

EFFECT OF SALT CONCENTRATION, KIND OF SALT, AND CLIMATE ON PLANT GROWTH IN SAND CULTURES

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(WITH NINE FIGURES)

Introduction

Many western farmers believe that soil alkali is more detrimental to crop growth during the hot weather than during the cooler seasons of the year. Other agricultural workers have noted that damage to crops due to alkali (soil salinity) is more serious in the hot interior valleys than along the coast where the climate is more moderable. It is not definitely known whether or not soil salinity concentrations are comparable between different seasons of the year or between respective areas. Yet, information on this question is pertinent to the development of management practices which would aid in ameliorating soil salinity conditions at different seasons of the year and under different climatic conditions.

In order to obtain definite information on this question, the Regional Salinity Laboratory planned a series of experiments to determine the tolerance of crop plants to the salts commonly found in irrigation waters and soils, and to what extent climate modified these effects. This paper presents a resume of the more pertinent results from these experiments conducted during 1939, 1940, and 1941.

TRELEASE and LIVINGSTON (10) were among the earliest authors to find that climatic conditions modified the crop growth obtained with the same culture solutions and to suggest that studies should be made on the effect of climate in modifying plant responses.

In 1938 AHI and POWERS (1) grew salt grass, alfalfa, and strawberry clover in the same culture solutions in greenhouses held at 55° and 75° F. They found germination and growth to be poorer at the higher temperature.

HAYWARD and LONG (6), and WALL and HARTMAN (11) have also published results indicating that climatic factors modify the action of salt on plants.

The amount of salt which plants can tolerate in sand cultures under normal climatic conditions has been reported by many authors, and the reader is referred to recent reviews by EATON (5), and HAYWARD and LONG (6). In general, salt tolerant plants can continue growth in nutrient solution at concentrations exceeding 6 atmospheres, while salt sensitive plants may succumb at solution concentrations below 2.5 atmospheres.

Experimentation

The work was done during the summers of 1939, 1940, and 1941 in large

† Contribution from the U. S. Regional Salinity Laboratory, Bureau of Plant Industry, Riverside, California, in cooperation with the eleven Western states and the Territory of Hawaii.

outdoor sand cultures at three locations, each having a distinctly different climate. These locations were Torrey Pines, near San Diego ; Riverside ; and Indio, in the Coachella Valley. The location of these places in Southern California is shown in figure 1. In spite of the diversity of climates the three locations were so near each other that the work could be adequately supervised and coordinated from Riverside. The stations were also in the same approximate latitude so that length of day was essentially the same at all three.

The sand culture tanks have been described by EATON (4) and each had a growing area of 3.248 square meters and a reservoir of culture solution containing 2400 liters. By means of motor pumps and time clocks the sand bed could be flooded with the culture solution at definite time intervals, thus bathing the plant roots in the culture solution, providing aeration, and insuring against accumulation of salts on the surface of the sand. The culture

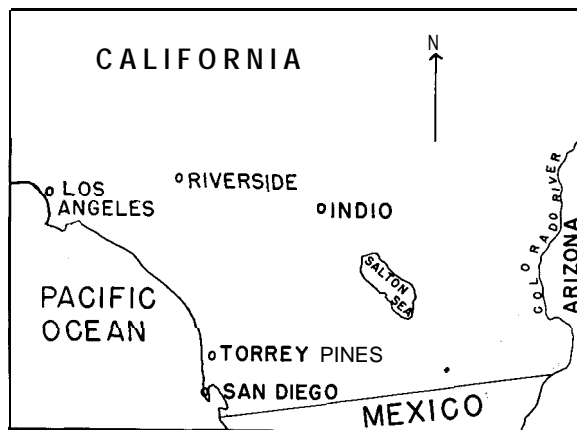


FIG. 1. Outline map of Southern California showing location of Salinity experiments to test effect of climate. These tests were conducted at Riverside, Indio, and Torrey Pines.

solution drained through the sand to the reservoir below. The sand contained 0.2 per cent. magnetite to provide the iron needed by crops as suggested by CHAPMAN (2). The composition of the culture solutions used in 1941 is given in table I. They were maintained at about pH 6.5.

The salts used in making up these solutions were carefully selected for low contents of boron and heavy metals.

Growth responses obtained in these culture solutions are believed to be qualitatively characteristic of plant growth in soil solutions of equal salt content, but it should be borne in mind that drainage, aeration, nutrient supply and other growth factors will differ in soils from conditions found in sand culture beds.

EFFECT OF SALT CONCENTRATION

Early investigators, who conducted culture solution experiments to explain the action of alkali on crops in the field, have shown that at high salt concentrations growth is reduced. In figure 2, results of this nature are

TABLE I

COMPOSITION AND CHARACTERISTICS OF CULTURE SOLUTIONS USED IN 1941

TREATMENT	CATIONS PER LITER			ANIONS PER LITER		TOTAL ANIONS* PER LITER	TOTAL SALTS	CONDUCTANCE	OSMOTIC CONCENTRATION
	Na	Ca	Mg	Cl	SO ₄				
	<i>mg. eq.</i>	<i>mg. eq.</i>	<i>mg. eq.</i>	<i>mg. eq.</i>	<i>mg. eq.</i>	<i>mg. eq.</i>	<i>p.p.m.</i>	<i>K × 10⁵ @ 25° C.</i>	<i>Atmospheres</i>
Base nutrient	2.6	3.2	2.3	2.5	1.8	10.7	1046	125	0.4
2.4 chloride	36.4	8.4	15.3	54.5	1.8	62.7	3929	649	2.4
4.4 chloride	68.9	13.2	27.8	104.5	1.8	112.7	6697	1137	4.4
2.4 sulphate	58.5	11.8	23.8	2.5	87.8	96.7	6896	753	2.4
4.4 sulphate	121.6	21.5	50.1	2.5	184.8	193.7	13520	1342	4.4
4.4 chloride sulphate mixture...	87.1	16.2	34.8	67.5	67.8	141.7	9119	1195	4.4

* All solutions also contained 3.45 mg. eq. of K; 6.0 mg. eq. of NO₃; 0.4 mg. eq. of H₂PO₄; and boron 0.6 p.p.m.; Mn 0.2 p.p.m. These are included in the totals above.

shown for Early Wonder garden beets, Early French forcing carrots, and Weber wax beans grown in culture solutions of varying chloride concentration at Riverside during 1941.

The nutrient concentrations reported in figure 2 are given in terms of atmospheres of osmotic concentration. It is recognized that workers in the field of salinity have used a number of other indices to measure the concentration of salt on a soil or soil solution basis, such as parts per million, milligram equivalents per liter, equivalents per million, conductance² of a soil paste, and conductance of a soil extract, in addition to osmotic values of soil solutions or culture solutions. In this paper osmotic concentration

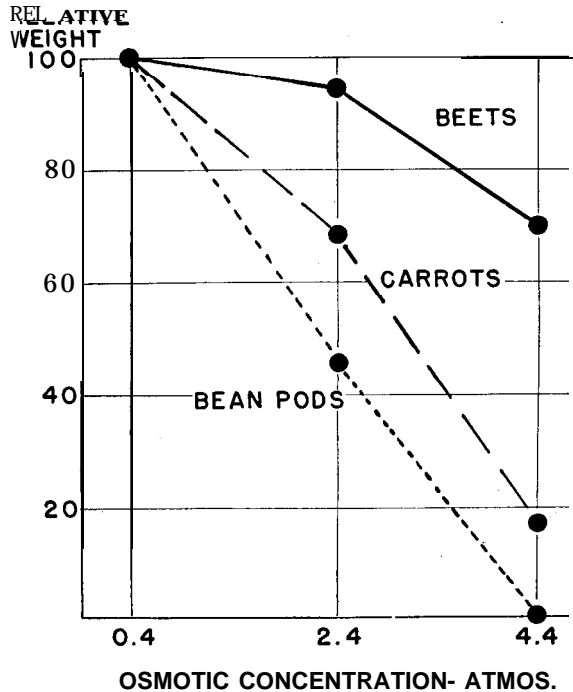


FIG. 2. Differential effect of culture solutions of varying concentration on growth of various plant species.

in atmospheres of the culture solution as determined by freezing point depression is used as our basic index. There seems to be increasing evidence (4, 5, 8) that water absorption is related to, or a part of, salinity effects, and osmotic values correlate with such phenomena. Table I gives values for the culture solutions used in 1941 in terms of milligram equivalents per liter, parts per million, conductance, and osmotic concentration.

The results shown in figure 2 are representative of a number of tolerance tests and were obtained at Riverside in the chloride series. The yield of plants grown in the base nutrient solution can be taken as 100 per cent., and

² Specific electrical conductances are given in reciprocal ohms and multiplied by 10^5 to avoid decimals. The values are therefore given in terms of $K \times 10^5$ at $25^\circ C$.

yields obtained in the 2.4 and 4.4 atmosphere culture solutions plotted as a percentage of the base yield. When this is done the relationship of yield to substrate concentration is nearly linear.

It is clear from the data in figure 2 that in the case of beans the percentage decrease in growth from 0.4 atmospheres to 2.4 atmospheres is equal to the decrease from 2.4 atmospheres to 4.4 atmospheres. The yield of carrot roots shows the same uniform percentage decrease in growth for each additional atmosphere of nutrient concentration. In the case of garden beets the yield at 2.4 atmospheres is greater than the mean of yields at 0.4

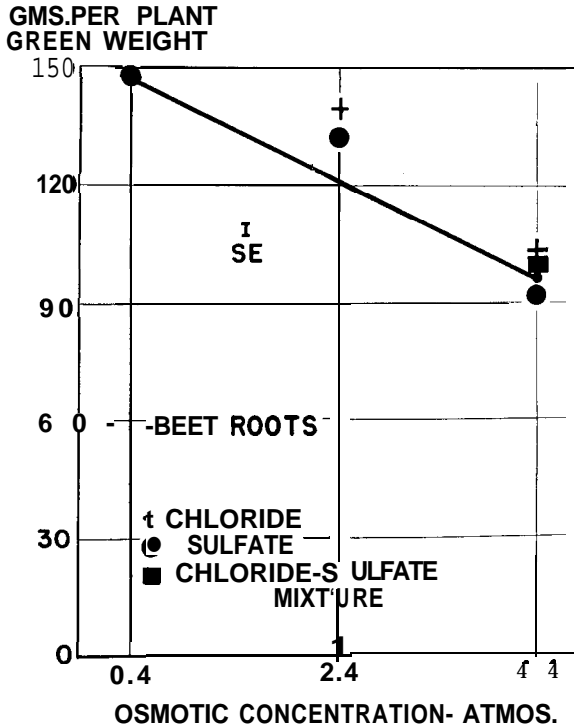


FIG. 3. The relative yield of garden beet roots grown in culture solutions of chloride, sulphate, and mixed chloride-sulphate salts at indicated osmotic concentrations. A measure of the accuracy is given by the length of the line S.E. (Standard error).

and 4.4 atmospheres, but the deviation from this mean is not statistically significant.

The relationship shown between yield and osmotic concentration is almost equally good between yield and conductance of the culture solution. This follows because conductance and osmotic concentrations of the solutions are directly related. This is shown by data in table I. These data show that the ratio of conductance to atmospheres of osmotic concentration lies between 250 and 300, depending on concentration and the nature of the salt present.

DIFFERENCES IN SALT TOLERANCE EXHIBITED BY VARIOUS PLANT SPECIES

Field experience has shown that some plants like Atriplex, Russian olive, sugar beets, and cotton have a high tolerance to salts, while others, such as beans and squash, are much less tolerant. Differences in tolerance to salinity exhibited by plant species are shown by the data in figure 2. The slope of the yield line is an index of tolerance, and beans with a steep slope are the least tolerant of the three crops shown. In fact at 4.4 atmospheres no fruit yield was obtained in the case of beans whereas a 68 per cent. yield of beets was harvested at this same concentration. Yield records at River-

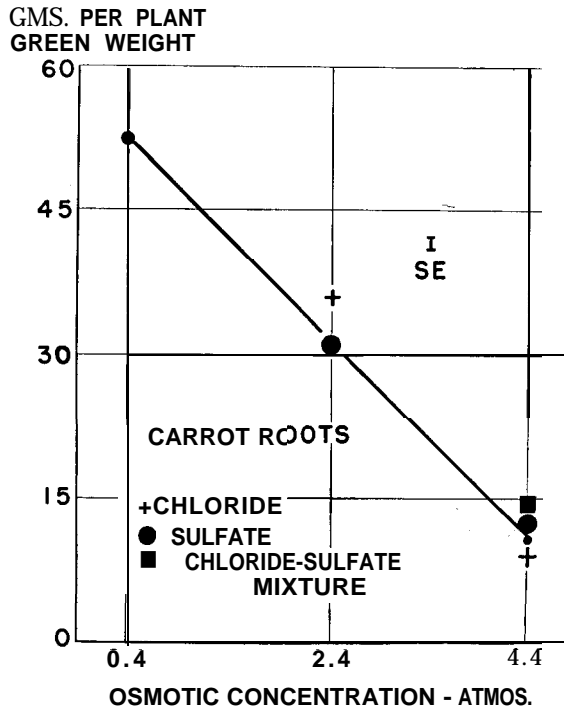


FIG. 4. The relative yield of carrots grown in culture solutions of chloride, sulphate, and mixed chloride-sulphate salts at indicated osmotic concentrations. A measure of the accuracy is given by the length of the line S.E. (Standard error).

side in the presence of chloride solutions suggest the following order for decreasing crop tolerance: Sugar beets, table beets, cotton, alfalfa, cowpeas, tomatoes, milo maize, carrots, squash, onions, and beans.

EFFECT OF ANION

The ions most prevalent in saline irrigation waters are sodium, calcium, and magnesium among the cations; and sulphates, chlorides, and bicarbonates among the anions. Almost always these six ions are found in the irrigation water or soil solutions and earlier investigators have studied the systems with a view toward determining if any one or more of the ions was

particularly toxic to plant growth. Such experiments have not been easy to conduct because equal quantities of cations and anions must be present in a culture solution, as well as the necessary plant foods. The action of particular anions has usually been obtained by comparison with equal moles or equivalents of anions in combination with the same cations in the culture medium. The results of experiments in 1939 and 1940 in which equal moles of chlorides and sulphates were compared suggested that comparable re-

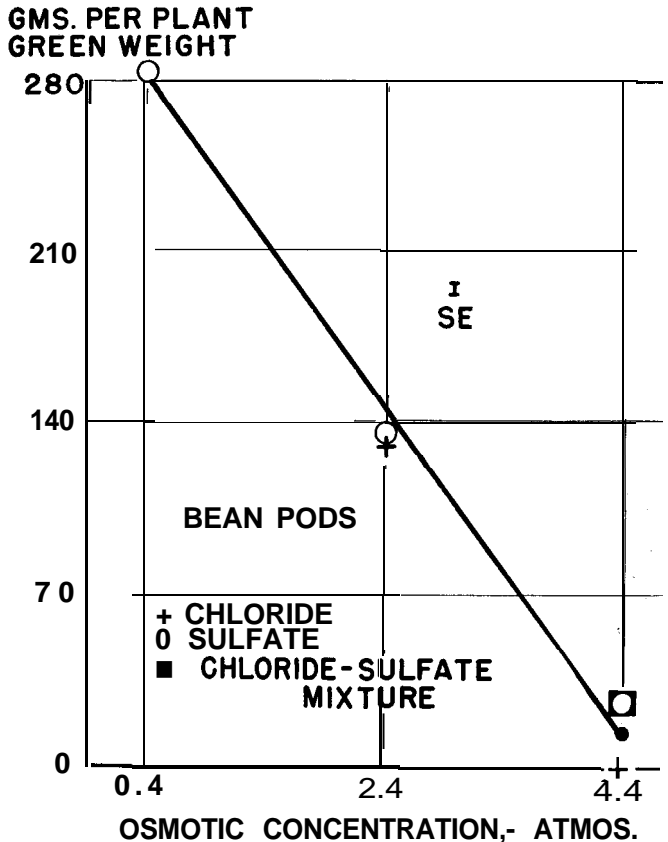


FIG. 5. The relative yield of beans grown in culture solutions of chloride, sulphate, and mixed chloride-sulphate salts at indicated osmotic concentrations. A measure of the accuracy is given by the length of the line S.E. (Standard error).

sponse might be secured if the culture solutions were prepared on an equal osmotic basis. This was done in 1941. The yields obtained on this basis for beets, carrots, and beans are shown in figures 3, 4, and 5. At equal osmotic concentrations the yield of these crops did not differ appreciably.

The data obtained in 1939 and 1940 for alfalfa show that chlorides were more toxic than sulphates at approximately equal osmotic values. This has also been found to be true for peaches (7). These results would indicate that for some crops chlorides and sulphates at equal osmotic concentrations

are equally harmful, while with other crops, chlorides are more toxic than sulphates at approximately equal osmotic values. More equivalents of sulphates than of chlorides are required to produce a given freezing point depression or osmotic value. Furthermore, the sulphate ion is somewhat heavier than the chloride ion. These facts explain why plants can withstand far greater amounts of sulphate than chloride when expressed on a parts per million basis.

EFFECT OF CATION

During 1939, sand culture tests were conducted which included treatments in which calcium, magnesium, and sodium each predominated. Thus in one treatment 95 equivalents out of a total of 111 were supplied as calcium ; in another 95 out of 112 were supplied as magnesium ; and in a third 47 out of 62 were supplied as sodium. Other treatments usually had 50 per cent., of the cations as sodium and 25 per cent. each as calcium and magnesium. Using data from 8 crops, some of them at 3 locations, and making comparisons at approximately equal osmotic concentrations yields were found to be slightly better when calcium was the predominant cation than when the ratio was 50 per cent. sodium, 25 per cent. calcium and 25 per cent. magnesium. The increase in yield due to a predominant calcium salt was particularly marked in the case of alfalfa.

Where magnesium was the predominant cation, yields were usually lower than when calcium or sodium was preponderant.

Where sodium constituted 76 per cent. of the cations present in terms of milliequivalents per liter, the yields were approximately the same as when the ratio of sodium to total cations was 50 per cent. Thus in sand cultures where the physical condition of the substrate is not a problem, sodium in the ratios used does not appear to be a particularly injurious cation for the plants grown.

EFFECT OF CLIMATE IN MODIFYING THE EFFECT OF SALTS ON PLANT GROWTH

It was believed that the effect of a certain salt concentration in reducing the relative yield would not be the same in two widely different climates. Thus if 2.4 atmospheres will reduce the yield of beans to 50 per cent. of normal at Riverside, should we expect the same yield reduction in a hotter climate where transpiration would be greater? This is an important question because if experimental data showed that climate did not modify the effect of salts on plant growth, it would be possible to carry on experiments at one location and expect similar results to be obtained under all climatic conditions.

In 1940 onions were grown at the three locations in a base nutrient solution, and in this base nutrient solution plus added chloride, sulphate-chloride mixture, and sulphate salts which had osmotic concentrations of 4.1, 4.3, and 4.5 atmospheres, respectively. Data on climate for the month of July at the three test locations are given in table II.

TABLE II

CLIMATIC DATA FOR INDIO, RIVERSIDE, AND TORREY PINES FOR JULY, 1940

LOCALITY	MEAN MAXIMUM TEMPERATURE	MEAN MINIMUM TEMPERATURE	AVE. EVAPORATION	AVE. RELATIVE HUMIDITY AT 8:00 A.M. & NOON		AVE. WIND	AVE. SUNSHINE
	° F.	° F.		%	%		
Indio	112	71	<i>ml./100 sq. cm./day</i> 1384	89	21	<i>mi./day</i> 26	<i>gm. cal./day</i> 716
Riverside	97	56	1061	78	32	33	628
Torrey Pines	78	59	544	72	67	31	678

* Gram calories per sq. cm. of horizontal surface per day. The record for Torrey Pines was based on July 4 to July 21, 1940.

From data given in table II we note that sunshine at the three locations during July is nearly equal. At Torrey Pines, because of its location within 1 mile of the ocean, relative humidities are high and temperatures are equable. At Indio, on the other hand, temperatures are high, noon humidity-

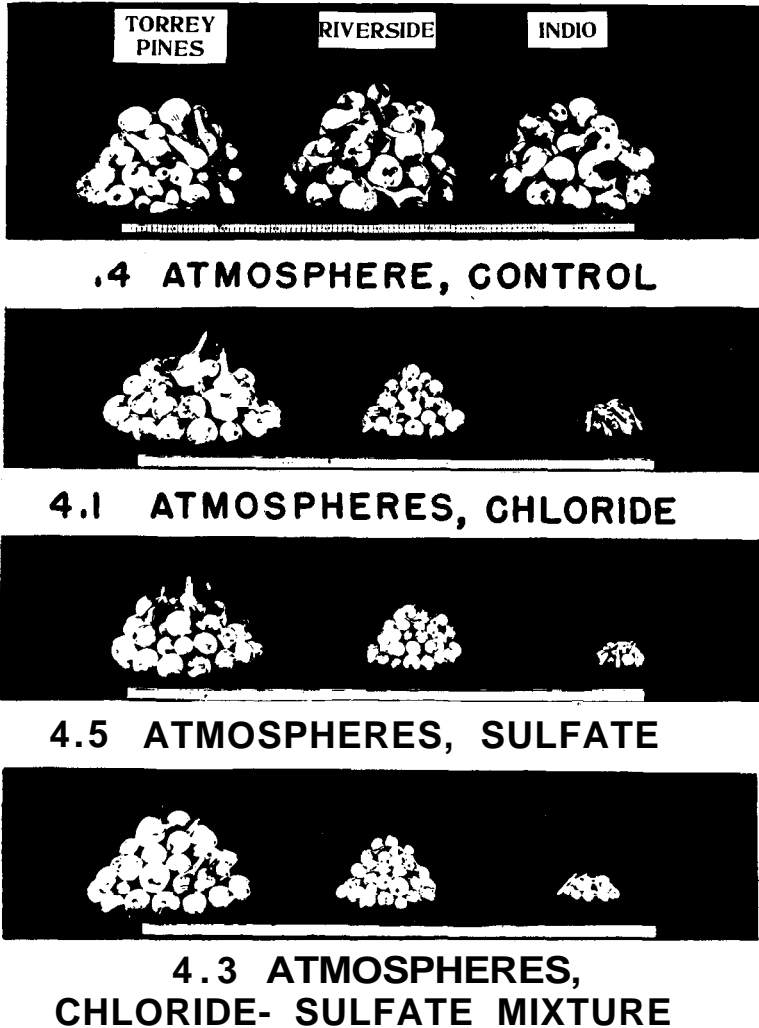


FIG. 6. Harvest yields of onions grown at three locations and at varying osmotic concentrations of substrate.

ties are low, and evaporation is high. Riverside has an intermediate climate with warm days and cool nights. Onions were grown during the period April 16 to July 26, 1940, and during the earlier part of this growth period the climatic conditions at the three stations were more similar than in July.

A picture showing onion yields is shown in figure 6.

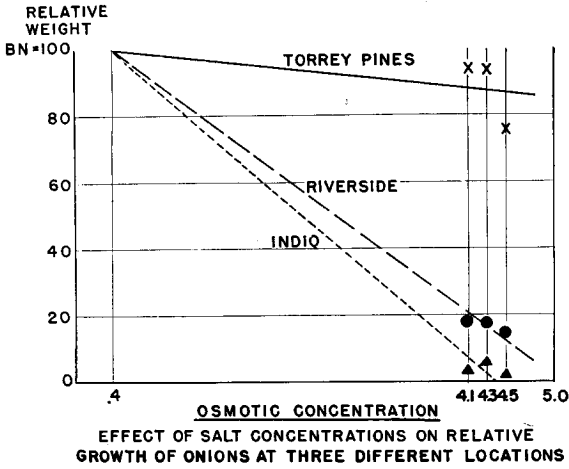


FIG. 7. Effect of salt concentration on relative growth of onions at three different locations.

One can compare the effect of salt, of climate, and of climate on salt effect at the three stations when the yields are placed on a common basis with

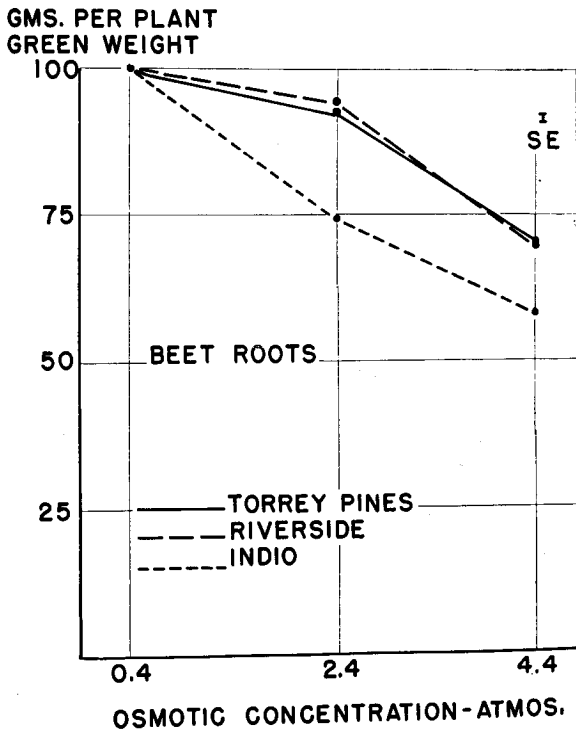


FIG. 8. Effect of salt concentrations on relative growth of roots of garden beets at three different locations. A measure of the accuracy is given by the length of the line S.E. (Standard error).

yield at each location in the base nutrient taken as 100. Actual yields in the base nutrient cultures at Indio, Riverside, and Torrey Pines were 5913, 6878, and 4577 grams of fresh bulbs respectively.

The data in figure 7 have been prepared on the relative basis and show that the yield of onions was only slightly reduced at the high salt concentrations at Torrey Pines. At Indio the reduction in relative growth at osmotic concentration of 4.1 to 4.5 atmospheres was very great, nearly 100 per cent. At Riverside the relative growth reductions were nearly as great as at Indio. This test involved three replicates and the regression lines are all significantly different from each other.

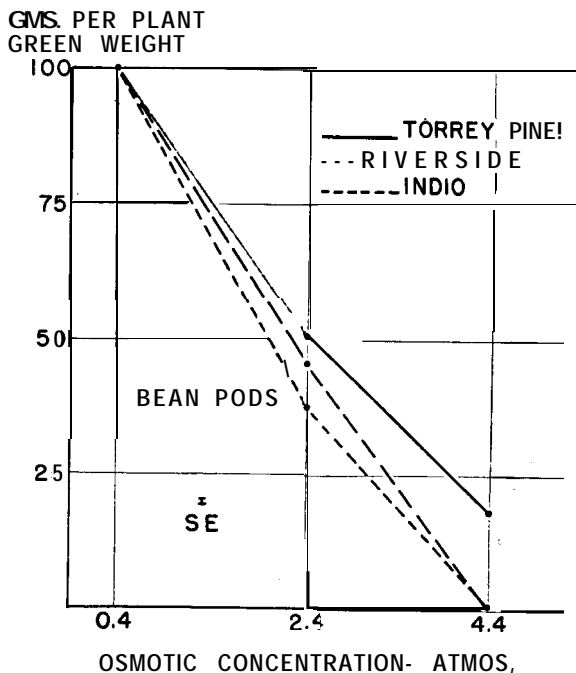


FIG. 9. Effect of salt concentrations on relative growth of beans at three different locations. A measure of the accuracy is given by the length of the line S.E. (Standard error).

When compared on this relative basis the curves in figure 7 show that in a cool climate salt concentrations in the range studied did not appreciably reduce the yield of onions. In the warmer climates as at Riverside and Indio the climate has affected the yield reduction caused by salt. In statistical terms there was a very significant interaction of climate on salt.

In 1941 additional data were obtained on beans and garden beets at the three climate locations. The data for chloride solutions are shown in figures 8 and 9.

The yields for garden beet roots shown in figure 8 indicate that on a relative basis the smallest yield reduction (base nutrient--4.4 atmospheres) occurred at Torrey Pines. On the same basis the greatest reduction in yield

with concentration was obtained at Indio. The difference in relative yield at 4.4 atmospheres at Torrey Pines and Indio was highly significant.

In the case of bean pods (fig. 9) the relative yield reduction at 4.4 atmospheres was almost the same at Riverside and Indio. The differences in relative yield between Torrey Pines and Indio were highly significant.

The data obtained in 1939 are subject to considerable variation but including only data and crops which are consistent the results for the three years can be tentatively summarized as follows:

1. A group of crops at a given salt concentration are depressed in relative yield more in warm than in cool climates. These include: in 1939, squash, and tomatoes; in 1940, onions, beans, sugar beets, alfalfa, and cotton; and in 1941, garden beets, carrots, and beans. Milo grown in 1940 grew best at Riverside and was least affected by salt at the Riverside climate.

2. Another group consists of crops for which no appreciable difference was found in the yield reduction by salt at various climates. This includes cowpeas and probably alfalfa. The data on these two crops were obtained in 1939. No alfalfa stand was obtained at Indio where daily maximum temperatures averaged 110° F.

Discussion

Best growth of a crop in nutrient solution takes place at a concentration of about 0.3 to 2.0 atmospheres, depending on the nature of the nutrient solution, volume of solution to crop, nature of crop, temperature, and other factors. It would appear that the optimum concentration should furnish an ample supply of nutrients, yet have such a low osmotic value that water absorption is not markedly reduced. In the present experiment the base nutrient solution yielded excellent crops with an osmotic concentration of 0.4 atmospheres. No tests were made with slightly greater or lower concentration. EATON (5) has indicated that small concentrations of chloride salts up to 10 milliequivalents per liter tended to improve tomato growth. The results reported in this paper do not bear on this point, but in nearly every case yields at the 2.4 atmosphere concentration were lower than in the controls. An exception occurred in the case of cotton at Torrey Pines, where the higher salt concentrations made the cotton less vegetative and the yield of bolls was greater in the salt treatments than in the controls.

The relative reduction in yield with increasing salt concentration beyond an optimum is often linear when plotted on an osmotic basis. This agrees roughly with the work of HAYWARD and LONG (6) with tomatoes. They found better growth, however, at 1.5 atmospheres than at 0.5 atmosphere, but their ratio of solution volume to growth produced was relatively low. In a base nutrient series where the osmotic concentration was achieved by using greater amounts of nutrient salts the growth was better than at comparable concentrations obtained by adding sodium chloride or sodium sulphate to a 0.5 atmosphere base nutrient solution.

EATON'S (5) data can be replotted on an osmotic concentration basis. When this is done the relationship between osmotic concentration and yields of beans, milo, seed cotton, and tomato fruits is nearly linear. Sugar beets showed a decidedly greater tolerance to chloride than to sulphate salts at equal osmotic concentrations.

AHI and POWERS (1) grew salt grass, alfalfa, and strawberry clover in various dilutions of sea water. In order to plot their yield results against osmotic values the present authors determined osmotic concentrations of Pacific Ocean water at a number of dilutions. The results obtained did not agree with a linear relationship, growth being better than expected on this basis at the high concentrations.

Work at this laboratory has dealt primarily with chloride and sulphate salts. The results to date indicate that in general, the growth reduction of crops grown in saline solutions made up of chloride and sulphate salts of calcium, magnesium, and sodium is roughly proportional to the osmotic concentration or to the conductivity of the solution. Individual crops may fall out of line somewhat, but these deviations should be checked further. Specific ion effects undoubtedly exist, but for the salts studied they appear to be of a second order, compared to the matter of total salt concentration.

While the results obtained in sand cultures indicate that there is little difference in cation effects, these results are wholly tentative. It is believed that if the range of each cation is varied widely, marked plant responses will occur. Sodium has a very profound effect on soil structure and sodium saturated soil takes on physical and chemical characteristics which are not conducive to plant growth. For this reason results with sodium in sand cultures are not expected to carry over completely into soils. Just how osmotic values affect growth is not known, but undoubtedly water intake, turgidity, and root extension are involved, together with other salt effects on the root and within the plant.

It is of interest to note that the soil solution of productive soils may have an osmotic concentration exceeding 1 atmosphere at soil moisture contents within the wilting range. Soils marginal because of salinity may have osmotic concentrations as great as 10 atmospheres at these moisture contents (9). These soil solution concentrations are of the same order as the concentrations of the culture solutions used in these sand culture experiments.

The results obtained in this study show that* most crops are injured by salt to a greater extent in warm than cool climates. The alfalfa data for 1939 gave no appreciable differences in the salt effect at Riverside and Torrey Pines. In 1940 when the alfalfa was seeded earlier in the season and good stands were obtained, decidedly poorer yields at the same salt treatments were obtained at Indio compared with Riverside and Torrey Pines. As in 1939, there was no appreciable difference in yields at Riverside and Torrey Pines in the comparable treatments.

The data of AHI and POWERS when plotted on a relative basis give

slightly, but probably not significantly, lower yields of alfalfa at warm temperatures in the presence of salt. Their cold temperature of 55° F. was about 10° less than the average temperature at Torrey Pines. These results would indicate that the temperature coefficient for salt injury in the case of alfalfa is low.

Because of the great differences in crop reaction to the combined effect of salt and temperature as shown in this paper it appears dangerous to extrapolate results from one set of climatic conditions to another.

Summary

1. Milo, cotton, alfalfa, sugar beets, barley, tomatoes, squash, cowpeas, onions, navy beans, garden beets, and carrots, were grown in large sand cultures in three diverse locations at various salt concentrations ranging from 0.4 to 4.5 atmospheres.

2. Total salt concentration expressed in atmospheres was a greater factor in determining the amount of growth reduction than effects caused by specific ions.

3. Growth reduction was in most cases linear with increasing osmotic concentration of substrate.

4. Conductance of the nutrient solution characterized the total salt effect probably as well as osmotic concentration.

5. Chloride and sulphate salts when compared on an equal osmotic basis, depressed growth to an equal extent with a number of crops. In the case of other crops, chloride salts were slightly more toxic than the sulphate at equal osmotic concentrations.

6. Within the ratios of cations used in the experiments, there was no great difference in the action of individual cations on plant response. Sodium did not appear to be an unduly toxic cation in sand cultures.

7. Crops do not behave alike in their reaction to the combined effect of salt and climate. Thus, some are reduced equally in relative yield at a given salt concentration irrespective of climate, while most crops at the same salt concentration are depressed in relative yield more in warm than in cool climates.

8. A number of crop species died in a culture solution having an osmotic concentration of 4.5 atmospheres.

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