DIVISION S-2—SOIL CHEMISTRY

Determining Soil Salinity from Soil and Soil-Paste Electrical Conductivities: Sensitivity Analysis of Models

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ABSTRACT

Models and relations used to determine soil salinity (EC_e) in the field from measurements of bulk soil electrical conductivity (EC_a), or from saturated soil-paste electrical conductivity (EC_p), and estimates of other influential soil parameters were analyzed to evaluate the degree to which salinity appraisal is affected by inaccuracies made in the estimates. Results show that the values of the parameters which can not be easily measured in the field (i.e., bulk density (ρ_b), particle density (ρ_s), clay percentage (% clay), and total and "immobile" volumetric soil water contents (θ_w and θ_{ws}, respectively) can be estimated sufficiently accurately for the purposes of practical soil salinity appraisal.

RECENTLY DEVELOPED MODELS of electrical current flow in undisturbed soils (Rhoades et al., 1989a) and in saturated soil-pastes (Rhoades et al., 1989b) have been shown to be applicable for the determination of soil salinity. Soil salinity in these models is expressed as the electrical conductivity of the saturation-extract (EC_e).

For undisturbed soils, the practical determination of EC_e requires the measurement of bulk soil electrical conductivity (EC_a) and estimates of (i) the volumetric content of soil particles and water (θ_s and θ_w, respectively), (ii) the volumetric content of soil water in the "series-coupled" pathway (θ_{ws}, essentially the water in the fine pores, or so-called "immobile" water), (iii) the average electrical conductivity of the soil particles (EC_s), and (iv) the bulk density of the undisturbed soil (ρ_b). The average density of the soil particles (ρ_s) must also be estimated, since θ_s is calculated from ρ_b/ρ_s. The values of θ_{ws} and EC_s are estimated using empirical relations established between θ_{ws} and θ_w and between EC_s and percent clay content (% clay) of the soil, respectively.

For soil samples, the practical determination of EC_e requires the measurement of the electrical conductivity of the saturated soil-paste (EC_p) and estimates of θ_s, θ_w, θ_{ws} for the saturated-paste condition, as well as EC_s. The values of θ_s and θ_w in saturated soil-pastes can be calculated from the gravimetric water content of the saturation paste (SP) with knowledge of ρ_s (Wilcox, 1951). In practice, SP is calculated from the weight of a known volume of the saturated soil-paste (W_p) and an assumed value of ρ_s; θ_{ws} and EC_s are estimated from empirical relations established between the difference ($\theta_w - \theta_{ws}$) and SP and between EC_s and SP (or % clay), respectively.

In order to evaluate the practicality and accuracy of these two field methods of soil salinity appraisal, it is necessary to know the degree to which EC_e is effected by errors made in estimating the parameter values, or, in other words, to know which parameters must be known accurately (hence must be measured) and which can be satisfactorily estimated without producing significant errors in the field appraisal of soil salinity. This paper describes the results of a "sensitivity" analysis of the two models and the empirical relations used to determine EC_e from EC_a and EC_p, to aid in this regard.

METHODS

The equations used to determine EC_e from EC_a are as follows:

$$EC_a = \left[\frac{(\theta_s + \theta_{ws})^2\, EC_{ws}\, EC_s}{(\theta_s)\, EC_{ws} + (\theta_{ws})\, EC_s}\right] + (\theta_w - \theta_{ws})\, EC_{wc}\,, \qquad [1]$$

$$\theta_s = \rho_b/\rho_s, \qquad [2]$$

$$\theta_{ws} = 0.639\theta_w + 0.011, \qquad [3]$$

and

$$EC_s = 0.023(\%\ \text{clay}) - 0.021, \qquad [4]$$

where ($\theta_w - \theta_{ws}$) is the volumetric content of soil water in the so-called "continuous" pathway (θ_{wc}, essentially the water in the large pores, or so-called "mobile" water), EC_{ws} and EC_{wc} are the electrical conductivities of θ_{ws} and θ_{wc}, respectively; and the other terms are defined above (after Rhoades et al., 1989a).

In order to solve Eq. [1] for EC_w (i.e., the average electrical conductivity of the soil water), the assumption was made that $EC_w = EC_{ws} = EC_{wc}$. Data are given later to support this assumption for typical situations. With this assumption, EC_w can be obtained from Eq. [1] using the quadratic formula,

$$EC_w = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}, \qquad [5]$$

where $A = -[(\theta_s)(\theta_w - \theta_{ws})]$, $B = [(\theta_s)(EC_a) - (\theta_s + \theta_{ws})^2(Ec_s)\,(EC_a)]$.

Soil salinity (EC_e) is then calculated as

$$EC_e = EC_w\left(\frac{\theta_w}{\rho_b}\cdot\frac{100}{SP}\right). \qquad [6]$$

The "sensitivity" analyses of these relations, with respect to the effects of the variables EC_a, EC_s, θ_w, θ_{ws}, ρ_b, ρ_s and % clay upon EC_e, were made by evaluating the magnitude of change in EC_e due to a change in each variable, while all the others were held constant. The ranges were selected to cover typical situations in semi-arid mineral soils of the southwestern USA: EC_a (0.2–10 dS/m), ρ_b (1.2–1.7 g/cm^3), θ_w (0.1–0.4), θ_{ws} (0.1–0.3), ρ_s(2.4–2.7 g/cm^3), % clay (5–60) and EC_s (0.1–1.0 dS/m).

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The assumption that $EC_{ws} \approx EC_{wc}$ was tested using two approaches and data sets. From measurements of EC_e, SP, ρ_b and θ_w, EC_w was determined using Eq. [6] and then EC_a was determined according to Eq. [1], where EC_w was used for both EC_{ws} and EC_{wc} and θ_{ws} was calculated from Eq. [3]. This predicted value of EC_a was compared with the actual value of EC_a, as measured with a four-electrode probe (Rhoades and van Schilfgaarde, 1976).

One data set ($n = 63$) consisted of soils of various textures (ls to c) which had been artificially leached with saline waters to produce a range of soil salinities and near field-capacity water contents. These "calibration" soils are described elsewhere (Rhoades et al., 1989a) and the salinizing procedure is described in more detail in Rhoades (1981). Since each soil was leached relatively extensively with waters of constant salinity, they would be expected to be reasonably uniform in salinity throughout the variously sized pores.

The other data set ($n = 710$–760) consisted of a wide sampling of field soils located within the South-Fork Kings River Watershed of the San Joaquin Valley. These soils varied in texture from ls to c and also in salinity, water content, crop condition, tillage condition, etc. These soils had not been subjected to any salinizing treatments and were in their natural field conditions. For this data set the values of ($EC_w\ \theta_w/\rho_b$) were compared with those of (EC_e SP/100), where EC_w was determined from Eq. [1] and measurements of EC_a and estimates of θ_w which were based on measurements of gravimetric water content and estimates of ρ_b. Since the calculation of EC_w in Eq. [5] assumes $EC_{ws} = EC_{wc}$, and ($EC_w\ \theta_w/\rho_b$) is essentially equivalent to (EC_e SP/100) (differing only by the degree to which additional salts may dissolve from the soil as the water content is increased from θ_w to that present in the saturation paste; the volumetric content of the latter is directly related to SP, see Eq. [8] and Rhoades, 1980), the regression of ($EC_w\ \theta_w/\rho_b$) vs. (EC_e SP/100) should give a slope of ≈ 1 and intercept of ≈ 0, if $EC_{ws} \approx EC_{wc}$.

The EC_a was measured using both four-electrode probe and Wenner-array techniques. The latter are described in Rhoades and Ingvalson, (1971). Measurements of EC_e, SP and gravimetric water content were made using standard techniques (Rhoades, 1982). The ρ_b was estimated from SP (Rhoades et al., 1989a).

The equations used to determine EC_e from EC_p are as follows

$$EC_p = \left[\frac{(\theta_s + \theta_{ws})^2\ EC_e\ EC_s}{(\theta_s)\ EC_e + (\theta_{ws})\ EC_s}\right] + (\theta_w - \theta_{ws})\ EC_e\,, \qquad [7]$$

$$\theta_w = SP/\left(\frac{100}{\rho_e \rho_s} + SP\right), \qquad [8]$$

$$\theta_s = 1 - \theta_w\,, \qquad [9]$$

$$(\theta_w - \theta_{ws}) = 0.0237(SP)^{0.6657}\,, \qquad [10]$$

$$EC_s = 0.019(SP) - 0.434\,, \qquad [11]$$

and

$$SP = \frac{100\rho_e\ \rho_s\ (\rho_s\ V_p - W_p)}{W_p\ (\rho_s - \rho_e) - \rho_e\ (\rho_s V_p - W_p)}\,. \qquad [12]$$

where ρ_e is the density of the extract (assumed to be 1.0 g/cm^3) and V_p is the volume of the saturated soil-paste (after Rhoades et al., 1989b). The eq. [12] is taken from Wilcox (1951).

In contrast to field soil, there is no distinction in EC between θ_{ws} and θ_{wc} in a saturated soil-paste, since the soil has been ground and pore structure has been essentially eliminated; hence, EC_e can be solved directly from Eq. [7] when it is arranged in the form of a quadratic as

$$EC_e = \frac{-\ B \pm \sqrt{B^2 - 4AC}}{2A}\,, \qquad [13]$$

where $A = [\theta_s(\theta_w - \theta_{ws})]$, $B = [\theta_s + \theta_{ws})^2\ EC_s + (\theta_w - \theta_{ws})(\theta_{ws}\ EC_s) - (\theta_s\ EC_p)]$ and $C = -(\theta_{ws}\ EC_s\ EC_p)$.

The "sensitivity" analyses of these relations, with respect to the effect of the variables EC_p, EC_s, $\theta_w - \theta_{ws}$, SP, ρ_s and % clay upon EC_e, were made by evaluating the change of EC_e due to a change in each variable, while all others were held constant. The ranges for each variable were selected to cover typical situations in semi-arid mineral soils of the southwestern USA: W_p (75–110 g/50 cm^3), SP (25–100), ρ_s (2.4–2.9 g/cm^3), % clay (5–60), EC_s (0.1–1 dS/m), $\theta_w - \theta_{ws}$ (0.1–0.6) and EC_p (0.1–16 dS/m).

RESULTS AND DISCUSSION

The regression analysis between measured and predicted EC_a values for the "calibration" set ($n = 63$) of soils yielded: (meas EC_a) = 0.970 (pred EC_a) + 0.065, with $r^2 = 0.95$. This close correspondence between measured EC_a and that predicted from EC_e showed that the assumption $EC_{ws} \approx EC_{wc}$ is valid for these extensively leached soils. The regression analyses between (EC_e SP/100) and ($EC_w\ \theta_w/\rho_b$) for the other set of field soils yielded: (EC_e SP/100) = 0.940($EC_w\ \theta_w/\rho_b$) + 0.475; $r^2 = 0.80$; $n = 710$, where EC_a was measured by the four-electrode probe. Where EC_a was measured by a Wenner array of electrodes inserted into the soil surface, the analogous results were: (EC_e SP/100) = 1.032 ($EC_w\ \theta_w/\rho_b$) − 0.129; $r^2 = 0.76$; $n = 760$. The close correspondence between ($EC_w\ \theta_w/\rho_b$) and (EC_e SP/100) showed that the assumption, $EC_{ws} \approx EC_{wc}$, was reasonable for these field soils in their natural conditions. Of course, there may be situations where this assumption is invalid. One likely exception is where soils are undergoing relatively rapid changes in salinity within the large pores, as is produced by saturated-flow leaching.

Modeling EC_e from EC_a

The practical use of field measurements of EC_a to determine EC_e requires that ρ_b, ρ_s, EC_s and θ_{ws} be estimated, since only EC_a is easy to measure in the field. The practicality of measuring θ_w is discussed separately later. In this method, ρ_b is estimated (from soil texture), ρ_s is assumed to be 2.65 g/cm^3, θ_{ws} and EC_s are calculated from estimated θ_w and clay percent, respectively, using empirical relations (Eq. [3] and [4]) established using data from a wide variety of semi-arid soils of the southwestern USA.

As shown in Fig. 1, ρ_s can vary over the range of likely average values for semi-arid land mineral soils without significant effect on EC_e, regardless of bulk soil electrical conductivity, soil water content, soil bulk density, or soil clay content. Based on these results, ρ_s will be taken as 2.65 g/cm^3 for all subsequent "sensitivity" analyses.

Bulk density primarily influences θ_s (see Eq. [1] and [2]) and the conversion of EC_w to EC_e (see Eq. [6]). The effect of errors made in bulk density estimates upon EC_e may be evaluated from the results given in Fig. 2. Errors of the magnitude likely to be made in bulk density estimates do not significantly affect EC_e in the low salinity range of most importance (EC_e = <10 dS/m). For example, a change in ρ_b from 1.5 to

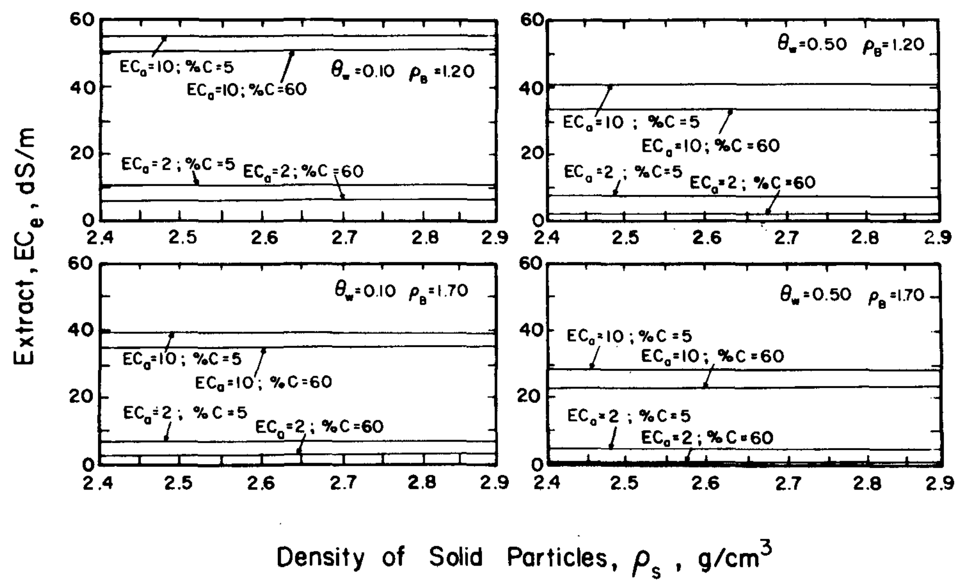

Fig. 1. Relations between the average density of soil particles, bulk soil electrical conductivity (EC_a), clay percentage (%C), volumetric content of soil water (θ_w), soil bulk density (ρ_b) and soil salinity (EC_e).

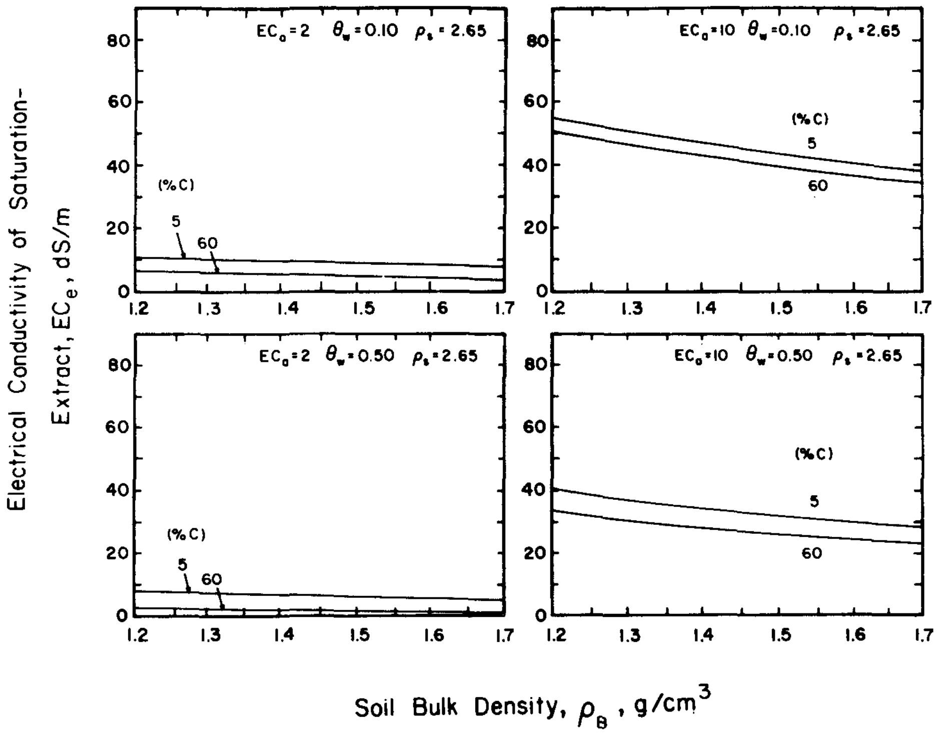

Fig. 2. Relations between soil bulk density, bulk soil electrical conductivity (EC_a), soil volumetric water content (θ_w), clay percentage (%C) and soil salinity (EC_e).

1.6 produces a change in EC_e from 4.5 to 4.0 dS/m (a change of only 11%) for a soil with $EC_a = 2$ dS/m, $\theta_w = 0.10$ and clay percent = 60. The effect of bulk density is greater for higher levels of salinity, but fortunately the required accuracy in salinity appraisal is much less for these levels.

The value of EC_s used in Eq. [1] must be estimated, as discussed earlier. For practical applications, it has been recommended that EC_s be estimated from clay percentage, which, in the field, must be estimated by feel (Rhoades, 1981; Rhoades et al., 1989a, 1989). Thus, two aspects of errors made in estimating clay content need to be evaluated. The first is the error due to mis-estimates of clay content per se; the second is that due to variation among soils in the relation between EC_s and clay percent. These effects may be evaluated from the derivative of Eq. [4] and the results of the "sensitivity" analyses given in Fig. 3 and 4. The effect of error made in the estimate of clay percent per se is seen to be trivial at high salinities (see Fig. 3). At low salinities the effect is greater, but still it is not significant within the typical ability of an experienced field soil scientist to determine clay content by feel. For example, it is unlikely that the estimate of clay

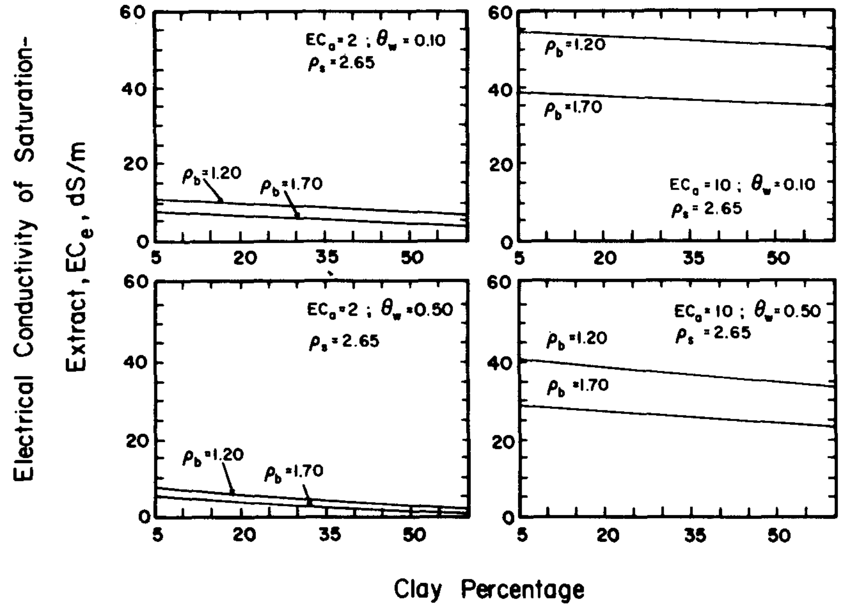

Fig. 3. Relations between clay percentage, bulk soil electrical conductivity (EC_a), soil volumetric water content (θ_w), soil bulk density (ρ_b) and soil salinity (EC_e).

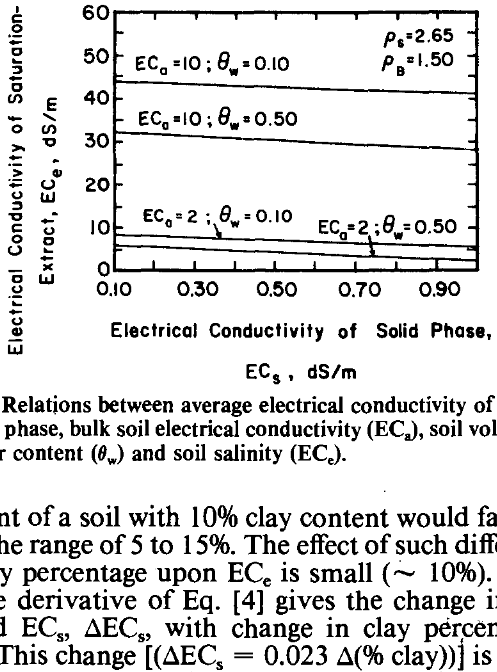

Fig. 4. Relations between average electrical conductivity of the soil solid phase, bulk soil electrical conductivity (EC_a), soil volumetric water content (θ_w) and soil salinity (EC_e).

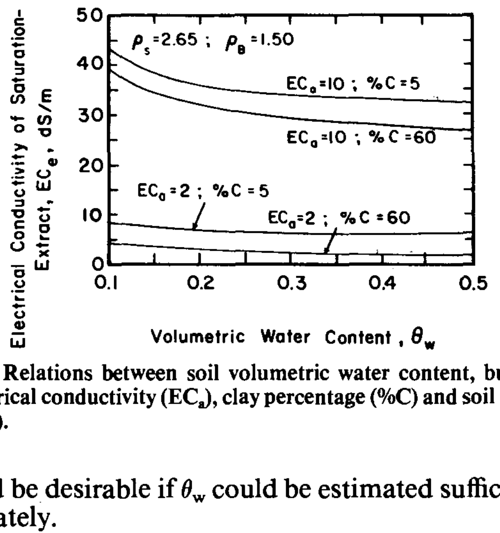

Fig. 5. Relations between soil volumetric water content, bulk soil electrical conductivity (EC_a), clay percentage (%C) and soil salinity (EC_e).

percent of a soil with 10% clay content would fall outside the range of 5 to 15%. The effect of such difference in clay percentage upon EC_e is small (~ 10%).

The derivative of Eq. [4] gives the change in estimated EC_s, ΔEC_s, with change in clay percent, Δ% clay. This change [($\Delta EC_s = 0.023\ \Delta$(% clay))] is small. A very inaccurate estimate would be required in this regard before any significant error would be incurred in determinations of EC_e, since substantial variation in EC_s can occur without causing meaningful differences in EC_e, as is shown in Fig. 4.

Although it would be desirable to measure all of the parameters used in Eq. [1], in order to estimate EC_e as accurately as possible, this will most likely never be practical in the field. The θ_w can be measured in the field with commercially available, portable equipment using the techniques of time domain reflectometry (TDR). There is considerable uncertainty about the accuracy and reliability of this technique in saline soils (Topp et al., 1988), however. A commercial unit tested did not give reliable readings of θ_w in soils with EC_a values of greater than about 2 dS/m (unpublished data of the authors, 1988). For practical reasons, it would be desirable if θ_w could be estimated sufficiently accurately.

The degree to which accuracy is required in θ_w values for purposes of field salinity appraisal may be evaluated from the "sensitivity" analysis results given in Fig. 5. Considerable variation in θ_w can occur without substantial effect on EC_e in the low salinity range where accuracy is most important, as long as θ_w is within the limits required according to the model described by Eq. [1]. The effect of errors made in estimating θ_w on salinity appraisal is much greater at high levels of salinity, but the accuracy needs are much less at such levels. Estimates of θ_w obtained by TDR techniques, or even when obtained by "feel" methods by experienced soil scientists, should be sufficiently accurate to meet the practical needs of this technique of EC_a measurement to appraise soil salinity (Rhoades, et al., 1989). Of course, with measurements of θ_w, EC_e appraisals will be more accurate.

The degree to which misestimates of θ_{ws} affect salinity appraisal may be judged from the derivative of Eq. [3] and the "sensitivity" results given in Fig. 6. The derivative of Eq. [3] shows that $\Delta\theta_{ws} \approx 0.639\ \Delta\theta_w$. Some soils may differ from this empirical relation, but

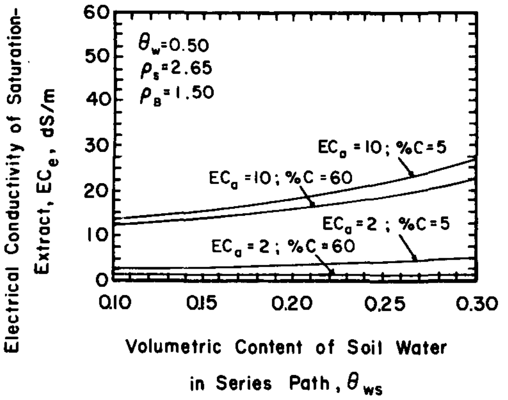

Fig. 6. Relations between the volumetric content of soil water in the series-coupled path, bulk soil electrical conductivity (EC_a), clay percentage (%C), and soil salinity (EC_e).

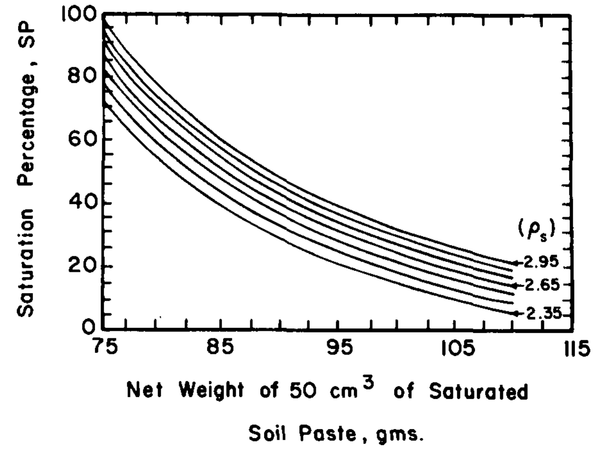

Fig. 7. Relation between weight of saturated soil paste in a "Bureau of Soils" cup, average density of soil particles and saturation percentage.

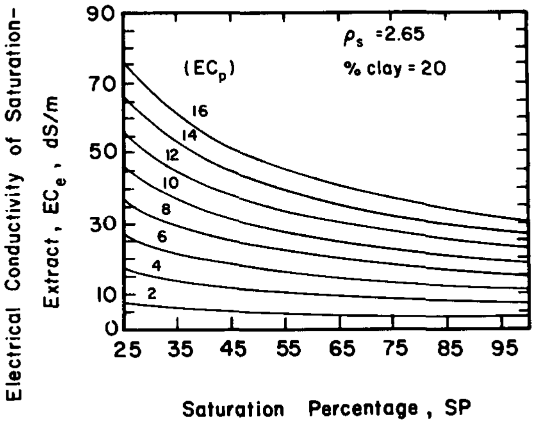

Fig. 8. Relation between saturation percentage, electrical conductivity of saturated soil-paste (EC_p) and soil salinity (EC_e) for a soil having a clay content of 20%.

such deviation should not unduely effect the determination of EC_e, as is seen from the results given in Fig. 6. Fortunately, the effect of $\Delta\theta_{ws}$ on EC_e appraisal is less at low salinity levels where accuracy requirements are greater. The greater error occurring at high levels of salinity are inconsequential for appraisal purposes. Thus it may be concluded that EC_e is not appreciably effected by the magnitude of error expected in the estimate of θ_{ws}.

It should be noted that the model used to derive Eq. [1] assumes that enough moisture is present for current flow to take place via water held within some relatively large pores in the soil (a continuous pathway). The θ_w must be at least 0.1, possibly more in sandy soils, to apparently satisfy the above requirement (see Rhoades et al., 1976). This limit will be met in most irrigated soils.

Modeling EC_e from EC_p

The practical use of EC_p measurements to determine EC_e in the field requires that SP, EC_s and ($\theta_w - \theta_{ws}$) be estimated. In the method recommended here of using the "Bureau of Soils Cup" to appraise soil salinity, SP is calculated from the net weight of the saturated soil-paste (W_p) held within the 50 cm^3 volume of the cup (V_p) using Eq. [12] with the assumption that the density of the soil particles is 2.65 g/cm^3 (see Fig. 4 of Rhoades et al., 1989b).

The effect of error in ρ_s upon the determination of SP is given in Fig. 7. These results indicate that normal deviations of ρ_s from the assumed typical value cause insignificant errors in SP or EC_e determinations. For example, a medium-textured soil whose paste of volume 50 cm^3 weighs 90 g would have SP values of 37, 40 and 43 for average soil particle densities of 2.55, 2.65 and 2.75 g/cm^3, respectively (see Fig. 7). Thus, the error in the estimate of SP would only be ±7.5%, as ρ_s deviates from the assumed value of 2.65 by ±0.10 g/cm^3. It is unlikely that arid land mineral soils will have average particle densities outside these limits because quartz, feldspars and silicate clay minerals make up the bulk of their solid phase (Brady, 1974).

The effect of error in SP upon the determination of EC_e is given in Fig. 8. These results indicate that the variation in SP produced from expected deviations in average soil particle density should not seriously affect the estimate of EC_e, especially in the range of most significance for salinity diagnosis (2–10 dS/m). For example, the error in EC_e would only be ~5% too high or low (±0.3 out of 5.6 dS/m) for the case where EC_p is 2 dS/m, clay content is 20% and SP was taken to be 40 but actually was as low as 37 or as high as 43 (the result of ρ_s being 2.55 or 2.75 g/cm^3, instead of the assumed value of 2.65) (see Fig. 8). As also seen in this figure, errors in SP will have an increasingly greater effect on EC_e as EC_p (or salinity) increases, especially in the lower range of SP (25–50). Fortunately, the need for accuracy is increasingly less as EC_p (or salinity) increases. For example, there is little practical significance in the difference between EC_e values of 28 or 32 dS/m, such as is the case for EC_p = 8 dS/m and SP varying between 37 to 43, as corresponds to ρ_s ranging between 2.55 and 2.75 g/cm^3. Thus, it is concluded that the errors in EC_e produced from errors made in the estimate of SP due to likely errors made in the estimate of ρ_s will not be generally significant for the practical field appraisal of soil salinity.

In addition to the error in EC_e caused by ρ_s deviation from 2.65 g/cm^3, an ρ_s error may also effect EC_e through its influence on the determination of θ_w (see Eq. [7] and [8]). This effect of ρ_s upon EC_e may be evaluated from the "sensitivity" analysis results given in Fig. 9. These results indicate that expected deviation of ρ_s from 2.65 g/cm^3 does not significantly affect

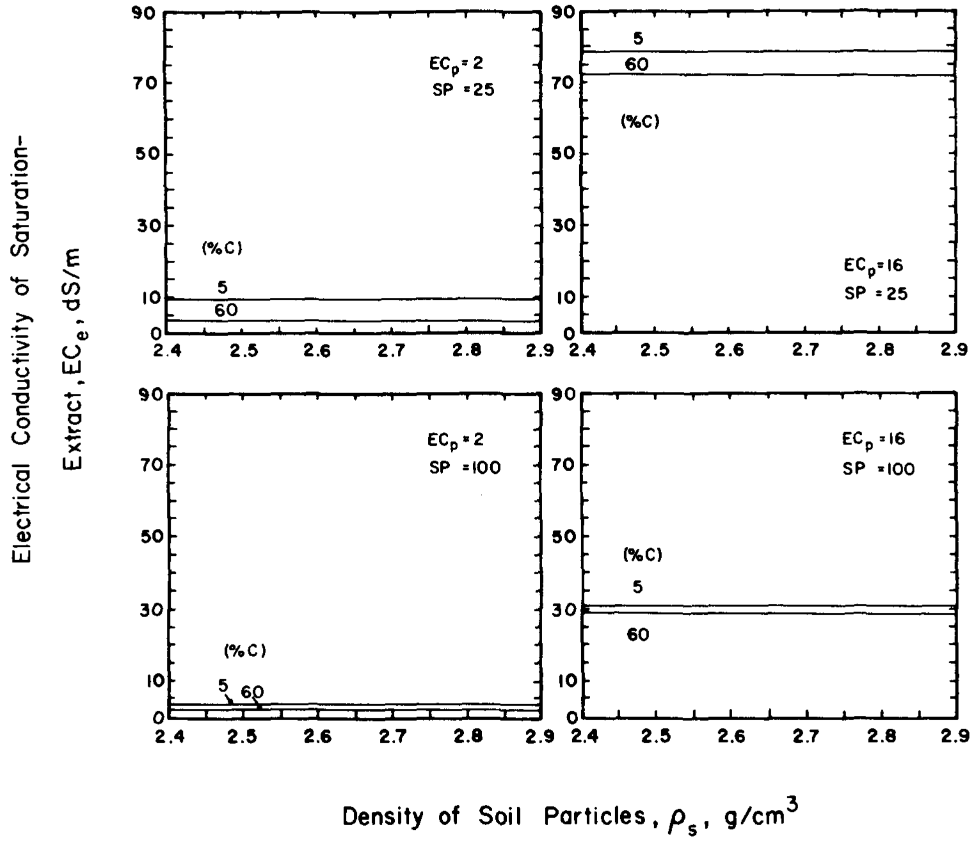

Fig. 9. Relations between average density of soil particles, percent clay content (%C), saturation percentage (SP), electrical conductivity of saturated soil-paste (EC_p) and soil salinity (EC_e).

the accuracy of the EC_e determination over the typical ranges of values of EC_p (2–16 dS/m), SP (25–100) and % clay (5–60).

The extent of error in EC_e, related to mis-estimates of EC_s resulting from errors made in estimating percent clay, may be deduced from the results given in Fig. 10 and 11. This error is seen to be trivial at high levels of SP; at low levels of SP, the error is greater but it should not be excessive, at least within the limits of a typical experienced person's ability to estimate clay content by feel. For example, one's estimate of the clay content of a soil having an actual clay content of 10% should certainly be within the range 5 to 15; this difference (5–15) only results in a change in the estimate of EC_e of ~10% (an EC_e ranging between ~8 to 9 dS/m instead of 8.5 dS/m for the case of EC_p = 2 dS/m and SP = 25), as may be seen in Fig. 10.

The other potential error in the determination of soil salinity associated with EC_s and clay content is that inherent within the assumed relation, EC_s = 0.023 (% clay) − 0.021. This empirical relation would not be expected to be exactly valid for all soils. One can evaluate the relative effect of such variation in soil property on the estimates of EC_e by examining Fig. 11. This figure shows that any reasonable estimate of EC_s (such as is given by the empirical relation and the estimate of clay content) will result in acceptable

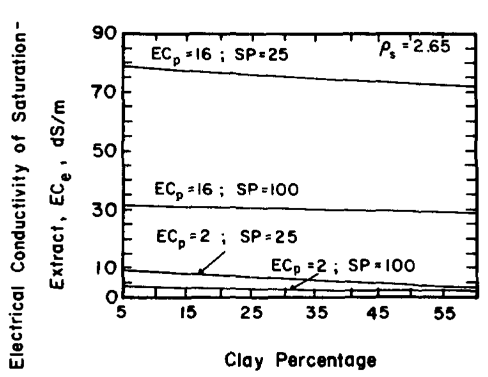

Fig. 10. Relations between clay percentage, electrical conductivity of saturated soil-paste (EC_p), saturation percentage (SP) and soil salinity.

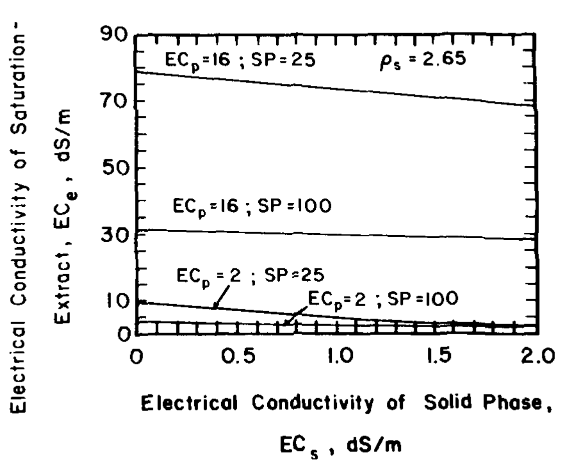

Fig. 11. Relations between electrical conductivity of the solid phase of soils, electrical conductivity of saturated soil-paste (EC_p), saturation percentage (SP) and soil salinity.

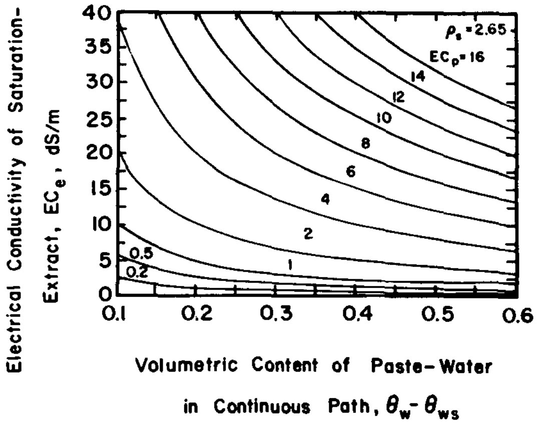

Fig. 12. Relation between volumetric content of paste-water in the continuous path ($\theta_w - \theta_{ws}$), electrical conductivity of saturated soil-paste (EC_p) and soil salinity.

accuracy in the estimate of EC_e, at least for the intended purposes of this method.

As was discussed in reference to Fig. 8, EC_e varies substantially with SP, as well as EC_p. The EC_p is measured and SP is determined by weighing a known volume of the saturated paste, however. This latter determination is subject only to the previously discussed insignificant errors related to deviation in particle density from the assumed value of 2.65 g/cm^3. Saturation paste is essentially a measure of the total volumetric water content of the saturated paste (θ_w) (see Eq. [8]). The fraction of θ_w which carries electrical current by way of the so-called "continuous" path ($\theta_{wc} = \theta_w - \theta_{ws}$) typically falls within the range of 0.2 to 0.4, as SP varies between 25 and 80, and is estimated (after Rhoades et al., 1989b; Fig. 2) using the relation ($\theta_w - \theta_{ws}$) = 0.0237 (SP)$^{0.6657}$, which was empirically established with data covering the SP range of 25 to 90. Thus, the error in EC_e due to an error made in the estimate of θ_{wc} from SP needs to be evaluated separately. This may be accomplished using the results given in Fig. 12 relating EC_e, EC_p and ($\theta_w - \theta_{ws}$). From these data we see that an error made in the estimate of ($\theta_w - \theta_{ws}$) fortunately has a minimal effect upon EC_e, given our ability to estimate ($\theta_w - \theta_{ws}$), especially in the low range of salinity where accuracy is most crucial (the lower left-hand corner of Fig. 12). For example, for a soil with EC_p = 2 dS/m and EC_e = 10 dS/m, the correct value for ($\theta_w - \theta_{ws}$) is 0.205. An error of ±20% in EC_e ($EC_e = 10 \pm 2$ dS/m) corresponds to a range of ($\theta_w - \theta_{ws}$) from 0.171 to 0.255, which is well within estimation ability.

CONCLUSIONS

These results show that reliable estimates of soil salinity should be obtainable from measurements of bulk soil electrical conductivity (EC_a) and estimates of soil water content (θ_w) and clay percentage (% clay), or from measurements of the electrical conductivity of saturated soil pastes (EC_p) and the weight of a known volume of paste (W_p).

Errors made in estimates of arid-land mineral soil particle density (ρ_s) have negligible effects in either method. In the former method, errors made in estimates of soil bulk density (ρ_b) do not significantly affect EC_e in the low salinity range of most importance. Errors related to mis-estimates of surface conductance (EC_s) are more sensitive to errors made in estimating soil clay content (% clay) than to differences in clay properties per se in this regard. Estimates of θ_w made by experienced soil scientists using feel methods should be sufficiently accurate to meet the practical needs of soil salinity appraisal from EC_a measurements.

In the paste method, the errors in EC_e related to mis-estimates of θ_w and θ_s are small since the latter are closely related to the volume weight of paste which is easily measured. Errors related to EC_s are small because the influence of EC_s per se on EC_e appraisal is small.

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