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Yield and Quality Response of Salt-stressed Garlic

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Abstract. **Garlic (*Allium sativum* L.) salt tolerance was determined in a 2-year field plot study. Saline treatments were imposed by irrigating with water that was salinized with 1 NaCl : 1 $CaCl_2$ (w/w). The electrical conductivities of the irrigation water was 1.4 (control), 3.1, 5.8, 8.8, 12.0, and 14.8 dS·m^{-1} in 1990 to 1991 and 1.4, 2.0, 3.9, 5.8, 7.8, and 9.9 dS·m^{-1} in 1991 to 1992. Considering both years, relative bulb yield was reduced 14.3% with each unit increase in soil salinity >3.9 dS·m^{-1}. Increasing soil salinity significantly reduced all yield components (i.e., bulb weight and diameter; plants per unit area). Percentage of solids in the bulb was significantly reduced as soil salinity increased. Leaf tissue accumulated significantly higher Cl, Na, and Ca concentrations then did bulb tissue.**

Garlic culture, like that of onion (*Allium cepa* L.), dates back to time immemorial. Although native to central Asia, garlic was grown and consumed in Egypt as early as 2780 B.C. (Yamaguchi, 1983). Garlic is first mentioned in the Americas with the arrival of Cortes in Mexico. It was thought to have been cultivated by the Choctaw Indians before 1775 and is mentioned in American gardening books as early as 1806 (Seelig, 1974).

Although southern Louisiana was probably the first area in the United States to grow garlic commercially (Seelig, 1974), most of the domestically grown garlic now is produced in California (Lorenz and Maynard, 1980). Garlic can be grown in almost all California agricultural areas, but the major production occurs in areas where salinity problems already exist or may develop from using saline irrigation water (Mann et al., 1961). There is a lack of information pertaining to garlic growth under saline conditions. My objective was to determine the yield and quality response of garlic, other than aromatic constituents, grown under increasing levels of salt stress.

Methods and Materials

This study was conducted at the Irrigated Desert Research Station, Brawley, Calif., on a Holtville silty clay soil [clayey over loamy, montmorillonitic (calcareous), hyperthermic Typic Torrifluvent]. Each plot was 6.0 × 6.0 m and enclosed by acrylic-fortified fiberglass borders that extended 0.75 m into the soil. The fiberglass borders protruded 0.15 m above the soil level of the plot and were covered with a berm 0.18 m high and 0.60 m wide. Walkways, 1.2 m wide, between plots and good vertical drainage effectively isolated each plot.

Preplant, triple superphosphate was mixed into the top 0.25 m of soil at 73 kg P/ha. To ensure adequate N fertility, $Ca(NO_3)_2$ was added at each irrigation at 0.14 kg N/ha per millimeter water applied. The soil contained adequate K levels, so no additional K was added.

Two ‘California Early’ type garlic breeding lines were planted in level plots on 27 Sept. 1990 and 2 Oct. 1991. The breeding lines used in 1990 were BFP 5512 and BFP 6115. Because the same breeding lines were not available the second year, BFP 5526 and BFP 6123 were used in 1991. Each plot contained 10 rows of each breeding line. The rows were planted 0.25 m apart, with the cloves placed ≈25 mm apart within the row. The potential population at this planting density was 143 plants/m^2.

The experiment consisted of six salinity treatments replicated three times in a randomized split-plot design, with salinity as main plots and breeding lines as subplots. Before planting each year, all plots were differentially presalinized to a 0.9-m depth with irrigation water identical to that used during the growing seasons. To ensure good germination, 60 mm of low-salinity water (1.4 dS·m^{-1}) was applied to each plot immediately after planting to leach salts from the top 0.15 m of soil. In addition, two 40-mm irrigations with low-salinity water were applied at ≈14-day intervals to prevent soil crusting during germination.

Differential saline irrigations were initiated 40 and 48 days after planting in 1990 and 1991, respectively. Due to uneven plant emergence with both breeding lines in both years, plant height ranged from 10 to 120 mm. To allow the plants to adjust osmotically, irrigation water salinities were increased stepwise in one-third increments over 2 weeks by adding equal weights of NaCl and $CaCl_2$ until desired salt concentrations were achieved. In 1990 to 1991, the electrical conductivities of the six irrigation waters (EC_{iw}) were 1.4 (control), 3.1, 5.8, 8.8, 12.0, and 14.8 dS·m^{-1}. The irrigation water salinity was decreased to 1.4, 2.0, 3.9, 5.8, 7.8, and 9.9 dS·m^{-1} in the 1991–92 season to reduce the severe yield reductions obtained from the previous year's higher salinities. During both growing seasons, all plots were irrigated at ≈2-week intervals to keep the soil matric potential of the control treatments above –85 J·kg^{-1} in the 0.15- to 0.3-m zone. The total irrigation water applied was 597 mm from 1990 to 1991 and 518 mm from 1991 to 1992.

The electrical conductivity of the saturated-soil extract (EC_e) was determined each year on soil samples taken ≈12, 20, and 29 weeks after salination. Two soil samples per plot were taken in 0.3-m increments to a depth of 0.9 m. Depth-averaged EC_e over the course of the experiment was 3.0, 4.2, 6.0, 7.2, 8.8, and 9.8 dS·m^{-1} in 1990 to 1991 for the six treatments and 2.3, 3.4, 4.2, 6.6, 7.7, and 8.3 dS·m^{-1} in 1991 to 1992.

The monthly mean high ranged from 20 to 33C in Jan. 1991 and May 1991, respectively; the corresponding monthly mean lows were 4 and 14C, respectively. During the 1991–92 growing season, the mean highs were 20 and 34C for Jan. 1992 and May 1992, respectively; monthly mean lows for the same period ranged from 4 to 17C. The cumulative Class A pan evaporation during the growing seasons was 1600 and 1400 mm in 1990 to 1991 and 1991 to 1992, respectively.

Mature, most recent, fully expanded leaves were sampled on 14 Apr. 1991 and 10 Apr. 1992. At the time of sampling, above-ground vegetative growth was nearly complete. Leaves were washed with distilled water, dried at 70C, and finely ground in a blender. Chloride concentration was determined on 0.1 M nitric acid in 1.7 M acetic acid extracts of the leaf material by the Cotlove (1963) coulometric-amperometric titration procedure. Nitric–perchloric acid digests of the ground leaves were analyzed for P by molybdovanadate-yellow colorimetry (Kitson and Mellon, 1944), and Na, Ca, Mg, and K by atomic absorption spectrophotometry.

Because salinity affected the maturation rate, plants within each treatment were harvested as they matured. Plants growing at the highest salinity treatment were harvested on 28 May 1991 and 3 June 1992; plants in the control treatments did not reach maturity until ≈3 weeks later. At maturity, the garlic bulbs showed a distinct knobbiness, and there were three to four leaf sheaths per bulb. After removal from the soil, all plants were placed on plastic sheets and allowed to dry for 2 weeks. After drying, the tops were removed by cutting them ≈40 mm above the bulb. To determine vegetative growth, the tops from all plants

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were dried in a forced-air drier at 70C until completely dry and then weighed. Before weighing bulbs, the roots were closely trimmed to the base of each bulb, and all extraneous soil was removed. Then, the bulbs were sized according to the U.S. grading standards for fresh-market garlic (Agricultural Marketing Service, 1981).

After the bulbs were weighed and sized, two 10-bulb random samples each were taken from each treatment for percent solids determination. The samples were finely chopped with a food chopper, weighed, and dried in a forced-air drier at 105C until completely dry. The percent solids then was determined gravimetrically.

An additional sample of bulbs was used for elemental analysis. For these analyses, the analytical methods were the same as those used to determine leaf elemental content.

Results and Discussion

Yield response. Total bulb weight was reduced significantly when the average root zone EC_e exceeded 3.0 $dS \cdot m^{-1}$ for both breeding lines in 1990 to 1991 (Table 1). Although BFP 5526 showed a significant linear yield decline at salinities >2.3 $dS \cdot m^{-1}$ in 1991 to 1992, the yield of BFP-6123 was not significantly reduced until salinity was >4.2 $dS \cdot m^{-1}$ (Table 2). The yield reduction at the lower salinities in both years was caused primarily by a reduction in individual bulb weight, rather than a decrease in the number of bulbs harvested per unit area. Only at the higher salinities did the reduced number of bulbs contribute significantly to yield reduction.

A significantly higher total yield per unit area was obtained in 1990 to 1991 than in 1991 to 1992. Due to a purple blotch [*Alternaria porri* (Ellis) cif.] infestation in the second year, the yields at all treatment levels were significantly lower than the average yield of garlic grown in California (i.e., ≈2000 $g \cdot m^{-2}$) (California Dept. of Food and Agriculture, 1993). However, the yield of both breeding lines in the 1990–91 planting equalled or exceeded the average California yields up to soil salinities ≥4.2 $dS \cdot m^{-1}$. The average bulb diameter tended to exceed the 39-mm-diameter requirement for U.S. no. 1 grade garlic (Agricultural Marketing Service, 1981) until EC_e was >6.0 and >4.2 $dS \cdot m^{-1}$ in 1990 to 1991 and 1991 to 1992, respectively.

In 1991, individual bulbs harvested from the control treatment tended to be ≈25% lower in weight than bulbs produced in California's San Joaquin Valley. Because bulb formation occurs in response to spring's gradual warming and day lengthening (Mann et al., 1961), the high temperatures during bulb formation in April and May at the experimental site may have limited bulb development.

Percent solids, a measure of quality for processing, was significantly reduced in both harvests by increasing soil salinity levels (Tables 1 and 2). With the exception of BFP 6123 in 1991 to 1992, the percent solids were at acceptable levels for the processing industry (i.e., >39%) until soil salinities were >4.2

Table 1. Bulb yield and vegetative growth of two garlic breeding lines grown in 1990 to 1991 at six salinity levels.

	Bulb					
Soil salinity ($dS \cdot m^{-1}$)	Total wt ($g \cdot m^{-2}$)	Avg wt (g/bulb)	Avg diam (mm)	Avg no./m^2	Soluble solids (%)	Vegetative dry wt ($g \cdot m^{-2}$)
			BFP 5512			
3.0	2506	27.5	50	92.0	40.6	445
4.2	1999	23.2	51	86.3	39.0	478
6.0	1681	18.7	46	90.0	36.9	453
7.2	1113	13.2	38	85.0	33.2	270
8.8	576	6.9	31	83.7	30.1	117
9.8	96	2.3	19	41.0	27.9	28
Significance[z]	L***	L***	L, Q***	L, Q***	L***	L, Q***
			BFP 6115			
3.0	2436	23.7	49	102.7	39.0	480
4.2	2128	21.8	48	98.3	38.7	528
6.0	1668	17.1	45	97.7	36.2	443
7.2	996	11.3	37	88.3	31.3	254
8.8	565	7.0	30	80.7	29.3	127
9.8	83	1.8	17	44.0	25.8	28
Significance	L***	L***, Q*	L, Q***	L***, Q*	L***, Q*	L, Q***

[z]L = linear; Q = quadratic.

*, ***Significant at $P \leq 0.05$ or 0.005, respectively.

Table 2. Bulb yield and vegetative growth of two garlic breeding lines grown in 1991 to 1992 at six salinity levels.

	Bulb					
Soil salinity ($dS \cdot m^{-1}$)	Total wt ($g \cdot m^{-2}$)	Avg wt (g/bulb)	Avg diam (mm)	Avg no./m^2	Soluble solids (%)	Vegetative dry wt ($g \cdot m^{-2}$)
			BFP 5526			
2.3	1856	18.2	44	102.0	39.6	419
3.4	1713	12.4	44	141.7	38.8	457
4.2	1604	12.8	40	126.7	39.0	442
6.6	1409	12.7	37	111.3	37.8	348
7.7	1159	12.9	32	91.0	34.4	279
8.3	1047	8.1	33	130.0	35.1	251
Significance[z]	L***	L***	L***	NS	L***	L***
			BFP 6123			
2.3	1496	13.4	41	111.3	38.2	413
3.4	1585	13.9	40	114.3	36.9	508
4.2	1474	12.4	39	118.7	36.9	511
6.6	1324	10.4	33	127.3	34.3	426
7.7	1019	10.9	31	94.3	32.1	327
8.3	879	8.9	29	98.7	32.2	249
Significance	L, Q***	L***	L***	L, Q***	L***	L, Q***

[z]L = linear; Q = quadratic.

NS, ***Nonsignificant or significant at $P \leq 0.005$.

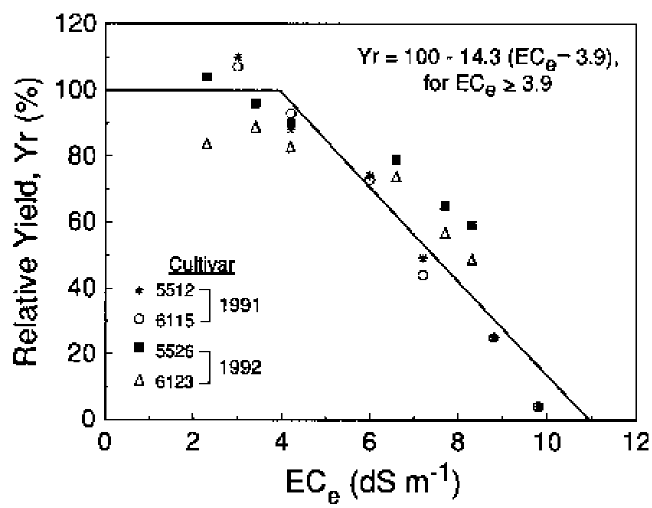

Fig. 1. Relative bulb yield of four garlic cultivars as a function of increasing soil salinity.

dS·m^{-1} (E.A. Kurtz, personal communication).

During the two years, bulb yield data were analyzed statistically for each breeding line with a piecewise linear response model (van Genuchten and Hoffman, 1984). The data indicated that the tolerance thresholds (the maximum allowable EC_e without a yield decline) were nearly the same for all breeding lines. Although the yield decline above the thresholds were slightly different between years, the bulb yield data for both breeding lines for both years were combined and analyzed. The combined data indicated a tolerance threshold of 3.9 dS·m^{-1} and a yield decline of 14.3% for each unit increase in salinity above the threshold (Fig. 1). Relative yield can be calculated with the function presented in Fig. 1 for any EC_e exceeding the threshold of 3.9 dS·m^{-1}.

The yield response curve does not fall within a single salt tolerance category as established by Maas and Hoffman (1977). The threshold value places garlic in the moderately tolerant category, but because of the steep slope, the curve drops sharply into the moderately sensitive category when EC_e is >5.0 dS·m^{-1}. Although the salt tolerance threshold tends to be slightly higher than most vegetable crops, yields drop rapidly once soil salinity values exceed the threshold (Maas and Hoffman, 1977).

Vegetative response. A progressive reduction in plant height associated with increased soil salinity was noted ≈1 month after initial salination. The first injurious effect of salinity was observed ≈1 month later, when leaf tip necrosis occurred on plants at the highest salinity levels. By harvest, plants in all treatments had developed necrotic tips on the oldest mature leaves. The severity of the leaf damage was related directly to the salinity treatment. The necrosis on control plants encompassed ≈35 mm of the leaf tip, whereas it encompassed ≈75 mm of the tip on the high-salt treatment both years. This necrosis is similar to that reported for onion grown under saline conditions (Bernstein and Ayers, 1953).

Vegetative growth was reduced significantly when EC_e was >4.2 dS·m^{-1} for both breeding lines both harvest years (Tables 1 and 2). The reduction in vegetative growth associated with increased salinity levels was undoubtedly due to the reduction in plant height and the loss of leaf photosynthetic tissues (i.e., increased necrotic tissue).

Mineral composition of leaves sampled was similar for both breeding lines in each year within a salinity treatment (Table 3). Increased substrate salinity caused an associated increase in Cl and Ca concentration in the leaf tissue. Compared to Cl, Na was almost excluded from the leaves; its concentration increased only moderately in 1990 to 1991 and not at all in 1991 to 1992. Although leaf Mg and K concentrations showed a small but significant reduction, P showed no response to increased soil salinity (data not presented). The average Mg, K, and P concentration in the leaf tissue for the breeding lines in both years was 117, 1240, and 88 mmol·kg^{-1} dry weight, respectively.

Although garlic clove tissue is foliar in origin, the Cl and Ca concentration in this tissue was significantly lower than that found in corresponding above-ground leaf tissue (Table 4). These large concentration differences between bulbs and leaves also occur in onions, which also have bulbs of foliar origin (Bernstein and Ayers, 1953). In contrast to onions, Na accumulation was significantly higher in garlic cloves than in leaves. The tendency of the 9.8 dS·m^{-1} treatment in 1990 to 1991 to exert an effect in increasing the Cl, Ca, and Na concentrations compared to the other salinity treatments was probably due to the virtual inhibition of bulb growth at 9.8 dS·m^{-1}.

This study shows that, although garlic tends to be slightly more salt tolerant than most vegetable crops, the need to maintain low soil salinity levels is essential for maximum yield. Once salinity exceeds the 3.9-dS·m^{-1} threshold, the yield and quality processing attributes are significantly reduced.

Table 3. Chloride, Na, and Ca concentrations in garlic leaves grown for two harvest seasons at six salinity levels.

Soil salinity (dS·m^{-1})	Concn (mmol/kg dry wt)[z] Cl	Na	Ca	Cl	Na	Ca
		BFP 5512			*BFP 6115*	
1990–91						
3.0	603	12.3	412	656	7.8	385
4.2	864	17.8	404	784	8.4	382
6.0	1155	11.7	570	1056	9.3	561
7.2	1529	17.2	634	1477	10.7	623
8.8	1563	16.4	584	1647	12.3	635
9.8	1705	24.1	662	1888	21.7	723
Significance[y]	L***	L***, Q*	L***, Q*	L***	L, Q***	L***
		BFP 5526			*BFP 6123*	
1991–92						
2.3	416	11.9	400	430	4.4	386
3.4	622	11.7	430	535	4.7	376
4.2	692	9.8	525	629	4.5	476
6.6	777	11.8	552	757	4.5	505
7.7	892	9.5	583	904	5.4	548
8.3	1044	9.7	628	963	4.8	568
Significance	L***	NS	L***	L***	NS	L***

[z]mg/kg dry wt = mmol·kg^{-1} × atomic weight.
[y]L = linear; Q = quadratic.
NS, *, *** Nonsignificant or significant at $P \leq 0.05$ or 0.005, respectively.

Table 4. Chloride, Na, and Ca concentrations in garlic bulbs grown for two harvest seasons at six salinity levels.

Soil salinity (dS·m^{-1})	Concn (mmol/kg dry wt)[z] Cl	Na	Ca	Cl	Na	Ca
		BFP 5512			*BFP 6115*	
1990–91						
3.0	24.4	8.9	38.7	24.8	8.4	37.2
4.2	44.6	14.2	41.7	46.6	12.2	32.7
6.0	80.9	24.6	37.7	87.5	22.4	28.4
7.2	142	43.4	35.8	159	46.4	39.5
8.8	227	55.3	34.0	208	53.4	34.9
9.8	412	122	48.8	469	172	53.8
Significance[y]	L, Q***	L, Q***	NS	L, Q***	L, Q***	L, Q***
		BFP 5526			*BFP 6123*	
1991–92						
2.3	21.7	3.9	14.5	35.4	2.0	14.6
3.4	26.9	3.6	13.7	42.3	3.0	14.3
4.2	56.4	5.4	12.8	66.3	8.2	16.2
6.6	70.2	10.8	11.5	83.8	14.2	14.5
7.7	98.6	20.0	12.5	113	19.8	15.7
8.3	102	22.8	12.9	119	20.3	14.0
Significance	L***	L***, Q*	NS	L***	L***	NS

[z]mg/kg dry wt = mmol·kg^{-1} × atomic weight.
[y]L = linear; Q = quadratic.
NS, *, *** Nonsignificant or significant at $P \leq 0.05$ or 0.005, respectively.

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