the electrical conductivity value significantly especially at the higher salinity levels.

Tables 3c and 3f present the data at the 5 and 15 bar suction levels respectively. At these levels good contact between the cell electrodes and the soil was hard to achieve; thus these data are questionable and will not be considered in the discussion.

The data in Table 3 were plotted in Figs. 2, 3, and 4 which express the electrical conductivity as a function of salinity at different moisture suction levels for the sand, loam, and clay loam soils respectively. As the salinity increased, bulk soil electrical conductivity increased approximately linearly. Decreasing the water content decreased the slope of the ECa vs. ECw lines.

In Fig. 2 for the sandy soil, the slope of the line decreased markedly when the suction increased from zero bar to 0.1 bar. The slope of the data for the loam soil, Fig. 3, decreased as much when the suction was raised to

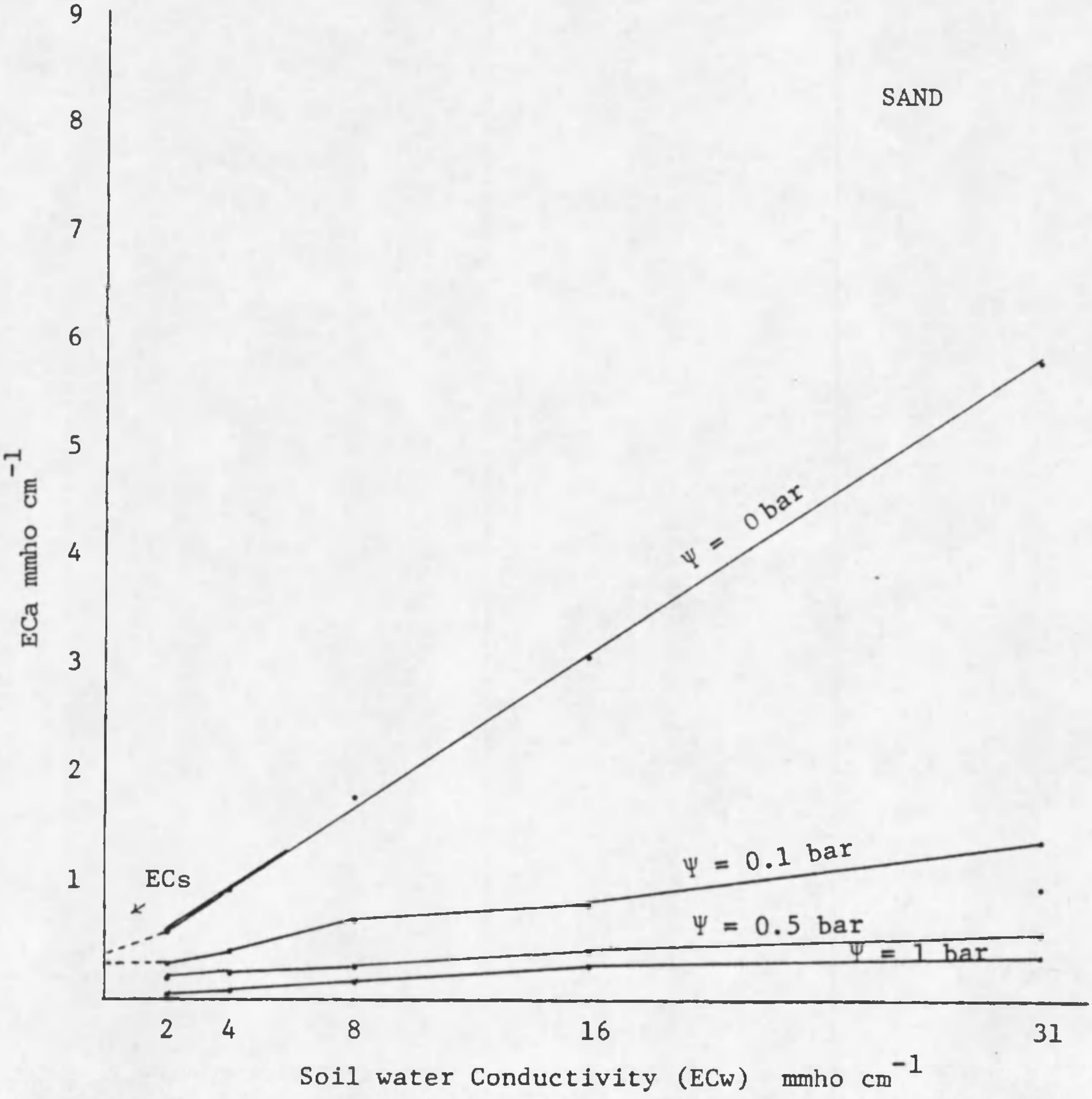

Fig. 2. Bulk soil electrical conductivity as a function of soil salinity (ECw) at various soil-moisture suctions for the sandy soil.

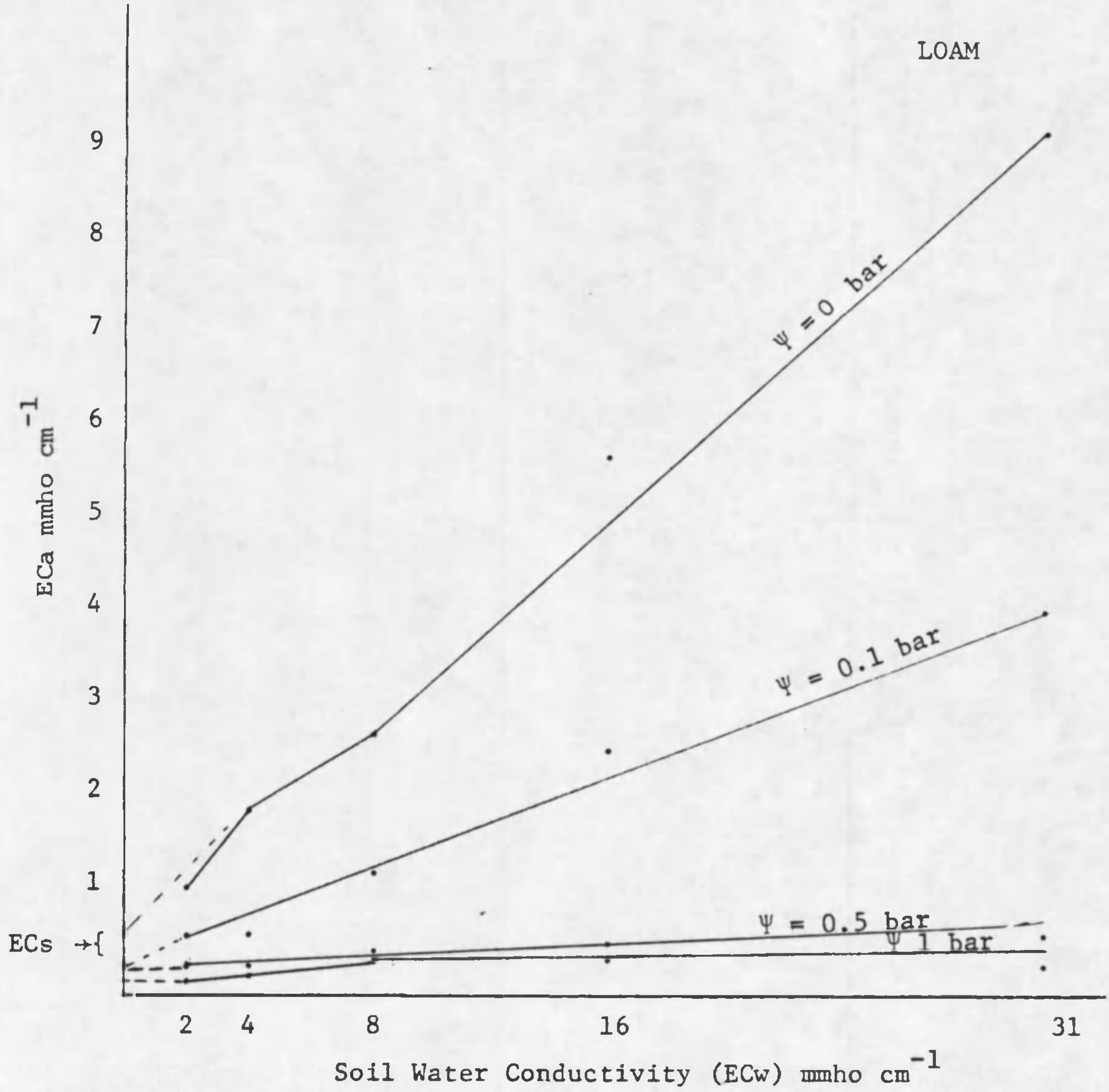

Fig. 3. Bulk soil electrical conductivity as a function of soil salinity (ECw) at various soil-moisture suctions for the loam soil.

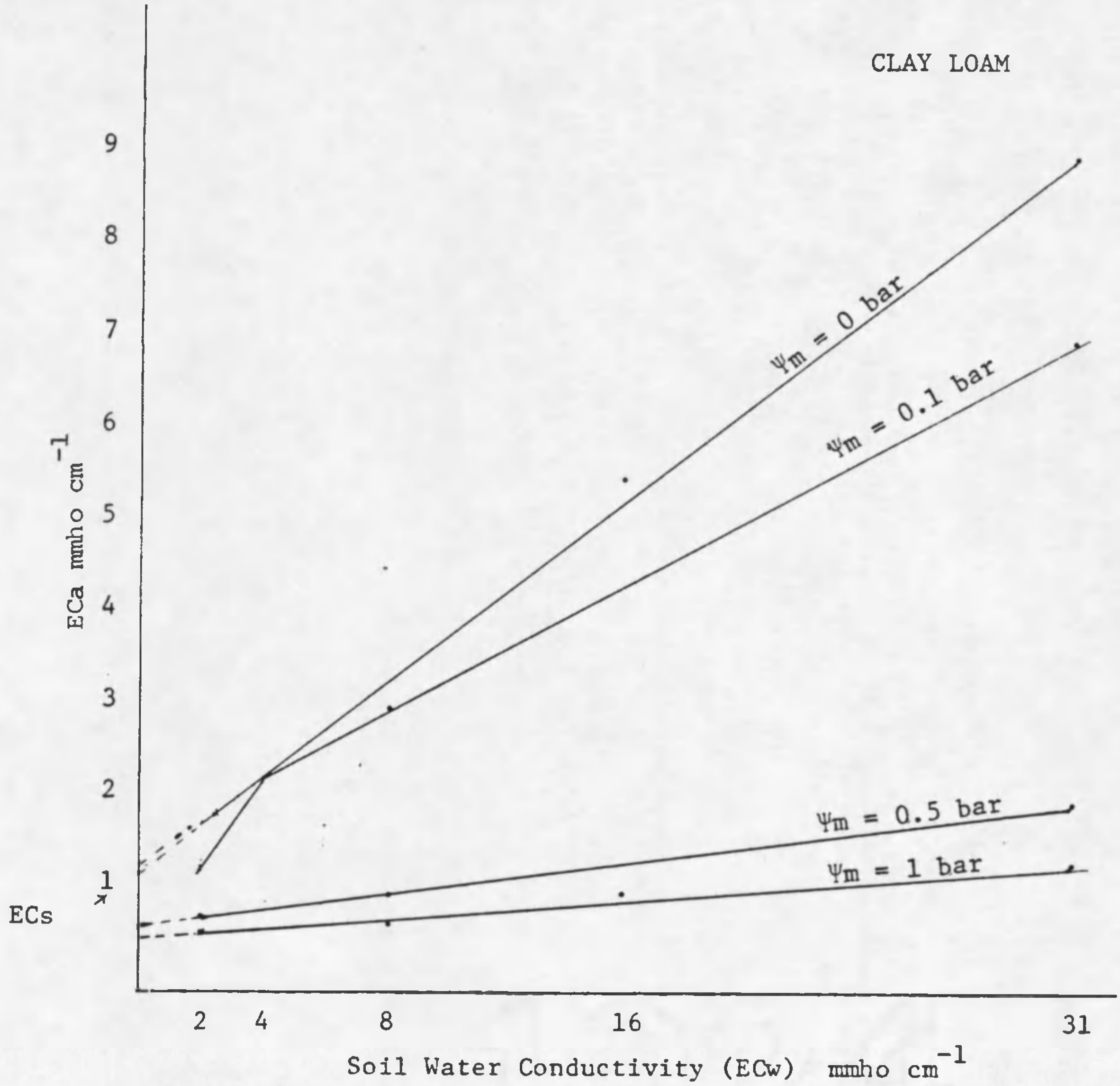

Fig. 4. Bulk soil electrical conductivity as a function of soil salinity (ECw) at various soil-moisture suctions for the clay loam soil.

0.1 bar as when raised to 0.5 bar. Figure 4 for the clay loam soil exhibits the largest decrease in the slope of the data line when the suction increased from 0.1 to 0.5 bar.

The curves in Figs. 2, 3, and 4 tend to diverge as the salinity level increases. That is, bulk soil electrical conductivity decreases as the soil dries, but this diminution tends to be greater as the salinity increases.

Extrapolating the curves to zero soil water conductivity (ECw) will give the value of the electrical conductivity of the soil due to the ions adsorbed on the double layer (ECs). This value as shown in the figures is relatively independent of water content and is higher for the fine textured soils.

By superimposing the three sets of curves, the slope of the line at a particular matric potential Ψ_m (except at Ψ_m=0) is found to increase with clay content. An increase, therefore, is expected in the slope of the ECa vs. ECw linear regression line as the clay content is increased.

The data was studied by conventional regression analysis on the individual soils and on the combined data for the three soils. Table 4 gives the regression equations and coefficients of determination (r^2) that resulted when ECa was related to ECw and θv. The equation that best represents the data for the three soils has an r^2 = 0.94:

Table 4. Regression equation and coefficients of determination (r^2) relating ECa, ECw and θ.

Regression Equation	r^2	Soil
ECa = $-1.23+0.05$ ECw$+10.62\ \theta$	0.64	loamy sand
ECa = $0.05-0.05$ ECW$+\ 0.85$ ECw $\cdot\ \theta$	0.96	loamy sand
ECa = $-2.27+0.08$ ECw$+12.30\ \theta$	0.67	loam
ECa = $0.07-0.10$ ECw$+0.73\ \ +\ 0.93$ ECw $\cdot\ \theta$	0.96	loam
ECa = $-2.68+0.12$ ECw$+11.56\ \theta$	0.77	clay loam
ECa = $0.73-0.12$ ECw$+\ 0.84$ ECw $\cdot\ \theta$	0.94	clay loam
ECa = $-0.45-0.05$ ECw$+2.96\ \theta + 0.69$ ECw $\cdot\ \theta$ $+0.48\ D_1^* + 0.07\ D_2^*$	0.94	combined soils

*D_1 and D_2 are variables that account for soil type such that:

soil type	D_1	D_2
sand	1	0
loam	0	1
clay loam	0	0

$$ECa = -0.45 + 0.69\ ECw \cdot \theta - 0.05\ ECw + 2.96 \cdot \theta + 0.48\ D_1 + 0.07\ D_2 \quad (9)$$

D_1 and D_2 are factors that account for soil type. These may be the clay contents or the cation exchange capacities of the soils.

Field Experiment

Bulk soil electrical conductivity as measured by the salinity probe (ECp), electrical conductivity of the saturated extract (ECse) and average volumetric water content (θv) are given in Tables 5, 6, and 7 for the loamy sand, loam, and clay loam soils respectively. The ECp values are the averages of two measurements taken at each site. No significant difference was found between measurements if these were made at identical probe depths. Two soil samples were taken from the same depth at which probe readings were made (0 - 30 cm) for the subsequent analysis of the electrical conductivity of the saturated extract. The ECse given is the average of these two values.

Gravimetric water content was determined on soil samples taken from the immediate vicinity of the salinity probe at the time of measurement. Small variations in water content were found among the five salinity plots of each soil at each time of ECp measurement. These five moisture content values were averaged and then multiplied by

Table 5. Bulk soil electrical conductivity (ECp) measured by the salinity probe corresponding to different salinity levels as represented by the electrical conductivity of the saturated extract (ECse) for the sandy soil at different volumetric water contents (θv).

	ECse mmho cm^{-1}	ECp mmho cm^{-1}
a. θv = 0.28	0.56	0.23
	3.55	0.98
	7.74	1.80
	22.58	3.33
	34.9	5.73
b. θv = 0.17	0.92	0.15
	2.20	0.43
	8.00	0.55
	10.66	1.44
	19.20	1.92
c. θv = 0.12	0.53	0.11
	1.84	0.29
	2.82	0.54
	7.74	0.61
	10.66	0.93

Table 6. Bulk soil electrical conductivity (ECp) measured by the salinity probe corresponding to different salinity levels as represented by the electrical conductivity of the saturated extract (ECse) for the loam soil at different volumetric water contents (θv).

	ECse mmho cm^{-1}	ECp mmho cm^{-1}
a. θv = 0.36	3.09	0.65
	6.00	1.36
	8.72	1.12
	12.00	1.55
	32.00	1.77
b. θv = 0.27	4.66	0.56
	6.66	1.24
	5.65	1.15
	11.16	1.15
	32.00	2.34
c. θv = 0.24	3.84	0.48
	6.85	0.93
	12.00	1.03
	20.21	1.6
	24.00	2.29

Table 7. Bulk soil electrical conductivity (ECp) measured by the salinity probe corresponding to different salinity levels as represented by the electrical conductivity of the saturated extract (ECse) for the clay loam soil at different volumetric water contents (θv).

	ECse mmho cm^{-1}	ECp mmho cm^{-1}
a. $\theta v = 0.35$	2.82	2.02
	4.8	2.71
	7.27	3.07
	13.71	4.53
	24.0	7.00
b. $\theta v = 0.27$	5.7	1.32
	6.4	1.54
	7.74	1.91
	10.2	2.85
	27.0	4.23
c. $\theta v = 0.23$	5.33	1.14
	7.62	1.5
	5.85	1.76
	10.21	2.13
	30.47	2.92

the bulk density of the soil to obtain θv. Thus, three sets of data were obtained, for each soil, corresponding to three moisture content levels encountered in the field.

In Table 5a for the loamy sand soil, bulk soil electrical conductivity increased uniformly as the saturated extract conductivity (or soil salinity) increased. In Table 5b, ECse decreased with the water content in three of the plots, while the bulk soil electrical conductivity decreased in all the plots. The trend continued to the lowest water content θv = 0.12, Table 5c.

The data in Table 5 were studied by regression analysis to explain the effect of water content on the relationship between soil salinity and bulk soil electrical conductivity. Figure 5 gives the ECse-ECp regression lines for the loamy sand at each water content. The correlation coefficients are high and a lower r^2 is obtained as the water content decreases. Increasing the water content decreases the slope of the regression line. All regression line intercepts are negative because of the soil conductance associated with the diffuse double layer of ions surrounding soil particles.

Data for the loam soil are presented in Table 6. The bulk soil electrical conductivity increased uniformly with salinity only at the low water content θv = 0.24 (Table 6c). Figure 6 gives the ECse vs. ECp regression

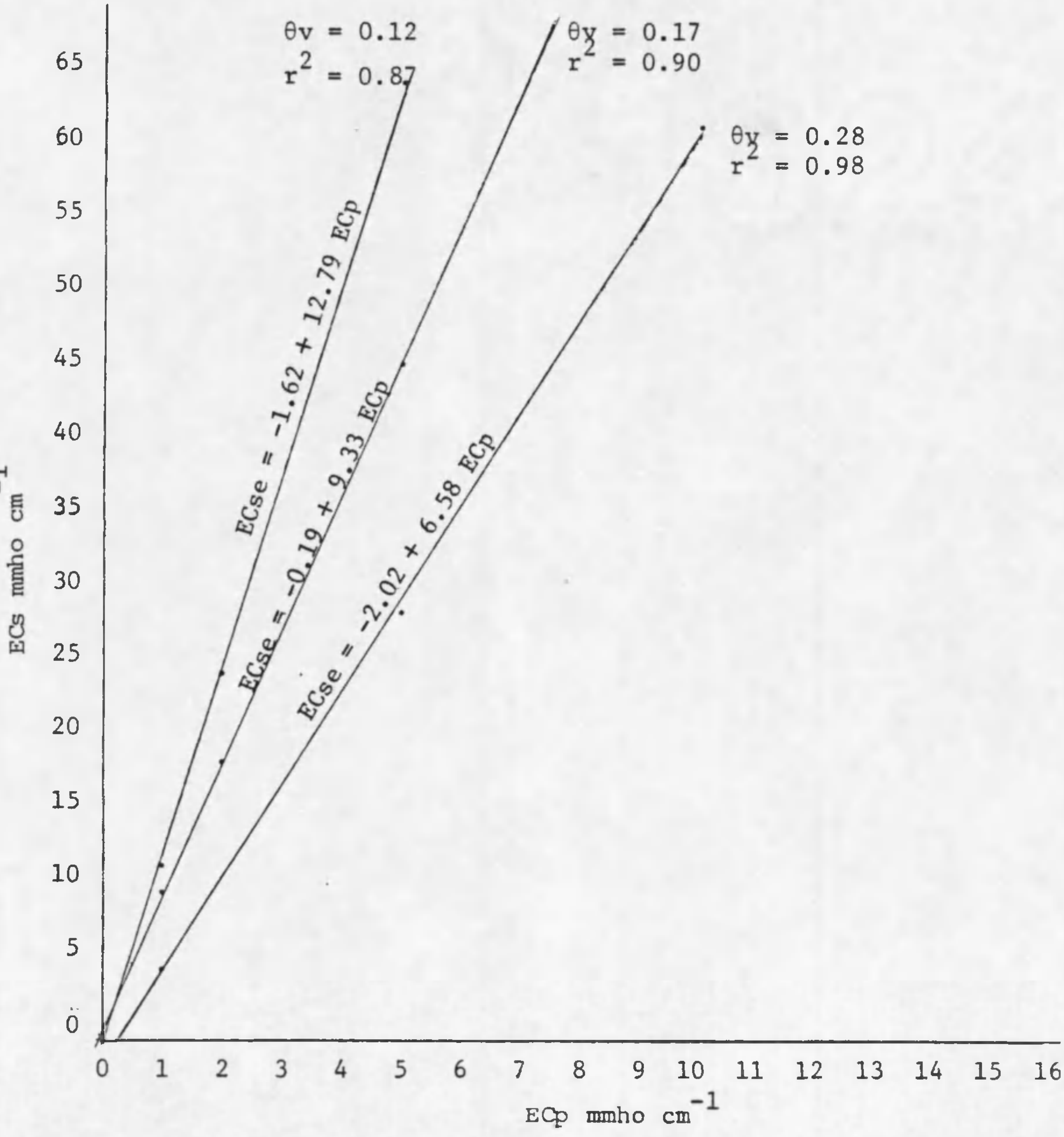

Fig. 5. ECse vs. ECp regression lines by volumetric water content (θv) for the sandy soil.

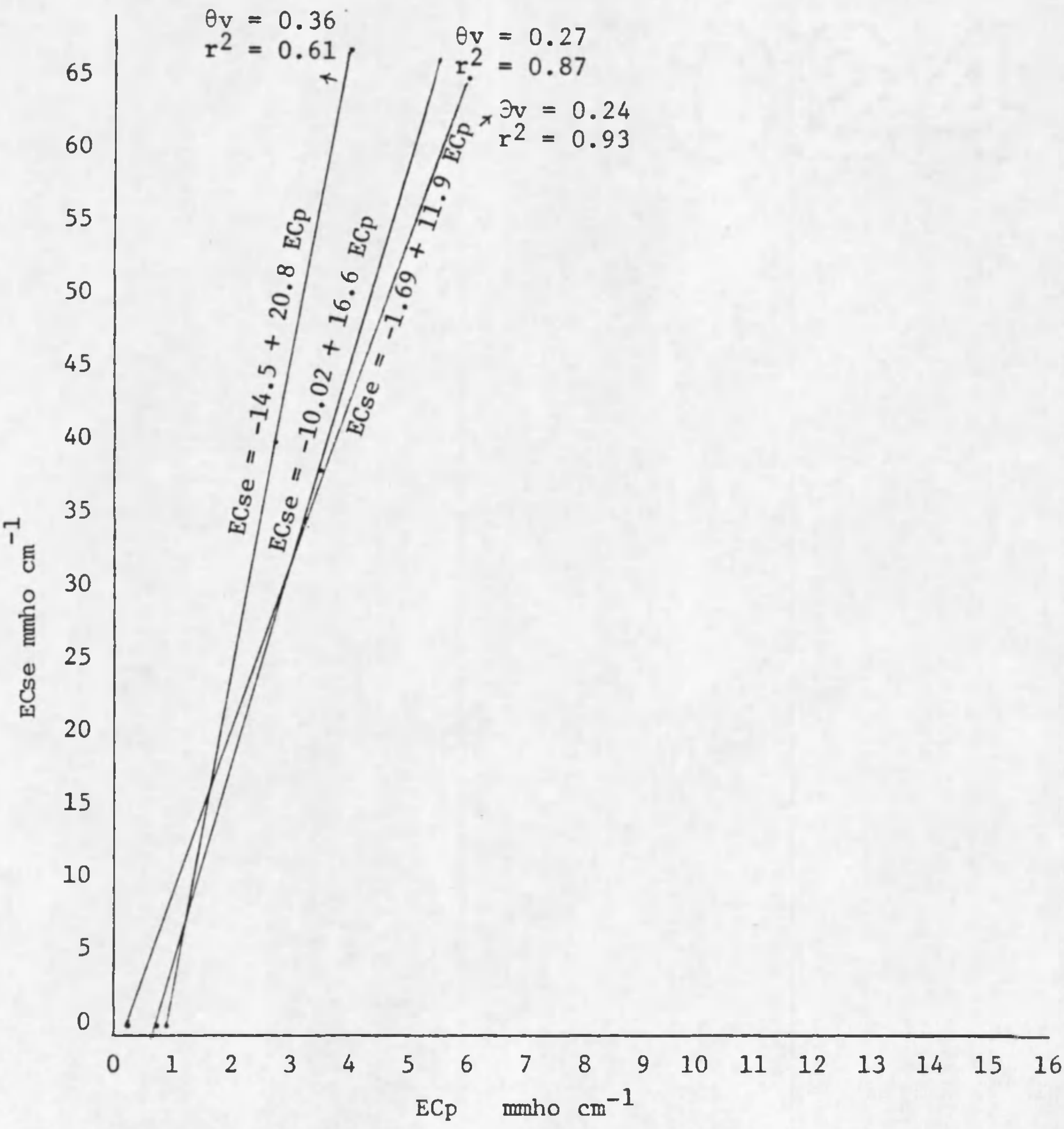

Fig. 6. ECse vs. ECp regression lines by volumetric water content (θv) for the loam soil.

lines for the loam soil. The relationship has the highest correlation $r^2 = 0.93$ at the low water content.

The relative effect of salinity and water content on bulk soil electrical conductivity measurements can be deduced from the results of the clay loam soil given in Table 7. The salinity of the soil solution increased in most of the plots as the soil dried. At each water content ECp increased uniformly with salinity. Decreasing the water content from its value at saturation decreased the bulk soil conductivity although the salinity increased.

Figure 7 gives the ECse vs. ECp regression lines for the clay loam soil at each water content. Increasing the water content increased the r^2, decreased the slope of the line, and decreased the intercept.

Data at the three water contents were then combined for each soil and studied by regression analysis. Table 8 gives the regression equations and coefficients of determination (r^2) when ECse is correlated with ECp/θv. The correlation coefficient was lower when the three soils were considered together than for individual soil. This suggests that calibration of bulk soil electrical conductivity with respect to saturation extract is needed for each soil type.

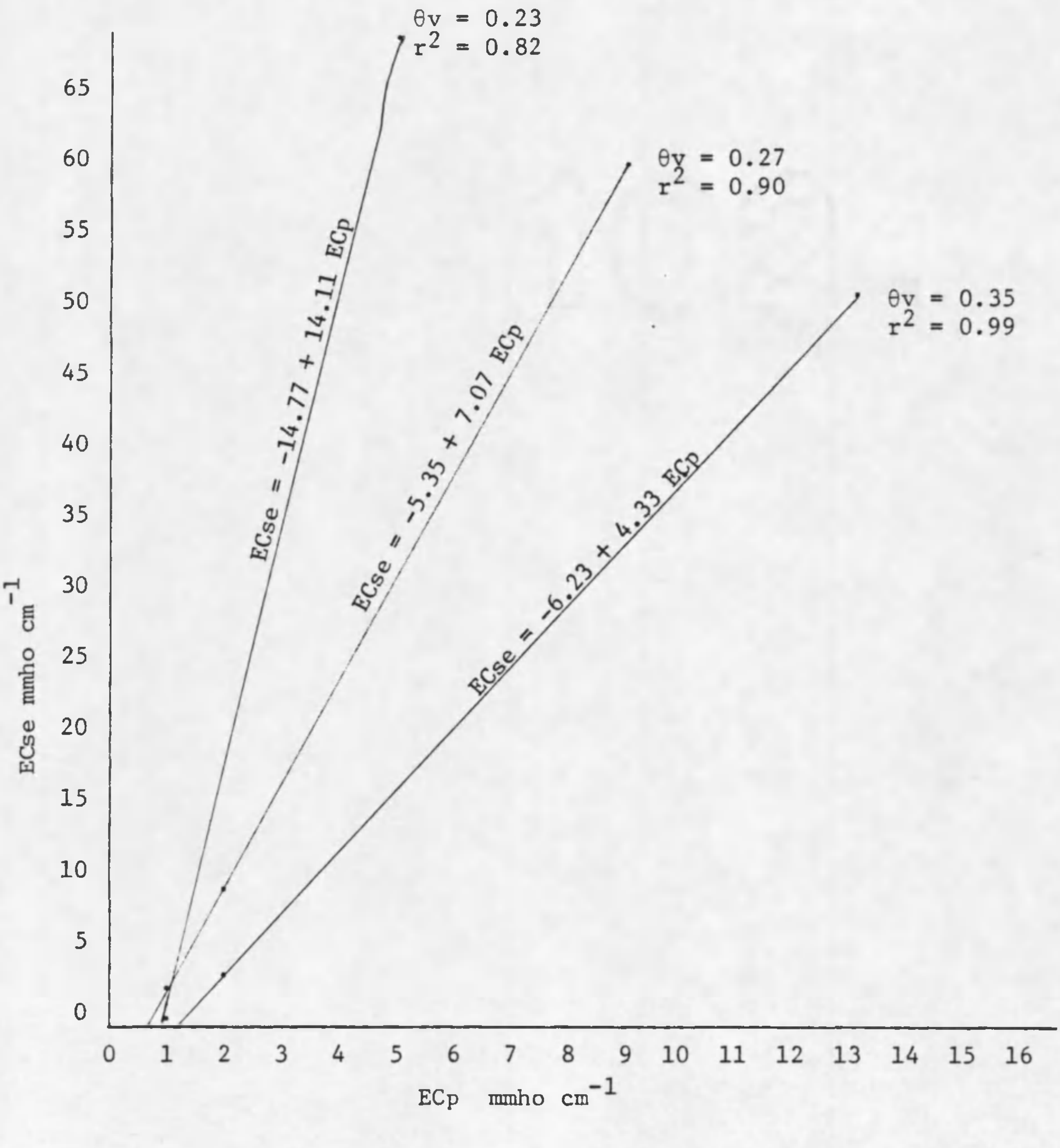

Fig. 7. ECse vs. ECp regression lines by volumetric water content (θv) for the clay loam soil.

Table 8. Regression equations and coefficients of determination (r^2) relating ECse, θv, and ECp for the three field soils.

Regression Equation	r^2	Soil
$ECse = 1.78\ (ECp/\theta v) - 1.83$	0.95	loamy sand
$ECse = 15.13\ (ECp) - 7.00$	0.74	loam
$ECse = 4.00\ (ECp/\theta v) - 6.8\ ECp - 7.70$	0.86	clay loam
$ECse = 1.52\ (ECp/\theta v) + 0.80$	0.55	combined soils

DISCUSSION

Laboratory Experiment

In this laboratory part of the experiment, bulk soil electrical conductivity (ECa) is correlated against soil salinity as represented by the <u>in situ</u> soil water salinity rather than the electrical conductivity of the saturated extract ECse. The reason behind this is that soil water salinity in the conductivity cell experiment is expected to remain constant with the application of various suction levels. The removal of water by the pressure plate apparatus will also remove salts thus maintaining the salinity level. In an irrigated field, however, evapotranspiration will remove water and leave the salts behind thus increasing the salinity of the soil solution. In the latter situation, therefore, it is necessary to monitor salinity variations through periodic measurement of the electrical conductivity of the saturated extract.

Effect of Water Content

In Table 3a ECa increased markedly in each soil as the salinity level increased. Also at each level of added salinity the values are higher for the finer textured soils. The ratio ECa/θv at a specific salinity level, say ECw = 8 mmho cm^{-1}, tend to be constant at 6, 7, and 6 for the sand, loam, and clay loam respectively. This is also observed at the other salinity levels except that at high salinities, say ECw = 31 mmho cm^{-1}, these ratios start to diverge (a value of 22 for the sand and 18 for the clay loam). At saturation, therefore, and for salinity levels encountered in the field, ECa is independent of soil type.

As the soil dried, the electrical conductivity decreased (Figs. 2, 3, and 4). Although the concentration of ions which conduct the current remained constant, the amount of soil water present governed the available paths for conduction. As water is removed, the water films on the soil particles became thinner and the larger pores drained. When these discontinuities occur, the resistance increases markedly because the area of conduction is reduced, tortuosity increases, and consequently the conductivity decreases.

The effect of water content on the measured bulk soil electrical conductivity can be deduced from Fig. 2 for the sandy soil. For example, a measurement of ECa of 0.5 mmho cm^{-1} corresponds to a salinity of 2 mmho cm^{-1} at saturation, 8 mmho cm^{-1} at 0.1 bar, and 31 mmho cm^{-1} at 0.5 bar suction. Similarly in Fig. 4 for the clay loam an ECa measurement of 2 mmho cm^{-1} corresponds to a salinity of 3.9 mmho cm^{-1} at saturation, 5 mmho cm^{-1} at 0.1 bar suction and 20 mmho cm^{-1} at 0.5 bar. It might be argued that a large error accompanies this method. However, the relative contribution of both salinity and water content should be taken into consideration in order for the measured ECa value to be meaningful. The ratio ECa/θv has a significant meaning at saturation and tends to be constant irrespective of soil type. This ratio is the function that contains the variables ECa and θv which affect soil salinity (ECw) i.e., ECw = f (ECa, θv). Conversely, bulk soil electrical conductivity ECa depends on the product ECw $\cdot$ θv. This is the product of the in situ soil salinity and the volumetric water content and is the total salt content that is conducting the current.

To minimize the effect of varying water content on bulk soil electrical conductivity, Rhoades suggested taking measurements immediately after irrigation or at field capacity (Rhoades, 1975). When drainage ceases after irrigation, crop water uptake decrease θv but most of the salts are left behind in the soil solution. Hence, except for the effect of salt precipitation, the product (ECw $\cdot$ θ) would be unchanged during the first few days after irrigation and changes in ECa over this time should be primarily related to the tortuosity.

The relative contributions of water content and soil salinity to the conductivity can be deduced from regression analysis of the data. Table 4 gives the regression equations and correlation coefficients when entering the variable ECw and θ separately and when as a product. A large improvement in the relationship ($r^2 = 0.96$ compared to $r^2 = 0.64$, for the loamy sand) is obtained when the ECw $\cdot$ θ is entered as a variable. This plus the fact that this factor was more significant than both ECw and θ alone when all three appear in the same equation (e.g., in the regression equation of the loam soil) illustrates the large dependence of ECa on the salt content of the soil solution.

The curves in Figs. 2, 3, and 4 show another important feature. These curves tend to diverge as the salinity level increased. That is bulk soil electrical conductivity decreased as the soil dried, but this diminution tended to be greater as the salinity increased. In a highly saline electrolyte ions will have a longer conduction path (more tortuous) than those in a low saline electrolyte when the area of conduction (i.e., water content) is reduced by an equal increment.

Effect of Soil Type

Surface conductance (ECs) or conductance due to the electrical double layer can be approximated by extrapolating the curves in Figs. 2, 3, and 4 to the ordinate axis. The values obtained are ECs = 0.10 mmho cm^{-1} for the sandy soil, 0.5 mmho cm^{-1} for the loam, and 0.85 mmho cm^{-1} for the clay loam. Surface conductivity, often called specific conductance, represents the situation when the soil solution contains no salts; the conductivity being due only to current transfers by the ions adsorbed on the colloidal particles in the soil. The surface conductivity as shown from the curves is higher for the fine textured soils and relatively independent of water content.

The set of curves in Figs. 2, 3, and 4 were superimposed in an attempt to explain the effect of soil type on the bulk soil electrical conductivity vs. soil water salinity relationship. In order to compare the curves a reference calibration water content should be taken. The water contents were approximately equal at matric potentials of zero for the sand, 0.1 bar for the loam and 0.5 bar for the clay loam. The volumetric water contents that correspond to these suctions are 0.30, 0.26, and 0.24 for the sand, loam, and clay loam respectively. By comparing the curves that correspond to these soil moisture suction levels, we find the slope of ECa vs. ECw data line to decrease with clay content.

Table 4 gives the correlation coefficients (r^2) for the individual soils and when all three soils were considered together. The regression equation for the combined soils had a lower r^2. When the soil type was included as a variable factor D, the variation among the soils were minimized and r^2 increased to 0.94.

Equation (9) shows the dependence of ECa on ECw, θ, and soil type:

$$ECa = -0.45 - 0.05\ ECw + 2.96\ \theta + 0.69\ ECw \cdot \theta + 0.48\ D_1 + 0.07\ D_2 \quad (9)$$

Knowing the type of the soil in question will ascertain values of D_1 and D_2 (see Table 4) and enable us to obtain the approximate equation for each soil type. D_1 and D_2 can be replaced by ECs and a relationship similar to the one given by Rhoades, Raats, and Prather (1976) will result: $ECa = T(ECw \cdot \theta) + ECs$ [Eq. (5)]. Equation (9) suggests that calibration for each type of soil is needed in the correlation of ECa vs. $ECw \cdot \theta$.

Field Experiment

The effects of water content and salinity on bulk soil electrical conductivity is different under normal field conditions than under laboratory ones. Normally in cropped fields the salinity is expected to increase as the soil dries. The soil will generally be at field capacity or lower and water losses by evapotranspiration will increase the soil-water salinity. But certain phenomena such as leaching, lateral movement of water, and precipitation cause loss of salts that are added to the field plots. In this experiment the plots were uncropped, and intermittent rain caused consecutive wetting and drying of the soil which probably lead to leaching and precipitation of the salts. As a consequence, the soil salinity as measured by the electrical conductivity of the saturated extract decreased in some of the plots as the soil dried.

It will be shown in the next section, however, that under decreasing moisture contents the bulk soil electrical conductivity will be largely determined by the water content. That is, bulk soil electrical conductivity ECa as measured by the salinity probe (ECp) is more related to water content when the soil is dry and more related to salt content when soil water content is high.

Effect of Water Content

Salinity variation with water content can be predicted from the results of the sand and clay loam soils. Regression coefficients of the ECse vs. ECp relationship for the two soils ranged from $r^2 = 0.82$ to $r^2 = 0.99$ (Figs. 5 and 7). A high correlation was still maintained at the lower water contents. This proves the ability of the salinity probe to predict salinity variations even at low moisture levels.

An increase in the slope of the regression line was obtained as the soil dried. In Table 7 for the clay loam soil the control plot had a salinity of 2.82 mmho cm^{-1} at saturation ($\theta v = 0.35$) and a corresponding bulk EC of 2.02 mmho cm^{-1}. As the soil dried to $\theta v = 0.27$, the salinity increased to 5.7 mmho cm^{-1} but the bulk soil electrical conductivity decreased to 1.32 mmho cm^{-1}. Similar argument can be made for the plots with higher salinity levels. A decrease in water content, therefore, lowered the bulk soil electrical conductivity although the salinity increased. The increase in the slope of the ECse vs. ECp regression line, therefore, illustrates the better response of the salinity probe to salinity variations at higher field moisture contents. This behavior was observed by Halvorson and Rhoades (1974) who used the four-electrode straight line configuration (Wenner array) for dry land salinity investigations. They showed that ECa was more related to salt content when soil water content was high and was more related to water content when the soil was dry.

Data of the loam soil (Table 6) shows an unexpected result. Here the increase in the bulk soil electrical conductivity with salinity is more uniform under low water contents. A high correlation coefficient is obtained under drier conditions (Fig. 6). The error can be largely attributed to the experimental conditions found on this site rather than to the instrument itself. The contact between the probe and the soil was poor due to the presence of large stones and gravel layers in the 30 cm-depth region. This caused an error in the electrical conductivity measurement. Kirkham and Taylor (1950) reported a fairly large error (11 to 70 percent range) accompanying the determination of the electrical conductivity when large cracks occurred in their tank.

Effect of Soil Type

To determine the effect of soil type on the bulk soil electrical conductivity vs. soil salinity relationship, a reference water content should be taken. The results of the loam soil are acceptable at water contents lower than saturation. At the field moisture content $\theta v = 0.27$ the slope of the regression line is higher for the loam soil (13% clay) than for the clay loam soil (26% clay) (Figs. 6 and 7). Therefore, the slope of the ECse vs. ECp regression line increases as the clay content decreases. For the sand soil, and at similar moisture content ($\theta v = 0.28$) the slope of the regression line is similar to that of the clay loam. This behavior may be attributed to the limitations mentioned at the beginning of this discussion.

The electrical conductivity of soil surfaces (ECs) can be deduced if the regression lines are extrapolated to ECse = 0. The ratio of the intercept to the slope will give the value of ECs. At the reference water content $\theta v = 0.27$, these values are 0.30 mmho cm^{-1}, 0.60 mmho cm^{-1}, and 0.75 mmho cm^{-1} for the sand, loam, and clay loam soils respectively. Hence the electrical conductivity of soil surfaces are higher in finer textured soils, due to their higher cation exchange capacity (Table 2) and more cations in their double layer.

Results of the laboratory experiment showed that the electrical conductivity of the saturated extract (there it was approximated by the *in situ* water salinity or ECw) is largely determined by the ratio of the bulk soil electrical conductivity to the water content, i.e., $ECp/\theta v$. By virtue of these results, data for the field experiment were studied by regression analysis to find the relative contribution of bulk soil electrical conductivity and water content to *in situ* soil salinity. It is found, as shown in Table 8, that a high correlation exists between ECse and $ECp/\theta v$ (excluding the results of the loam soil, for reasons cited before). Soil salinity, therefore, can be determined by the electrical conductivity of the bulk soil over the entire field moisture range, if the moisture content at the time of measurement is known. Since the correlation coefficient is lower for the combined soils than for individual soil, knowledge of the soil type is also necessary. Such that calibration of bulk soil electrical conductivity with respect to saturation extract conductivity is needed for each soil type.

SUMMARY AND CONCLUSION

Soil salinity can be assessed under field conditions from soil conductivity determinations if the water content and soil type are known. A laboratory experiment was established using four-electrode conductivity cells to evaluate the relationship between four-electrode conductivity and soil salinity at different water contents. Results indicated that over the moisture range of practical concern, bulk soil electrical conductivity is related to the product of the <u>in situ</u> soil water salinity and water content, i.e., the soluble salt content. ECa vs. ECw calibration curves at different water contents were presented. Such calibrations eliminate the need to limit the four-electrode technique to soils that are not at a particular reference water content, like field capacity. The equation that best represents the relationship between soil salinity and four electrode conductivity is of the form:

$ECw = a\ (ECa/\theta v) + b.$

A field experiment was established to measure the bulk soil electrical conductivity (ECa) by the salinity probe. The equation that best represents the relationship between the electrical conductivity at arbitrary water contents has the same form of the equation above. Increasing the water content decreased the slope of the ECse vs. ECp regression line. Also, as soil clay content increased the slope of the regression line decreased. The water content and the soil type must be known for accurately estimating *in situ* field salinity by the four-electrode conductivity method.

For general salinity estimates, the method proved adequate. The amount of time spent taking salinity probe measurements and doing the calculations in the field was small compared to the traditional method of measuring the electrical conductivity of the saturated extract.

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