# Determination of the Properties of Saline and Alkali Soils

This chapter discusses determinations that give information on the chemical and physical properties of saline and alkali soils and thus serve as a basis for their diagnosis, treatment, and management. The status of knowledge on this subject is such that it is not yet possible to prepare a brief handbook containing a few simple measurements that will give all the necessary information. A number of different types of measurements are presented. Some of these must be regarded as tentative and subject to change and improvement. In some cases alternate procedures are proposed, and the individual worker will need to decide what kind and how many measurements will be required for the problem at hand. The purpose, application, and interpretation of the various determinations are discussed in this chapter. Detailed directions for making the measurements are given in chapter 6.

## Soil Sampling

There is no standard procedure for obtaining soil samples for appraising salinity and alkali. Usually the details of procedure will depend upon the purpose for which the sample is taken. If the objective is to obtain a general evaluation of salinity in a given area, the average salt content of a number of samples provides an index for the over-all appraisal. The variation among samples gives an index of the variation in salt content that may be encountered in the field. The larger the number of samples, the more accurate the appraisal will be. Too few samples may give a completely erroneous index of the salinity status. The deviation between the actual conditions existing in an area and the evaluation of the situation from the sampling procedure is designated as the "sampling error." It is evident that the larger the number of samples and the more carefully they are selected, the smaller the sampling error will be.

Salt concentration in soils may vary greatly with horizontal or vertical distance and with time. The nature of the soil, microrelief, and the cause and source of salinity should be considered. Factors that cause migration of salt, such as seasonal precipitation, irrigation, and phase in the crop cycle, should be taken into account in relation to the time of sampling. In cultivated areas, soil management history may be the most important single factor in determining salinity status, and field boundaries may enter the problem of where to sample and how to composite the samples.

The interpretation and use of salinity and alkali measurements necessarily depend on the completeness and accuracy of observational data recorded at the time of sampling. A record of the species and condition of the plant cover is of particular importance. When attempting to correlate crop conditions in the field with soil-salinity measurements, it is necessary to take samples from the active root zone of the plants.

The following suggestions are offered on where and how to sample:

($a$) Visible or suspected salt crusts on the soil surface should be sampled separately and the approximate depth of sample recorded.

($b$) If the soil shows evidence of profile development or distinct stratification, samples should be taken by horizons or layers.

($c$) In the absence of profile development or distinct stratification, the surface samples (excluding the surface crust) should be taken to the plow depth, usually to a depth of 6 or 7 inches.

($d$) Succeeding samples may be taken at intervals of 6 to 18, 18 to 36, and 36 to 7.2 inches, or other convenient depths, depending on the depth of the root zone, the nature of the problem, and the detail required.

($e$) Sometimes soil samples taken for salinity and alkali determinations may be composited to reduce analytical work.

($f$) The size of samples will depend on the measurements that are to be made.

Detailed suggestions on taking and handling soil samples along with a sample of the field data sheet used at the Salinity Laboratory are given in Method 1.

## Estimation of Soluble Salts From Electrical Conductivity

The choice of a method for measuring salinity depends **on such things as the reason for making the measurements, the number of samples to be handled, and the time and effort available for doing the work. Accurate**

methods usually require more time and, therefore, limit the number of determinations.

Electrical-resistance measurements can be made quickly and accurately and have long been used for estimating soluble salts in soil (Whitney and Means, 1897) ; however, electrical conductance, which is the reciprocal of resistance, is more suitable for salinity measurements, because it increases with salt content, thus simplifying the interpretation of readings. Moreover, expressing results in terms of specific conductance or conductivity makes the determination independent of the size and shape of the sample.

Electrical conductance is expressed in mhos, i. e., reciprocal ohms, while electrical conductivity has the dimensions of mhos per centimeter. In this handbook, the symbol *"EC"* is used to represent electrical conductivity.[3]

The salt content of the soil can be estimated roughly from an electrical-conductivity measurement on a saturated soil paste or a more dilute suspension of soil in water. A better estimate of soluble salts can be obtained from the conductivity of a water extract of the soil. In general the higher the moisture content, the easier it will be to obtain the extract, but the less representative the extracted solution will be of the solution to which plant roots are exposed in the soil.

Soil solutions in the field-moisture range can be extracted for study and analysis by the displacement method (White and Ross, 1937) or with the pressure-membrane apparatus (Method 3d). These methods are used mainly for research and special chemical studies.

Plants in saline soil are responsive to the concentration of the soil solution, and the relation of concentration to the normal field-moisture range is sometimes overlooked. There is more than a tenfold range in the wilting percentage of various soils. Consequently, the field-moisture range may vary greatly from one soil to another. For example, a sand and a clay could have the same soluble-salt content expressed as percent, dry weight basis, but the soil-solution concentration when near the wilting percentage could be 10 times as high for the sand as for the clay.

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[3] **The standard unit for conductivity (mho/cm.) is a large unit, so that most solutions have a conductivity that is much less than one unit. For instance, a measurement on one sample of water from the Rio Grande at the Elephant Butte Dam gave EC= 0.000694 mho/cm. For such cases, with physical and chemical measurements, it is customary to choose a small subunit that gives a more convenient location of the decimal point when recording or expressing data. For example, the unit $EC \times 10^3$ is called the millimho per centimeter. This is a convenient, practical conductivity unit for most soil salinity work. Until recently $EC \times 10^5$ (or $K \times 10^5$) has been in common use. ECX 10" designates conductivity expressed in micromhos per centimeter. This is the unit most generally used for expressing the conductivity of waters. The conductivity of the Rio Grande sample mentioned above, when expressed in these various units, is:**

$$EC = 0.000694 \text{ mho/cm.}$$
$$EC \times 10^3 = 0.694 \text{ millimho/cm.}$$
$$EC \times 10^5 = 69.4 \, (= K \times 10^5)$$
$$EC \times 10^6 = 694 \text{ micromhos/cm.}$$

## Conductivity of the Saturation Extract and the Saturation Percentage

The conductivity of the saturation extract is recommended as a general method for appraising soil salinity in relation to plant growth. The method is somewhat less rapid than a resistance measurement of the soil paste, but the result is easier to relate to plant response. The procedure involves preparing a saturated soil paste by stirring, during the addition of distilled water, until a characteristic endpoint is reached. A suction filter is then used to obtain a sufficient amount of the extract for making the conductivity measurement.

The special advantage of the saturation-extract method of measuring salinity lies in the fact that the saturation percentage is directly related to the field-moisture range. In the field, the moisture content of the soil fluctuates between a lower limit represented by the permanent-wilting percentage and the upper, wet end of the available range, which is approximately two times the wilting percentage. Measurements on soils indicate that over a considerable textural range the saturation percentage $(SP)$ is approximately equal to four times the 15-atmosphere percentage $(FAP)$, which, in turn, closely approximates the wilting percentage. The soluble-salt concentration in the saturation extract, therefore, tends to be about one-half of the concentration of the soil solution at the upper end of the field-moisture range and about one-fourth the concentration that the soil solution would have at the lower, dry end of the field-moisture range. The salt-dilution effect that occurs in fine-textured soils, because of their higher moisture retention, is thus automatically taken into account. For this reason, the conductivity of the saturation extract (EC,) can be used directly for appraising the effect of soil salinity on plant growth.

Table 1 gives some of the experimental data supporting the foregoing statements. Since the 15-atmosphere percentage appears to be the most significant moisture property that can be readily measured, this retentivity value was used to separate soil samples into three textural groups: Coarse, medium, and fine (table 1). The $FAP$ ranges arbitrarily selected to designate these textural groups were: Coarse, 2.0–6.5; medium, 6.6–15.0; and fine, greater than 15.1. The numbers in the $FAP$ column of table 1 are the actual $FAP$ values for the available samples in the various textural groups. The $SP/FAP$ ratio of the medium-textured group, which is largest in number, is approximately 4 and the standard deviation is small; whereas the ratios for the fine-textured and high organic matter groups are somewhat lower (Campbell and Richards, 1950).

The saturation percentage for sands, when determined by the standard procedure, gives values that, relative to the field-moisture range, are higher than for other soils. This occurs because in sands the large pores that are filled with water at the saturation-paste condition do not correspondingly retain water under field conditions. Consequently, $EC_e \times 10^3$ for sands, when referred to the regular saturation-extract scale, gives an

TABLE l.-*Relation of saturation percentage* (SP) *to 15-atmosphere percentage* (FAP) *as influenced by soil texture*

| Soil group | Soil samples | FAP | | | SP | | | SP/FAP | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Minimum | Maximum | Average | Minimum | Maximum | Average | Minimum | Maximum | Average | Standard deviation |
| | Number | | | | | | | | | | |
| Coarse............ | 10 | 3.4 | 6. 5 | 5.0 | 16.0 | 43. 1 | 31. 8 | 4.68 | 8. 45 | 6.37 | 1. 15 |
| Medium.......... | 23 | 6. 6 | 14.2 | 10. 8 | 26.4 | 60.0 | 42. 5 | 3. 15 | 5. 15 | 3.95 | . 48 |
| Fine............. | 11 | 16. 1 | 21.0 | 18. 5 | 41.8 | 78. 5 | 59. 5 | 2.03 | 4.26 | 3.20 | . 60 |
| Organic.......... | 18 | 27. 6 | 51.3 | 37. 9 | 81.0 | 255 | 142 | 2.53 | 4. 97 | 3.66 | . 75 |

**optimistic index of** salinity, i. e., underrates the salinity condition. Method 3b gives a tentative procedure for **estimating the upper limit of** the field-moisture range. From this, a moisture content for extraction is determined and a procedure for obtaining a conductivity value that can be used on the regular saturation-extract scale is suggested. **This new procedure is tentative because it has not** been subjected to extensive testing, but it has given good results for soils with *SP* values of approximately 25 or less.

It would be more reliable to appraise salinity by using measurements of extracts of the soil solution in the field-moisture range. However, difficulty of obtaining such extracts would make them prohibit&e for routine use. The next higher feasible moisture content appears to be the saturation percentage. The following scale is recommended for general use in appraising the effect of soluble salts on crops. It shows the relation of crop response to soil salinity expressed in terms of the conductivity of the saturation extract.

Use of the conductivity of the saturation extract as an index of soil salinity was introduced at the Rubidoux Laboratory in 1939 for the Pecos River Joint Investigation. The salinity scale given in the earlier draft of this handbook was substantially the same as the scale originally proposed by Scofield in his report on the Pecos River Joint Investigation (United States National Resources Planning Roard, 1942, pp. 263334). The scale given here has been modified somewhat from those previously used.

It is often desirable, because of the extra information provided on soil texture and moisture retention, to determine the soil-moisture content at saturation, i. e., the saturation percentage *(SP)* when saturated soil paste is prepared for salinity measurements. A rapid procedure for *SP* determination based on the weight of a known volume of saturated paste has been described by Wilcox (1951) and is included as Method 27c.

The endpoint for mixing a saturated soil paste is **reasonably definite; and, with a little training, good agreement can** be **obtained among various operators. Slight variations in technique, such as adding** practically all the water to the soil sample before stirring or adding the air-dry soil to a known amount of water, do not appreciably affect the saturation percentage of most soils. Special precautions, however, must be taken with very fine and very coarse textured soils. For example, in some clay soils the amount of water that must be added to bring about saturation can be varied 10 percent or more, depending upon the rate of adding water and the amount of stirring. The more rapid the rate of water addition in relation to stirring, the lower the saturation percentage may be. The lower value is desirable to reduce the time and effort during mixing and also to minimize puddling of the soil. Campbell and Richards (1950) found that the conductivity of the saturation-extract method is applicable also for the measurement of salinity in peat soils. With air-dried peats, an overnight wetting period is necessary to obtain a definite endpoint for the saturated paste.

### Relation of Conductivity to Salt Content and Osmotic Pressure

The relation between the electrical conductivity and the salt content of various solutions is shown graphically in several figures. The curves (fig. 2) for the chloride salts and $Na_2SO_4$ almost coincide, but $MgSO_4, CaSO_4,$ and $NaHCO_3$ have lower conductivities than the other salts at equivalent concentrations. When the concentration is given in percent salt or parts per million, the curves (fig. 3) are more widely separated.

| Salinity effects mostly negligible | Yields of very sensitive crops may be restricted | Yields of many crops restricted | Only tolerant crops yield satisfactorily | Only a few very tolerant crops yield satisfactorily |
|---|---|---|---|---|
| 0 | 2 | 4 | 8 | 16 |

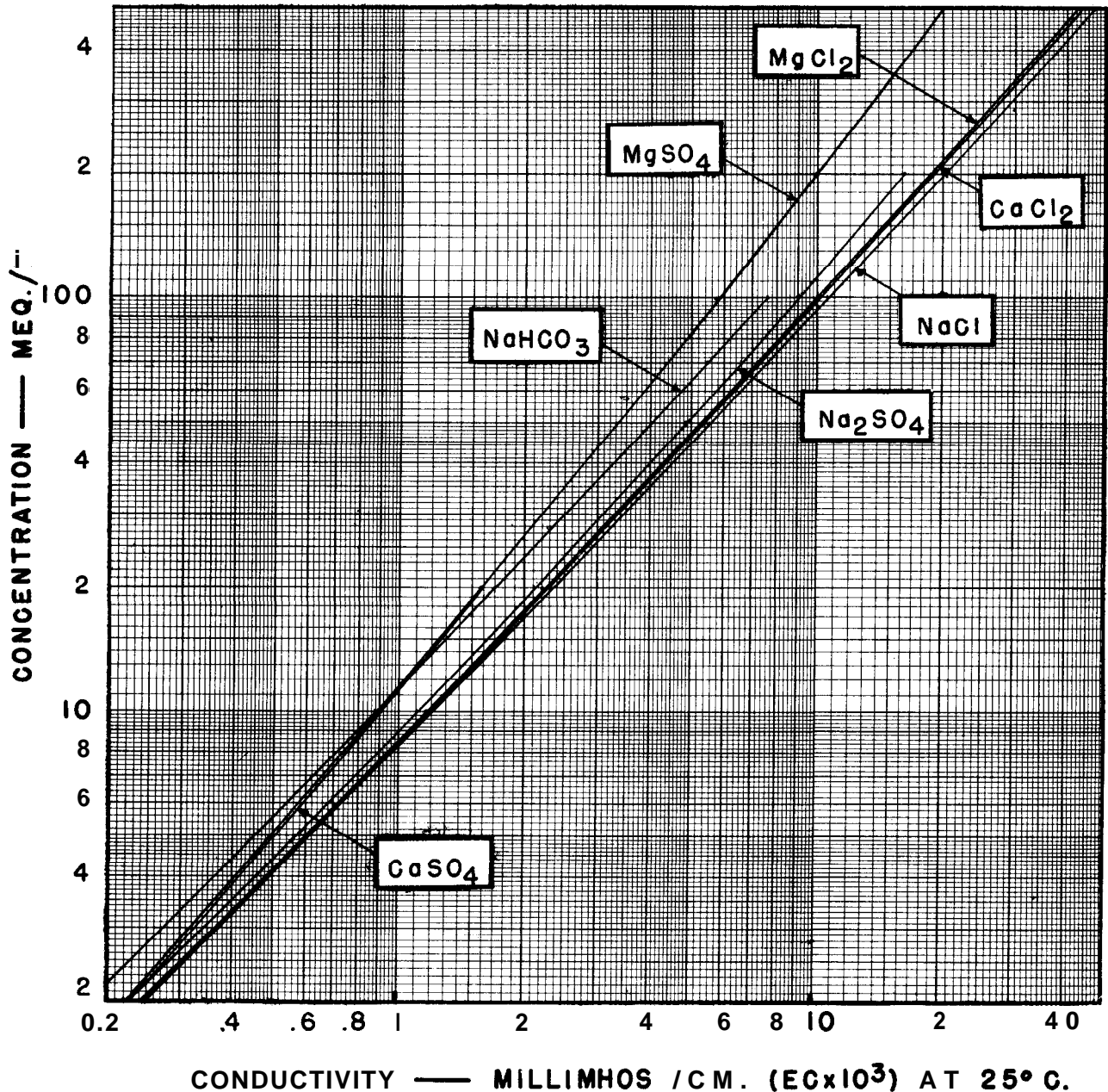**Scale of conductivity** (millimhos **per centimeter at** 25° C.)

FIGURE 2.-Concentration of single-salt solutions in milliequivalents per liter as related to electrical conductivity.

With soils from widely separated areas in western United States, the concentration range was higher (fig. 4) than that shown in figures 2 and 3 ; consequently, the electrical conductivity is expressed in millimhos per centimeter. This is a convenient unit to use for extracts from saline soils. Soils represented by points that are considerably above the average line usually contain a relatively high amount of calcium or magnesium sulfate. Information on the salt content of irrigation water in relation to electrical conductivity is given in chapter 5.

Experimental work conducted at the Salinity Laboratory by Hayward and Spurr (1944), Wadleigh and Ayers (1945), and workers elsewhere indicates that the osmotic pressure of the soil solution is closely related to the rate of water uptake and growth of plants in saline soils. The osmotic pressure (OP) of solutions expressed in atmospheres is usually calculated from the freezing-point depression, in degrees C., $\Delta T$, in accordance with the relation, $OP = 12.06 \Delta T - 0.021 \Delta T^2$, given in the International Critical Tables. The relation between osmotic pressure and electrical
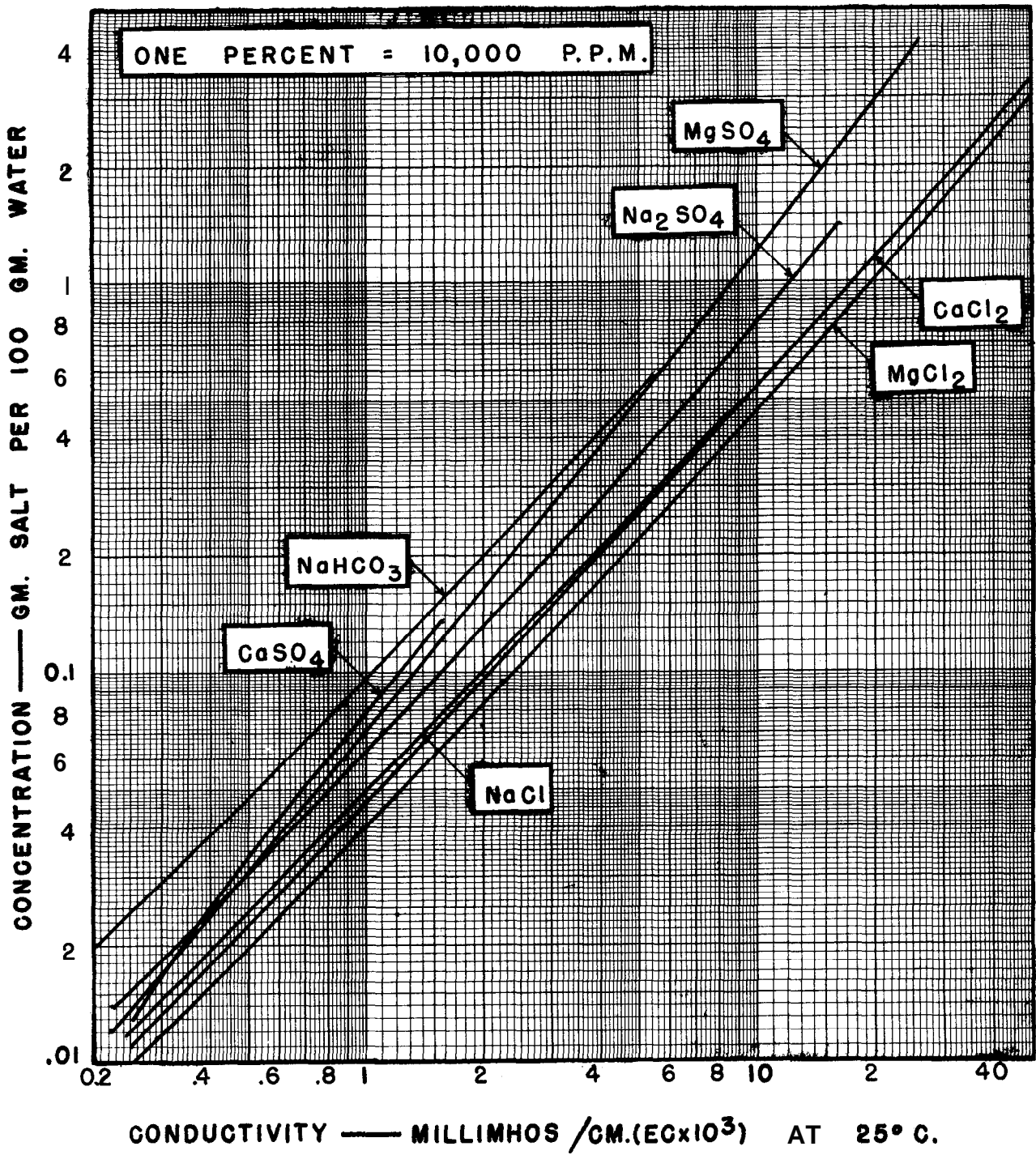
FIGURE J.-Concentration of single-salt solutions in percent as related to electrical conductivity.
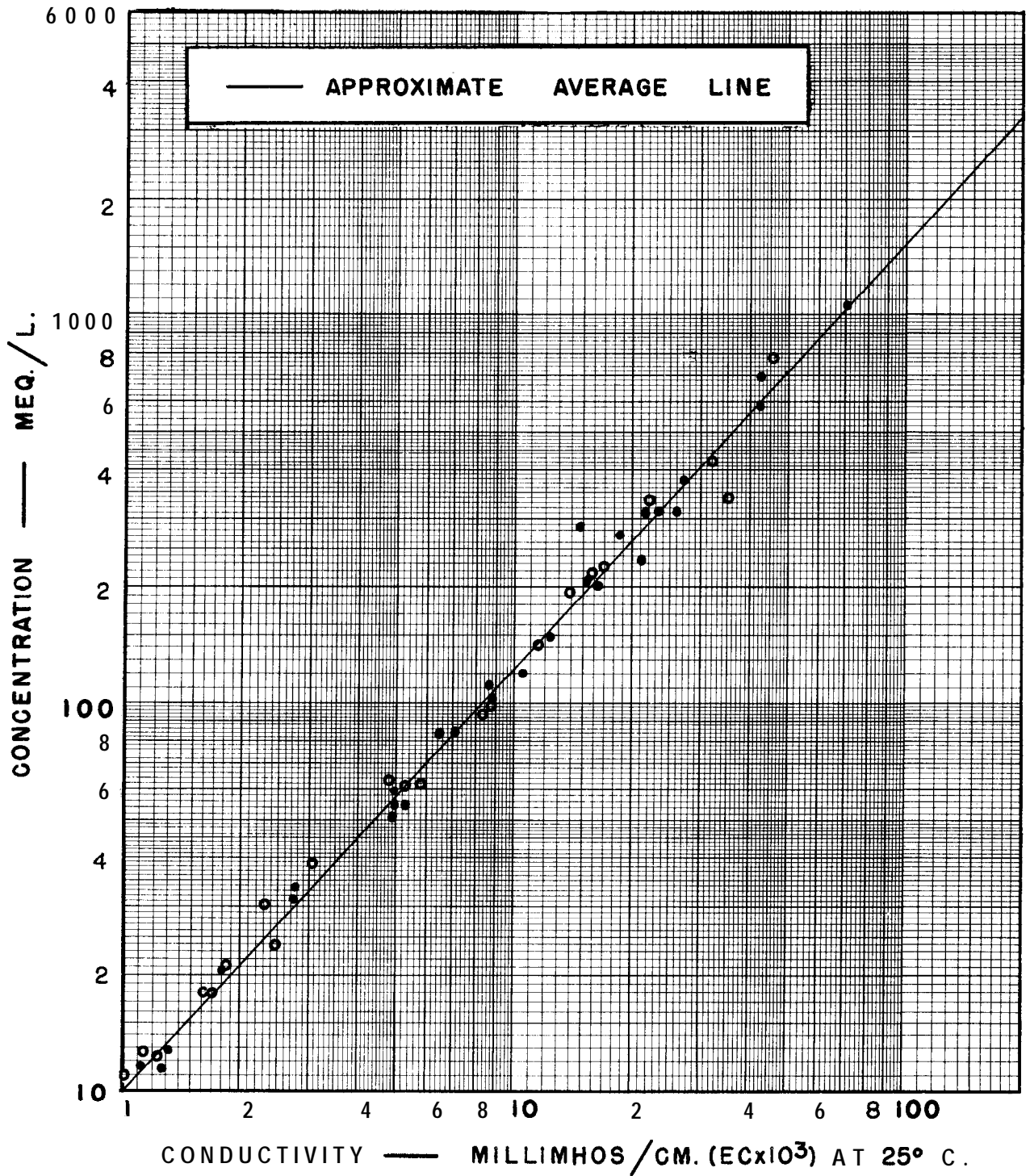
Figure 4.-Concentration of saturation extracts of soils in milliequivalents per liter as related to electrical conductivity.

conductivity (fig. 5) is useful for some agricultural purposes. This measurement is in general use and can be more readily measured than freezing-point depression. The relation between OP and $EC$ for salt mixtures found in saline soils is indicated in figure 6 from data reported by Campbell and coworkers (1949). The $OP$ values were calculated from freezing-point measurements. In the range of $EC$ that will permit plant growth, the relation $OP = 0.36 \times EC, \times 10^3$ can be used for estimating the osmotic pressure of soil solutions from conductivity measurements.

### Conductivity of 1: 1 and 1: 5 Extracts

For soil: water ratios of 1: 1 and 1: 5, the extract is obtained by filtering without the use of vacuum or pressure. The conductivity of these extracts is sometimes used for estimating salinity from the line in figure 4 or, preferably, from special curves that apply for the salts and soil in question.

Salinity estimates based on the conductivity of 1: 1 and 1: 5 extracts are convenient for rapid determinations, particularly if the amount of soil sample is limited, or when repeated samplings are to be made in the same soil to determine the change in salinity with time or treatment. The reliability -of such estimates depends upon the kind of salts present. For chloride salts, the results will be only slightly affected by moisture content, but, if sulfate or carbonate salts, which have relatively low solubility, are present in appreciable quantities, the apparent amount of soluble salt will depend on the soil : water ratio (table 2). In an experiment conducted by Wadleigh, Gauch, and Kolisch (1951) to determine the salt tolerance of orchardgrass, the salts shown in the table were individually added to a loam soil. During the course of the experiment, many samples were taken to check distribution of the salt in the soil and conductivity measurements were made of the saturated soil *(EC,),* the saturation extract *(EC,),* the 1: 1 extract *(EC,),* and the 1: 2 extract $(EC_2)$. The regression coefficients, which are the slopes of the best fit straight lines, were calculated for various comparisons among the data (table 2) **.**

The theoretical values given in the table are based on the saturation percentage of 30 for the soil used. Except for small changes in the activity coefficients of the ions with dilution, the conductivity ratios should be inversely proportional to the moisture contents of the soil at extraction if the total dissolved salt is independent of the moisture content at which the extraction is made. The average measured conductivity ratios were always greater than the theoretical. The differences were not large for the chloride salts, but when $NaHCO_3$, $Na_2SO_4$, or $MgSO_4$ were added to this soil. in which the exchange complex was largely saturated with calcium, some $CaSO_4$ and $CaCO_3$ were precipitated. It is evident from the table that the regression coefficients are quite different for extracts obtained at high moisture contents if the less soluble salts are present in the soil. This example illustrates why the estimation of salinity from the conductivity of the extract at 1: 1 or at higher moisture contents is not recommended for general use. These higher moisture contents may be used to advantage in certain cases, but the limitations of the method should be clearly understood.

### Salinity Appraisal From the Electrical Resistance of Soil Paste

Salinity determinations based on the electrical resistance of a standard sample of wet soil have been in use for many years (Whitney and Means, 1897; Briggs, 1899). The Bureau of Soils cup and the data published by Davis and Bryan (1910) have been widely used by various agencies in this country for estimating the percentage of soluble salts in soils. The apparatus is simple and rugged, the measurements can be quickly made, and the results are reproducible.

To obtain the relation between wet-soil resistance and percent salt, Davis and Bryan made measurements using 4 soil samples representing the textural groups of sand, loam, clay loam, and clay. These samples of soil were composited from various types of nonsaline soils. A mixture of chloride and sulfate salts was used to obtain 5 levels of added salt ranging from 0.2 to 3 percent, and resistance values were obtained on the saturated pastes. Making use of these 20 readings on the synthetic soil and salt mixtures, Davis and Bryan used graphical interpolation to obtain the relation of soil-cup resistance to percent salt for mixed sulfates and chlorides. The Davis and Bryan procedure for the Bureau of Soils method of determining soluble salt in soil is given in Method 5. The method is also described in the Soil Survey Manual (1951, *p.* 343).

TABLE *2.-Regression coefficients* (b) *between various criteria for evaluating soil salinity by a conductance procedure*

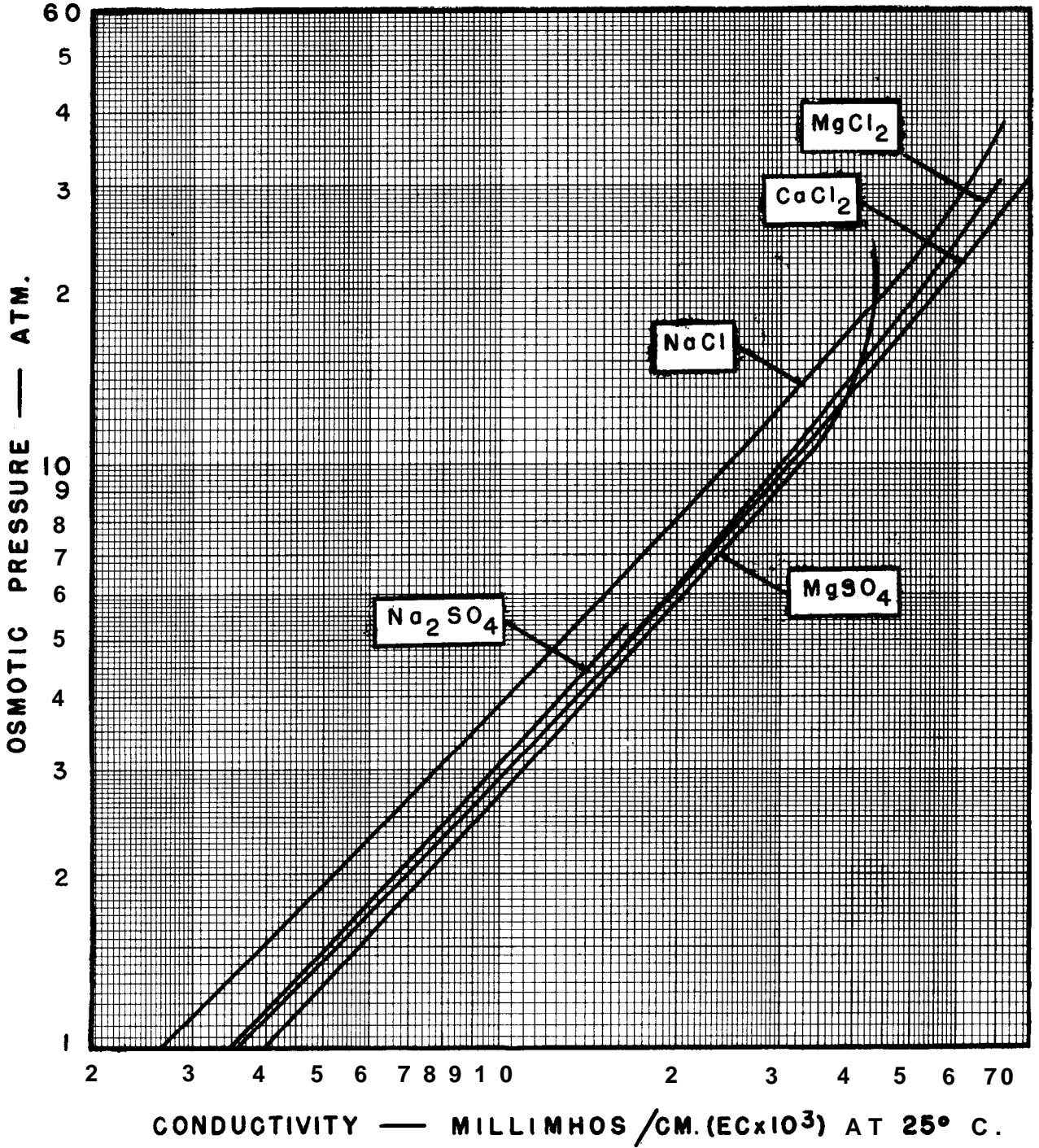| Soils containing— | $b_{EC_1 \cdot EC_e}$ | $b_{EC_2 \cdot EC_e}$ | $b_{EC_2 \cdot EC_1}$ | $b_{EC_e \cdot EC_e}$ |
|---|---|---|---|---|
| NaCl | $0.359 \pm 0.0070$ | $0.185 \pm 0.0037$ | $0.514 \pm 0.0069$ | $0.235 \pm 0.0066$ |
| CaCl$_2$ | $.356 \pm .011$ | $.191 \pm .0028$ | $.534 \pm .0046$ | $.242 \pm .0078$ |
| MgCl$_2$ | $.376 \pm .010$ | $.192 \pm .0042$ | $.507 \pm .012$ | $.237 \pm .019$ |
| NaHCO$_3$ | $.379 \pm .027$ | $.227 \pm .017$ | $.589 \pm .011$ | $.222 \pm .013$ |
| Na$_2$SO$_4$ | $.590 \pm .023$ | $.355 \pm .010$ | $.600 \pm .011$ | $.217 \pm .015$ |
| MgSO$_4$ | $.600 \pm .068$ | $.471 \pm .060$ | $.780 \pm .027$ | $.226 \pm .0054$ |
| Theoretical | $.333$ | $.167$ | $.5$ | .............. |

FIGURE 5.-Osmotic pressure of single-salt solutions as related to electrical conductivity.   (Data from International Critical Tables.)
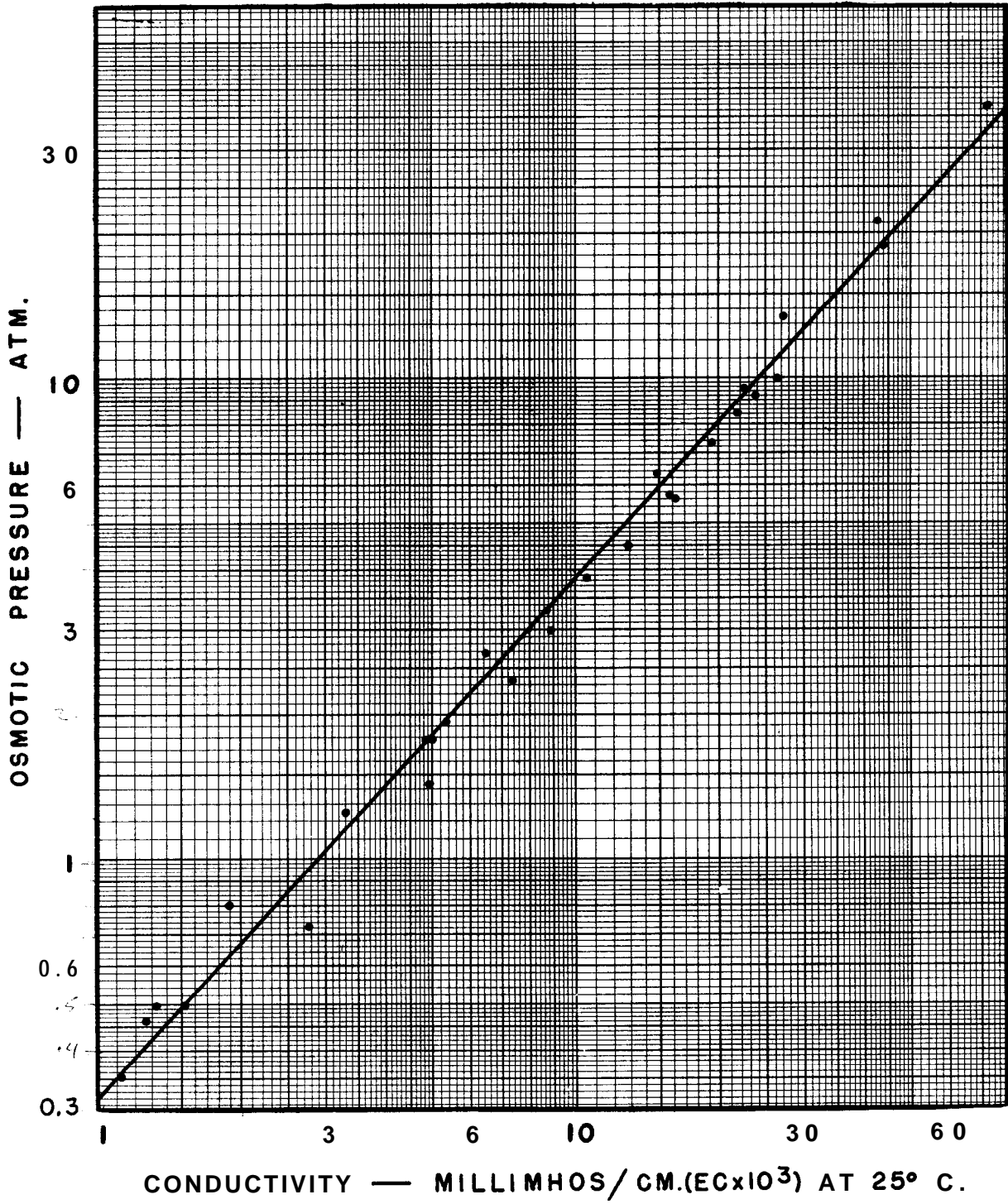
FICURE 6.-Osmotic pressure of saturation extracts of soils as related to electrical conductivity.

TABLE 3.—*Comparison of measured and calculated values of* EC, *after correcting for effect of* S P

| Soils from— | Number of samples | Average EC, X $10^3$ at 25° C. | | Difference | Standard deviation of differences |
| --- | --- | --- | --- | --- | --- |
| | | Measured | Calculated | | |
| Lower Rio Grande Valley, Texas. | 6 | 9.93 | 11.10 | 1. 17 | 1. 30 |
| Grand Junction district, Colorado. | 12 | 8.64 | 9.45 | .81 | . 85 |
| Tucumcari district, New Mexico. | 11 | 9.63 | 11.85 | 2.22 | 1.16 |
| Gem County, Idaho.. | 7 | 5. 73 | 16.24 | 10.51 | 2.90 |
| Four Western States. | 12 | 10.25 | 13.05 | 2.80 | 1.76 |

A similar procedure was used by Davis and Bryan to obtain calibration data for "carbonate" salts, presumably sodium carbonate. Tests at the Laboratory, however, indicate that table IV of Davis and Bryan for carbonate salts is unreliable and should not be used. The unreliability of the calibration data for these salts is a result of cation-exchange reactions that were not generally understood at the time the original work was done.

The conductivity of the saturation extract (EC,) is recommended in this handbook as a measurement for general use for indicating soil salinity, but the method based on the soil-paste resistance (R,) is still commonly used. The electrical conductivity of the soil paste (EC,) is related to paste resistance by the relation $EC_s = 0.25/R_s$, where 0.25 is the constant for the Bureau of Soils electrode cup. In a study by Reitemeier and Wilcox (1946), it was found that the relation between *EC,* and *EC,* is markedly influenced by variations in the saturation percentage, the salinity, and the conductivity of the soil minerals. From unpublished work at the Laboratory, Bower concluded that there is no easy method for simplifying the relation of *EC,* (or $R_s$) to *EC,.* He equilibrated a group of western soils with various concentrations of a 1: 1 mixture of sodium and calcium chloride and found that on the average $EC_e/EC_s = 5.4 - 0.07(SP)$. Using this average relationship and *SP* values calculated from the weight of the soil paste as described by Wilcox (1951), he calculated values for *EC,* based on $R_s$ measurements. The degree of correspondence between measured and calculated values is indicated by the data in table 3.

The calculated average values for *EC,* are somewhat high but are acceptable except for the soils from Gem County, Idaho. These soils had a low salinity level hut were high in exchangeable sodium. The large discrepancy here and for some other locations apparently is owing to conduction by the clay minerals, when they contain exchangeable sodium. Bower found, for example, that the electrical conductivity of a 5-percent suspension of calcium-saturated montmorillonite was 0.072 mmhos/cm., but when saturated with sodium, the conductivity was 0.446 mmhos/cm.

No method has been found for improving the reliability of the paste-resistance method that does not destroy its simplicity. The method may be acceptable for estimating salinity for purposes of soil classification, but for soils like those of Gem County, Idaho, it does not have acceptable reliability.

## Conversion of Conductivity Data to a Standard Reference Temperature

The electrical conductivity of solutions and of soils containing moisture increases approximately 2 percent per degree centigrade increase in temperature. To simplify the interpretation of salinity data, it is customary either to take the measurements at a standard-reference temperature or to determine the temperature at which the measurement is made, and then, by means of correction tables or a correction dial on the bridge, to convert the measurement to a standard-reference temperature.

Whitney and Briggs (1897) measured the resistance of 9 soils at 13 temperatures and calculated the average relation of resistance to temperature. Whitney and Means (1897) used these temperature data to construct a table used in converting resistance measurements of saturated soil to the standard temperature of 60" F. Data from this table, which has been widely used since its publication 50 years ago, are given in table 16 in chapter 6, along with instructions for its use.

More recently a study was made by Campbell, Bower, and Richards (1949) to determine the effect of temperature on the electrical conductivity of soil extracts. Saturation extracts from 21 soils were measured at 5 temperatures, ranging from 0" to 50" C. The temperature coefficient of the electrical conductivity for these representative soil extracts varied somewhat with temperature, but in the range from 15" to 35" it was verified that for each degree centigrade increase in temperature the conductivity increased very nearly 2 percent of the value at 25". The details of the procedures for measuring electrical conductivity and making temperature corrections are given in Method 4.

## Comparison of Percent Salt in Soil and Extract Measurements

The diagram shown in figure 7 facilitates the interpretation of salinity in relation to crop response. It is based on the following assumptions: $P_{sw} =$ p. p. m./ $10,000 = 0.064 \times EC \times 10^3$; $P_{ss} = (P_{sw} \times P_w)/100$; *OP*

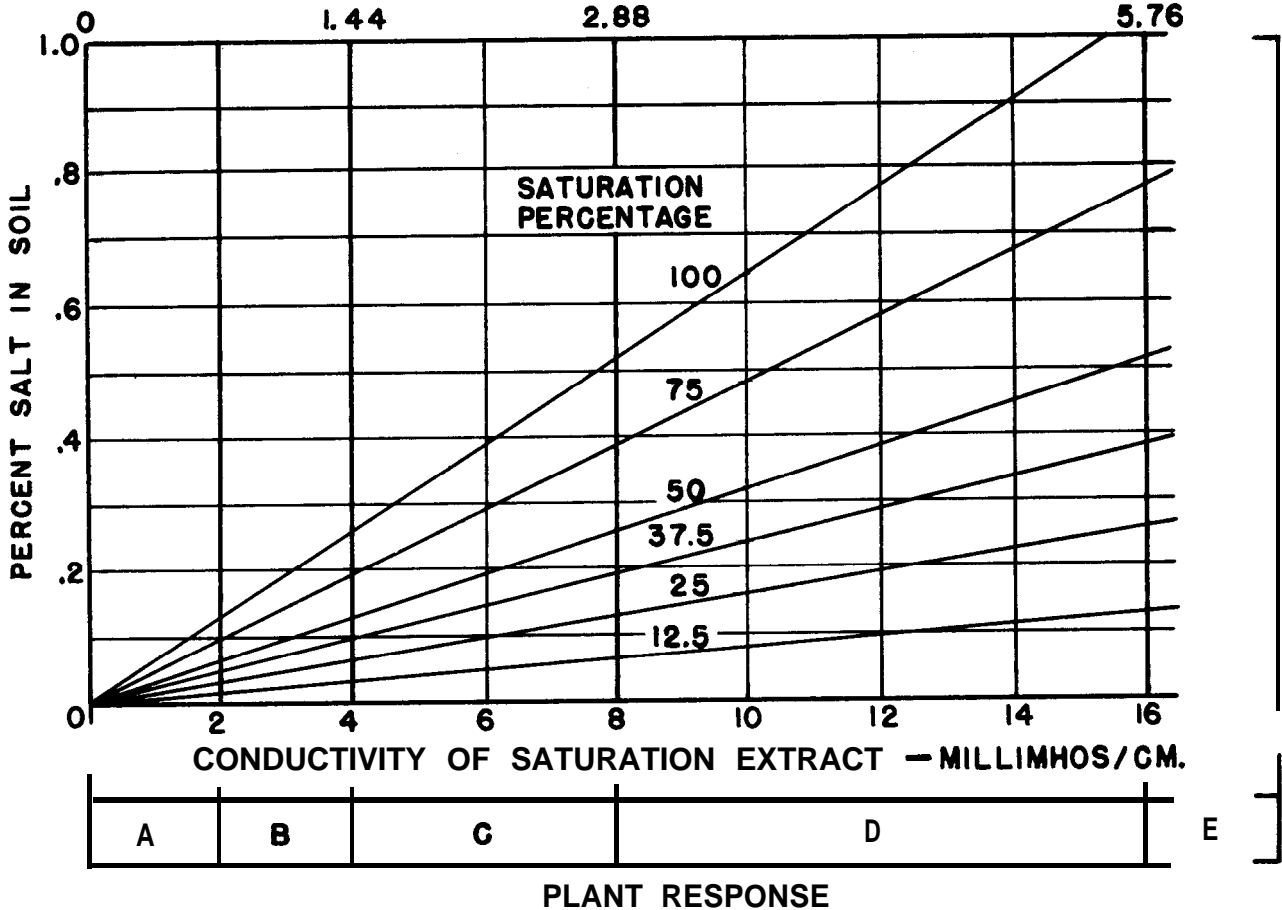## OSMOTIC PRESSURE OF SATURATION EXTRACT — ATMOSPHERES



FIGURE 7.-Relation of the percent salt in the soil to the osmotic pressure and electrical conductivity of the saturation extract and to crop response in the conductivity ranges designated by letters. These ranges are related to crop response by the salinity scale on page 9.

$= 0.36 \times EC \times 10"$. $P_{sw} =$ percent salt in water; $P_{ss} =$ percent salt in soil; $P_w =$ percent water in soil ; and $OP =$ osmotic pressure in atmospheres. The lower scale gives values for the conductivity of the saturation extract. The top scale shows the osmotic pressure of the saturation extract. The osmotic pressure of the soil solution at the upper limit of the field-moisture range will be approximately double these values.

The diagonal lines help correlate the conductivity of the saturation extract with the percent salt content for various soil textures. For example, at $EC, X10^3 = 4$, nearly all crops make good growth and for a soil with a saturation percentage of 75, as seen in the diagram, this corresponds to a salt content of about 0.2 percent. On the other hand, 0.2 percent salt in a sandy soil for which the saturation percentage is 25 would correspond to EC, $X10^3 = 12$, which is too saline for good growth of most crop plants. Partial lists of crop plants in their order of tolerance to soil salinity are given in chapter 4.

The diagram indicates the growth conditions of crops to be expected for various degrees of salinity in the active root zone of the soil, i. e., the soil volume that is permeated by roots and in which moisture absorption is appreciable. Obviously, the diagram does not apply for soil in which salt has been deposited after the roots have been established and have become nonabsorbing, or to soil adjacent to the plant, either high or low in salt, that has not been permeated by roots. With mature row crops, for example, salt may have accumulated in the ridge to such an extent that the roots no longer function as moisture absorbers and, therefore, the ridge cannot be considered as characteristic of the active plant-root environment.

### Chemical Determinations

#### Soil Reaction—pH

The pH value of an aqueous solution is the negative logarithm of the hydrogen-ion activity. The value may be determined potentiometrically, using various electrodes (Method 21), or colorimetrically, by indicators

whose colors vary with the hydrogen-ion activity. There is some question as to the exact property being measured when methods for determining the pH values of solutions are applied to soil-water systems. Apparent pH values are obtained, however, that depend on the characteristics of the soil, the concentration of dissolved carbon dioxide, and the moisture content at which the reading is made. Soil characteristics that are known to influence pH readings include: the composition of the exchangeable cations, the nature of the cation-exchange materials, the composition and concentration of soluble salts, and the presence or absence of gypsum and alkaline-earth carbonates.

A statistical study of the relation of pH readings to the exchangeable-sodium-percentages of soils of arid regions has been made by Fireman and Wadleigh (1951). The effect of various factors such as moisture content, salinity level, and presence or absence of alkaline-earth carbonates and gypsum upon this relationship was also studied. Some of the more pertinent statistical data obtained are presented in table 4. While all the coefficients of correlation given in the table are highly significant, the coefficients of determination show that at best no more than 54 percent of the variance in exchangeable-sodium-percentage is associated with the variance in pH reading. The data on the effect of moisture content indicate that the reliability of prediction of the exchangeable-sodium-percentage from pH readings decreases as the moisture content is increased. Similarly, the data on the effect of salinity indicate that the reliability of prediction is lowest when the salt level is either low or very high. An increase in pH reading of 1.0 or more, as the moisture content is changed from a low to a high value, has been found useful in some areas for detecting saline-alkali soils. However, the reliability of this procedure should be tested before use on any given group of soil samples.

Experience and the statistical study of Fireman and Wadleigh permit the following general statements regarding the interpretation of pH readings of saturated soil paste: (1) pH values of 8.5 or greater almost invariably indicate an exchangeable-sodium-percentage of 15 or more and the presence of alkaline-earth carbonates; (2) the exchangeable-sodium-percentage of soils having pH values of less than 8.5 may or may not exceed 15; (3) soils having pH values of less than 7.5 almost always contain no alkaline-earth carbonates and those having values of less than 7.0 contain significant amounts of exchangeable hydrogen.

### Soluble Cations and Anions

Analyses of saline and alkali soils for soluble cations and anions are usually made to determine the composition of the salts present. Complete analyses for soluble ions provide an accurate determination of total salt content. Determinations of soluble cations are used to obtain the relations between total cation concentration and other properties of saline solutions, such as electrical conductivity and osmotic pressure. The relative concentrations of the various cations in soil-water extracts also give information on the composition of the exchangeable cations in the soil.

The soluble cations and anions commonly determined in saline and alkali soils are calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, and chloride. Occasionally nitrate and soluble silicate also are determined. In making complete analyses, a determination of nitrate is indicated if the sum of cations expressed on an equivalent basis significantly exceeds that of the commonly determined anions. Appreciable amounts of soluble silicate occur only in alkali soils having high pH values. In analyses made by the usual methods, including those recommended in this hand-

TABLE 4.—*Coefficient of correlation* $(r)$[1] *and coefficient of determination* $(r^2)$ *for the relation of pH reading to exchangeable-sodium-percentage as influenced by moisture content, salinity level, and presence or absence of alkaline-earth carbonates and gypsum*

| Moisture content (percent) | Salinity as EC, x $10^3$ at 25° C. | Alkaline-earth carbonates | Gypsum | Samples | $r$ | $r^2$ |
|---|---|---|---|---|---|---|
| | | | | *Number* | | *Percent* |
| Saturation. ......... | Variable. ........ | V a r i a b l e . | V a r i a b l e . | 868 | 0. 66 | 44 |
| 500............... | ....do......... | d o ........... | : do. | 271 | . 65 | 43 |
| 1,000.. ............ | ....do......... | d o ........... | d o | 289 | . 53 | 28 |
| 6,000.. ............ | ....do......... | d o . | d o ........... | 346 | . 48 | 24 |
| S a t u r a t i o n . | o-4............. | d o ........... | . do............ | 349 | . 56 | 31 |
| D o | 4-8............. | d o ........... | do............ | 91 | . 72 | 52 |
| D o | 8-15............. | d o ........... | d o ........:.... | 115 | . 70 | 49 |
| D o | 15-30............ | do. | d o ........... | 87 | 74 | 54 |
| D o | > 30............ | d o ........... | do. | 69 | : 49 | 24 |
| Do. | Variable. ........ | P r e s e n t . | P r e s e n t | 237 | . 72 | 52 |
| Do. | ....do......... | ...do. .. | A b s e n t . | 452 | . 56 | 32 |
| Do. | ....do......... | Absent. | do | 154 | . 41 | 17 |

[1] All values are significant at the l-percent level.

book, any soluble silicate present is determined as carbonate.

As shown by Reitemeier (1946) and others, values obtained from determinations of the soluble-cation and soluble-anion contents of saline and alkali soils are markedly influenced by the moisture content at which the extraction is made. The total dissolved quantities of some ions increase with increasing moisture content, while concurrently those of others may decrease; almost invariably values obtained for total salt content increase with increasing moisture content at extraction. Processes that are responsible for the changes in the relative and total amounts of soluble ions which occur with increasing moisture content include cation-exchange reactions, negative adsorption of ions, hydrolysis, and the increased solution of silicate minerals, alkaline-earth carbonates, and gypsum. Ideally, the determination of soluble ions should be made on extracts obtained at a moisture content in the field-moisture range. However, the preparation of such extracts is time-consuming and requires the use of special extraction equipment (Method 3d). Saturation percentage is the lowest practical moisture content for obtaining extracts on a routine basis. Use of the saturation extract is, therefore, recommended for the determination of soluble ions. Methods are available that permit determination of the electrical conductivity and the common soluble constituents on 10 to 50 ml. of saturation extract. As a rule, about one-fourth of the moisture in a saturated soil paste can be removed by ordinary pressure or vacuum filtration.

The choice of methods for the determination of the various cations and anions depends upon the equipment available and the personal preference of the analyst. No attempt is made here to present all of the methods that are suitable. The methods given were chosen on the basis of their convenience and reliability. Owing to the fact that the amount of extract available for analysis is usually limited, most of the methods selected are of the semimicro type. They generally involve the use of a centrifuge, a flame photometer, and a photoelectric colorimeter. Where the amount of extract is not limited, the macromethods employed for water analysis given in chapter 8 may be used. Most of these methods do not require the use of a centrifuge or photoelectric colorimeter.

## Soluble Boron

The importance of soluble boron from the standpoint of soil salinity lies in its marked toxicity to plants when present in relatively small amounts. Toxic concentrations of boron have been found in the saturation extracts of a number of saline soils. It is necessary, therefore, to consider this constituent as a factor in the diagnosis and reclamation of saline and alkali soils. High levels of boron in soils can usually be reduced by leaching. During the leaching process, boron may not be removed in the same proportion as other salts. If the concentration of boron is high at the outset, a considerable depth of leaching water may be necessary to reduce

the boron content to a safe value for good plant growth. This is illustrated by a recent leaching test. At the beginning of the test, the conductivity of the saturation extract of the top 12 inches of soil was 64.0 mmhos/cm. After 4 feet of irrigation water had passed through the soil, the conductivity was reduced to 4.2 mmhos/cm.; after 8 feet, the conductivity was 3.4 mmhos/cm.; and after 12 feet, it was 3.3 mmhos/cm. The concentration of boron in the saturation extract at the start of the test was 54 p. p. m. After the passage of 4 feet of water, the concentration was 6.9 p. p. m.; after 8 feet, it was 2.4 p. p. m.; and after 12 feet, it was 1.8 p. p. m. Thus, leaching with 4 feet of water reduced the salinity to a safe level, but the boron content was still too high for good growth of plants sensitive to boron.

Permissible limits for boron in the saturation extract of soils can at present be given only on a tentative basis. Concentrations below 0.7 p. p. m. boron probably are safe for sensitive plants (ch. 4); from 0.7 to 1.5 p. p. m. boron is marginal; and more than 1.5 p. p. m. boron appears to be unsafe. The more tolerant plants can withstand higher concentrations, but limits cannot be set on the basis of present information. For land on which crops are being grown, a better appraisal of boron conditions often can be made by an analysis of plant samples (ch. 4) than can be obtained from an analysis of soil samples.

## Exchangeable Cations

When a sample of soil is placed in a solution of a salt, such as ammonium acetate, ammonium ions are adsorbed by the soil and an equivalent amount of cations is displaced from the soil into the solution. This reaction is termed "cation exchange," and the cations displaced from the soil are referred to as "exchangeable." The surface-active constituents of soils that have cation-exchange properties are collectively termed the "exchange complex" and consist for the most part of various clay minerals and organic matter. The total amount of exchangeable cations that a soil can retain is designated the "cation-exchange-capacity," and is usually expressed in milliequivalents per 100 gm. of soil. It is often convenient to express the relative amounts of various exchangeable cations present in a soil as a percentage of the cation-exchange-capacity. For example, the exchangeable-sodium-percentage ($ESP$) is equal to 100 times the exchangeable-sodium content divided by the cation-exchange-capacity, both expressed in the same units.

Determinations of the amounts and proportions of the various exchangeable cations present in soils are useful, because exchangeable cations markedly influence the physical and chemical properties of soils. The exchangeable-cation analysis of saline and alkali soils is subject to difficulties not ordinarily encountered with other soils, such as those from humid regions. Saline and alkali soils commonly contain alkaline-earth carbonates and a relatively high concentration of soluble salts. They may have low permeability to aqueous solutions and to alcohol. Solutions capable of displac-

ing exchangeable cations from soils dissolve most or all of the soluble salts and significant amounts of the carbonates of calcium and magnesium if they are present. The soluble salts should not be washed out of the soil prior to extracting the exchangeable cations, because of significant changes that take place as a result of dilution and hydrolysis. The dissolving of salts, therefore, necessitates independent determinations of soluble-cation contents and correction of the exchangeable-cation analysis for their presence, while the occurrence of calcium and magnesium carbonates prevents accurate determination of exchangeable calcium and magnesium. Furthermore, the low permeability of many alkali soils renders the conventional leaching techniques for displacement of cations time-consuming and inconvenient.

Neutral normal ammonium acetate is the salt solution most commonly used for the extraction of exchangeable cations and for the saturation of the exchange complex in the determination of cation-exchange-capacity. Although this solution has many advantages for exchangeable-cation analysis, some saline and alkali soils fix appreciable amounts of ammonium as well as potassium ions under moist conditions. The fixation of ammonium does not interfere with the extraction of exchangeable cations, but values obtained for cation-exchange-capacity by ammonium saturation are low by amounts equal to the quantity of ammonium fixed. The desirability of using a cation not subject to fixation for the determination of cation-exchange-capacity is, therefore, evident.

As discussed in a previous section, the determined values for the soluble-ion contents of soils vary with the moisture content at which the extraction is made. Because equilibria exist between the soluble and exchangeable cations in soils, the changes in relative and total concentrations of soluble cations with variations in moisture content are accompanied by changes in the relative composition of the exchangeable cations. In a strict sense, therefore, values for exchangeable-cation contents apply only at the moisture content used for the extraction of soluble cations. Owing to difficulties involved in the determination of soluble cations at moisture contents in the field range, it is convenient to determine exchangeable-cation contents at the saturation percentage.

Consideration of the various factors involved in the determination of the exchangeable cations and the cation-exchange-capacity of saline and alkali soils has led to the adoption of the following scheme of analysis:

(a) Extract a sample of the soil with an excess of neutral normal ammonium acetate solution and determine the milliequivalents of the various cations removed per 100 gm. of soil.[4]

(b) Prepare a saturation extract of the soil and determine the milliequivalents of the various soluble cations per 100 gm. of soil."

(c) Calculate the exchangeable-cation contents of the soil by subtracting the amounts of the various cations dissolved in the saturation extract from the

amounts extracted by the ammonium acetate solution.

(d) Determine the cation-exchange-capacity by measuring the milliequivalents of sodium adsorbed per 100 gm. of soil upon treating a sample with an excess of normal sodium acetate solution of pH 8.2.

The difficulties encountered in leaching soil samples of low permeability are overcome by shaking and centrifuging samples in centrifuge tubes with successive portions of the extraction and wash liquids. Neutral normal ammonium acetate solution is used for the extraction of exchangeable plus soluble cations, because its interference in analytical procedures is easily eliminated. Of the common cations, sodium appears to be the most suitable for determining cation-exchange-capacity. As mentioned previously, ammonium and potassium are subject to fixation in difficultly exchangeable form and the usual presence of calcium and magnesium carbonates in saline and alkali soils precludes the use of extractants containing calcium or magnesium. The fact that sodium is a prominent cation in most saline and alkali soils also favors its use in the determination of cation-exchange-capacity (Method 19).

### Gypsum

Gypsum is found in many soils of arid regions, in amounts ranging from traces to several percent. In some soils, gypsum was present in the sedimentary deposits from which the soil was derived; whereas, in other soils the gypsum was formed by the precipitation of calcium and sulfate during salinization. Owing to leaching, gypsum commonly occurs at some depth in the former instance, while in the latter its content is usually greatest in the surface layers of the soil.

Information regarding the gypsum content of alkali soils is important, because it usually determines whether the application of chemical amendments will be required for reclamation. Also, the presence of considerable amounts of gypsum in the soil might permit the use of an irrigation water having an unfavorably high sodium content.

The precise determination of gypsum in soils is difficult, because of inherent errors involved in the extraction of this mineral by water. Studies by Reitemeier (1946) and others show that at least three factors other than the solution of gypsum may influence the amounts of calcium and sulfate extracted from gypsiferous soils. They are: (1) The solution of calcium from sources other than gypsum; (2) exchange reactions in which soluble calcium replaces other cations, such as sodium and magnesium; and (3) the solution of sulfate from sources other than gypsum.

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[4] If the soil is known to contain carbonates of calcium and magnesium, determination of these cations is omitted. Likewise, if the soil is known to contain gypsum not completely soluble in the saturation extract, the determination of calcium is omitted. In the absence of prior knowledge regarding the calcium and magnesium carbonate and gypsum contents of the soil, the calcium and magnesium determinations are disregarded if upon completion of the exchangeable-cation analysis the sum of the values obtained for exchangeable-cation contents is found to exceed the cation-exchange-capacity value.

Three methods are given in chapter 6 for the estimation of gypsum in soils. Methods 22a and 22b are based on the low solubility of the salt in an aqueous solution of acetone. Method 22a is essentially qualitative, although a rough estimate of gypsum content may be obtained by visual observation of the amount of precipitate obtained. This method can be successfully employed under field conditions. In Method 22b the separated and washed gypsum precipitate is determined quantitatively. The use of Method 22c is advantageous when characterization of the soil includes the determination of calcium plus magnesium in the saturation extract. It is based on the increase in soluble-divalent-cation content as the moisture content of the soil is increased from the saturation percentage to a moisture content sufficient to dissolve the gypsum present. It should be noted that this method can give negative values for gypsum content as a result of the replacement of exchangeable sodium and potassium by calcium as the moisture content of the soil is increased. This is likely to occur only in alkali soils containing little or no gypsum.

## Alkaline-Earth Carbonates (Lime)

The alkaline-earth carbonates that occur in significant amounts in soils consist of calcite, dolomite, and possibly magnesite. Owing to low rainfall and limited leaching, alkaline-earth carbonates are usually a constituent of soils of arid regions. The amounts present vary from traces to more than 50 percent of the soil mass. Alkaline-earth carbonates influence the texture of the soil when present in appreciable amounts, for the particles commonly occur in the silt-size fraction. The presence of fine alkaline-earth carbonate particles is thought to improve the physical condition of soils. Conversely, when alkaline-earth carbonates occur as caliche or as cementing agents in indurated layers, the movement of water and the development of root systems is impeded. Alkaline-earth carbonates are important constituents of alkali soils, for they constitute a potential source of soluble calcium and magnesium for the replacement of exchangeable sodium. As discussed in another section, the choice of chemical amendments for the replacement of exchangeable sodium is directly related to the presence or absence of alkaline-earth carbonates.

Effervescence upon application of acid (Method 23a) can be used to detect as little as 0.5 percent of alkaline-earth carbonates in soils. This test suffices for most purposes. When a better estimate of the alkaline-earth-carbonate content of soils is desired, Methods 23b or 23c may be used. A quantitative determination of small amounts of alkaline-earth carbonates in soils is sometimes desirable in connection with proposed applications of acid-forming amendments. For precise determinations, the reader is referred to the methods of Williams (1949) and Schollenberger (1945).

## Physical Determinations

The problem of evaluating soil physical conditions has recently been separated into components by the American Society of Agronomy (1952) ; and they are discussed under the headings of mechanical impedance, aeration, soil water, and soil temperature. These are logical ultimate aspects; but, for practical work on alkali soils, measuring methods are needed that yield immediate results having more or less direct diagnostic significance. Some progress is being made toward evaluating the physical status of soil in terms of physical properties, i. e., intrinsic qualities of soil that can be expressed in standard units and that have values which are substantially independent of the method of measurement. Infiltration rate, permeability, bulk density, pore-size distribution, aggregation, and modulus of rupture appear to be such properties. Experience indicates that the physical status of any given soil is not static. There is a range of variation of physical status that is related to productivity, and this is reflected in corresponding ranges in the values of pertinent physical properties.

Information on the existing physical status of a problem soil is useful for purposes of diagnosis or improvement, but it might also be useful to know how much better or worse the status can be made by chemical and physical treatments simulating those applicable under field conditions. Soils can be treated to increase the exchangeable-sodium-percentage and then puddled to indicate how unfavorable the physical status can be made. It should also be possible by use of soil amendments and chemical aggregants to get some indication of how favorable the physical status can be made. Practical use of the concept that there is a range of physical states for any given soil may have to wait for refinements in measuring methods, but the idea seems to be pertinent to the improvement of alkali soils.

### Infiltration Rate

Water-movement rates attainable in soil under field conditions relate directly to irrigation, leaching, and drainage of saline and alkali soils. Infiltration refers to the downward entry of water into soils and the term "infiltration rate" has special technical significance in soils work. Definitions of soil-water terms adopted by the Soil Science Society of America (1952) are followed, and are included in the Glossary.

The infiltration rate of soil is influenced by such factors as the condition of the soil surface, the chemical and physical status and nature of the soil profile, and the distribution of water in the profile. All of these factors change more or less with time during infiltration.

The infiltration rate is measured under field conditions. The principal methods used have involved flooding or impounding water on the soil surface, sprinkling to simulate rain, and measuring water entry from rills or furrows. In addition to the multitude of local physical conditions that are encountered in the field,

the availability of equipment, materials, and services will largely decide what method to use in measuring infiltration. Although many measurements have been made, as evidenced by the extensive bibliography of Davidson (1940), there does not seem to be a generally accepted procedure applicable to all situations. Many of the infiltration measurements made by this Laboratory have been in connection with basin irrigation on test plots ranging from 10 to 20 feet square. The water-subsidence rate in a large plot is probably the best indication of the infiltration rate as related to leaching operations, but this method is usually not feasible for exploratory or diagnostic measurements in new areas. The cylinder method of Musgrave (1935) is probably the most versatile of the various methods available. A guard ring is needed if lateral spreading is excessive. Procedures for making infiltration measurements are given in Method 28.

Water having the same quality as that which will be used for irrigation or leaching must be used for infiltration tests in the field, otherwise the results may be misleading. The length of time the tests should be conducted and the depth of water to be applied depend upon the purpose of the test and the kind of information that is sought. If it is a matter of appraising an irrigation problem, the depth corresponding to one irrigation may be sufficient; but, if information on infiltration for planning a leaching operation is needed, it may be desirable to apply the full depth of leaching water to a test plot. It often happens that subsurface drainage is sufficiently restricted to cause the infiltration rate to decrease considerably with time. It should be kept in mind, therefore, that although small area tests will give useful information on soil changes during leaching, the infiltration values thus obtained will apply to large areas only if underdrainage is not limiting.

Experience indicates that the infiltration rate of a given soil can be high or low, depending on physical status and management history. Infiltration rate is often critically influenced by surface soil conditions, but subsurface layers also are sometimes limiting. Water distribution in the profile and depth of water applied are modifying factors. The infiltration rate can be undesirably high or undesirably low. It is the low end of the range that may be a critical limiting factor in the agricultural use of alkali soils. It is difficult to specify a boundary limit between satisfactory and unsatisfactory infiltration rates at the low end of the range, because so many factors are involved, including the patience and skill of the farmer. However, if the infiltration rate is less than 0.25 cm./hr. (0.1 in./hr.) special water-management problems are involved that may make an irrigation enterprise unprofitable for average operators.

## Permeability and Hydraulic Conductivity

The permeability of soil, in a qualitative sense, refers to the readiness with which the soil conducts or transmits fluids. In a quantitative sense, when permeability is expressed with numbers, it seems desirable that per-

meability be defined as a property of the porous medium alone and independent of the fluid used in its measurement. The term "hydraulic conductivity," on the other hand, is used to refer to the proportionality factor in the Darcy flow equation. These distinctions represent increased specialization in the use of these terms as approved by the Soil Science Society of America (1952). *No* change in the qualitative use of the word "permeability" is involved. In the quantitative sense, involving numerical values, the term "intrinsic permeability" will mostly be used and will refer to a length-squared measurement that may be identified in a general way to the cross-sectional area of some equivalent or effective size of pore.

An immediate consequence of this clarification of nomenclature is a new method for evaluating pore-space stability or structural stability of soil. For porous media with fixed structure, such as sandstone or fired ceramic, measurements of intrinsic permeability with air, water, or organic liquids all give very nearly the same numerical value. Gravity, density, and the viscosity of the liquid are taken into account in the flow equation. However, if the intrinsic permeability for a soil as measured with air is markedly greater than the permeability of the same sample as subsequently measured using water, then it may be concluded that the action of water in the soil brings about a change in structure indicated by the change in permeability. The ratio of air to water permeability, therefore, is a measure of the structural stability of soils, a high ratio indicating low stability.

Intrinsic-permeability measurements are based on the equation $v = k'dgi/\eta$, where v is the flow velocity, $k'$ is the intrinsic permeability, $d$ is the density of the fluid, $g$ is the acceleration of gravity, i the hydraulic gradient, and $\eta$ is the viscosity. Procedures for measuring intrinsic permeability with gases and liquids are given as Methods 37a and 37b. The air-water permeability ratio increases greatly as the exchangeable-sodium content of the soil increases, indicating that exchangeable sodium decreased the water stability of the soil structure.

It is seen from the Darcy equation, $v = ki$, that $k$, the hydraulic conductivity, is the effective flow velocity or discharge velocity of water in soil at unit hydraulic gradient, i. e., when the driving force is equal to 1 gravity. Methods 34a and 34b give procedures for measuring hydraulic conductivity on undisturbed and disturbed soil samples.

Under some circumstances, especially when the soil surface has been subject to submergence by water for a considerable period and when the hydraulic conductivity is nearly uniform with depth, the hydraulic gradient beneath the soil surface may approach unity, i. e., the downward driving force is composed entirely of the gravity force with no pressure gradient. Under this condition the infiltration rate is equal to the hydraulic conductivity, but this is probably the exception rather than the rule under field conditions. Consequently, the relation between infiltration rate and hydraulic conductivity is not a simple one. For ex-

ample, at the Malheur Experimental Area in Oregon, very low hydraulic-conductivity values were obtained and yet infiltration was adequate to support good crops with sprinkler irrigation. It was found by use of tensiometers that values for the hydraulic gradient during infiltration ranged up to 10 in some cases. This soil was deep and silty and the suction gradient in the soil added significantly to the rate of downward movement of water. If the downward flow is interrupted by a layer of very low conductivity, then the hydraulic gradient may approach zero as the soil pores become filled and the condition of static equilibrium under gravity is approached.

It is to be expected that if the hydraulic conductivity of surface soil is as low as 0.1 cm./hr. (0.04 in./hr.) leaching and irrigation may present serious difficulties. Irrigation agriculture under average conditions of management skill, water quality, and drainage conditions would have doubtful success unless the hydraulic conductivity could be increased appreciably by soil-improvement measures.

## Moisture Retention by Soil

The effect of soil salinity on crops is related to the range over which the moisture content of the soil varies, because the concentration of the soil solution depends both on the amount of soluble salt and the amount of water present. The permanent-wilting percentage, as indicated in the review by Veihmeyer and Hendrickson (1948), is generally accepted as being the lower limit of water available for plant growth in nonsaline soil. For all practical purposes, the 15-atmosphere percentage (Method 31) can be used as an index of the permanent-wilting percentage and, therefore, also as an acceptable index of the lower limit of the available range of soil moisture. This lower limit appears to be an intrinsic property of the soil that is largely determined by soil texture and appears to be substantially independent of the kind of plant grown on the soil.

It is much more difficult to set an upper limit for the range of water content available to plants in the field. In addition to dependence upon soil texture at the point in question, the upper limit depends also on the variation throughout the profile of such factors as pore-size distribution and water conductivity. The distribution of water with depth influences the hydraulic gradient, and, therefore, also the rate of downward movement of water. For example, with or without active roots, the moisture content in the surface layers of a deep permeable soil will decrease more slowly if the profile is deeply wetted than if only a shallow depth is wetted and the underlying soil is dry. Also, the total amount of water actually available from any given layer of surface soil depends on the rooting depth and transpiration rate of the crop. The hydraulic boundary conditions that characterize the field situation would be extremely difficult to reproduce for a soil sample removed from the profile, and it is not surprising that no generally satisfactory laboratory method has been found for estimating the upper limit of water available

for crop growth under field conditions. A field determination under representative field conditions is the best method for obtaining the upper limit of the field-moisture range.

For most medium- to fine-textured soils, the upper limit of available water is approximately twice the moisture percentage of the lower limit. This does not hold true for the coarse-textured soils. It has been found by the United States Bureau of Reclamation (1948) that for the sandy soils occurring on the Yuma Mesa, Arizona, the water retained in a sample of soil at the $1/10$-atmosphere percentage (Method 29) satisfactorily approximates the upper limit of available water under field conditions.

## Density and Porosity

The bulk density (apparent density) of soil is the mass of soil per unit volume, and the porosity of soil is the fraction of the soil volume not occupied by soil particles. Bodman (1942) has discussed soil density in connection with water content and porosity relationships and has prepared useful nomograms (fig. 8).

The bulk density of soil can be measured by several methods. For a certain range of moisture contents with soils that are comparatively free of gravel and stones, it is possible to press into the soil a thin-walled tube having a suitable cutting edge. The soil is then smoothed at each end of the tube and oven-dried at 105" C. The bulk density is the mass of soil contained in the tube divided by the volume of the tube, as indicated in Method 38.

The porosity of soil ($n$) may be obtained directly from air-pycnometer measurements or can be calculated from the relation $n = (d_p - d_b)/d_p$, where $d_p$ is the average density of the soil particles and $d_b$ is the bulk density.

The particle density of many soils averages around 2.65 gm. cm.?. The average particle density for peat soils or for pumice soils is much lower. Direct measurements of particle density can be made with pycnometer bottles (Method 39).
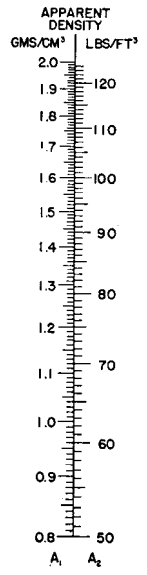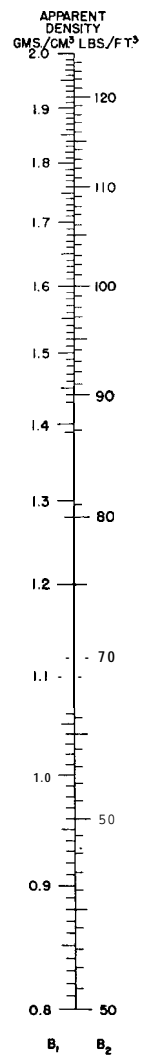
The bulk density of most soils ranges from 1.0 gm. cm.? for clays, to 1.8 gm. cm.? for sands. This corresponds to the range of 62.4 to 112 lb. ft.?. The corresponding porosity range will be from about 0.60 to 0.30. Bulk density may become a critical factor in the productivity of soil. Veihmeyer and Hendrickson (1946) found that plant roots were unable to penetrate a gravelly loam soil when the bulk density exceeded a value of around 1.8 gm. cm.?. Also, when the bulk density of medium- to fine-textured subsoils exceeds about 1.7 gm. cm.$^{-3}$, hydraulic conductivity values will be so low that drainage difficulties can be anticipated.

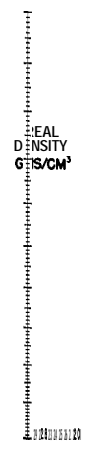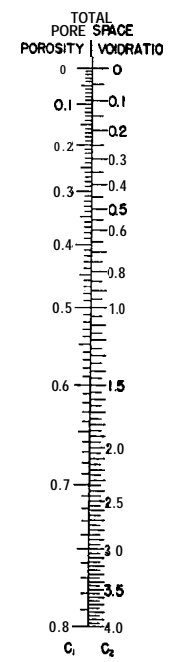## Aggregation and Stability of Structure

The arrangement of soil particles into crumbs or aggregates that are more or less water stable is an important aspect of soil structure. Alkali soils often have a dense, blocky, single-grain structure, are hard to till when dry, and have low hydraulic conductivity when
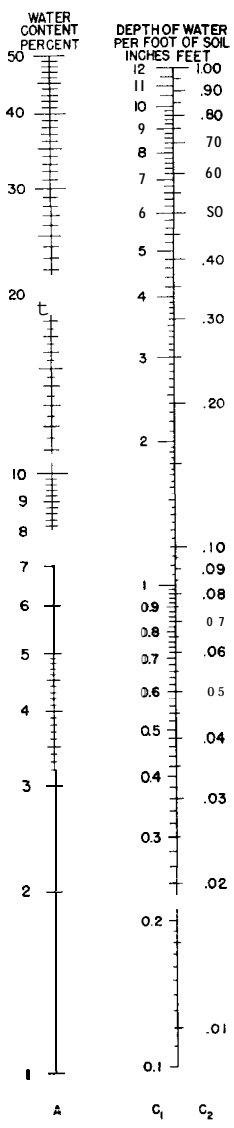
DENSITY AND SOIL WATER          DENSITY AND SOIL AIR SPACE

FIGURE 8.-Nomograms giving soil density, soil water, and soil air space relationships (Bodman, 1942).

wet. This is generally because the aggregates and also the pores of such soils are not stable. The aggregates slake down in water, and the pores become filled with fine particles.

Several methods have been proposed for measuring the water stability of soil aggregates, the most common being the wet-sieving method proposed by Yoder (1936). A modification of the Yoder procedure is given as Method 42a. Soils that are low in organic matter and contain appreciable amounts of exchangeable sodium seldom contain aggregates of larger sizes and for that reason measuring procedures adapted for the smaller aggregates are included as Method 42b. This determination is related to Middleton's (1930) "dispersion-ratio," but Method 42a gives the percentage by weight of particles smaller than $50\mu$ that are bound into water-stable aggregates greater than $50\mu$. Insufficient data are available at the present time to specify limits that will help to distinguish between problem and nonproblem soils as far as aggregate-size distribution is concerned.

Childs (1940) followed the change in moisture-retension curves with successive wettings to get an index of the stability of structure, or, more precisely, the stability of the pore-space arrangement. Reeve and co-workers (fig. 1) have shown that the ratio of the air permeability to the water permeability for soils is also a useful index of the stability of soil structure (Method 37).

Recent studies by Allison (1952) and by Martin and associates (2952) indicate that dispersed soils may be rapidly and effectively improved by application of aggregating agents of the polyelectrolyte type. Applied at the rate of 0.1 percent on the dry-soil basis, this material has effectively improved the physical condition of alkali soils on which it has been tried. Salinity appears to have little or no effect on the process. A higher degree of aggregation was obtained where the aggregating agent in solution was sprayed on dry soil and mixed in than when it was applied dry to a moist soil followed by mixing. Regardless of the manner of application, large increases in infiltration rate and hydraulic conductivity resulted from its use.

Although not yet economically feasible for general agricultural use, aggregating agents can be an effective research tool for investigational work with saline and alkali soils. By their use, for instance, plant response to different levels of exchangeable sodium or different $Ca : Na$ ratios may be studied on "conditioned" soils in the absence of poor structure and accompanying conditions of deficient aeration and low water-movement rates ordinarily present in alkali soils,

It seems likely, also, that soil-aggregating chemicals may provide a rapid method for appraising the structural improvement potentially attainable from organic-matter additions. Organic-matter additions, while slower to give results, have long been used in agriculture. There may be soils, such as those high in silt and low in clay, in which coarse organic matter may give improvements in physical condition that are unattainable with chemical aggregants.

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## Crust Formation

Soils that have low stability of structure disperse and slake when they are wetted by rain or irrigation water and may develop a hard crust as the soil surface dries. This crust presents a serious barrier for emerging seedlings, and with some crops often is the main cause of a poor stand. Alkali soils are a special problem in this regard, but the phenomenon is by no means limited to these soils.

Factors influencing development of hard surface crusts appear to be high exchangeable sodium, low organic matter, puddling, and wetting the soil to zero tension, which occurs in the field with rain or irrigation. Crust prevention would, therefore, involve removal of exchangeable sodium, addition of organic matter, and care to avoid puddling during tillage and other operations. Where possible, the placement of the seed line somewhat above the water level in a furrow is desirable so that the soil above the seed will be wetted with water at appreciable tensions, thus lessening the tendency for soil aggregates at the surface to disintegrate.

The procedure for measuring the modulus of rupture of soil (Method 43) was developed for appraising the hardness of soil crusts, since a satisfactory measuring method is essential in developing and testing soil treatments for lessening soil crusting.

## Choice of Determinations and Interpretation of Data

### Equilibrium Relations Between Soluble and Exchangeable Cations

Cation exchange can be represented by equations similar to those employed for chemical reactions in solutions. For example, the reaction between calcium-saturated soil and sodium chloride solution may be written : $CaX_2 + 2NaCl \rightleftharpoons 2NaX + CaCl_2$, where X designates the soil exchange complex. As shown by the equation, the reaction does not go to completion, because as long as soluble calcium exists in the solution phase there will be adsorbed calcium on the exchange complex and vice versa. Equations have been proposed by various workers for expressing the equilibrium distribution of pairs of cations between the exchangeable and soluble forms. For metallic cation pairs of equal valence, many of the equations assume the same form and give satisfactory equilibrium constants, but variable results are obtained with the different equations when cations of unequal valence are involved. According to the work of Krishnamoorthy and Overstreet (1950), an equation based on the statistical thermodynamics of Guggenheim (1945) is most satisfactory for cation pairs of unequal valence. All of the equations become less satisfactory when applied to mixtures of cation-exchange materials having different equilibrium constants.

The use of cation-exchange equations for expressing the relationship between soluble and exchangeable

cations in soils of arid regions involves inherent difficulties. The difficulties arise from the presence of mixtures of different kinds of cation-exchange materials in soils and from the fact that usually four cation species must be dealt with. Moreover, there are no accurate methods available for determining exchangeable calcium and magnesium in soils containing alkaline-earth carbonates and gypsum. Despite these difficulties, some degree of success has been attained in relating the relative and total concentrations of soluble cations in the saturation extract of soils to the exchangeable-cation composition, using a somewhat empirical approach. Direct determinations show that, when soils are leached with salt solutions containing a mixture of a monovalent cation and a divalent cation until equilibrium between the soil and solution is established, the proportions of exchangeable monovalent and divalent cations present on the soil-exchange complex vary with the total-cation concentration as well as with the monovalent :divalent cation ratio of the salt solutions. Gapon(1933), Mattson and Wiklander (1940), Davis (1945), and Schofield (1947) have proposed, in effect, that the influence of total-cation concentration is taken into account and a linear relation with the exchangeable monovalent: divalent cation ratio is obtained when the molar concentration of the soluble monovalent cation is divided by the square root of the molar concentration of the soluble divalent cation.

Two ratios of the latter type, designated as the sodium-adsorption-ratio $(SAR)$ and potassium-adsorption-ratio (PAR) , are employed for discussing the equilibrium relation between soluble and exchangeable cations. The sodium-adsorption-ratio and potassium-adsorption-ratio are defined as $Na^+/\sqrt{(Ca++ + Mg^{++})/2}$ and $K^+/\sqrt{(Ca^{++} + Mg^{++})/2}$, respectively, where $Na^+, K^+, Ca^{++}$, and $Mg^{++}$ refer to the concentrations of the designated soluble cations expressed in milliequivalents per liter.

The relationship between the sodium-adsorption-ratio and the ratio exchangeable sodium : (exchange capacity minus exchangeable sodium) at the saturation moisture percentage for 59 soil samples representing 12 sections in 9 Western States is shown in figure 9. A similar relationship involving the potassium-adsorption ratio, exchange capacity, and exchangeable potassium is given in figure 10. The correlation coefficients for the two sets of values are sufficiently good to permit practical use of the relations. Data for soils having exchangeable sodium/ (exchange capacity minus exchangeable sodium) and exchangeable potassium/ (exchange capacity minus exchangeable potassium) ratios greater than 1, which correspond to exchangeable-cation-percentages of more than 50, are not included in the graphs. Limited data indicate that for these soils the relations shown in the graphs are somewhat less precise. Using the data presented in figure 9, the relation between the exchangeable-sodium-percentage $(ESP)$, and the sodium-adsorption-ratio (SAR) is given by the equation :

$$ESP = \frac{100 \, (-0.0126 + 0.01475 \, SAR)}{1 + (-0.0126 + 0.01475 \, SAR)}$$

Similarly, the relation between the **exchangeable-potassium-percentage** $(EPP)$ and the potassium-adsorption-ratio (PAR) is given by the equation :

$$EPP = \frac{100 \, (0.0360 + 0.1051 \, PAR)}{1 + (0.0360 + 0.1051 \, PAR)}$$

The former equation was employed to obtain the average relation between exchangeable-sodium-percentage and the sodium-adsorption-ratio, which is shown by the nomogram given in figure 27, chapter 6.

## Chemical Analyses of Representative Soil Samples

Data of typical chemical analyses of saline, nonsaline-alkali, and saline-alkali soil samples are given in table 5. Similar analyses of samples of normal soils from arid regions are also given for comparative purposes. These analyses are presented to show the differences in the chemical characteristics of the four classes of soils and to illustrate how the analyses may be interpreted and cross-checked for reliability.

### Nonsaline-Nonalkali Soils

Samples numbered 2741, 2744, and R-2867 are classed as normal with respect to salinity and alkali, because the electrical conductivity of their saturation extracts is less than 4 mmhos/cm. and their exchangeable-sodium-percentage is less than 15. The reaction of the samples ranges from slightly acid to slightly alkaline. While the composition of the soluble ions varies somewhat, the amounts present are small, and all of the saturation extracts have low sodium-adsorption-ratios. Alkaline-earth carbonates may or may not be present. Also, gypsum may or may not be present, although none of the samples selected contains this constituent.

### Saline Soils

The electrical conductivity of the saturation extracts of these samples is in excess of 4 mmhos/cm., but the exchangeable-sodium-percentage is less than 15. In no case does the pH reading exceed 8.5. Chloride and sulfate are the principal soluble anions present in these samples, the bicarbonate content is relatively low, and carbonate is absent. The soluble-sodium contents exceed those of calcium plus magnesium somewhat, but the sodium-adsorption-ratios are not high. Gypsum and alkaline-earth carbonates are common constituents of saline soils. As shown by the values for the electrical conductivity of the saturation extracts, the salinity levels are sufficiently high to affect adversely the growth of most plants. Reclamation of the soils will require leaching only, providing drainage is adequate.

### Nonsaline-Alkali Soils

The exchangeable-sodium-percentages of these soil samples exceed 15, but the soluble-salt contents are low.
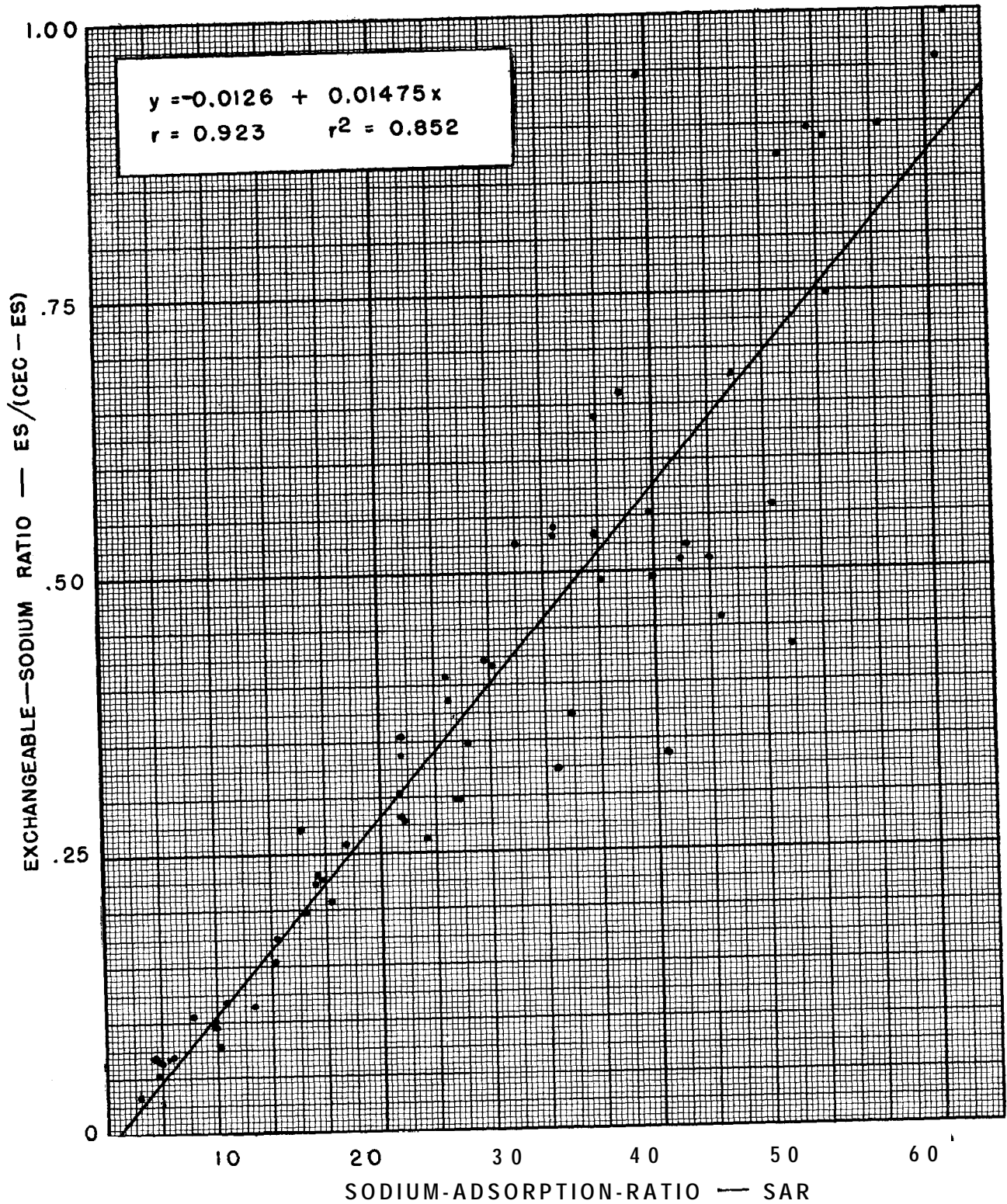
FIGURE 9.-Exchangeable-sodium ratio $(ES/[CEC-ES])$ as related to the sodium-adsorption-ratio $(SAR)$ of the saturation extract. *ES*, exchangeable sodium; CEC, cation-exchange-capacity.
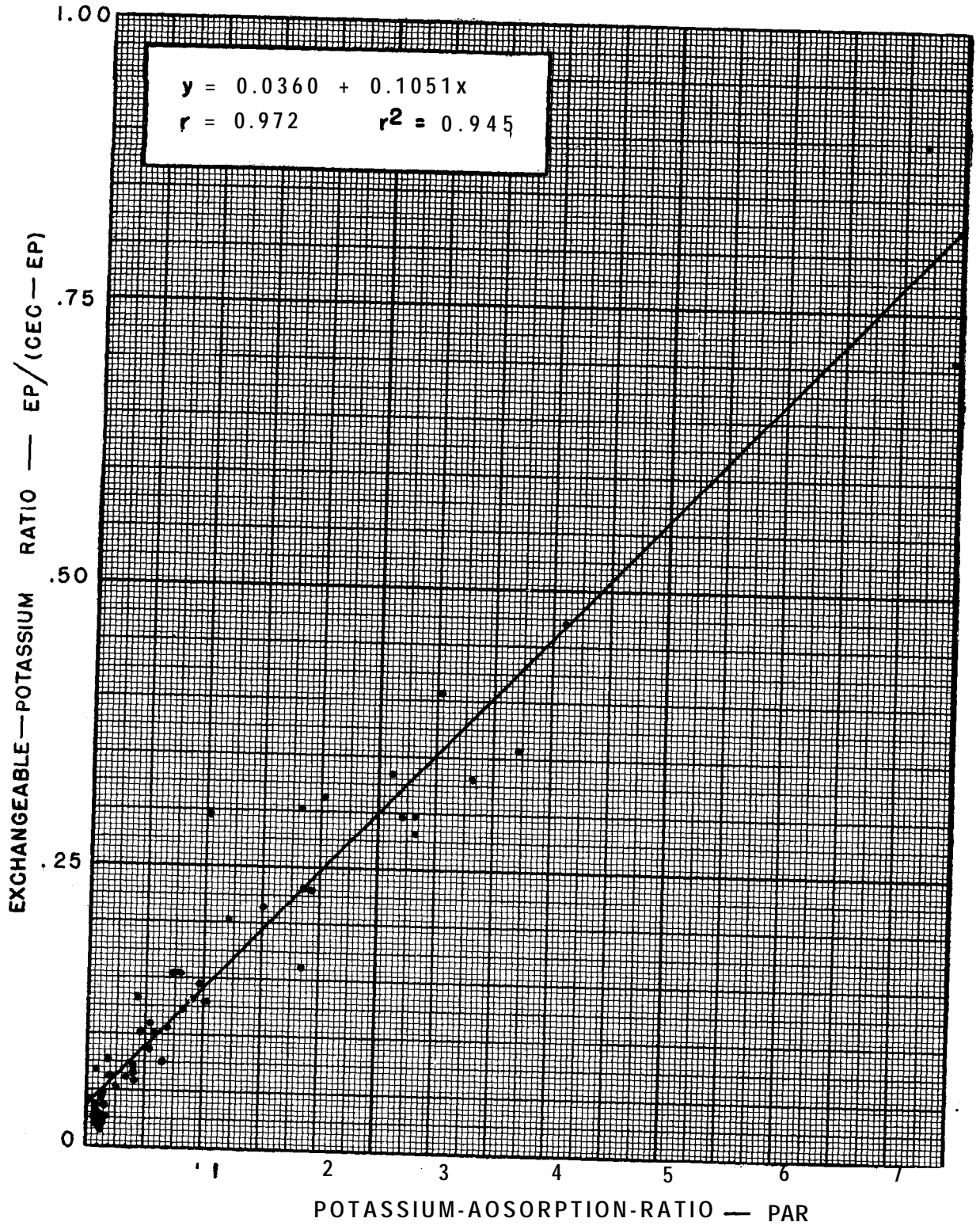
FIGURE IO.-Exchangeable-potassium ratio $(EP/[CEC-EP])$ as related to the potassium-adsorption-ratio (PAR) of the saturation extract. $EP$, exchangeable potassium; CEC, cation-exchange-capacity.

TABLE 5.—*Chemical analyses of soil samples from arid regions*

SOIL DETERMINATIONS

| Soil and sample No. | Saturation percentage | pH of saturated soil | Cation-exchange-capacity | Exchangeable-cation-percentages | | | | | Gypsum | Alkaline-earth carbonates [1] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Na | K | Ca | Mg | H | | |
| | | | Meq./100 gm. | | | | | | Meq./100 gm. | |
| Normal soils: | | | | | | | | | | |
| 2741. | 35.6 | 6.4 | 20.3 | 2 | 8 | ...54 | 29 | 7 | 0 | — |
| 2744 | 32.4 | 7.8 | 29.4 | 10 | 1 | | ........ | 0 | 0 | + |
| R-2867 | 40.4 | 7.9 | 17.4 | 3 | 1 | | ........ | 0 | 0 | + |
| Saline soils: | | | | | | | | | | |
| 574 | 52.0 | 7.9 | 14.4 | 13 | 3 | | ........ | 0 | 7.1 | + |
| 756 | 46.5 | 8.0 | 17.0 | 8 | 2 | | ........ | 0 | 0 | + |
| 575 | 40.0 | 8:0 | 18.6 | 10 | 17 | | ........ | 0 | 0 | + |
| Nonsaline-alkali soils: | | | | | | | | | | |
| 2747 | 58.8 | 8.3 | 33.4 | 18 | 3 | | ........ | 0 | 0 | + |
| 2738 | 61.2 | 7.3 | 34.2 | 24 | 2 | 31 | 30 | 13 | 0 | — |
| 535 | 38.7 | 9.6 | 21.9 | 46 | 32 | | ........ | 0 | 0 | + |
| Saline-alkali soils: | | | | | | | | | | |
| 2739 | 61.5 | 7.3 | 35.7 | 26 | 2 | 27 | 35 | 10 | 0 | — |
| 2740 | 59.7 | 7.8 | 40.3 | 26 | 2 | .. | ........ | | 42 2 | + |
| 536 | 35.8 | 9.3 | 26.2 | 63 | 8 | ........ | ........ | 8 | 0' | + |

SATURATION EXTRACT DETERMINATIONS

| Soil and sample No. | Electrical conductivity | Cations | | | | | Anions | | | | | Sodium-adsorption-ratio (SAR) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ca++ | Mg++ | Na+ | K+ | Total | CO3= | HCO3- | SO4= | Cl- | Total | |
| | Mmhos/cm. | Meq./l. | Meq./l. | Meq./l. | Meq./l. | Meq./l. | Meq./l. | Meq./l. | Meq./l | Meq./l. | Meq./l. | |
| Normal soils: | | | | | | | | | | | | |
| 2741 | 0.60 | 2.71 | 2.26 | 1.20 | 0.91 | 7.08 | 0 | 2.60 | 2.09 | 0.87 | 5.56 | 0.8 |
| 2744 | 1.68 | 3.33 | 1.94 | 12.2 | .70 | 18.17 | 0 | 6.14 | 4.28 | 4.93 | 15.35 | 7.5 |
| R-2867 | .84 | 2.76 | 1.69 | 5.22 | .18 | 9.85 | 0 | 6.63 | 2.67 | .44 | 9.74 | 3.5 |
| Saline soils: | | | | | | | | | | | | |
| 574 | 13.9 | 31.5 | 37.2 | 102.0 | .21 | 170.91 | 0 | 4.50 | 90.0 | 78.0 | 172.50 | 17.4 |
| 756 | 12.0 | 37.0 | 34.0 | 79.0 | 40 | 150.40 | 0 | 7.20 | 62.2 | 47.0 | 148.40 | 13.3 |
| 575 | 8.8 | 28.4 | 22.8 | 53.0 | 1:10 | 105.30 | 0 | 5.20 | 74.0 | 29.0 | 108.20 | 10.5 |
| Nonsaline-alkali soils: | | | | | | | | | | | | |
| 2747 | 1.74 | 1.10 | 1.42 | 15.6 | .42 | 18.54 | | 6.51 | 8.48 | 2.86 | 17.85 | 13.9 |
| 2738 | 2.53 | 1.41 | 1.01 | 21.5 | .28 | 24.20 | 8 | 3.29 | 3.80 | 16.7 | 23.79 | 19.6 |
| 535 | 3.16 | 1.10 | .30 | 29.2 | 4.10 | 34.70 | 8.40 | 18.70 | 4.60 | 7.50 | 39.20 | 35.0 |
| Saline-alkali soils: | | | | | | | | | | | | |
| 2739 | 9.19 | 6.73 | 9.85 | 79.5 | .48 | 96.56 | 0 | 2.35 | 20.1 | 72.0 | 94.45 | 27.6 |
| 2740 | 16.7 | 32.4 | 38.3 | 145.0 | .51 | 216.21 | 0 | 3.29 | 105.0 | 105.0 | 213.29 | 24.4 |
| 536 | 5.6 | .60 | .90 | 58.5 | 1.6 | 61.60 | 5.00 | 19.9 | 21.5 | 16.3 | 62.70 | 67.6 |

[1] +, Present; —, absent.

[2] Includes 32.0 meq./l. of NO3.

Usually the pH readings are greater than 8.5, but they may be lower if the exchangeable-sodium-percentage does not greatly exceed 15 (sample No. 2747) or if alkaline-earth carbonates are absent (sample No. 2738). Gypsum seldom occurs in these soils. The chief soluble cation is sodium, and appreciable amounts of this cation may be present as the bicarbonate and carbonate salts. The sodium-adsorption-ratio of the saturation extract may be quite high. Sample No. 2738 is an example of a nonsaline-alkali soil that is free of alkaline-earth carbonates and contains some exchangeable hydrogen. Replacement of exchangeable sodium will be required for its reclamation. Gypsum is a suitable amendment, but the application of acid or acid-forming amendments may cause excessive soil acidity unless limestone is also applied. The application of limestone alone will tend to replace the exchangeable sodium. Sample Nos. 2747 and 535 will

also require replacement of exchangeable sodium for reclamation; but, owing to the presence of alkaline-earth carbonates, acid, any acid-forming amendment, or gypsum may be applied. The application of limestone alone will obviously be of no value.

### Saline-Alkali Soils

Soils of this class are characterized by their appreciable contents of soluble salts and exchangeable sodium. The electrical conductivity of the saturation extract is greater than 4 mmhos/cm., and the exchangeable-sodium-percentage exceeds 15. The pH reading may vary considerably but is commonly less than 8.5. Except that a higher proportion of the soluble cations consists of sodium, the composition of the soluble salts usually is similar to that of saline soils. Although only the most salt-sensitive plants will be affected by the salinity level of sample No. 536, the exchangeable-sodium-percentage is too high to permit the growth of most crops. Both replacement of exchangeable sodium and leaching are required for reclamation of these soils. With respect to the suitability of various amendments for the replacement of exchangeable sodium, sample No. 2739, like No. 2738, will require the application of soluble calcium, whereas sample No. 536, like samples 2747 and 535, can be treated with soluble calcium, acid, or acid-forming amendments. Owing to its high content of gypsum, sample No. 2740 will not require the application of amendments for the replacement of exchangeable sodium.

### Cross-Checking Chemical Analyses for Consistency and Reliability

A means of locating gross errors in the chemical analyses of soils is provided by the considerable number of interrelations that exist among the values obtained for various determinations. An understanding of the principles involved in these interrelations aids in the interpretation of the analyses.

ELECTRICAL CONDUCTIVITY AND TOTAL CATION CONCENTRATION.-The $EC$ of soil solutions and saturation extracts when expressed in millimhos per centimeter at 25" C. and multiplied by 10 is approximately equal to the total soluble-cation concentration in milliequivalents per liter.

CATION AND ANION CONCENTRATION.-The total soluble-anion concentration or content and the total soluble-cation concentration or content, expressed on an equivalent basis, are nearly equal.

pH AND CARBONATE AND BICARBONATE CONCENTRATIONS.—If carbonate ions are present in a soil extract in titratable quantities, the pH reading of the extract must exceed 9. The bicarbonate concentration seldom exceeds 10 meq./l. in the absence of carbonate ions, and at pH readings of about 7 or less seldom exceeds 3 or 4 meq./l.

pH AND CALCIUM AND MAGNESIUM CONCENTRATIONS.—The concentration of calcium and magnesium in a saturation extract seldom exceeds 2 meq./l. at pH readings above 9. Therefore, calcium plus magnesium is low if carbonate ions are present in titratable amounts, and calcium plus magnesium is never high in the presence of a high concentration of bicarbonate ions.

CALCIUM AND SULFATE IN A SOIL-WATER EXTRACT AND GYPSUM CONTENT OF THE SOIL.—The solubility of gypsum at ordinary temperatures is approximately 30 meq./l. in distilled water and 50 meq./l. or more in highly saline solutions. However, owing to the common ion effect, an excess of either calcium or sulfate may depress the solubility of gypsum to a value as low as 20 meq./l. Hence, the saturation extract of a non-gypsiferous soil may contain more than 30 meq./l. of both calcium and sulfate (i. e. saline soil No. 756), and that of a gypsiferous soil may have a calcium concentration as low as 20 meq./l. As a general rule, soils with saturation extracts that have a calcium concentration of more than 20 meq./l. should be checked for the presence of gypsum.

pH AND ALKALINE-EARTH CARBONATES.-The pH reading of a calcareous soil at the saturation percentage is invariably in excess of 7.0 and generally in excess of 7.5; a noncalcareous soil may have a pH reading as high as 7.3 or 7.4.

pH AND GYPSUM.—The pH reading of gypsiferous soils at the saturation percentage is seldom in excess of 8.2 regardless of the $ESP$.

pH AND $ESP$.-A pH reading at the saturation percentage in excess of 8.5 almost invariably indicates an $ESP$ of 15 or more.

$ESP$ AND $SAR$.-In general, $ESP$ increases with $SAR$. There are occasional deviations, but generally low $SAR$ values of the saturation extract are associated with low $ESP$ values in the soil, and high $SAR$ values denote high $ESP$ values.

$CEC$ AND SP.-Because both cation-exchange-capacity and moisture-retention properties are related to the texture of soils, there generally exists a fair correlation among these properties, particularly in soils with similar parent materials and mode of origin.

### Factors That Modify the Effect of Exchangeable Sodium on Soils

As might be expected, alkali soils having similar exchangeable-sodium-percentages may vary considerably with respect to their physical properties, their ability to produce crops, and their response to management practices, including the application of amendments. Although the reasons for the variable behavior of alkali soils are imperfectly understood, experience and limited data indicate that the effect of exchangeable sodium may be modified by several soil characteristics. Determinations of some or all of these characteristics are often of value in the investigation of alkali soils.

### Texture

It is well known that the distribution of particle sizes influences the moisture retention and transmission properties of soils. Particle-size analysis may be made, using Method 41. As a rule, coarse-textured soils have low-moisture retention and high permeability, whereas

fine-textured soils have high-moisture retention and generally have lower permeability. However, owing to a high degree of aggregation of the particles, there are notable examples of fine-textured soils that are moderately permeable. The presence of a high percentage (50 or more) of silt-size particles (effective diameter $2\mu$ to $50\mu$) often causes soils to have relatively low permeability. There is also evidence that some silt-size particles, presumably those having a platy shape, are more effective in reducing permeability than others. In general, the physical properties of fine-textured soils are affected more adversely at a given exchangeable-sodium-percentage than coarse-textured soils. For example, the hydraulic conductivity of a coarse-textured soil having an exchangeable-sodium-percentage of 50 may be as great as that of a fine-textured soil having an exchangeable-sodium-percentage of only 15 or 20. Inasmuch as fine-textured soils generally have higher cation-exchange-capacities than coarse-textured soils, expressing the critical levels of sodium in milliequivalents per 100 gm. tends to eliminate the texture factor in evaluating the effect of exchangeable sodium.

### Surface Area and Type of Clay Mineral

Soil particles may be considered to have two types of surfaces: external and internal. Primary minerals such as quartz and feldspars and the clay minerals kaoiinite and illite have external surfaces only. Clay minerals of the expanding lattice type such as montmorillonite, which exhibits interlayer swelling, have internal as well as external surfaces. The external surface area of soils is directly related to texture, whereas internal surface area is related to the content of minerals that exhibit interlayer swelling. Determinations of the amounts of ethylene glycol retained as a monomolecular layer by heated and unheated samples of soil (Method 25) permit estimation of the external and the internal surface areas, provided appreciable amounts of vermiculite and endellite minerals are not present. In any case, the ethylene glycol retained bv unheated soil in excess of that retained by a corresponding heated sample is an index of interlayer swelling.

As determined by Method 25, the external surface areas of most soils lie in the range 10 to 50 m.$^2$/gm. (square meters per gram), whereas the internal surface area varies to a greater extent, being nil in soils that contain no interlayer swelling minerals and as high as 150 m.$^2$/gm. or more in soils with a high content of expanding lattice-type minerals. X-ray diffraction patterns indicate that the clay fraction (particles $<2\mu$ effective diam.) of many soils of arid regions are predominantly interstratified mixtures of various proportions of montmorillonite and illite, although sometimes individual crystals of these minerals occur. The amount of kaolinite present is usually small.

It is generally recognized that soils containing clay of the expanding lattice (montmorillonitic) type exhibit such properties as swelling, plasticity, and dispersion to a greater extent than soils containing equivalent amounts of nonexpanding lattice (illitic and kaolinitic) clays, especially when appreciable amounts of exchangeable sodium are present. Whether the more adverse physical properties imparted by the former type of clays are caused by their greater total surface area or to the fact that they exhibit interlayer swelling is not definitely known. Further studies may show that the susceptibility of soil to injury by exchangeable sodium is related to total surface area as measured by ethylene glycol retention.

### Potassium Status and Soluble Silicate

Several medium- to fine-textured alkali soils have been examined at the Laboratory and have been found to be much more permeable than would ordinarily be expected on the basis of their high exchangeable-sodium-percentages. In some cases, the permeability is such that the soils can be leached readily with large quantities of irrigation water and the excess exchangeable sodium removed without the use of chemical amendments. The soils have several characteristics in common, which include a high pH value (9.0 or higher), a high exchangeable-potassium-percentage (25 to 40), and an appreciable content of soluble silicate. The silicate concentration of the saturation extracts of these soils has been found to vary from 5 to 40 meq./l., and additional quantities of this anion as well as sodium are removed upon leaching. As shown by ethylene glycol retention, Dyal and Hendricks (1952) and Bower and Gschwend (1952), saturation of montmorillonite clays and soils with potassium followed by drying decreases interlayer swelling. Moreover, Mortland and Gieseking (1951) have shown by means of X-ray diffraction studies that montmorillonite clays, when dried in the presence of potassium silicate, are changed to micalike clays that would have less tendency to swell and disperse under the influence of exchangeable sodium. Ethylene glycol retention determinations made on some of the alkali soils having high exchangeable-potassium-percentages and containing appreciable soluble silicate give relatively low values for interlayer swelling. While further research is needed to clarify the role of exchangeable potassium and soluble silicate, there is a distinct indication that alkali soils containing unusually high amounts of these constituents are less susceptible to the development of adverse physical conditions.

### Organic Matter

While the organic-matter content of soils of arid regions is usually low under virgin conditions, it commonly increases with the application of irrigation water and cultivation, especially when crop management is good. Aside from its value as a source of plant nutrients, organic matter has a favorable effect upon soil physical properties.

There is considerable evidence that organic matter tends to counteract the unfavorable effects of exchangeable sodium on soils. Campbell and Richards (1950)

FIGURE Il.-Sequence of determinations for the diagnosis and treatment of saline and alkali soils: *H,* High; *L,* low; *R*s, electrical resistance of soil paste; *SAR,* sodium-adsorption-ratio; *ESP,* exchangeable-sodium-percentage; CEC, cation-exchange-capacity.

and Fireman and Blair [5] found that peat and muck soils containing appreciable quantities of exchangeable sodium had good physical properties, and numerous investigators have demonstrated a beneficial effect of organic matter additions upon alkali soils. For example, Bower and associates (1951) found that the application of manure at the rate of 50 tons per acre to an alkali soil of the "slick spot" type increased the degree of aggregation of the surface soil significantly and the infiltration rate approximately threefold. The available data indicate that organic matter improves and prevents deterioration of the physical condition of the soil by its interaction with the inorganic cation-exchange material, by serving as energy material for micro-organisms which promote the stable aggregation of soil particles, and by decreasing the bulk density of soils.

The organic-matter content of soils is ordinarily obtained by multiplying the organic-carbon content by 1.72. The dry-combustion method is most accurate for the determination of organic carbon, but it is time-consuming and cannot be applied to soils containing carbonates. Wet-combustion methods such as the one given in Method 24 are suitable for use on soil containing carbonates, but the application of a correction factor is required to compensate for the incomplete oxidation of the organic matter.

## Sequence of Determinations for Soil Diagnosis

The salinity status and the hydraulic conductivity are measured for all samples. The sequence of further determinations depends on whether the result obtained from a previous determination (fig. 11) is considered to be high or low. Criteria for distinguishing high and low values are discussed in chapter 6.

The determinations are ordinarily discontinued when the guide lines of the two main branches of the diagram lead to a heavy-walled box, except in the case of an

alkali problem where alkaline-earth carbonates should also be determined if the use of acid or acid-forming amendments is contemplated. At two places in the diagram, dotted lines indicate where optional alternate determinations can be made. The alternate determinations cost somewhat less but have lower reliability.

Hydraulic-conductivity measurements on disturbed samples provide an indication of the moisture-transmission rate of the soil. It has been found for most soils that exchangeable sodium is not excessive if this rate is high. However, coarse soils such as sands and peats may contain sufficient amounts of exchangeable sodium to be toxic to plants and yet have high permeability. If the hydraulic conductivity is low, the total extractable sodium or the sodium-adsorption-ratio $(SAR)$ should be determined. If either of these is low, the low hydraulic-conductivity value previously obtained may be the result of an inherently unfavorable physical condition related to texture, low content of organic matter, or high-swelling type clay rather than the presence of exchangeable sodium. For these samples, organic matter, ethylene glycol retention, and particle-size analyses may yield useful information.

If the total extractable-sodium content or the $SAR$ value is high, the exchangeable sodium should be determined or, alternatively, the exchangeable-sodium-percentage can be estimated from the $SAR$ value. If the exchangeable-sodium content or exchangeable-sodium-percentage is high, a gypsum determination should be made. A high-gypsum value indicates that leaching only is required, while a low-gypsum value indicates need for amendments,. When there is a low-gypsum value, the presence or absence of alkaline-earth carbonates is ascertained to indicate the type of chemical amendment that can be used for the replacement of exchangeable sodium. The addition of amendments should be followed by leaching. Other determinations, such as pH, saturation percentage, cation-exchange-capacity, exchangeable potassium, toxic ions, and texture, provide additional information and are made if circumstances warrant.

[5] FIREMAN, M., and BLAIR, G. Y. CHEMICAL AND PHYSICAL ANALYSES OF SOILS FROM THE HUMBOLDT PROJECT, NEVADA. [Unpublished.] January 1949.