THE INTERRELATIONSHIPS OF SALT CONCENTRATION AND SOIL MOISTURE CONTENT WITH THE GROWTH OF BEANS

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THE effect of various soil moisture treatments upon plant growth is of particular interest to the grower of crops on saline soils for it is possible that differences in soil moisture may either decrease or intensify the salt effect.

Even when no harmful concentrations of salt occur in the soil, there is a diversity of opinion as to the proper time to irrigate to get the best growth. The individual farmer follows a practice which he feels is best suited to his conditions and to the crop he is growing. It is the custom in many localities, for instance, to irrigate potatoes, lettuce, and other truck crops far more frequently than would be necessary on the basis of the amount of water used by the plants.

Veihmeyer (21),[3] Hendrickson and Veihmeyer (11, 12), and Conrad and Veihmeyer (3) concluded from their experiments that as long as the soil moisture was above the permanent wilting percentage moisture was available to the plant and that any fluctuations between field capacity and the permanent wilting percentage would not be reflected in fruit yield or amount of growth.

Results published by Aldrich, et al. (1) indicated that whenever the average soil moisture in the first 3 feet. fell below 70% of the available capacity on a clay adobe soil, the rate of growth of the pear fruits was reduced. They point out., however, that their results were conditioned by the difficulty of roots in permeating this heavy soil and by the rate of moisture movement through such a soil.

Davis (4), growing nut grass in r-gallon pots of soil at five different irrigation schedules, found that growth was reduced if the soils were allowed to dry below the moisture equivalent before they were re-wetted.

The best results with spring lettuce in Arizona were obtained by Schwalen and Wharton (20) when the soil was kept relatively moist up until the harvest period.

The relation of plant growth to variation in the available soil moisture is further complicated in those soils which contain harmful quantities of salts. As such a soil drys out, the concentration of salts in the soil solution increases. The concentration of salts in the soil solution of a soil which is at the permanent wilting percentage would be much greater than that of the same soil when only a fourth or a half of its available moisture had been utilized. These differences might easily be reflected by differences in plant growth. In other words, a plant might grow better in a saline soil which is irrigated when only

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3Figures in parenthesis refer to "Literature Cited", p. 809.

part of the available moisture has been utilized than in a similar soil in which the soil moisture is allowed to approach the permanent wilting percentage before irrigation takes place.

The material presented in this paper bears upon this complex question of soil moisture relations and plant growth in soils containing appreciable amounts of salts.

METHODS AND MATERIALS

Thirty-six 10-gallon steel drums were each filled with 102 pounds of surface soil from a location on the grounds of the Salinity Laboratory, Riverside, Calif. This soil was mapped as Sierra loam in an early survey but probably would be designated now as Fallbrook loam. As determined by the method proposed by Richards and Weaver (18), this soil held 6.2% moisture when moistened and allowed to come to equilibrium under a tension of 15 atmospheres. This 15-atmosphere value has been shown by Richards and Weaver to be in the wilting range. The permanent wilting percentage determined with sunflower plants was 6.1 and agrees closely with the I5-atmosphere value. The moisture equivalent was 14.7%. The saturated soil paste of the original soil had a pH of 7.6. At the conclusion of the experiment the soil pH values ranged from 6.6 to 8.0, depending upon treatment and the depth at which the sample was taken. Calcium was the predominating cation in the exchange complex at the start of the experiment, and there were no accumulated soluble salts in the original soil.

EXPERIMENTAL DESIGN

The experimental variables were four salt treatments, viz., no added NaCl, 1,000 p.p.m. added NaCl on dry soil basis, 2,000 p.p.m. added NaCl on dry soil basis, and 4,000 p.p.m. added NaCl on dry soil basis; and three irrigation schedules. These schedules were as follows:

A low tension series, irrigated when only small amounts of the available moisture had been utilized by the plants as explained later; a medium tension series, irrigated when moderate amounts of the available moisture had been utilized by the plants; and a high tension series, irrigated when the plants showed severe moisture stress.

The 36 drums were divided into three blocks. This gave one drum of each combination of salt and irrigation schedule per block.

The screened (¼ inch) soil was mixed in an eccentric box with the proper amount of salts for each treatment. Besides the designated sodium chloride, 3.4 grams of potassium chloride and 10.1 grams of 18% superphosphate were added to each drum of soil. One hundred and seven pounds of the soil at a moisture content of 5% were placed in each container with the aid of a mechanical mixer and packer. Nitrate was supplied by scratching I 1.3 grams of sodium nitrate into the soil surface of each drum just before the initial irrigation. These amounts of fertilizing materials corresponded to an application of 1,000 pounds of 6-8-6 fertilizer per acre.

Tensiometers were placed at depths of 4 inches and at 15 inches (bottom) of each drum in one block. Enough tap water[4] was added to bring the soil to an average moisture content of 20% This amount wet the soil above the moisture

4The Riverside tap water used in this experiment is a very good quality of irrigation water. It contains only 270 p.p.m. of dissol-ved salts (cations 45% sodium).

equivalent but did not give any free drainage. The drums were weighed daily and when the moisture content reached a designated degree of depletion, sufficient tap water was added to reestablish the 20% level.

On January 31, 1942, after the irrigated soils had been standing for several days, six germinated dwarf red kidney beans were placed in each pot. When the seedlings were well established, they were thinned to the three most uniform in each container.

Red kidney bean plants were selected for this experiment because of (a) their high sensitivity to soil salinity, (b) their rapidity in completing the reproductive cycle, and (c) then relatively small size which permitted an equable relationship between plant size and the 10-gallons of soil used in each culture.

MOISTURE TENSION AND TIME OF IRRIGATION

The plants maintained under low soil moisture tension conditions were watered when the soil moisture tension at the 4-inch depth reached 250 cm of water. This was found to correspond to an average moisture content of 15% for all the soil in the container, and all pots in this moisture series were watered when the moisture percentage dropped to this value. Soil-moisture tension readings taken at the bottom of the soil columns were usually lower than those taken 4 inches below the surface, but never indicated any excessive concentration of moisture. (Tensions were always greater than 50 cm of H_2O.) The group of plants in the medium tension series was allowed to withdraw moisture from the soil until the tensiometers at the 4-inch depth registered a soil moisture tension of 750 cm of water.[6] This corresponded to an average moisture content of 11% A third group of plants-high tension series-was not watered until the plants were appreciably wilted by mid-morning. These plants were turgid at sunrise and always recovered after irrigation. Only in those drums in which no added sodium chloride was present did the plants dry the entire soil mass to a degree approaching the 15 atmosphere percentage (6.2) which is within the wilting range. By, observation of plant response and soil moisture percentages it was found 'that the plants wilted by mid-morning when the average moisture content of the entire soil mass was reduced to the following approximate figures:

Treatment, p.p.m. NaCl	Average moisture, %
0	7.5
1,000	9.0
2,000	9.5
4,000	10.0

At this time the tensiometer readings at the 4-inch depth in all soil treatments were "off scale" and in the "O" NaCl group the tensiometers at the bottom of the drum were also off scale.

When the beans were fully matured (April 8, 1942), the fruits were picked, weighed, counted, and photographed. The soil was sampled by taking portions from each third of the container according to depth. The top third was designated

5Tension or negative pressure is here measured by the height of the column of mercury or water which it supports.

6Tensiometer readings much above 800 cm of H_2O are not considered accurate and the scale used to measure tensions is not graduated past 850. Further, the water column between the porous cup and the mercury manometer usually breaks near this latter tension range.

as 1/3, the middle third as 2/3 and the bottom third as 3/3. Specific electrical conductance determinations were made on the saturated soil paste from these samples.

RESULTS

Differences in treatment resulted in differences in the growth response of the plants and modifications in the physical and chemical characteristics of the soil. Trends in plant growth differences were evidenced early in the. experiment and became more marked with time.

Representative pots from each treatment at the time of maximum growth are shown in Fig. 1. Increased additions of sodium chloride to the soil progressively reduced plant growth. In pots having the same salt content, growth was greatest in the pots irrigated most fre-

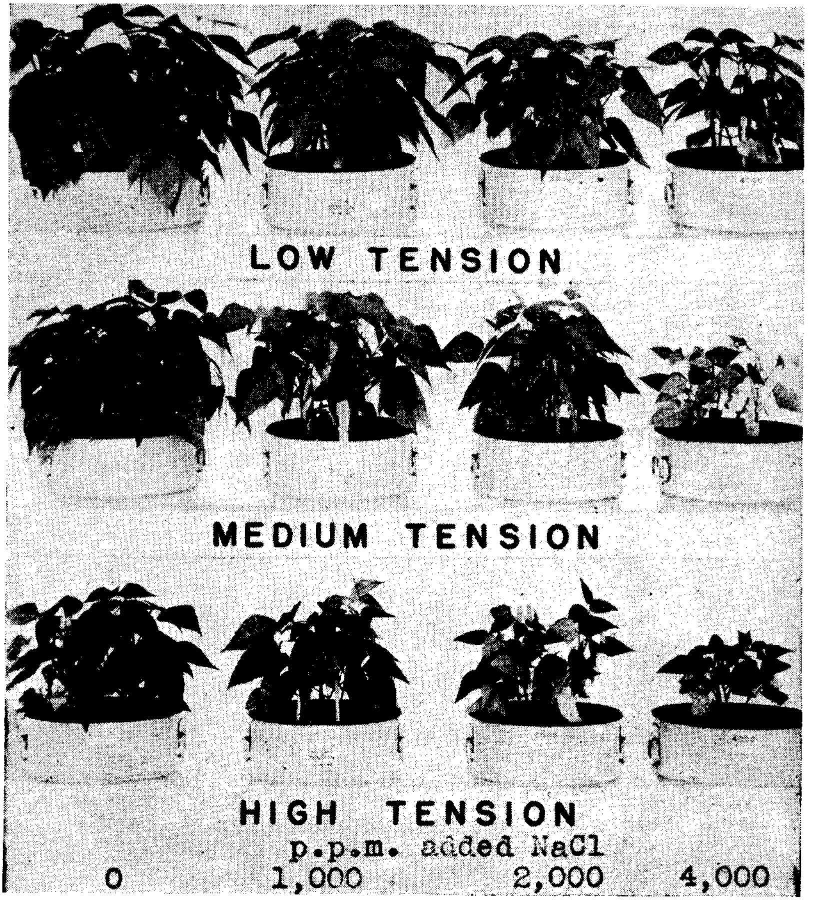

FIG. 1.--Growth of beans at four salt levels and irrigated at three soil moisturt tensions.

quently and hence maintained at the lowest tension and was poorest in the pots receiving the fewest irrigations.

The plant responses to different treatments were reflected in fruit yields as well as in vegetative growth. The average number of pods, number of beans, and weight of the beans in grams per pot is given in Table 1. Actual beans harvested from the triplicate pots are shown in Fig. 2.

Table 2 presents the F values for the various sources of induced

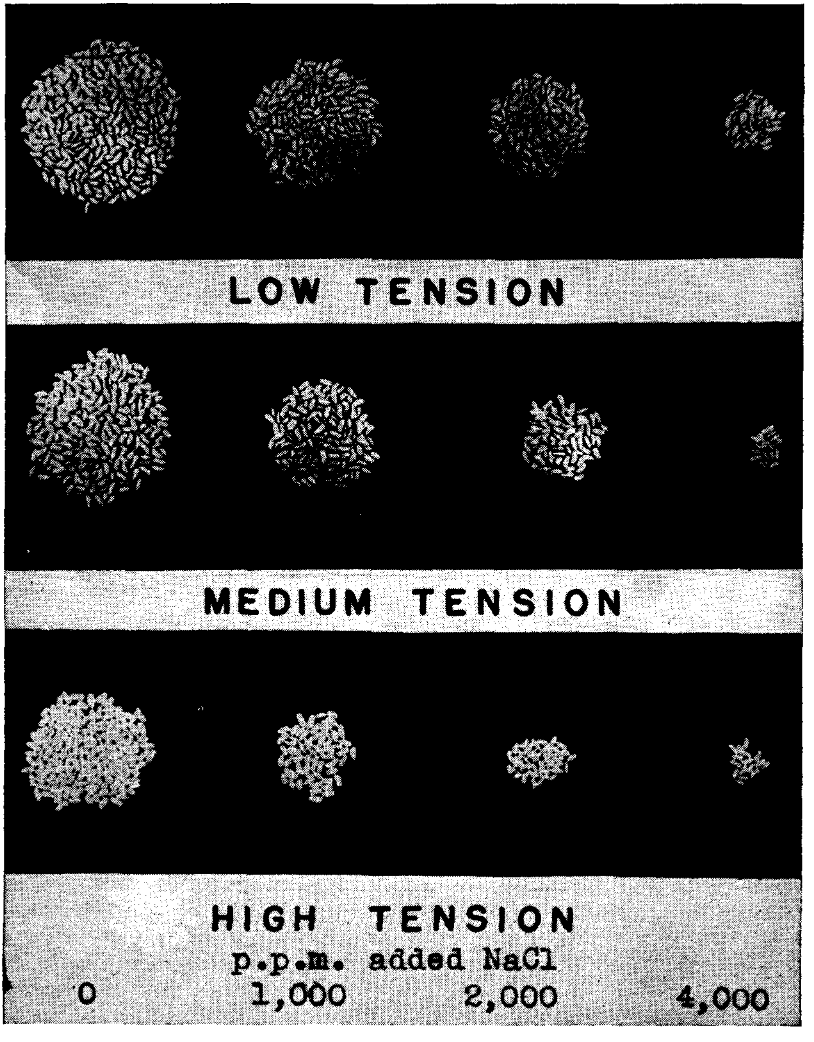

FIG. 2.-Yield of beans grown at four salt levels and irrigated at three soil moisture tensions.

variations upon the yield of beans per pot as well as the standard error and coefficient of variation.

TABLE 1.-Average yield *of beans per pot.*

Added NaCl, p.p.m.	Tension at time of irrigation								
	Low			Medium			High		
	No. of pods	No. of beans	Grams of beans	No. of pods	No. of beans	Grams of beans	No. of pods	No. of beans	Grams of beans
0	38.7	164.0	81.2	29.7	116.3	59.5	18.0	59.0	33.2
1,000	23.0	84.0	36.6	15.0	50.7	24.4	7.7	20.0	9.9
2,000	14.0	50.0	20.0	9.0	28.7	12.2	5.7	12.7	4.2
4,000	6.7	16.0	5.6	4.0	5.7	2.0	3.3	5.3	1.8

TABLE 2.-F values *for weight of beans-per pot.**

T_1 low tension-high tension	384.25**
T_2 low tension+high tension − 2 medium tension	0.18
S_1 0 NaCl − 1,000 NaCl	612.13**
S_2 2,000 NaCl − 4,000 NaCl	42.50**
S_3 (0+1,000 NaCl) − (2,000 NaCl+4,000 NaCl)	1 142.83**
T_1S_1	39.17**
T_1S_2	12.47**
T_1S_3	130.99**
T_2S_1	0.16
T_2S_2	0.35
T_2S_3	1.42
Standard error	0.627
Coefficient of variation	12.14%

*Induced effects were segregated according to a single degree of freedom analysis (22). A chi square test of individual error terms indicated their homogeniety and the validity of using a pooled error term.
**Highly significant.

Distribution of the salts within the potted soils at the end of the experiment is indicated by specific electrical conductance measurements made on the saturated soil paste. These measurements are summarized graphically in Fig. 3.

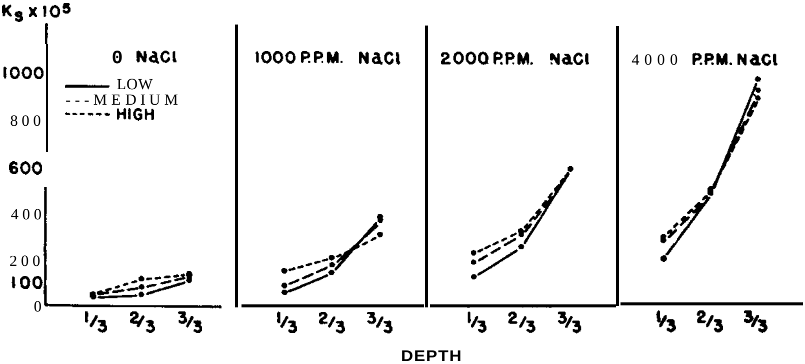

FIG. 3.-Conductance of saturated soil paste at 25° C.

Effect of treatment upon rate of growth and characteristics of fruit produced will be covered in a separate paper.

DISCUSSION

PLANT GROWTH IN THE "O" NaCl SERIES

As indicated in Figs. 1 and 2 and Table 1, the best growth and the highest yield of bean seeds were obtained in those containers which were maintained at low soil moisture tensions and to which no sodium chloride had been added. This treatment produced an average of 81 grams of beans per culture. Under the conditions of the medium moisture tension schedule, the vines produced an average of but 59 grams of beans per pot. This yield reduction occurred, although the plants were never wilted and there was always available moisture present. When irrigation was withheld from the plants until wilting[7] at mid-morning was in evidence (high moisture tension schedule), growth and yield were still further reduced. Under these conditions, each culture produced an average of only 33 grams of beans. The precision of this experiment was such (Table 2) that the above yield differences were well beyond the range required for high significance. Furthermore, the yield obtained from the medium tension pots was not significantly different from the mean of the low and high tension treatments. This is shown in Table 2 by the lack of a significant value for T_2.

The differences in yield obtained with the three irrigation schedules cannot be explained on the basis of root distribution. At the close of the experiment, examination showed that roots were well distributed throughout the entire soil mass in the "0" NaCl series. Increasing tensiometer readings also indicated that water was being removed from the lower depths as well as from the upper portions during the course of the experiment.

These reductions in the growth and yield of beans as the soils were allowed to dry to higher soil moisture tensions before being rewetted are in accord with the recent work of Davis (4) on nut grass. Previously, Furr and Taylor (7) and Aldrich, et al. (1), showed that with decreasing soil moisture the growth rate of lemon and pear fruits was retarded before the average soil moisture content reached the wilting range. Schneider and Childers (19) observed marked reductions in apparent photosynthesis and transpiration and an increase in respiration before wilting was evident in young apple leaves.

On the other hand, Veihmeyer (21), Conrad and Veihmeyer (3), and Hendricks and Veihmeyer (11, 12) found no decrease in plant growth under the conditions of their experiments as long as the soil was above the wilting point. Conrad and Veihmeyer (3) held that

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[7]It is more difficult to describe the wilting of beans than of many common plants. The leaves of succulent plants with adequate water supply but suddenly subjected to a high transpirational stress will droop markedly in the conventional manner. However, plants which are gradually subjected to water stress respond by orienting their leaves parallel to the sun's rays and by inversion of the leaves. Actual drooping is not prevalent except on some of the oldest leaves. This latter type of response by the plant is referred to in this paper as "evidence of wilting".

even though the greater amount of roots or absorbing surface was in the top dry layers, roots in the deeper layers could absorb enough moisture to satisfy the needs of the plant, except under conditions of high evaporation.

In studying the daily growth of maize, Loomis (14) observed that direct sunlight inhibited the extension of the young leaf and attributed this to a temporary water stress brought about within the plant by the sunlight. A comparison of the leaf extension 'of a plant growing in moist soil and one growing in a relatively dry soil but still above the permanent wilting percentage, pointed to a higher average growth rate and longer growing period under the moist condition. Loomis found that the plant in the drier soil did not grow during the afternoon but did grow during the night. Apparently the growth of maize depends upon a liberal supply of water in the growing region. Sunlight, low relative humidity, and low soil moisture may check this growth by creating a moisture stress within the plant. This same sort of mechanism may influence the growth of beans and other plants.

When plants are unable to exert forces of sufficient magnitude to get water from the soil at a rate necessary to satisfy their needs, the plants wilt and death may be the final result. During this drying out process of the soil, the osmotic concentration of the plant sap increases (8, 13). This increase in the osmotic concentration of the plant sap, the decreased growth rate of lemon (7) and pear (1) fruits, and the reduction in photosynthesis and transpiration in apple leaves (19) as the soil moisture approaches but is not yet within the wilting range, indicate that increased water stresses are occurring within the plant as the soils become progressively drier.

A group of plants growing in moderately or partly dry soil will be under some water stress and, according to Loomis' theory, should have their growth retarded during periods of direct sunlight. Similar plants growing in moist soil should have less of an initial moisture stress and should therefore have shorter and less frequent periods of reduced growth and a faster growth rate. Other things being equal, the group of plants having the longest periods of actual growth and the highest rate should make the most growth. This reasoning could account for differences in growth between the low and medium moisture tension series.

PLANT GROWTH IN THE 1,000, 2,000, AND 4,000 P.P.M. NaCl SERIES

Presence of added amounts of NaCl in the soil reduced growth. This was shown in Figs. 1 and 2 and Tables 1 and 2. F values for S_1, St, and S_3 indicate the reductions in the weight of beans produced to be highly significant. If the bean yield in the best treatment, no added NaCl at low soil moisture tension, is taken as 100 and if the other yields are plotted as a percentage of this figure, total relative yields are obtained as shown in Fig. 4. Besides the effect of NaCl, this graph demonstrates the relationship between yield and soil moisture tension at time of irrigation under the conditions of this experiment.

Breazeale (2), Eaton (6), Magistad, et *al.* (15), and others have correlated plant growth in culture solutions with the excessive concentration of salts in the solution. The concentration of salts in the soil solution in contact with and surrounding the plant roots plays a similar role in the soil. Breazeale (2) recognized this when he suggested that salts in the soil should be reported on the basis of the moisture content of the soil at the wilting point rather than as a percentage of the dry weight of the soil. Conductivity measurements of the saturated soil (Fig. 3) give a relative measure of the expected concentrations of these soil solutions. The actual magnitude of these concentrations for several selected samples is shown in Table 3, together with the calculated changes occurring in concentration as the soil dries from a percentage slightly above the "field capacity" to a point where plants in the nonsaline soil begin to wilt. Solutions were extracted from these soils at approximately 12% moisture by the

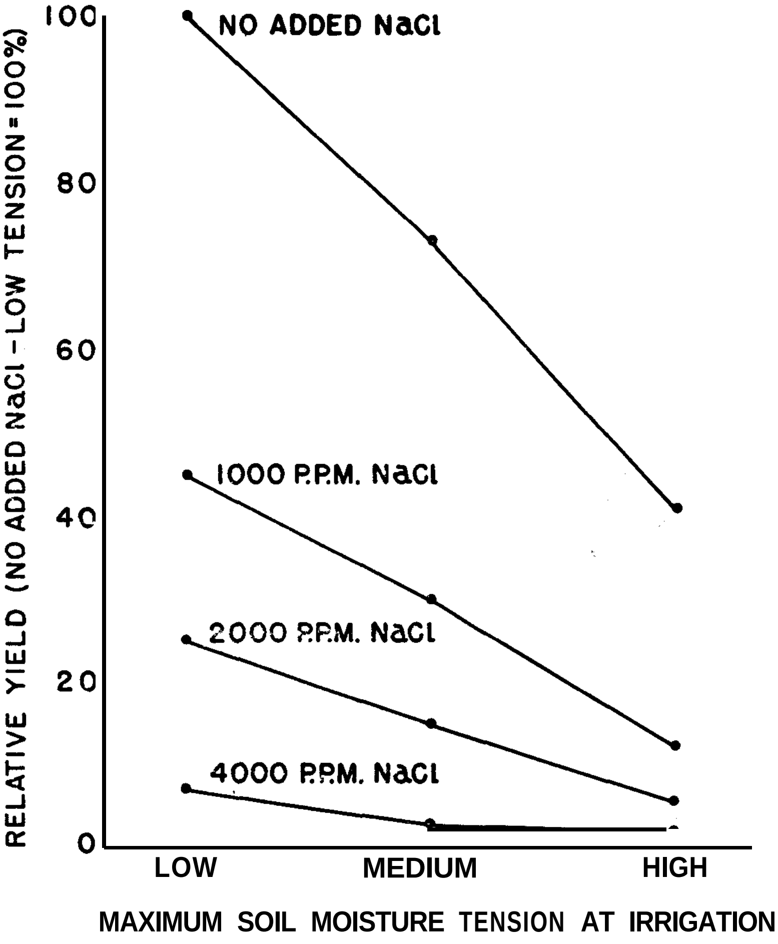

FIG. 4.-Relative yield of bean plants as conditioned by the various experimental treatments.

TABLE 3.—*Concentration of soil solution at close of experiment.*

Added NaCl, p.p.m.*	Depth, inches	Conductance soil paste, $K_s \times 10^5$@25°C†	Soil moisture, %	Conductance soil solution, $K \times 10^5$@25°C	Concentration soil solution, atmosphere‡	Calculated concentration of soil solution at four soil moisture percentages, atmos.§			
						7%	11%	15%	20%
0	0–5	51	11.27	284	1.04	1.67	1.07	0.78	0.59
0	5–10	86	11.35	630	2.63	4.26	2.71	1.99	1.49
0	10–15	122	11.02	1,075	3.55	5.59	3.56	2.61	1.96
1,000	0–5	92	11.71	711	2.64	4.41	2.81	2.06	1.55
1,000	5–10	199	12.56	1,800	7.00	12.6	7.99	5.86	4.40
1,000	10–15	369	12.57	3,480	14.3	25.7	16.3	12.0	8.99
2,000	0–5	165	12.84	1,405	5.34	9.80	6.23	4.57	3.43
2,000	5–10	305	12.96	2,840	11.08	20.5	13.1	9.57	7.18
2,000	10–15	574	12.82	5,540	23.31	42.7	27.2	19.9	14.9
4,000	0–5	271	11.64	2,560	11.3	18.8	12.0	8.77	6.58
4,000	5–10	494	11.98	4,260	19.9	34.0	21.7	15.9	11.9
4,000	10–15	915	11.94	8,590	50.4	86.0	54.7	40.1	30.1

*All samples from medium tension series.
†Saturated soil paste contained 37% moisture.
‡Osmotic concentration of solution in atmospheres calculated from freezing point depression.
§Values calculated assuming only simple dilution or concentration.

pressure-membrane apparatus described by Richards (16) 'and concentrations at the other moisture contents calculated. Obviously, there is a tremendous change in concentration as the soils dry.

In order to show the effect of the moisture treatment in the presence of salts, the bean yields were recalculated on a relative basis using the yield of the low moisture tension treatment for each salt level as 100. Averages of the three replications are plotted in Fig. 5. The slopes of these curves show that when salts were present in the soil, increasing the soil moisture tension at the time of irrigation increased the severity of the salt treatment.

The reasoning that growth differences in soils at several moisture contents above the permanent wilting percentage may be due to

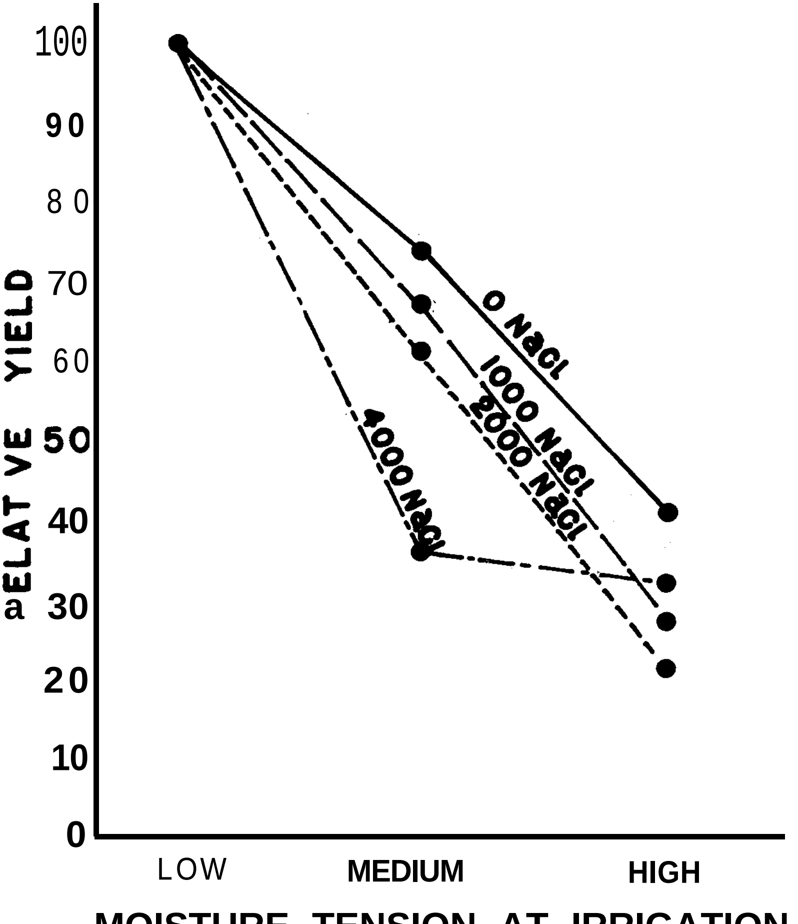

FIG. S.-Relative yield of beans grown at four salt levels and irrigated at three soil moisture tensions using the yield at the low moisture tension at each salt level as 100.

water stresses affecting the total time and rate of actual growth is also applicable to the growth of plants in soils containing added NaCl. Decreased relative yields in the saline soils irrigated at increasing soil moisture tensions may be a reflection of the water stresses produced in the plant under these conditions.

OSMOTIC EFFECT OF SOIL SOLUTION

With respect to the energy relations, more work is required to remove a gram of water from a solution as its concentration increases. Plants growing in saline soils must then do more work to obtain a given amount of water than plants growing in a less concentrated soil solution. Moisture treatments will affect the concentration of this soil solution. As shown in Table 3, soils which are allowed to dry to a point just above the wilting range will have for considerable periods of time a much more concentrated soil solution than similar soils which are kept relatively moist. In substantiation of the osmotic effect of the soil solution, Eaton (5) has brought out the fact that roots absorb more water from dilute than from the more concentrated solutions.

It is noteworthy that the soil to which no sodium chloride had been added revealed very significant osmotic concentrations of the soil solution. These concentrations arose mainly from the- moderately heavy application of fertilizing materials. In the cultures in which the moisture content of the soil became low, it is evident that the concentration of the soil solution was sufficient to be definitely inhibitive to the growth of beans (15). This situation was unquestionably involved in the growth decreases accompanying the increased degree of soil moisture depletion prior to irrigation. Nevertheless, it should be emphasized that the yield of the plants in the cultures with 1,000 p.p.m. of added salt in the low tension series was higher than that from the "no salt" cultures of high tension series, even though the osmotic concentrations of these soil solutions within their respective limits of soil moisture content was just the reverse. This is shown as follows:

	High tension, no salt	Low tension, 1,000 p.p.m. salt
Grams of beans	33.2	36.6
Osmotic concentration of soil solution at:		
0-5 in.	1.67	2.06
5-10 in.	4.26	5.86
10-15 in.	5.59	12.0

The above observations suggest that far more attention should be given to osmotic relationship of soil solutions in non-saline as well as in saline soils. It would seem that particular study should be made of osmotic concentrations occurring when large fertilizer applications are made to heavy soils, and of the effect of such conditions on plant growth, apart from the plant food effect.

EXTENSION OF ROOTS INTO NEW SOIL AREAS

The inhibiting action of concentrated soil solutions upon the extension of the plant root system into new soil areas may be even more important than the direct osmotic effect upon water absorption. Movement of water from unsaturated moist soil into dry soil is extremely slow. If the roots do not grow into new soil masses, water absorption is limited to areas already occupied by these roots and this available moisture may be quickly utilized. In the case of annual plants and rapidly growing young perennials, the extension of the root system is imperative for continued vigorous growth from the standpoint of the rate of absorption of both water and nutrients.

Eaton (5) showed that concentrated salt solutions definitely retard root growth. Additions of NaCl to soil in this experiment limited root distribution. This was evidenced from excavations made at the conclusion of the experiment as shown in Table 4, and from soil moisture tension measurements made in the pot during the growth period.

TABLE 4.—*Approximate depth of root penetration in inches.*

Added NaCl, p.p.m.	Soil moisture tension at time of irrigation		
	Low	Medium	High
0	15*	15	15
1,000	12	11	10
2,000	9	8	8
4,000	8	7	6

*Total depth of soil 15 inches.

DECREASED ABSORPTIVE CAPACITY OF ROOTS

High concentrations of salts in the soil solution which limit root growth may affect moisture absorption by plants in still another manner. Maximum moisture absorption occurs just back of the root tip in the area where elongation is taking place and secondary thickening has not yet started (10). Roots in concentrated salt solutions grow slowly (5), becoming quickly suberized and having little rapidly absorbing root area (5, 9). Any factor, such as moisture level or the addition of NaCl, which affects the concentration of the soil solution will affect the amount of new roots being produced. Other things being equal, plants with a high percentage of young, rapidly absorbing roots should be able to take up water at a faster rate than plants having an equal amount of older roots.

Many factors undoubtedly play important roles in the effect of salts upon growth of plants in soils, It is not intended that climate, leaching, aeration, soil structure, soil reaction, direct toxicity of specific ions, and other effects be overlooked or minimized; but consideration should also be given to the part played by moisture stresses within the plant and the soil-root relationships which may affect these stresses. Relationships which should not be overlooked include (a) the increased work necessary to obtain water from the soil as the soil moisture tension increases; (b) the increased work necessary to obtain water from the soil solution as the osmotic concentration of the soil solution is increased; (c) the inability of the plant roots to grow into areas of undepleted soil moisture because of the presence of high concentrations of salts in these areas; and (d) the inability of the plant to produce new roots having a maximum absorptive capacity because of the presence of high concentrations of salts in the soil solution. Each of these factors may be affected directly or indirectly by the frequency of irrigation and may have a bearing upon irrigation practice in saline soils.

SUMMARY

Dwarf red kidney beans were grown to maturity in 10-gallon containers filled with loam soil. These soils contained 0, 1,000, 2,000, and 4,000 p.p.m. of added sodium chloride on the dry soil basis. The 36 containers were divided into three moisture tension series. Water was added when the soil moisture tension at the 4-inch depth had reached 250 cm of water and 750 cm of water for the first two series, respectively. Water was added to the third series when the plants were wilted by mid-morning, corresponding to tensions exceeding 800 cm of water.

Bean growth and yield were reduced as the soil moisture tension at time of irrigation increased, even though in some of the treatments the soil moisture was always above the wilting range.

Progressive additions of sodium chloride to the soil caused progressive decreases in growth and yield of beans.

The relative effect of sodium chloride on the reduction in yield of bean fruits was greater in those treatments in which the soil moisture tensions were greater at the time of irrigation.

Attention is called to a consideration of moisture stresses within the plant in relation to growth and to certain factors which may affect these stresses.

LITERATURE CITED

1. ALDRICH, W. W., LEWIS, M. R., WORK. R. A., RYALL, A. L., and REIMER, F. C. Anjou pear responses to irrigation in a clay adobe soil. Ore. Agr. Exp. Sta. Bul. 374. 1940.
2. BREAZEALE, J. F. A study of the toxicity of salines that occur in black alkali soils. Ariz. Agr. Exp. Sta. Tech. Bul. 14. 1927.
3. CONRAD, J. P., and VEIHMEYER, F. J, Root development and soil moisture. Hilgardia, 4:1 13-134. 1929.
4. DAVIS, CHARLES HOMER. Responses of Cyperus rotundus L. to five moisture levels. Plant Physiol., 17:311-316. 1942.
5. EATON, F. M. Water uptake and root growth as influenced by inequalities in the concentration of the substrate. Plant Physiol., 16:545-564. 1941.
6. ———. Toxicity and accumulation of chloride and sulfate salts in plants: Jour. Agr. Res., 64:357-399. 1942.
7. FURR, J. R., and TAYLOR, C. A. Growth of lemon fruits in relation to moisture content of the soil. U. S. D. A. Tech. Bul. 640.1939.
8. ——— and REEVE, M. 0. The range of soil moisture percentages through which plants undergo permanent wilting in some soils from semiarid irrigated areas. (In preparation.)
9. HAYWARD, H. E., and BLAIR, WINIFRED M. Some responses of Valencia orange seedlings to varying concentrations of chloride and hydrogen ions. Amer. Jour. Bot., 29:148-155. 1942.

10. ——— and SKALING, P. E. Device for measuring entry of water into roots. Bot. Gaz., 104:152-160 1942.
11. HENDRICKSON! A. H., and VEIHMEYER, F. J. Some factors concerning soil moisture of mterest to horticulturists. Amer. Soc. Hort. Sci. Proc., 26:105-108.1929.
12. ——— Irrigation experiments with pears and apples. Calif. Agr. Exp. Sta. Bul. 667. 1942.
13. HERRICK, ERVIN M. Seasonal and diurnal variations in the osmotic values and suction tension values in the aerial portions of ***Ambrosia*** trifida. Amer. Jour. Bot., 20:18-34. 1933.
14. LOOMIS, W. E. Dally growth in maize. Amer. Jour. Bot., 21:1-6. 1934.
15. MAGISTAD, 0. C., AYERS, A. D., WADLEIGH, C. H., and GAUCH, H. G. Effect of salt concentration,, kind of salt, and climate on plant growth in sand cultures. Plant Physiol., 18:151-166. 1943.
16. RICHARDS, L. A. A pressure-membrane extraction apparatus for soil solutions. Soil Sci., 51:377-386. 1941.
17. ——— Soil moisture tensiometer materials and construction. Soil Sci., 53:241-248. 1942.
18. ——— and WEAVER, L. R. Moisture retention by some irrigated soils as related to moisture tension. (In press.)
19. SCHNEIDER, G. WILLIAM, and CHILDERS, N. F. Influence of soil moisture on photosynthesis, respiration, and transpiration of apple leaves. Plant Physiol., 16:565-583. 1941.
20. SCHWALEN, H. C. and WHARTON, M. F. Lettuce irrigation studies. Ariz. Agr. Exp. Sta. Bul. 133. 1930.
21. VEIHMEYER, FRANK J. Some factors affecting the irrigation requirements of decidious orchards. Hilgardia, 2:125-291. 1927.
22. WADLEIGH, C. H., and THARP, W. H. Factorial design in plant nutrition experiments in the greenhouse. Ark. Agr. Exp. Sta. Bul. 401. 1940.