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SOIL SOLUTION CONCENTRATIONS AT THE WILTING POINT AND THEIR CORRELATION WITH PLANT GROWTH[1]

O. C. MAGISTAD AND R. F. REITEMEIER
U. S. Department of Agriculture

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Despite a half-century of research on "soil alkali," a need exists for a semi-quantitative index of the degree of plant injury to be expected from various ranges of soil salinity. It is realized that salinity stresses may be modified or masked by other factors of soil, plant, and climate. Nevertheless, if an approximate quantitative relationship could be established between soil solution concentration and plant growth, it would be of value in the diagnosis of salinity effects.

The purpose of this paper is to show the ranges of soil solution concentration and composition that occur in irrigated soils and their correlation with plant growth. These relationships are compared to those that have been obtained with plants grown in sand and water cultures of controlled salinity. A collection at this laboratory of stock soil samples from important agricultural areas of the West provided an excellent opportunity for making the type of investigation reported here. Plants growing in soils necessarily respond to the actual soil solution concentration and composition and not to the values calculated from an extraction of salts at artificial moisture contents, which may result in extremely erroneous interpretations. This study, therefore, has involved the securing of the soil solutions actually existent at field moisture contents.

It is recognized that the soil solution may not represent the true culture medium of the plant, particularly with respect to nutrients that are slowly released by soils, such as phosphorus and potassium. As regards concentrations of salt, and their effect on plant growth, the soil solution does represent conditions to which plant roots are subjected. The wilting percentage[2] represents the lowest moisture content at which a plant can grow. For a constant amount of salts, the concentration found in the soil solution at the wilting percentage is the maximum to which the plant will be subjected, because of the general inverse relationship between concentration and moisture content. Consequently, all soil solution concentrations discussed here have been referred to the wilting percentage by appropriate calculations. Since most of the soil solutions were obtained at soil moisture contents near the wilting range, changes made in the concentrations by these calculations are relatively small.

[1]Contribution from the U. S. Regional Salinity Laboratory, Bureau of Plant Industry, Agricultural Research Administration, in cooperation with the 11 Western States and the Territory of Hawaii.

[2]Though the term "wilting percentage" is used for brevity, it is understood that wilting takes place over a moisture range, as shown by J. R. Furr and J. O. Reeve in a manuscript entitled, "The range of soil moisture percentages through which plants undergo permanent wilting in some soils from semiarid irrigated areas."

LITERATURE REVIEW

Harris and co-workers (5) compiled extensive data showing that the osmotic pressure of plant saps was related to the soil environment on which the plants were grown and summarized the earlier literature on this question. They say (5, p. 919): "The salts of the soil may conceivably be detrimental to crop production in two ways: first, chemically, through the toxicity of certain of the constituents; second, physically, through the attainment of an osmotic concentration greater than that which can be tolerated by crop plants."

Recent work on the response of plants to salinity in sand and solution cultures has been summarized by Eaton (4), Hayward and Long (6,7), and Magistad et al. (12). In general, these investigations have shown a linear negative correlation between relative plant growth (based on yields in the base nutrient solution as 100 per cent) and the osmotic pressure of the substrate. Superimposed on this major concentration effect are lesser effects due to the nature of the ions and ionic ratios. Thus Hayward and Long obtained better yield of tomatoes in a nutrient solution concentrated to 3 atmospheres than in the same original nutrient solution with additions of sodium chloride to attain the same osmotic pressure. Furthermore, experiments have shown that differences in temperature and sunlight will modify the growth of plants grown in the same substrate.

Some crops are more tolerant to salt than are others. Kearney and Scofield (8) published an extensive list of crop plants in order of tolerance. The staff of the Salinity Laboratory have shown that garden beets, sugar beets, and cotton, with relative yields of 70 per cent when grown in a substrate of 4 atmospheres, may be classed as tolerant to common salts, whereas wax beans provided less than a 20 per cent yield at this concentration. Yields at 0.5 atmosphere in the base nutrient solution were taken as 100 per cent. As an example of a salt-sensitive plant, and of specific ion effects, Hayward and Long (7), in a recent paper, showed that peaches died at 3.4 atmospheres of chloride salts whereas growth continued at 3.6 atmospheres of sulfate salts.

In a recent experiment with alfalfa, Gauch and Magistad[3] obtained a linear relationship between salt concentration and growth. Yields from the second cutting are reproduced in figure 1.

Linear relationships similar to that shown in figure 1 have been found for most crops tested when plotted in a similar manner. Salt-tolerant crops have a slightly sloping regression line, whereas salt-sensitive crops have a steeply sloping one. Extrapolation of the regression lines for sugar beets and milo, for instance (12), would indicate that growth of these crop plants would cease at about 10 to 12 atmospheres. No sand culture experiments have been conducted at this laboratory at concentrations in excess of 7.7 atmospheres to verify the validity of such extrapolated values. Tottingham (18) in a study of nutrient solutions of varied composition grew wheat at 0.5, 2.46, and 7.63 atmospheres. At the highest value, wheat plants in some cultures were not markedly injured at the

[3] Gauch, H. G., and Magistad, O. C. Growth of strawberry clover varieties and of alfalfa and Ladino clover as affected by salt. [Manuscript.]

end of 24 days. Yield of top plus root at this concentration reached 3 gm. compared with yields of 6 gm. at 2.46 atmospheres. Harris *et al.* (5) showed that Allenrolfia and Salicornia, two salt-tolerant desert shrubs, grew where the soil water had osmotic pressures of 30 to 38 atmospheres. Two samples of soil water ranging above 45 atmospheres were taken from places devoid of vegetation. Various authors have reported growth of plants and molds in sugar solutions having osmotic pressures above 10 atmospheres. Salt-sensitive plants such as beans die if the substrate concentration exceeds 4 atmospheres.

Very few data have been published in which salt concentrations in solutions from saline soils at low moisture contents are correlated with plant growth. Eaton and Sokoloff (3) report a few analyses of displaced solutions from saline soils. One such soil solution contained a total of 308 m.e. of salts per liter. Orange production on this soil was poor. These authors point out the desirability of using low soil-water ratios to obtain an accurate picture of the composi-

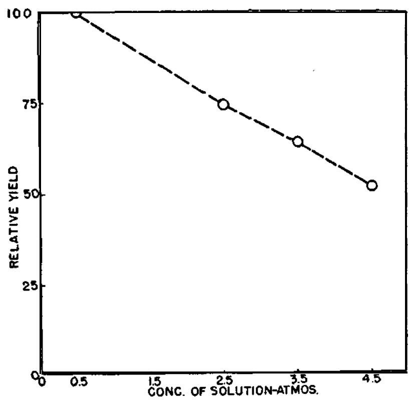

FIG. 1. RELATIVE YIELD OF ALFALFA IN SAND CULTURES OR VARIED OSMOTIC PRESSURES

tion and concentration of the soil solution. Anderson, Keyes, and Cromer (1) have recently made an excellent review of solution concentrations in humid soils. The concentrations of the displaced soil solutions ranged from 600 to 2900 p.p.m.

It has long been realized that the availability of soil water to plants is decreased both by a lowering of the moisture content and by an increase in salinity. More recently, the investigation of energy relations of soil water has made it possible to relate these phenomena on a quantitative basis. Thus, Day (2) has derived a differential equation for the moisture potential of a soil, which is related to the forces involved in a transfer of water from the soil to the plant:

$$d\mu = -sdT + vdP + d\omega$$

in which

$d\mu$ = moisture potential term
$-sdT$ = temperature differential term
vdP = pressure potential term
$d\omega$ = osmotic potential term.

The magnitude of $-sdT$ is negligible for small temperature differences within the system. Thus, for most conditions, the moisture potential of the soil water is composed of two additive values, the pressure potential and the osmotic potential. The pressure potential relates to the pressure by which water is held in the soil. The osmotic potential is caused by presence of solutes in the soil water. The value of vdP can be measured by tensiometers, pressure-membrane apparatus, and similar techniques, and *do* can be measured by removing the soil solution and determining the activity of the water component, such as by freezing-point depression, or by vapor-pressure lowering.

In sand and solution cultures, vdP becomes zero, and the moisture potential of the substrate depends on its concentration. In most soils, both terms have appreciable values. Consequently, as in this report, when all soil solution concentrations are calculated to a common tension value (15 atmospheres), the pressure potential term is equal for all soils and the plant response becomes directly related to the osmotic potential.

MATERIALS AND METHODS

Seventeen soil samples from the laboratory collection were used in this investigation. Soil solutions were obtained from fifteen of these soils at field moisture by the pressure-membrane method (15).[4] Subsamples of the stock samples, which had been sieved through a $\frac{1}{8}$-inch screen, were sprinkled with sufficient distilled water to bring them to predetermined moisture contents. The relative moisture percentages of the fifteen samples varied because some of the samples were used also for other work than that reported here. The moistened samples were kept in air-tight tinned cans in a constant temperature room at 21°C. for at least 2 weeks prior to extraction. At 2-4-day intervals during this period, the samples were removed and mixed by manual working and rolling on a Koroseal mixing cloth. When satisfactory moisture. and salt equilibria had been attained, the soils were placed in the pressure-membrane apparatus and the soil solutions were extracted under a nitrogen pressure of 250-270 pounds per square inch (17-18.5 atmospheres).

It has been shown by Richards and Weaver (16) that although the wilting range may vary over a considerable range of soil moisture tension, the moisture held at a tension of 15 atmospheres is usually a reliable index of the wilting point. In this work, the 15-atmosphere value has been used as equivalent to the wilting percentage. This value is determined in the pressure-membrane apparatus by allowing the soil moisture to come to equilibrium with this gas pressure. The fifteen samples were extracted at moisture contents varying from 1.15 to 2.2 times the 15-atmosphere percentage. Usually, coarse soils must be extracted at higher relative moisture contents for satisfactory results and to provide an adequate volume of solution.

The two remaining samples, 207 and 211, were too small to enable extraction

4Also Reitemeier, R. F., and Richards, L. A. The reliability of the pressure-membrane method for the extraction of soil solutions, including a comparison with the displacement method. [Incomplete manuscript.]

at field moisture. Solutions were extracted from them at the saturation percentage (17, p. 9) by filtration under suction on a Büchner funnel.

TABLE 1

Soil solution concentrations in the wilting range and their relationship to plant growth

SOIL NO.	SOIL TYPE	MOISTURE CONTENT AT			SOIL SOLUTION CONCENTRATION AT 15 ATM. MOISTURE CONTENT				PLANT GROWTH
		Extraction	15 atm.	⅓ atm.			Osm.P.*	$K \times 10^5$ at 25°C.*	
		%	%	%	*m.e./l.*	*p.p.m.*	*atm.*		
75	Yolo fine sandy loam	15.8	11.7	25.2	32	2,370	1.32	232	Very good walnuts, alfalfa
66	Millville loam	13.6	7.6	22.6	41	2,900	1.36	307	Very good wheat
83	Fort Collins loam	14.5	10.1	21.9	44	3,330	1.59	312	Very good wheat, small grains
65	Palouse loam	15.6	10.6	23.7	51	3,950	1.79	344	Very good wheat
77	Silted Superstition sand	14.5	6.6	12.5	57	4,060	1.81†	453†	Good grapefruit
183	Hesperia sandy loam	8.1	4.7	10.6	58	4,260	1.81	525	Good cotton
84	Gila adobe clay	28.9	22.5	41.2	68	4,560	2.02	597	Good cotton
56	Imperial clay	17.4	15.1	29.7	104	6,800	3.1†	840†	Good alfalfa
79	Cajon silty clay loam	24.8	12.0	28.2	132	9,550	4.0†	1,100†	Good wheat
85	Regan clay loam	20.3	11.4	23.2	232	15,600	5.8	1,300	Medium cotton
58	Indio fine sandy loam	12.7	6.2	21.6	235	15,900	7.0†	1,915†	Fair dates
222	Ephrata (?) silt loam	9.6	5.5	27.5	317	21,000	8.6	2,230	Pears and apples retarded
211	Greenhouse soil	121	27.0	49.0	367	25,600	9.1	2,500†	Begonia and ferns dying
86	Fort Collins loam	15.5	12.3	22.4	515	33,200	10.4	2,780	Poor pasture
207	Merced silty clay loam	57.6	15.0	29.0	1,470	88,500	47‡	10,700†	Alfalfa failed
57	Imperial clay	27.2	20.4	36.2	2,220	126,000	84†‡	14,000†	Barren
62	Oasis clay loam	15.2	8.7	25.1	5,700	339,000	235‡§	24,200†	Barren

*Calculated values are corrected for nonlinear variation of osmotic pressure and equivalent conductance with concentration. (K = specific conductance.)

†Values calculated from measurements made on synthetic solutions.

‡Values include corrections for the change of osmotic pressure with temperature.

§The freezing-point depression exceeded the thermometer scale, and the osmotic pressure was calculated from published freezing-point data for NaCl solutions.

The 15-atmosphere values of all the soils and their moisture contents prior to extraction are shown in table 1.

Determinations made on the soil solutions included ionic constituents, electrical conductivity, and osmotic pressure by means of freezing-point depressions. The chemical analyses were made primarily by the semimicroanalytical methods described elsewhere,[5] in conjunction with the macromethods used at this laboratory and at the adjacent Rubidoux Laboratory of the Division of Irrigation Agriculture (20). Dissolved salts in terms of parts per million were calculated from the analytical results; because of organic matter, these figures were lower than the total dissolved solids obtained by evaporation. Osmotic pressures were calculated from freezing-point depressions measured with a Beckmann thermometer. For eight soils insufficient samples were available for conductivity and freezing-point measurements. Synthetic solutions were prepared therefore in accordance with the analyses, and these two determinations were

TABLE 2

Composition of soil solutions of table 1

Results in milliequivalents per liter

SOIL NO.	IONIC CONCENTRATIONS IN EXTRACTED SOLUTIONS									TOTAL SALTS
	Cations				Anions					
	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	NO_3*	
75	6.9	11.7	4.6	0.7	0.0	4.7	1.9	2.4	14.3	23.9
66	14.3	7.0	1.4	0.2	0.0	6.7	1.3	3.1	10.2	22.9
83	25.4	3.5	1.1	0.5	0.4	3.7	1.1	1.1	22.5	30.5
65	24.8	8.0	1.2	0.8	0.0	7.6	1.1	2.5	[23]	34.8
77	11.1	4.7	9.8	0.5	1.1	6.5	7.4	5.2	5.7	26.1
183	20.4	6.6	4.3	1.8	0.3	3.4	4.3	5.3	[19]	33.1
84	23.3	6.0	22.7	1.0	0.3	4.1	26.3	14.8	[7]	53.0
56	24.4	19.8	40.9	0.9	0.0	3.1	49.5	27.0	11.3	90.9
79	27.8	14.8	19.2	2.1	0.3	6.7	17.4	10.4	28	63.9
85	45	52	24	9	1	6	53	20	43	130
58	6.4	1.7	100	2.1	5.6	5.6	66.2	28.1	9.0	115
222	25	29	125	2.5	0.2	3.0	128	27	15	182
211	37.4	15.6	25.3	3.9	0.0	2.6	40.7	16.1	[22]	82
86	12.3	210	183	3.3	0.4	12.9	325	31.2	13	409
207	89.9	65.8	224.2	3.5	0.0	2.8	51.0	296	[33]	383
57	787	317	561	2.9	0.0	3.9	19.4	1553	89	1668
62	50	190	2906	97	0.0	4.7	284	2954	18.9	3262

*Nitrate concentrations in brackets were determined by combining analytical values with appreciable anion deficits, because of apparent loss of nitrate prior to the time of analysis.

made on them. The four methods of expressing concentration comprise those in common use by different investigators.

Concentrations were calculated to the soil moisture content at the 15-atmosphere value by multiplying the actually determined values by the ratio of extraction moisture percentage to the 15-atmosphere percentage. For the osmotic pressure and conductivity calculations, additional factors were used to correct for the nonlinear change of thermodynamic activity and equivalent conductance with concentration. These factors were determined from available

6Reitemeier, R. F. 1941 The semimicroanalysis of soil solutions of saline soils. Bureau of Plant Industry, U. S. Department of Agriculture. [Mimeographed.]

thermodynamic data (10, 14) and from conductivity data in the International Critical Tables (13). Osmotic pressures in atmospheres were calculated from freezing-point depressions by the equation derived by Lewis (9), namely, O.P. = $12.064 - 0.021\Delta^2$. For solutions of high concentration, this equation is exactly correct only at the freezing-point, and the calculated values were referred to 25°C. by applying additional corrections involving the heat of dilution (10, pp. 346-363). As these corrections involve various assumptions, some of the reported figures, especially the highest values, are approximations.

RESULTS AND DISCUSSION

Tables 1 and 2 contain the numerical results of the investigation. Table 1 includes descriptions of the soil samples, moisture percentages, salt concentrations at the wilting point expressed in four units, and notes on the plant growth. Table 2 comprises the ionic compositions of the extracted soil solutions.

Relationship of soil solution concentration at the wilting point to plant growth

The data in table 1 show that good or very good plant growth was obtained in the first nine soils. The soil solution of these soils at the wilting percentage had an osmotic pressure of 4 atmospheres or less. The first four soils were from the Experiment Station Farms at Davis, California; Logan, Utah; Fort Collins, Colorado; and Pullman, Washington, respectively. These soils produce very good yields. As an example of salinity concentrations encountered in the soil solution under plant growth conditions, and of their variation with the soil moisture content, specific data on Cajon silty clay loam are given. This soil was extracted at 24.8 per cent moisture, and at this moisture content the soil solution had an osmotic pressure of 2.05 atmospheres. At a tension of $\frac{1}{3}$ atmosphere, this soil contains 28.2 per cent moisture. Richards and Weaver (16) have shown that the +-atmosphere value is approximately equal to the moisture equivalent. Between irrigations the moisture content of this soil might have varied from about 30 per cent to 12 per cent, and the osmotic pressure of the soil solution from 2 to 4 atmospheres. Very likely the moisture content of this soil was never reduced to the wilting percentage during the growth of the wheat. It seems fair to assume that although 4 atmospheres is given as a limiting value for the osmotic pressure of the soil solution, wheat growth took place mainly in the range from 2 to 3 atmospheres.

Plant growth observations shown in the last column of table 1 were based on local ideas of good crop yields. It is recognized that what may be called a good crop on an area uniformly saline might be considered a mediocre crop in more fertile and less saline lands.

In soils having a soil solution concentration above 4 atmospheres at the wilting point, crop yields were definitely not good even by local standards. At values above 40 atmospheres plant growth failed.

Table 1 also gives values for the conductivity of the soil solutions. On this basis we note that where the conductivity exceeded about 1,200, crop growth diminished; at values between 3,000 and 10,000, growth failed.

Recently Scofield[6] made a survey of soils in the Pecos River Basin of New Mexico and Texas. Soil samples were taken from "locations that appeared to represent. the several stages or degrees of soil salinity." These samples were brought to the saturation percentage, the "solution extract" was removed by a filter press, and the extract was analyzed. The saturation percentage is about, twice that at field capacity and this in turn is about twice that at the wilting percentage. The water content of these soils at the time of filtering therefore was assumed to be roughly four times the wilting percentage. Scofield concluded that where the solution extracts involve a conductivity of 800, salt-sensitive plants do not thrive, but salt-tolerant crops like alfalfa and cotton do well. Where the conductivity of the solution extracts is above 1,500, these salt-tolerant crops do not do well. The Pecos soils contain much gypsum, and the conductivity of these soil solutions at the wilting percentage probably would be less than expected from conductivities at the saturation percentage corrected for the diminished water content.

It has been customary to correlate plant behavior with the salt content of a soil expressed in terms of percentage or parts per million on a dry soil basis. It is more logical to give salt concentrations on the basis of soil solution rather than of soil. Such values are given in column 7 of table 1. Here we see that where the soil solution concentration at wilting exceeded 10,000 p.p.m., growth was markedly retarded. Where the concentration exceeded 40,000 p.p.m., growth ceased.

It should be noted that in soil 62 the total concentration of salts in the soil solution at the wilting percentage approaches the solubility of sodium chloride in water.

For the benefit of those who wish to make comparisons between plant growth and soil solution concentration in units of milliequivalents per liter, these values are included in column 6 of table 1.

Livingston, in 1942 (11), reviewed the general subject of the effect of salts, salt proportions, and concentration on plant, growth. He concluded in general that the concentration of a good nutrient solution affects plants mainly through its osmotic value and that this is modified by the kinds of salt, and salt ratios present. He pointed out (11, p. 90), "With continuous flow a good solution may be much weaker than 0.017 *M*, but total concentrations greater than about 0.060 *M* (or about 2.5 atm. osmotic pressure) generally retard water absorption, somewhat as a soil does when too dry for healthy growth."

A fertile soil replenishes plant, food to the soil solution and acts like a flowing culture. The concentrations in osmotic values and milliequivalents per liter found in the solutions of soils giving good yields and tabulated in table 1 agree with the conclusions of Livingston.

It should be borne in mind that the soil solution concentrations listed in table 1 are calculated concentrations existing in the soil solution at the wilting per-

[6] Scofield, C. S. 1941 The Pecos River joint investigation 1939-1940. Soil salinity investigation. Bureau of Plant Industry, U. S. Department of Agriculture. [Mimeographed.]

centage, and that the plants were, for the most part, growing at concentrations somewhat below these. The relationships shown in the table between plant growth and salt concentration are of the same order as those obtained by other investigators in sand and solution cultures.

Composition of soil solutions

The composition of the solutions as extracted are shown in table 2. These analyses are included because so few data are available on soil solution composition at low soil moisture contents, and because great variance is shown in the composition of solutions from soils from various parts of the western United States. In general, with increasing total salt content there has been a parallel increase in sodium, sulfate, and chloride concentrations. Of particular interest are the high nitrate values of the first four fertile soils, in which nitrates account for one half or more of the anions present.

About half of these soils contained undissolved gypsum. In the solutions from such soils, the product of calcium and sulfate agreed well with expected values as given by Vanoni and Conrad (19).

In the solutions from soils 75, 85, 222, 86, and 62, the concentration of magnesium exceeded that of calcium. It is usually found that the amount of dissolved calcium exceeds that of magnesium in soil solutions of fertile soils.

SUMMARY

Seventeen soils representing a wide range of salinity conditions were collected, together with notes on plant growth. Soil solutions of these soils were obtained at moisture contents within normal field range. These solutions were analyzed and the values extrapolated to the 15-atmosphere (wilting percentage) value. Concentrations of salt are given in osmotic units, conductivity units, parts per million, and milliequivalents per liter. The relationship between plant growth and osmotic pressure of soil solution was similar to and of the same order as that obtained in sand culture and solution culture experiments. Above 40 atmospheres concentration, the soils were barren. Normally fertile irrigated soils had a soil solution concentration at wilting percentage of 1.3 to 1.8 atmospheres, conductance values ($K \times 10^5$) of 200 to 350, 2,000 to 4,000 p.p.m. and 30 to 50 m.e. per liter of salts.

The soil solutions as extracted varied greatly in composition. Nitrates formed half the anions in the solutions from fertile soils. In a few solutions the magnesium content exceeded that of calcium.

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