FIELD MEASUREMENTS OF SOIL SALINITY BY THE FOUR-ELECTRODE AND THE SALINITY PROBES

by

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In the name of Allah,
The most Gracious,
The most Merciful

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure | Page

LIST OF TABLES

ABSTRACT

Soil salinity measurements by electrical conductivity (EC) of the EC-probe (salinity probe) and four-electrode Wenner array were conducted in experimental plots irrigated with salinized water at EC = 4, 10, 20, and 40 mmho/cm of $NaCl + CaCl_2$ solutions at the same SAR, plus a control with tap water at EC = 0.4 mmho/cm.

These treatments were used on three different Arizona soils near Tucson. The bulk electrical conductivity measured by the salinity probe (EC_p) and Wenner array (EC_a) were closely related to each other, and to the electrical conductivity of the saturation extract (EC_e). The functional relationship between EC_p, EC_a, and EC_e was $EC_p = a \circ \theta \circ EC_e + C$ and $EC_a = b \circ \theta \circ EC_e + C$. The correlation coefficients (r^2) exceeded 0.88.

Linear regressions between saturation extract electrical conductivity (EC_e) and bulk soil electrical conductivity (EC_p) and (EC_a) were developed for the above soils. Most correlation coefficients (r^2) exceeded 0.95. Clay content and water content affected the bulk soil electrical conductivity, the higher the clay and water contents of a given soil, the lower the slope of the EC_e vs. EC_a and EC_e vs. EC_p linear regression lines.

INTRODUCTION

Saline and alkali soils are a major problem in arid and semi-arid regions. They greatly affect the value and productivity of farming lands in every continent of the world. The salinity problem is salt accumulation in the crop root zone, to the extent that the salt affects plant growth because of its osmotic effect. High salt concentration increases the osmotic forces holding water in the soil and it makes it more difficult for plant roots to extract the soil moisture.

A sodium problem is often associated with a salt accumulation. It reduces water infiltration into and through the soil. The poor soil permeability makes it more difficult to supply the crop with water and increases cropping difficulties through crusting of seed beds, water logging of surface soil, and accompanying disease, water oxygen and nutritional problems. In addition specific ions, i.e., Na, B, and Cl taken up by plants can result in toxicity problems as well as reduction in yield. Proper water management requires a reliable method of assessing soluble salt concentrations in soils, and the change of salt concentration in time and space.

A common procedure for determining the soluble salt concentration is to measure the electrical conductivity of saturated soil extract (U. S. Salinity Laboratory Staff, 1954). The saturation extract is used because it is easily reproducible and tends to cancel out the matric effects due to soil texture between different soils. The saturation extract is made by adding a small amount of pure water to the beaker. Then fill the beaker approximately two-thirds full of air-dried soil. Add pure water to the soil in the beaker while stirring with a spatula. At saturation the soil paste glistens as it reflects light, flows slightly when the container is tipped, and the paste slides freely and cleanly off the spatula for all soils but those with a high clay content. After mixing, the sample should be allowed to stand for an hour, and then the criteria for saturation should be rechecked. Free water should not collect on the soil surface nor should the paste stiffen markedly or lose its glisten on standing. If paste is too wet, additional dry soil may be added and mixed again (Method of Soil Analysis, 1965).

Pure water is a very poor conductor of electrical current, whereas water containing the dissolved salts conducts current approximately in proportion to the amount of salt present. Based on this fact, the measurement of the electrical conductivity of an extract is an indication of the total concentration of ionized constituents (Method of Soil Analysis, 1965). Because most soil minerals are insulators, electrical conduction in saline soils is primarily through the water, which contains dissolved electrolytes (salts). The contribution of exchangable cations to electrical conductivity is relatively small in saline soils because these cations are less abundant and mobile than the soluble electrolytes (Rhoades and Halverson, 1977).

The determination of electrical conductivity is made by measuring the electrical resistance between parallel electrodes immersed in the solution or extract. In such a system, the solutions between electrodes becomes an electrical conductor to which the physical laws relating electrical resistance apply. The electrical resistance (R) is directly proportional to the distance (L) between electrodes, and inversely proportional to the cross-sectional area (A) of the electrodes. Thus $R = rL/A$ where r is a proportionality constant known as the electrical resistivity, the value of which depends on the nature of the solution. If R is measured in ohms, L in cm, and A in cm^2, the units of r are ohms/cm. The reciprocal of the electrical resistivity i.e., $1/r$, is the electrical conductivity (EC). The units of $1/r$ or EC are mho per cm, or in SI units siemens per meter, where 1 siemens m^{-1} = 10 mho cm^{-1}.

The development of a reliable method for soil investigation, without having to remove the soil sample is highly desirable. Whitney, Gardner, and Briggs (1897) made use of electrical resistance for soil investigation. Their method was to use only two electrodes and an alternating current to avoid polarization. This technique responds to moisture content, salt concentation, and temperature of soil. The two-electrode method measures the sum of both the soil resistance and the contact resistance between the electrode and the soil. The contact resistance between the electrodes and the soil is erratic. Any expansion or contraction of the soil around the electrodes will lower or raise that contact resistance.

Salinity sensors used by Kemper (1959), Richards (1966), Enfield and Evans (1969), Reicosky, et al. (1970), and Oster and Willardson (1971) are considered reliable monitors of salt concentration in the soil. Salinity sensors measure the electrical conductivity of a porous insulater embedded in the soil and saturated with soil water. Kemper (1959) and Richards (1966) showed that the electrical conductivity (EC) of the soil solution can be measured _in situ_ with such a salinity sensor.

Kirkham and Taylor (1950), Shea and Luthin (1961), and Keller and Frischknecht (1966) discussed the principles of four electrodes in a straight line equidistant apart. A known current is fed through the primary circuit by means of the outer electrodes, and the resistance is measured across the secondary circuit connecting the inner electrodes.

The four-electrode resistivity technique for measuring bulk soil electrical conductivity (EC_a) has been used by Rhoades and Ingvalson (1971) on irrigated soils and Halverson and Rhoades (1974) on dry land and saline seep areas to estimate soil salinity in the field. Rhoades and van Schilfgaarde (1976) introduced the EC-probe (salinity probe) for measuring the bulk soil electrical conductivity (EC_p). It consists of four annular rings placed between insulators to form a vertical four-electrode array. This "salinity probe" is slightly tapered so that it can be inserted into the hole made by an Oakfield Soil Sampler. Therefore, for a given soil type and water content, soil salinity can be correlated with soil electrical conductivity. The principles of the EC-probe and four-electrode array are the same, except the way the electrodes are arranged in both devices, as previously described.

The objective of this research is to:

a) measure bulk soil salinity by use of the four-electrode technique and the salinity probe in the field,

b) study the effect of soil texture and its different water content on bulk soil electrical conductivity, and

c) compare the use and accuracy of these devices in the field.

LITERATURE REVIEW

Frank Wenner (1916) stated that a knowledge of earth resistivity or specific resistance might be of value in determining something of the composition of earth, such as moisture content and soil salinity, providing that the earth should be kept undisturbed during measurement. He suggested the following method: four holes were made in the earth approximately uniformly spaced in a straight line. The diameter of the holes was not more than ten per cent of the distance between them, and all extended to approximately the same depth, at which the resistivity was of most concern. In each hole was placed an electrode, which makes electrical contact with the earth only near the bottom.

Wenner's potentiometer arrangement shown in Figure 1 (using alternating current to obviate the more serious difficulties which might arise on account of polarization with direct current). The current terminals (1 and 4) or electordes are connected to a source of alternating voltage and to a transformer. The low-voltage side of the transformer is connected to the ends of a slide wire, one end of which is also connected to one of the terminals (2 and 3). The other terminal is connected through a vibration galvanometer to the adjustable contact of the slide wire. An ammeter is

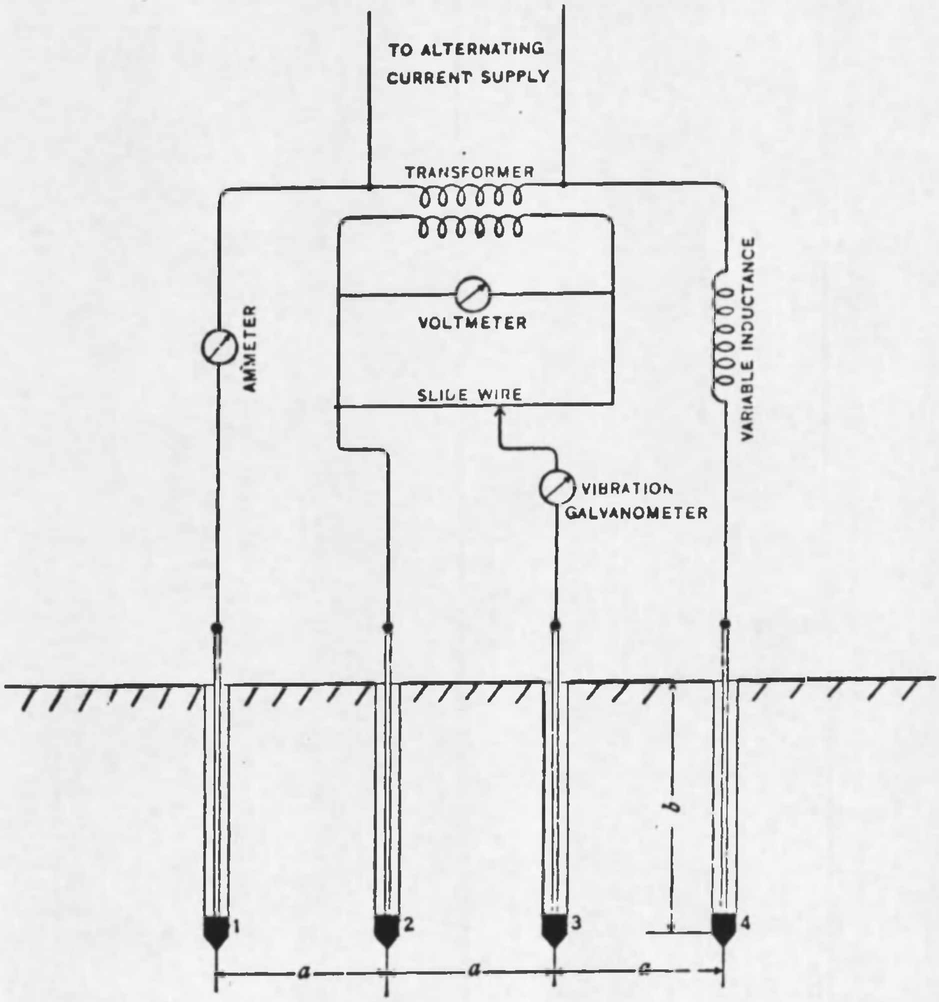

Figure 1. Arrangement for measuring four-terminal earth resistance by potentiometer-voltimeter-ammeter method. (After Frank Wenner, 1916.)

connected into a lead to one of the current terminals (1 and 4) and a voltmeter across the ends of the slide wire, or, if the ratio of the transformer is known when connected to the terminals of the slide wire, the voltmeter may be connected across the line. On account of phase displacement resulting from polarization at the current electrodes, a variable inductance is connected into one of the leads, so that the test current may be brought in phase with the voltage of the low side of the transformer. This is one of the conditions necessary for a zero current through the galvanometer.

The result obtained depends mainly upon the resistivity near and between the inner or potential electrodes, and very little upon the resistivity at distances equal to, or more than, the distance between the outer or current electordes, providing the four electrodes are approximately uniformly spaced. In order to calculate the resistance between the inner or potential electrodes, Ohm's law must be applied.

When a is the distance between holes (1 to 2, 2 to 3, and 3 to 4), b is the depth of the holes, p is the resistivity, and R is the measured resistance, then

$$p = \frac{4\pi aR}{n} \qquad (1)$$

where n has a value between 1 and 2 depending upon the b/a ratio, the depth of the electrodes to the distance between them. When b is large in comparison with a,

$$p = 4\pi aR. \tag{2}$$

When b is small in comparison with a,

$$p = 2\pi aR. \tag{3}$$

Rhoades and Ingvalson (1971) employed a field method for determining soil salinity. Soil resistance was measured with an array of four electrodes placed in the immediate soil surface utilizing a newly developed earth resistance meter. Their studies were conducted at near constant soil water content. Since water content is reproducible and available throughout the season, they recommended that soil conductivities be just following the irrigation. Loss of water by evapotranspiration will increase the salt concentration, and would tend to compensate for the relative small change in water content. They found that with this Wenner array technique, Figure 2, the electrical conductivity is measured to a soil depth approximately equal to the interelectrode spacing a. They used this hypothesis to measure bulk soil electrical conductivity of saline soils at different depths by increasing or decreasing the outer electrode spacing.

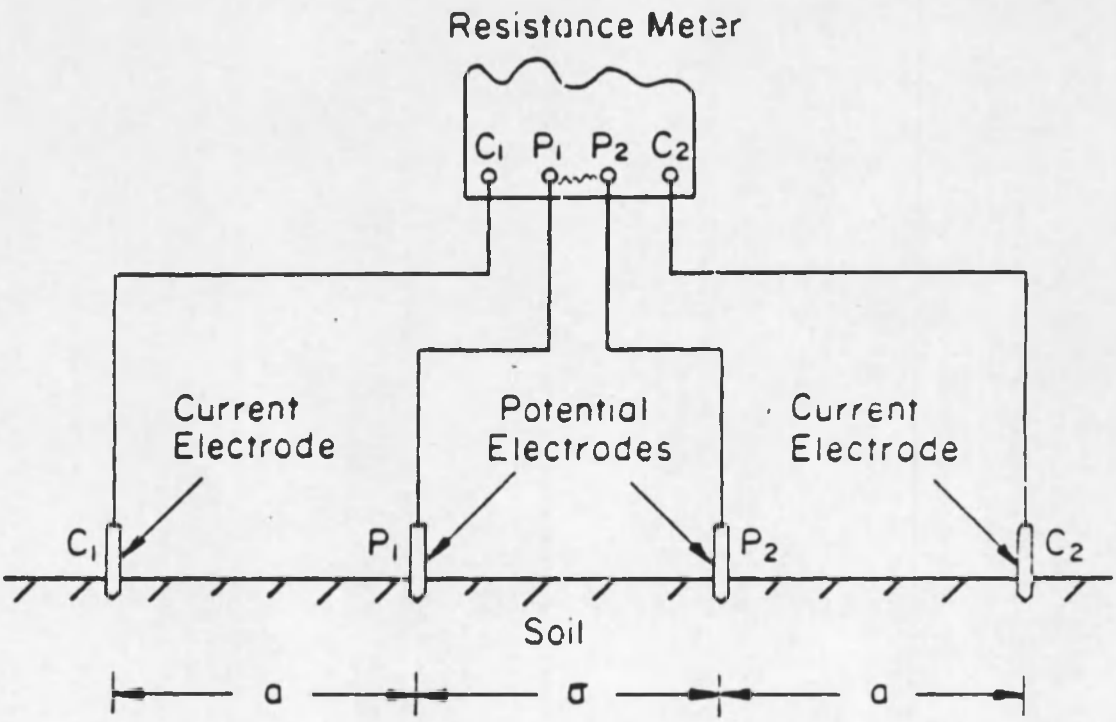

Figure 2. Wenner array of electrodes used in soil electrical conductivity determination where a represents the interelectrode spacing; c_1 and c_2, the current electrodes; and p_1 and p_2 the potential electrodes. (After Rhoades and Ingvalson 1971.)

They gave this equation for calculating the electrical conductivity of the soil solution EC_a as

$$EC_a = \frac{1000 \times f_t}{2\pi a R_t} \tag{4}$$

where R_t is measured resistance (in ohms) for an equidistant interelectrode spacing a (in cm), and f_t is a factor to adjust the reading to a reference temperature of 25°C. This technique also measures the average salinity of relatively large soil volume, about $5a\pi^3/6$, Figure 3.

Because salinity is not uniform vertically as well as laterally, accurate measurement of soil salinity distribution within the root zone is desirable. An alternative to the horizontal four-electrode method would be useful.

Rhoades and van Schilfgaarde (1976) used a single probe for electrical conductivity (referred to as a salinity probe) for determining soil salinity EC_p, in which the four electrodes are mounted as annular rings, Figure 4. The spacing between the electrodes is 2.6 cm. Determination of EC_p of the soil depth(s) of interest is made after inserting the salinity probe into the soil to the desired depth(s). The volume of soil measured encircling the probe is about 90 cm^3 ($5\pi a^3/3$), Figure 4. The probe is slightly tapered towards the tip so that all four electrodes firmly contact the soil upon insertion of the probe in the hole.

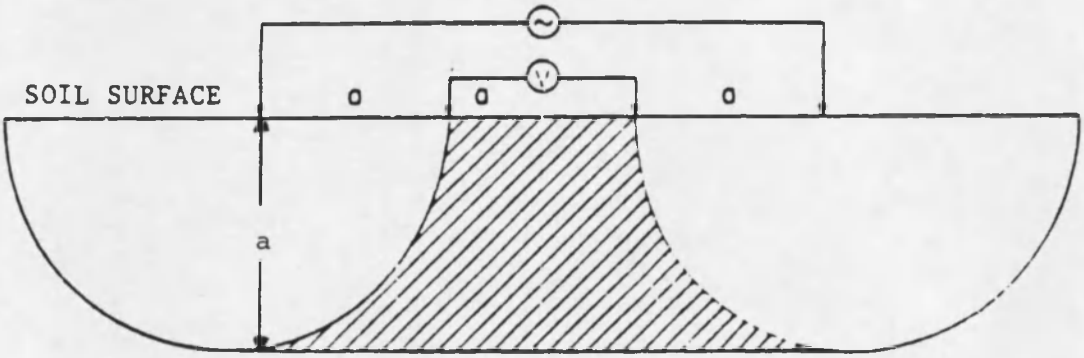

Figure 3. Volume of soil measured using Wenner array method. Conductivity is measured for diagonally hatched mass of soil. (After Rhoades and Halvorson 1977.)

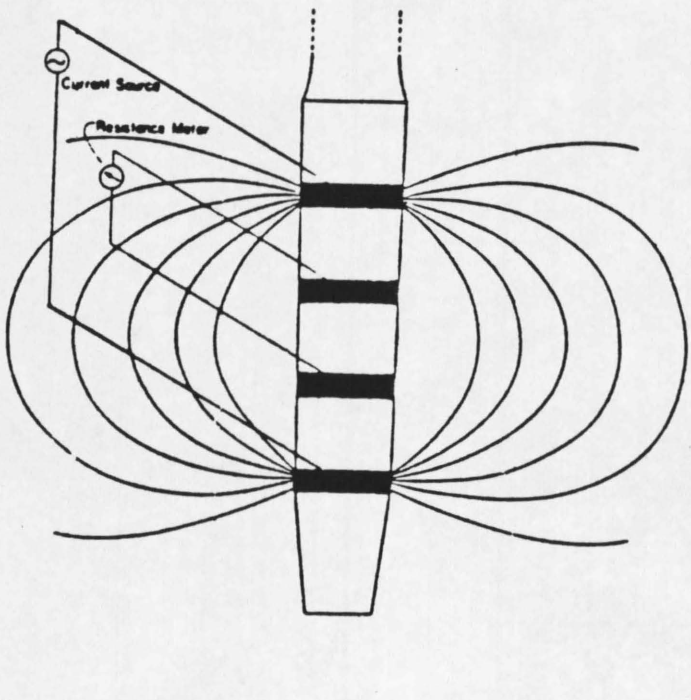

Figure 4. Schematic illustrating the principle of the soil-salinity probe. (After Rhoades and Van Schilfgaarde 1976.)

Soil electrical conductivity of such discrete intervals is designated by EC_x which is calculated by

$$EC_x = \frac{Kf_t}{Rt} \tag{5}$$

where K is a calibration constant determined by submerging the probe in a large volume of solution of known EC.

Rhoades and van Schilfgaarde (1976) concluded that the salinity probe can more accurately determine soil salinity of a discrete depth interval in the soil profile than can the surface-positioned four-electrode technique. The probe has some of the same limitations as *in situ* salinity sensors (i.e., soil must be removed with a soil sampling tube, although analysis is not required), and it responds to a relatively small localized region within the soil. The EC_p of the salinity probe is calibrated to the electrical conductivity saturated extract (EC_e).

Salinity Appraisal

Soil can be considered as a difficultly soluble compound. It will be studied through the salt solution, and its electrical properties. When salt is dissolved in water, the salt dissociates into ions. These ions carry charges of electricity and it is upon these ions that the electrical conductivity of solution depends. The more dilute the solution the greater the relative effective concentation in terms of higher activity coefficients and less complex formation. Such solutions have certain physical properties, and among them the important property of electrical conductivity. It depends on

(1) the amount of salt solution (soil moisture)

(2) the temperature

(3) the concentration of solution.

It is possible to determine the soluble salt content of soils from the electrical conductivity provided the temperature and water content are known (Whitney and Means, 1897).

Because most soil minerals are insulators, electrical conduction in saline soils is primarily through the pore water which contains electrolytes. In addition, soils may conduct current via the exchangable cations on the surfaces of charged soil minerals and that are electrically mobile to some extent. Surface conductance is most significant in soils high in clay content, low soluble salts, and high exchangable sodium. (Shainberg, et al. 1980).

Hence, the electrical conductivity of saline soils is affected by the number, size, and continuity of soil pores, as well as salt and water contents (Rhoades and Ingvalson 1971).

Effect of Water Content on EC of Soils

Whitney, Gardner, and Briggs (1897) stated that, when more water is added to the soil, the salt solution will be diluted and more of the solid substance will be dissolved. On the other hand, when water is drying out from the soil through evaporation or transpiration through plants, the concentration of the solution increases. Thus the concentration of salts as well as the amount of water in the soil can vary continuously.

They investigated the electrical resistance of soils by a two-electrode method and a source of alternating current to avoid polarization. Their general conclusion was that the variations in salt concentrations were too great to allow the use of the resistance method for measuring variation in moisture content.

Edlefson and Anderson (1941) reported that the most obvious source of difficulty with any electrical resistance method is the variation in amount of dissolved salts in the soil solution. They used a four-electrode method for measuring soil water content under field conditions (four electrodes rather than two electrodes eliminates the contact resistance between the electrodes and soil material) to see whether the variations in salt content were too great to allow the use of this method as an indicator of soil water content through the entire season. They used a soil tube to drill the holes for the electrodes, and the electrodes were designed to be placed in the soil-tube holes. The electrodes were inserted in the holes after these had been partly filled with a thin mud made from the soil withdrawn from the holes. After settling had taken place, the electrodes were pushed a bit further into the wet soil so as to make better electrical contact. The rest of the holes were then filled with earth. They found out that the use of the four-electrode method eliminated the variations in the contact resistance between the electrodes and the soil, and the resistance of the soil between the electrodes was determined of surprising consistency.

Kirkham and Taylor (1950) also used the four-electrode method to determine soil moisture content of the soil in the field. This method was to measure the specific electrical conductivity, and hence, moisture content of the soil. They determined the specific electrical conductivity by measuring electrical current through two outer electrodes of the probes, as well as the potential drop across the two inner electrodes. According to their observations, deviation of each inner electrode due to horizontal displacement from equal distance results in an error of 11.2% for each 0.05 foot displacement. Increasing the electrode spacing eliminates the error of electrode deviation. A highly significant relationship was found between specific electrical conductivity and water content by weight; the slight variation was due to soil salinity.

Since soil salinity is considered a major obstacle for assessing soil moisture content Shea and Luthin (1961) used the four-probe method to measure the soil salinity at varying soil water suctions. A tank filled with soil of specific physical properties was used. Various levels of salinity, and water content were produced by irrigating the soil with artificially salinized water of different electrical conductivity values. They investigated the relations between EC and moisture content in order to determine the range of soil moisture suction (0 - 125 cm of water) for further soil salinity measurements. They concluded that, as the soil dried, the specific electrical conductivity decreased and the salinity of soil solutions remained constant. But under field conditions, as moisture is lost by evapotranspiration, soil salinity will increase. They concluded also that the interelectrode spacing depends mainly upon the uniformity of soil profile as well as the depth of electrodes.

Gupta and Hanks (1972) studied the influence of water content on electrical conductivity of the soil, using special cups paced with soils at various water and salt contents. Four-probe conductivity measurements were made on the soils. Then electrical conductivity of the saturation extracts, and (1:5) extracts were measured. They found that increasing water content and/or salinity would increase the specific electrical conductivity of the soil.

Based on the above studies, Halvorson and Rhoades (1974), examined the use of soil resistance measurements to identify potential saline-seep areas and to measure soil salinity in the field under dry conditions. Significant correlations were obtained between apparent soil conductivity (EC_a) and electrical conductivity of solution extract, (EC_e). They found a relation between EC_a and salt concentration in wet soil (field capacity), while in dry soil EC_a was related to the water content.

Rhoades, Raats, and Prather (1976) extended the use of four-electrode method to arbitrary water contents. They studied EC in the laboratory as a function of water content (θ) and *in situ* water conductivity (EC_w). Undisturbed core samples of four soil types were collected in Lucite cylinders, with electrodes inserted in place. These cells were leached with solutions of desired EC_w. A pressure membrane apparatus was used to achieve the desired water content (θ). The function relationship between EC_a and θ was in the form

$$EC_a = (EC_w \circ \theta) \circ T + EC_s \qquad (6)$$

where T is the transmission coefficient and accounts for the tortuosity of the soil pores, and EC_s is the surface conductance. They found that the EC_a measurement was related to the tortuosity T of the current lines.

Effect of Soil Texture on EC of Soil

Since water holding capacity varies from coarse to fine textured soils, the amount of soil water present governs the available path for current conduction. As water is removed from the soil, the water films on the soil particles become thinner and the large pores are drained. Since $(\theta \times EC_w)$ is the volumetric salt concentration, so EC_a measures dissolved salts in the volume measured. Hence, the resistance increases.

In order for current to transfer, the salts have to be in ionized form. Some of these ions are absorbed on the colloid particles of the soil. Shea and Luthin (1961) reported that textural differences in soil will affect the specific electrical conductivity and the value of specific conductance will vary between soil types depending on the adscorbed cations on the exchange complex, on effective soil porosity, and on the degree of water saturation. Because there is a relation between soil salinity and soil electrical conductivity they suggested that additional information on the physical properties is required.

Dutt and Anderson (1964) derived an expression similar to Equation (6) 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 texture on the specific conductivity.

Rhoades and Ingvalson (1971) found that the ions on the double layer had little effect on the specific conductance, as well as on the relations between EC_e vs. EC_a.

Gupta and Hanks (1972) observed that the correlation coefficients for individual soils were generally higher than the combined soils. Hence, they suggested that calibration is required separately for each soil type.

Halvorson, Rhoades, and Reule (1977) studied the influence of soil texture, soil geographic location, and parent material on the linear EC_e - EC_a relationship. They found that geographic locations and parent material have little effect on the above relationship. Clay content affected the slope of the linear regression lines, the higher the clay content the lower the slope.

MATERIALS AND METHODS

Technique and Equipment

The EC-probe (salinity probe) described by Rhoades and van Schilfgaarde (1967) (Micron Engineering, Riverside, Calif.) consists of four annular rings placed between insulators to form a vertical probe, which is slightly tapered so that it can be inserted into the hole made by an Oakfield Soil Sampler. After the hole is made, the EC-probe is inserted to the depth(s) of interest. Wires from the four annular electrodes are led through the center of the probe shaft and connected to a resistance meter.

The probe's cell constant (K) was determined by immersing the probe in 0.01 M KCl solution that has an electrical conductivity (EC_{25}) of 1.4118 mmho/cm at 25°C. The cell constant was then calculated using

$$K = EC_{25} \cdot R_t \cdot \frac{1}{f_t} \qquad (7)$$

where R_t is the resistance (ohms) of the probe measured in the reference solution at temperature t, and f_t is the appropriate temperature correction factor. The K for the EC-probe was 21.6 cm^{-1}.

The four-electrode method consists of four electrodes made of noncorrosive metal (stainless steel) to insure a good conductance and minimize extraneous current due to corrosion. The electrodes were 0.5 cm in diameter and 22 cm long. The resistance of both the EC-probe and four-electrode probe was measured by a model 63251, Biddle null balance earth tester. This unit has a measuring resistance range from 0.01 to 10,000 ohms.

These methods were used to evaluate the relationship between bulk soil electrical conductivity (EC_a) and soil salinity (EC_e) at different water contents.

Field Experiment Procedure

The experiment was carried out at three sites near Tucson containing three different Arizona soils: Gila loam, Vinton loamy sand, and Pima clay loam. Their soil properties are listed in Table 1. Five plots (1.2 × 0.3 m) were established at each site, leveled and surrounded by a 0.3 m dike. To adjust salinity, waters of four different salinities: EC = 4, 10, 20, and 40 mmho/cm at constant sodium absorption ratio (SAR = 8) of $NaCl + NaCl_2$ solutions, were applied to four plots. About seventy-five liters of saline water were required to wet the soil to a depth of 30 cm. A fifth plot was left as control and irrigated with tap water (EC = 0.4 mmho/cm).

Table 1. Properties of soils in the field study.

Soil Type	CEC,* meq/100 g	Bulk Density,** g/cm^3	Sand %	Silt %	Clay,*** %
Gila loam Mixed (calcareous), thermic typic Torrifluvent	3.4	1.8	51.0	35.4	13.0
Vinton loamy sand Mixed, thermic typic Torrifluvent	2.5	1.5	80.3	10.5	9.1
Pima clay loam Mixed (calcareous), thermic typic Torrifluvent	5.3	1.5	44.2	30.9	26.8

*By an acetate method of USSL Staff, 1954.

**By the core method.

***By Hydrometer method.

Two or three days later, when the soil had drained to about field capacity, a soil sample was removed from the salinized soil (0 to 30 cm) with an Oakfield Soil Sampler. The four-electrode array having an interelectrode spacing of 30 cm was inserted into the soil, and the EC_a value of 0 to 30 cm depth was determined using equation (4). The EC-probe was then centered in the sample hole (the hole from which the soil sample was taken by the Oakfield Soil Sampler) and the EC_p value for the same depth was determined using equation (5)

After the EC-probe was removed, a soil sample (0 to 30 cm) is then taken with a soil auger. Some of this sample was used to determine the gravimetric moisture content, and the rest of the sample, to measure EC_e (electrical conductivity of saturated extract) using the U. S. Salinity Laboratory (1954) method. Soil temperature at the same depth was measured with a field thermometer at each reading taken by the EC-probe or four-electrode array.

This procedure was repeated for each soil measurement of EC by both methods were taken during the months of November and December two, thirteen, twenty-six, and forty-seven days after the free water had drained from the soil, i.e., after field capacity was attained.

RESULTS

Bulk soil electrical conductivity as measured by the salinity probe (EC_p) and four-electorde (EC_a) methods, electrical conductivity of the saturated extract (EC_e), and average volumetric water content (θv) are given in Tables 2, 3, and 4 for the Gila loam, Vinton loamy sand, and Pima clay loam soils, respectively. The EC_p and EC_a values are the averages of two measurements taken at each site. A significant difference was found between the field EC measurements, if these were made at 0 to 30 cm depth for the four-electrode and salinity probe. The EC_p values were consistently greater and more responsive to the soil salinity. Two soil samples were taken from the same 0 to 30 cm depth at which the four-electrode and probe readings were made for the subsequent analysis of the electrical conductivity of the saturated extract. The EC_e given is the average of these two values.

The gravimetric water content was determined on soil samples from the immediate vicinity of the salinity probe and four-electrode at the time of measurement. Small variations in water content were found among the five salinity plots of each soil at each time of EC_a and EC_p measurements. These five moisture content values were averaged and

Table 2. Bulk soil electrical conductivity (EC_a) and (EC_p) measured by the four-electrode and the salinity probe respectively, corresponding to different salt treatments, salinity levels of saturated extract (EC_e), and volumetric water contents (θ_v) for Gila loam.

θ_v	Salt Treatment	EC_a	EC_p	EC_e
		mmho/cm		
	control	0.32	0.33	1.3
	4	0.45	0.56	2.3
0.28	10	0.67	0.94	4.0
	20	0.98	1.48	6.4
	40	1.26	2.01	8.7
	control	0.23	0.27	1.9
	4	0.33	0.42	3.0
0.20	10	0.49	0.66	4.8
	20	0.72	1.02	7.4
	40	1.09	1.45	10.6
	control	0.23	0.24	2.2
	4	0.33	0.42	3.6
0.17	10	0.46	0.60	5.3
	20	0.69	0.98	8.7
	40	0.92	1.38	12.0
	control	0.19	0.22	2.4
	3	0.35	0.44	4.8
0.13	10	0.49	0.62	6.9
	20	0.66	0.84	9.6
	40	0.88	1.16	13.3

Table 3. Bulk soil electrical conductivity (EC_a) and (EC_p) measured by the four-electrode and the salinity probe respectively, corresponding to different salt treatments, salinity levels of saturated extract (EC_e), and volumetric water content (θ_v) for Vinton loamy sand.

θ_v	Salt Treatment	EC_a	EC_p	EC_e
		mmho/cm		
0.19	control	0.14	0.16	0.8
	4	0.27	0.32	2.1
	10	0.41	0.44	3.2
	20	0.58	0.62	4.8
	40	0.75	0.81	6.4
0.12	control	0.10	0.12	1.0
	4	0.21	0.22	2.5
	10	0.27	0.28	3.4
	20	0.37	0.39	5.0
	40	0.52	0.55	7.4
0.10	control	0.10	0.11	1.2
	4	0.17	0.19	2.8
	10	0.20	0.22	3.7
	20	0.28	0.30	5.6
	40	0.39	0.41	8.3
0.08	control	0.10	0.10	1.0
	4	0.17	0.16	3.1
	10	0.20	0.20	4.2
	20	0.27	0.26	6.8
	40	0.37	0.37	10.7

Table 4. Bulk soil electrical conductivity (EC_a) and (EC_p) measured by the four-electrode and the salinity probe respectively, corresponding to different salt treatments, salinity levels of saturated extract (EC_e), and volumetric water contents (θ_v), for Pima clay loam.

θ_v	Salt Treatment	EC_a	EC_p	EC_e
		mmho/cm		
	control	1.48	1.63	2.5
	4	1.9	2.10	4.4
0.32	10	2.40	2.77	6.9
	20	3.10	3.60	10.2
	40	4.68	5.63	17.8
	control	1.18	1.22	4.3
	4	1.41	1.60	5.9
0.25	10	1.82	1.90	7.5
	20	2.84	3.16	13.3
	40	3.85	4.35	19.2
	control	0.91	1.10	5.3
	4	1.21	1.45	7.4
0.20	10	1.50	1.85	9.8
	20	2.30	2.50	14.8
	40	3.22	3.73	21.8
	control	0.83	1.00	5.8
	4	1.07	1.25	7.6
0.17	10	1.23	1.45	8.9
	20	1.95	2.35	15.00
	40	3.10	3.44	24.00

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

For the Gila loam soil, bulk soil electrical conductivity (EC_a and EC_p) increased uniformly as the saturated extract EC_e (the conventional measure of soil salinity) increased.

The data in Table 2 were studied by regression analysis to explain the effect of water content on the relationship between soil salinity and bulk soil electrical conductivity. Figures 5 and 6 give the EC_e vs. EC_a and EC_e vs. EC_p regression lines for the Gila loam at each water content. High correlation coefficients (r^2) were obtained. Increasing the water content decreases the slope of the regression lines.

Table 3 presents data for the Vinton loamy sand. The bulk soil electrical conductivity EC_a and EC_p increased uniformly as soil salinity increased. Figures 7 and 8 give the EC_e vs. EC_a and EC_e vs. EC_p regression lines for the Vinton soil. High correlation coefficients (r^2) were obtained.

In Table 4 for the Pima clay loam, bulk soil electrical conductivity EC_a and EC_p increased uniformly as the soil salinity increased. Figures 9 and 10 give the

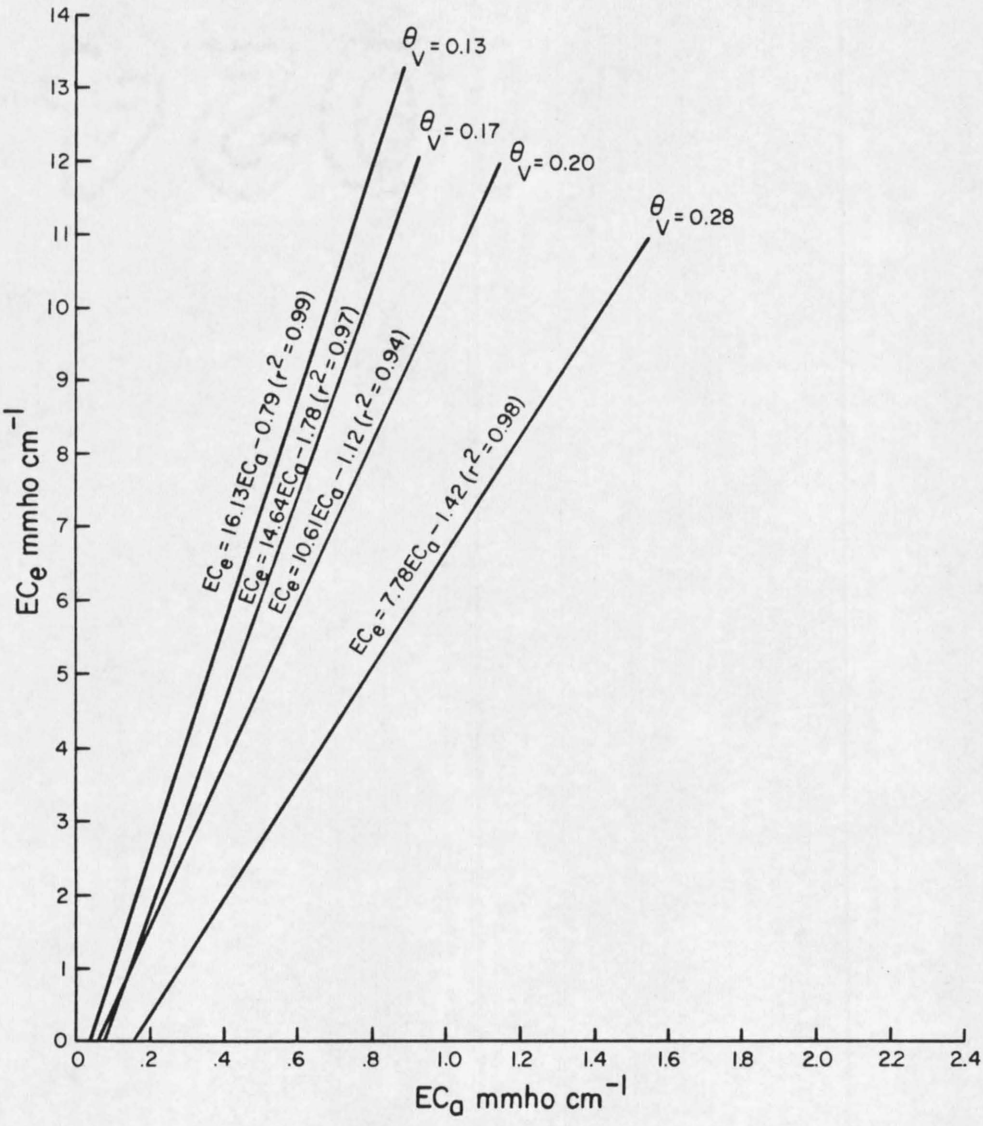

Figure 5. Effect of water content (θ) on slope of EC_e vs. EC_a for Gila loam.

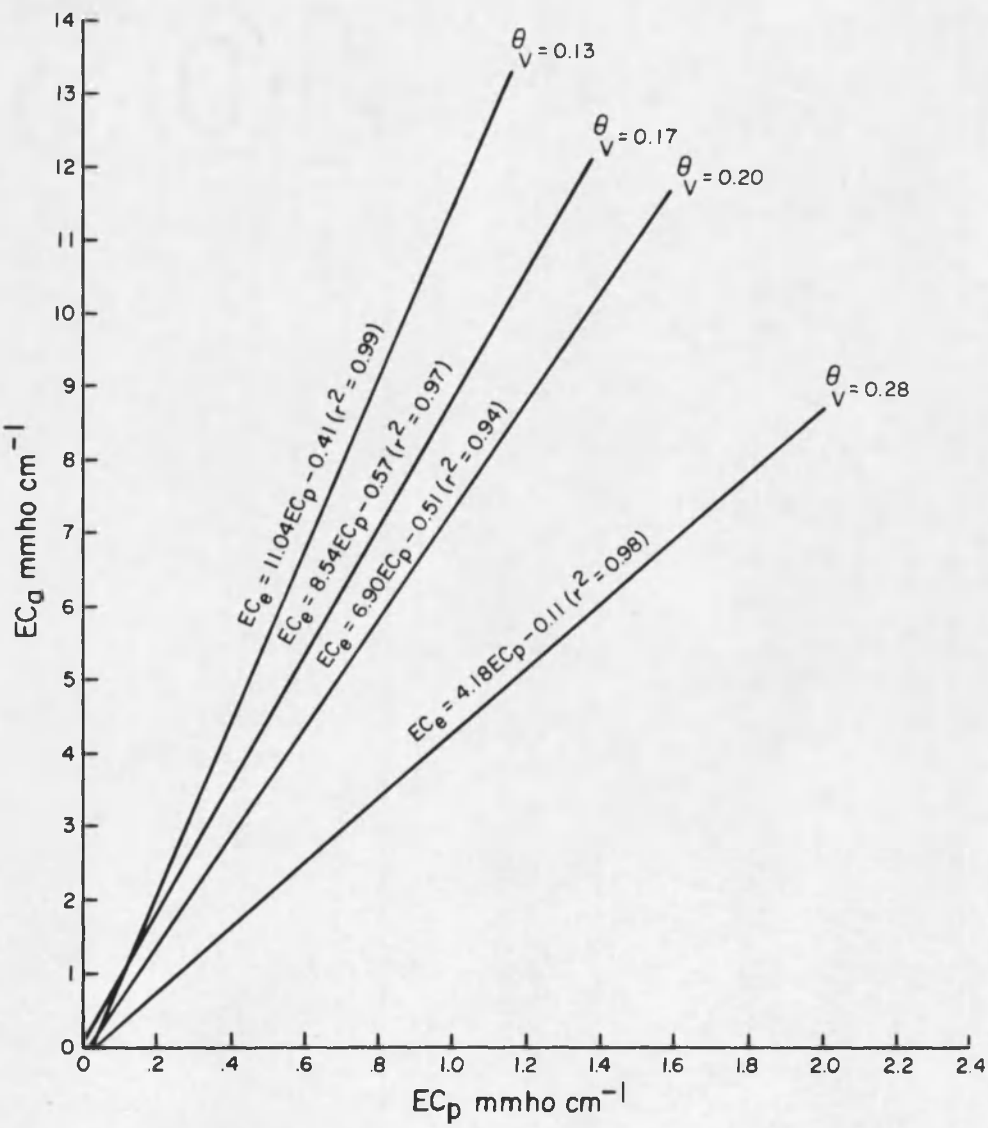

Figure 6. Effect of water content (θ) on slope of EC_e vs. EC_p for Gila loam.

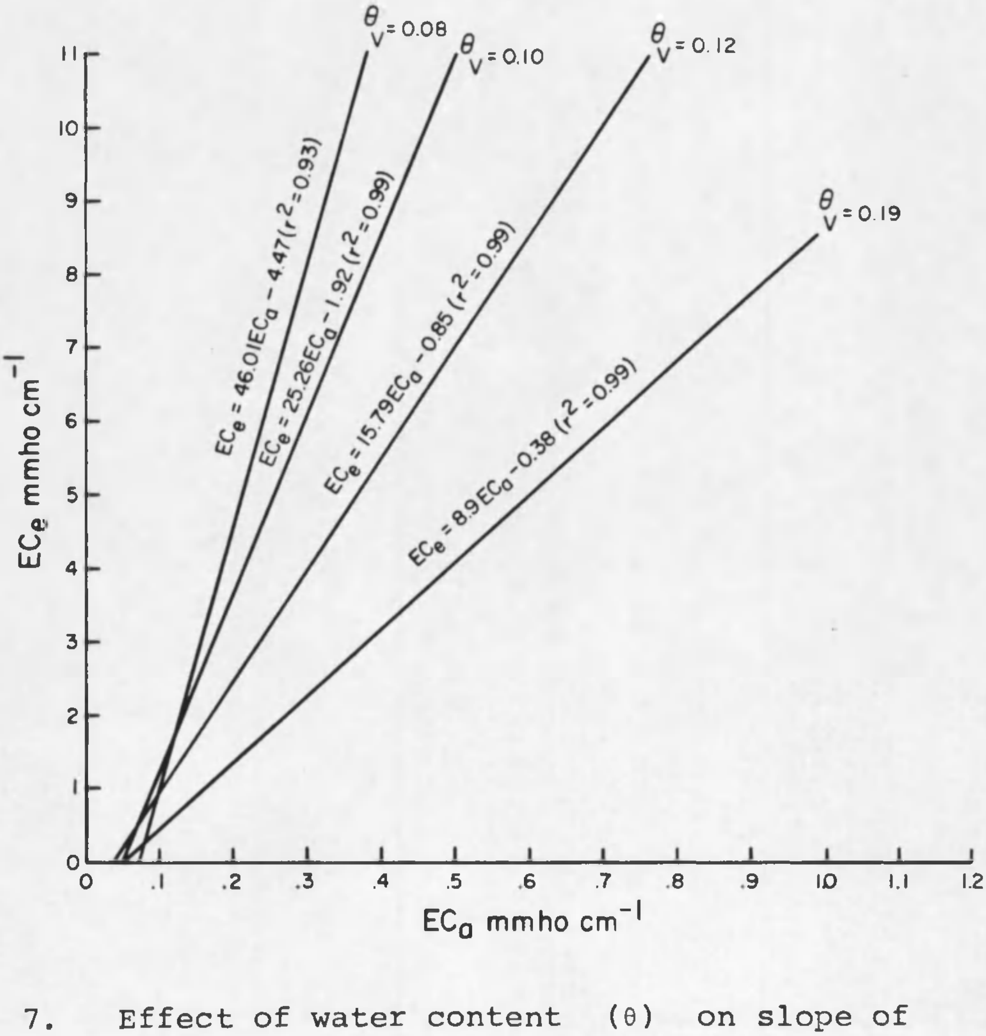

Figure 7. Effect of water content (θ) on slope of EC_e vs. EC_a for Vinton loamy sand.

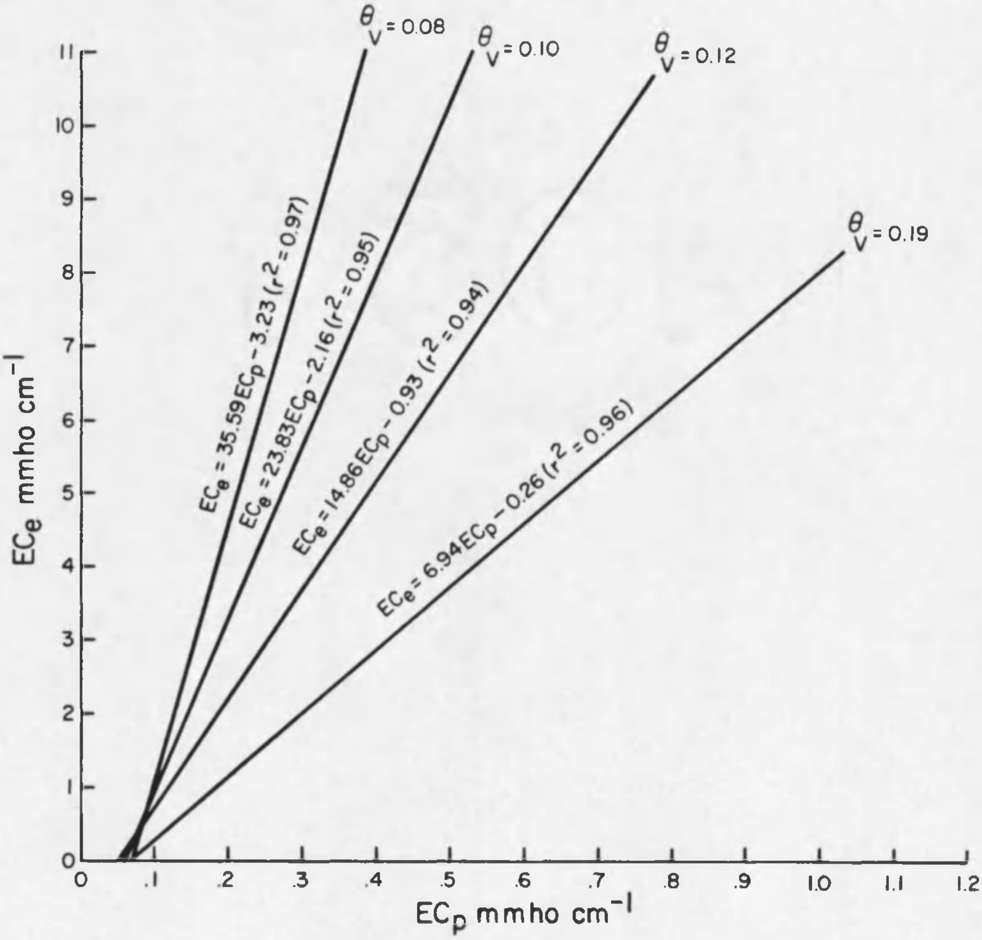

Figure 8. Effect of water content (θ) on slope of EC_e vs. EC_p for Vinton loamy sand.

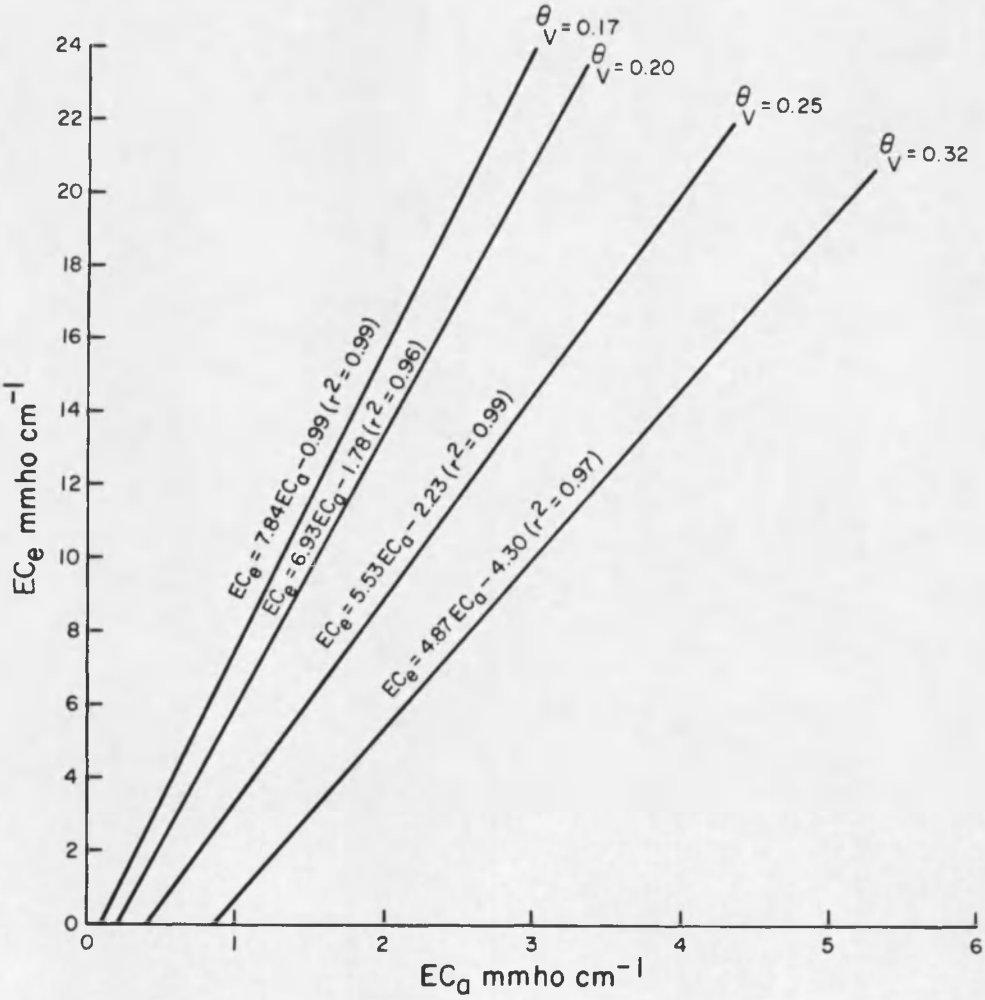

Figure 9. Effect of water content (θ) on slope of EC_e vs, EC_a for Pima clay loam.

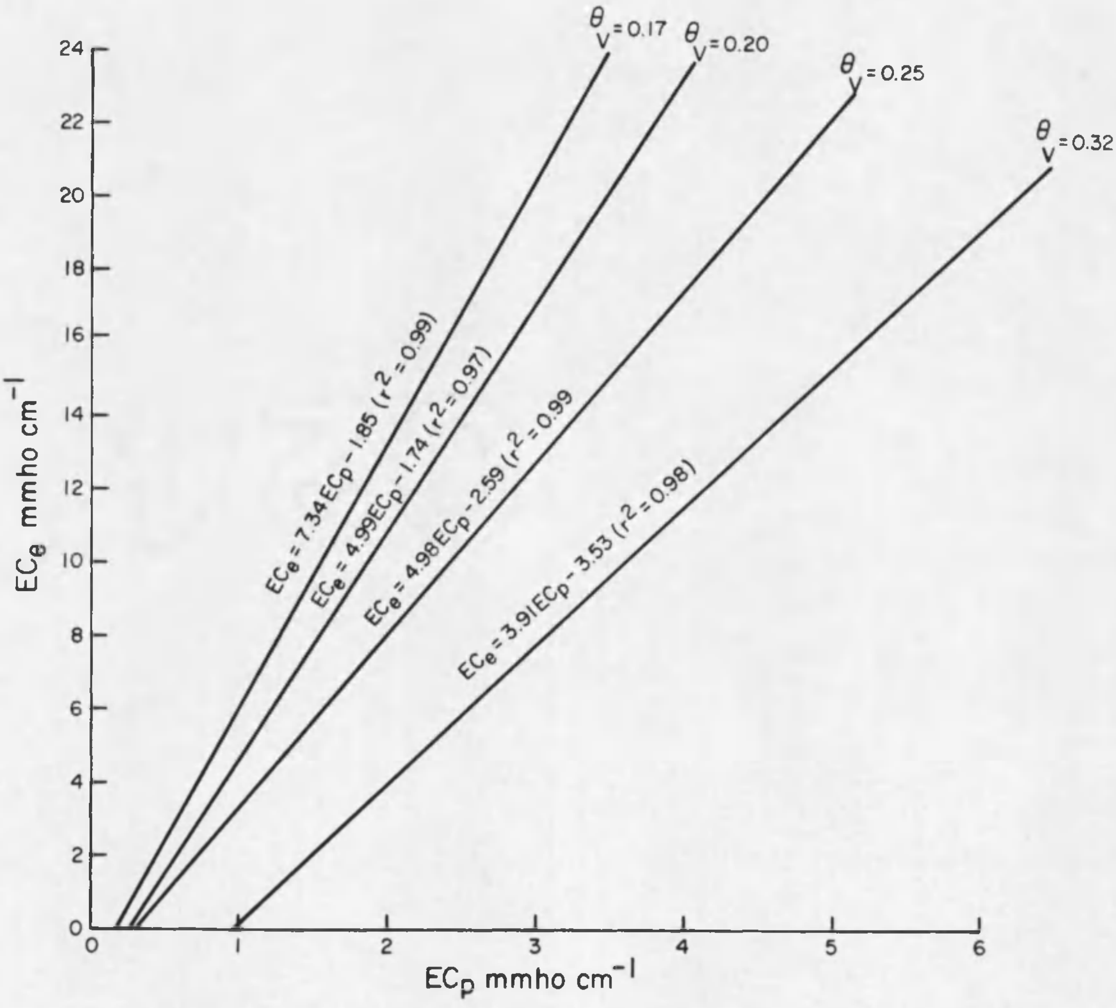

Figure 10. Effect of water content (θ) on slope of EC_e vs. EC_p for Pima clay loam.

EC_e vs. EC_a and EC_e vs. EC_p regression lines for the clay loam at each water content. Decreasing water content increasing the slope of the lines. High correlation coefficients were obtained.

From the regression lines the three soils, at different water contents the salinity of soil solutions increased in all the plots as the soil dried. Increasing the water content decreased the slope of the regression lines and increased the intercept.

Then, the data was studied by conventional regression analysis on individual soils. Table 5 gives the regression equations and coefficients of determination (r^2) that resulted when EC_a and EC_p were related to EC_e and θv.

Table 5. Regression equations and coefficients of determination (r^2) relating EC_e, θ, EC_a and EC_p for the three different field soils.

Regression Equation	r^2	Soil
$EC_e = 1.25\frac{EC_a}{\theta} - 1.28$	0.97	Gila Loam
$EC_e = 0.79\frac{EC_p}{\theta} - 0.32$	0.94	Gila Loam
$EC_e = 2.00\frac{EC_a}{\theta} - 1.35$	0.88	Vinton Loamy Sand
$EC_e = 1.92\frac{EC_p}{\theta} - 1.31$	0.91	Vinton Loamy Sand
$EC_e = 0.95\frac{EC_a}{\theta} - 2.35$	0.97	Pima Clay Loam
$EC_e = 0.84\frac{EC_p}{\theta} - 2.59$	0.97	Pima Clay Loam

DISCUSSION

Electrical current conductance in saline soil is primarily through the soil solution. Hence, the bulk soil electrical conductivity will be effected by the amount of salt and water content. Water loss due to evaporation from the soil, and traspiration through the plants, tends to increase the soil salinity. On the other hand, precipitation, lateral water movement, and leaching may cause loss of salts in the profile. Therefore under normal field conditions electrical conductivity is greatly affected by the amount of water and salt content in the soil.

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. The salt content of the soil solution as measured by the electrical conductivity of the saturated extract increased in all the plots, as the soil dried.

Since water content is a major factor in determining bulk soil electrical conductivity in the field, the EC_a and EC_p measured by the four-electrode array and EC-probe, respectively, is more related to the water content when the soil is dry, and more related to the salt content when the soil is wet.

Effect of Water Content

The results of loam, loamy sand, and clay loam soils show that as the soil dries the salinity increases, and the bulk soil electrical conductivity as measured by the two methods can predict the salinity variation with water content. High regression coefficients of EC_e vs. EC_a and EC_e vs. EC_p relationship for the three soils were obtained, even at low soil water content. This indicates that the four-electrode array and EC-probe have the ability to predict the salinity variation under dry conditions.

Soil drying decreased the slope of the regression lines. The decrease in the slope illustrates the better response of both devices to salinity variation at higher field moisture content.

Rhoades and Halverson (1974), when using the four-electrode array for soil salinity determination under dry conditions, observed that the electrical conductivity was more related to the salt content, when soil moisture content was high and was more related to the water content when the moisture content was low.

Effect of Soil Texture

Soil testure is another factor which affects the bulk soil electrical conductivity vs. soil salinity relationship. The clay contents in the loam and clay loam soil, i.e., thirteen percent and twenty-six percent respectively. The slope of the EC_e vs. EC_a is higher for the Gila loam than for the Pima clay loam when the field moisture content $\theta v = 0.20$ (Figures 5a, b and 7a, b). Hence, increasing clay content increases the EC_a value for a given salt concentration. This behavior was observed by Shea and Luthin (1961) who used the four-electrode probe for measuring soil salinity in the field. They showed that value of specific electrical conductivity and specific conductance varies between soil types, depending on the absorbed cations on the exchange complex.

SUMMARY AND CONCLUSION

Utilizing the bulk soil electrical conductivity measurement by the four-electrode and the EC-probe, soil salinity can be assessed in the field providing that the amount of water and soil texture are known.

A field experiment was conducted to measure bulk soil electrical conductivity EC_a and EC_p by the above methods. The relationship between soil electrical conductivity EC_a and EC_p and EC_e at different levels of moisture content is in the form:

$$EC_a = a \circ \theta \circ EC_e + C$$
$$EC_p = b \circ \theta \circ EC_e + C.$$

The slope of the EC_e vs. EC_a and EC_e vs. EC_p regression lines decreases with increasing water content. Increasing soil clay content decreases the slope of regression lines.

For salinity determination, information on soil water and clay contents is required prior to the use of the four-electrode, and the EC-probe techniques.

The accuracy of the above methods are generally promising, and they are less time consuming compared to the traditional method of determining the electrical conductivity of the saturated extract.

Comparing the two methods, the EC-probe can measure soil salinity to desired discrete depth(s) intervals in the soil profile better than the four-electrode array. The EC-probe requires that soil be removed with soil sampling tube, even though there is no analysis required. While the four-electrode array method requires less work, and does not disturb the soil profile during field measurements because the device is positioned on the surface of the soil.

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