J. AMER. SOC. HORT. SCI. 116(2):215-221. 1991.

Tomato Fruit Yields and Quality under Water Deficit and Salinity

J.P. Mitchell and C. Shennan[1]
Department of Vegetable Crops, University of California, Davis, CA 95616

S.R. Grattan
Department of Land, Air and Water Resources, University of California, Davis, CA 95616

D.M. May
University of California Cooperative Extension, Fresno, CA 93702

Additional index words. drainage water, irrigation, *Lycopersicon esculentum,* solids

Abstract. **Effects of deficit irrigation and irrigation with saline drainage water on processing tomato *(Lycopersicon esculentum* Mill, cv. UC82B) yields, fruit quality, and fruit tissue constituents were investigated in two field experiments. Deficit irrigation reduced fruit water accumulation and fresh fruit yield, but increased fruit soluble solids levels and' led to higher concentrations of hexoses, citric acid, and potassium. Irrigation with saline water had no effect on total fresh fruit yield or hexose concentration, but slightly reduced fruit water content, which contributed to increased inorganic ion concentrations. Fruit set and marketable soluble solids (marketable red fruit yield x percent soluble solids) were generally unaffected by either irrigation practice. Water deficit and salinity increased starch concentration during early fruit development, but, at maturity, concentrations were reduced to < 1%, regardless of treatment. Higher fruit acid concentrations resulted from water deficit irrigation and from irrigation with saline water relative to the control in one year out of two. These results support the contention that deficit irrigation and irrigation with saline drainage water may be feasible crop water management options for producing high quality field-grown processing tomatoes without major yield reductions. Appropriate long-term strategies are needed to deal with the potential hazards of periodic increases in soil salinity associated with use of saline drainage water for irrigation.**

Numerous management techniques have been proposed to increase yields and improve flavor and quality components of tomatoes for processing. Considerable effort has been directed by plant breeders toward developing improved cultivars with enhanced yield and quality characteristics (Stevens and Rudich, 1978). Growers in recent years have attempted to develop water management practices that maintain yields but impose a moderate, controlled level of stress on their crops to improve fruit quality. Controlled periods of soil water deficit have been imposed, for example, by increasing the intervals between irrigations (Aljibury and May, 1970), or by withholding irrigations before harvest (Martin et al., 1966), These methods have improved fruit quality by increasing total and soluble solids concentrations (SSC) in fruits of field-grown processing tomatoes. Saline water has been used to improve fruit quality of tomatoes grown in nutrient film culture (Ehret and Ho, 1986; Ho et al., 1987), on sand dunes (Mizrahi et al., 1988), and under field conditions (Lapushner et al., 1986; Pasternak et al., 1986; Shalhevet and Yaron, 1973). The improvements gained by water deficit or saline water irrigation are, however, commonly accompanied by reduced yields (Aljibury and May, 1970; Ho et al., 1987; Shalhevet and Yaron, 1973).

In California, which accounts for ≈85% of the total U.S. production of processing tomatoes (Calif. Agr. Stat. Rev., 1984), there is increasing grower interest in using irrigation water more efficiently and in using saline drainage water to partially satisfy crop water requirements, particularly in areas with limited supply of good quality water and excessive amounts of saline agricultural drainage water (Beck, 1984). For such practices to be optimally productive, a better understanding of the physiological and metabolic effects of these practices on tomato growth, yield, and fruit quality characteristics during crop development is needed. Consequently, we have conducted sand culture and field experiments to directly compare the effects of water deficit irrigation and irrigation with saline water on solute and water accumulation in tomato fruit throughout development, and to contrast these effects with previously published information for concentrated macronutrient $KNO_3/Ca(NO_3)_2$ salinity (Ehret and Ho, 1986). In a sand culture experiment (Mitchell et al., 1991), fruit osmotic potentials (Y_p) were significantly reduced by both water deficit and salinity and corresponded primarily to reductions in fruit water import rather than increases in solute accumulation. This "concentration" of fruit solutes resulted in considerable improvements in fruit quality characteristics of SSC and acidity. Total inorganic ion accumulation on a dry weight basis was increased 5% by salinity and decreased 28% by water deficit relative to the control. Increases in the fruit cation : anion ratio resulted in significantly higher titratable acidity levels and organic acid accumulation under salinity throughout fruit development and at maturity under water deficit.

In this study, we conducted field experiments to examine the effects of 1) withholding late-season irrigations and 2) irrigation with saline drainage water on yield, fruit water content, and solute accumulation during fruit development. Specific objectives of these experiments were to test under field conditions whether: 1) the primary effect of water deficit or salinity is to reduce fruit water import, thus increasing SSC, and to test whether fruit set, dry-weight accumulation, and import or synthesis of organic solutes is less sensitive to either stress, and 2) salinity leads to increased fruit inorganic ion import, particularly cation import such that changes in the cation : anion ratio stimulate

Received for publication 27 Feb. 1990. We thank Mitzi Aguirre for assistance with the fruit quality analyses and Richard A. Jones, Oscar Lorenz, and Vincent Rubatzky for constructive comments on the manuscript. Mention of company names and products is for the benefit of the reader and does not imply endorsement, guarantee, or preferential treatment by the university or its agents. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

[1]Author to whom correspondence should be addressed.

Table 1. Average irrigation water quality for 1985 and 1986.

Water source	Composition $(mol \cdot m)_3^-$									
	EC	pH	Na^+	K^+	Ca^{+2}	Mg^{+2}	Cl^-	SO_4^{-2}	B	NO_3^-
Nonsaline[z]	0.34	7.6	1.6	0.06	0.42	0.41	1.2	0.3	0.01	0.01
Saline[y]	8.1	7.5	56.5	0.02	9.97	9.88	16.9	38.5	0.60	0.61

[z]Calif. Dept. of Water Resources. EPA storet data system water quality analysis for California Aqueduct. Sacramento, Calif.
[y]U.S. Geological Survey. Water quality data for state well number: 185/17E-27F2. Water Resources Div. Sacramento, Calif.

increased organic acid production and lower the pH of fruit relative to control plants.

Materials and Methods

Cultural practices. Experiments were conducted on a Panoche clay loam soil (fine-loamy, mixed Calcareous, thermic Typic torrienthent) at the Univ. of California Westside Field Station (WSFS) at Five Points, Calif., in 1985 and 1986. Processing tomato 'UC82B' was direct-seeded in double rows 36 cm apart on each treatment plot (1.8 × 45.7 m). Each treatment plot consisted of one bed of tomato plants plus a border row. Tomatoes were planted on 15 Feb. in 1985 and 1 Apr. in 1986. All plots were sprinkle-irrigated for stand establishment using water from the California Aqueduct (EC = 0.3 $dS \cdot m^{-1}$). Plants were thinned to one plant per 10 cm of row, During the growing season, water was applied weekly by furrow irrigation in quantities sufficient to replace evapotranspirative losses. A summary of the quality and amount of irrigation water used in each experimental treatment is presented in Tables 1 and 2, respectively. Crop evapotranspiration (ET) was estimated weekly using reference values provided by a weather station located at the WSFS, and crop coefficient values developed for tomatoes at this site (Phene, 1984).

Preplant broadcast monoammonium phosphate fertilizer was applied at 12 kg N/ha to all plots. An additional 168 kg N/ha was sidedressed at thinning in all treatments in 1985, and in the control and water deficit treatments in 1986. No sidedress fertilizer was applied to the salinity treatments in 1986 to compensate for the high levels of NO_3 measured in the saline drainage water during 1985. Plots were maintained essentially weed-free by the combined use of *N,N*- diethyl-2-(naphthalenyloxy) propanamide (devrinol) applied on surface of beds before planting, and 2,6-dinitro-N, N-dipropyl-4-(trifluoromethyl)benzenamine (trifluralin) applied at thinning, cultivation, and hand-weeding.

Experimental treatments. Four experimental treatments were imposed in 1985 and five in 1986 (Table 2). Two water deficit treatments were tested, in which final irrigations were applied 50 days and 75 days before projected harvest dates and are referred to as 50- and 75-day irrigation cutoffs, respectively. A salinity treatment, using saline drainage water from a perched water table ≈10 m under the soil surface, was imposed from "first-flower" (i.e., when 50% of the plants had at least one flower) onward in both years. The first-flower stage corresponded with the seven true-leaf stage of plant development. An additional salinity treatment was imposed in 1986 with saline water being applied from the time plants were thinned (4 weeks before first-flower). Final irrigations for the control and saline treatments were applied 21 days before harvest in 1985 and 26 days before harvest in 1986. Treatment plots were replicated four times in a randomized complete-block design and were separated by a border plot of equal dimensions.

Table 2. Quantities of irrigation water applied in 1985 and 1986.

Treatments	Water applied (mm)		
	Nonsaline	Saline	Total
	1985		
Control	610	0	610
75-day cutoff	194	0	194
50-day cutoff	357	0	357
Saline from first flower	127	483	610
	1986		
Control	516	0	516
75-day cutoff	178	0	178
50-day cutoff	281	0	281
Saline from first flower	250	266	516
Saline from thinning	127	389	516

Soil water content and soil salinity measurement. Volumetric soil water content was measured twice each week at 30, 60, 90, and 120 cm using a Campbell Nuclear Model 503 Hydroprobe (Campbell Pacific Nuclear, Pacheco, Calif.) in access tubes located in the plant bed at the center of each plot. Electrical conductivity of the irrigation water was measured weekly using a Myron L DS Meter (Extech, Waltham, Mass.).

Bulk soil electrical conductivity (EC_b) was monitored in situ three times during the period of fruit development in each experiment using a modified four-electrode soil salinity probe and a Martek Model SCT Soil Conductivity Monitoring System (Martek Instruments, Irvine, Calif.). Soil EC_b measurements were made ≈24 hr after an irrigation. Readings were taken in the center of each bed at five locations along the plot at depths of 30, 60, and 90 cm. Bulk electrical conductivity readings in 1986 were converted to saturation paste electrical conductivity values (EC_e) using a calibration curve generated from 40 samples taken adjacent to locations where salinity probe measurements had been taken. Soil saturation extracts were prepared and readings corrected for temperature using 250-g subsamples. Electrical conductivity was measured using an alternating current Wheatstone Conductivity Bridge, Model RC 16b (Industrial Instruments, Cedar Grove, N.J.). However, only bulk electrical conductivity values were determined for 1985 since the salinity probe became inoperable before a calibration curve could be obtained to convert EC_b to EC_e.

Fruit development, economic and biological yield determination. In 1986, 20 plants were marked at random locations along the entire plot length in each of the four replications. Five flower clusters per plant were tagged, giving a sample size of 400 flower clusters per treatment. Total numbers of flowers per plant at the time of inflorescence and subsequently total numbers of fruit per cluster at harvest (percent fruit set) were counted.

A 55.8-m^2 section in the middle of each treatment plot was machine-harvested in the 1985 experiment and a 11.2-m^2 section in the middle of each treatment plot was hand-harvested in

the 1986 experiment. Harvested fruit were weighed to estimate total yield, and random subsamples (10 kg) were sorted into red, green, rotten, and those affected by solar injury or blossom-ed rot. Average fruit size was approximated by counting the number of fruit in a l-kg subsample of red fruit. Harvests of 2.4 m^2 were taken at maturity and the above-ground "plant biomass separated into shoots and fruit for fresh- and dry-weight determinations.

Fruit composition. Samples (4 kg) of red fruit were collected at random from each treatment plot 1 day before the final harvests. In 1986, fruit were also sampled four times, approximately every 2 weeks, before the final harvest. Each sample was washed, dried, blended, and poured through a laboratory pulper with a 0.033-mesh screen (Food Processing Equipment, Kalamazoo, Mich.) to remove seeds and skins. Percent water content of the puree was determined with a CEM 80 Automatic Volatility Computer (CEM, Indian Trail, N.C.). Subsamples were filtered and the serum used for SSC measurements by a REC 80 digital refractometer (Bellingham and Stanley, Kent, U.K.). Titratable acidity (TA) was determined by titration of the serum with 0.1 N NaOH and is expressed as percent citric acid in the tomato serum. A 25-ml aliquot of the puree samples from each harvest of the 1986 experiment was immediately frozen and subsequently freeze-dried. Samples were stored in a dessicator before organic and inorganic constituent analyses.

Sugar (glucose, fructose, and sucrose), and organic acid (citrate and malate) contents in the freeze-dried puree were determined by grinding 50-mg dried samples over ice in 1 ml of 60% ethanol and the combined solution centrifuged at 4000 rpm for 8 min at 10C. The supernatant was decanted and a 20-µl aliquot analyzed by high performance liquid chromatography. Separation of sugars and organic acids was accomplished on a BioRad HPX-87H column (Bio-Rad, Richmond, Calif.) with 0.05 N H_2SO_4 as the mobile phase, at a flow rate of 0.4 ml·min^{-1}. Sugars were detected with a differential refractometer and organic acids by UV absorbance at 210 nm. Starch was analyzed by the enzymatic method of Macrae as modified by Dinar and Stevens (1981).

In 1985, fresh fruit samples were dried at 60C and ground in a Wiley mill (Wiley, Philadelphia). Contents of K^+, Na^+, Ca^{+2} Mg^{+2}, Cl-, and SO_4^{-2} were determined by digesting a 0.2-g subsample for 6 hr in 5 ml concentrated HNO_3 maintained at ≈ 90C. After appropriate dilution, cations were determined with a Perkins Elmer 600 atomic absorption spectrophotometer. Recovery rates were 91% of K^+, 95% of Ca^{+2}, 96% of Mg^{+2}, and 100% of Na^+. Tissue Cl- and SO_4^{-2} concentrations of puree samples were quantified by ion chromatography using a Dionex high performance AS4A anion exchange column (Dionex, Sunnyvale, Calif.) and a conductivity detector. Soluble Cl- and SO_4^{-2} from 0.1 g of dry tissue were extracted in 30 ml of HNO_3 at 15.7 mol·m^{-3} for 24 hr. The solution was made up to 100 ml with deionized water, passed through a 0.4-µm filter, and injected into the HPIC system. The sample was eluted with Na_2CO_3 at 1.8 mol·m^{-3} and $NaHCO_3$ at 1.8 mol·m^{-3} at a flow rate of 2 ml·min^{-1}. Identical digestion procedures were used for the freeze-dried puree samples of 1986.

Statistical analysis. Yields, quality, and tissue constituent data for mature fruit were analyzed using a two-way analysis of variance (MSTAT3; Michigan State Univ., 1982). Treatment means were separated using least significant difference (LSD) analysis at $\alpha \leq 0.05$. Quantities measured repeatedly during the experiment were analyzed using a two-way factorial analysis with irrigation treatment as the first factor and harvest date as the second. Factorial analysis results are given in the figure legends. LSD was calculated using the error mean square from the factorial analysis and a = 0.05 for *t* values.

Results

Soil water content. Seasonal patterns of soil water contents were similar in both experiments (Fig. 1). Total soil water content of the top 120 cm of soil in both years was reduced in the deficit irrigation treatments during the mid- and late stages of fruit growth and development. Average soil water content during the 5 weeks before harvest was 18.7% for the 75-day cutoff, 22% for the 50-day cutoff, and 27.2% for the control in 1985, and 23.8%, 25.2%, and 28.6% for the 75-day cutoff, 50-day cutoff, and control treatments, respectively, in 1986. Differences in soil water content between treatments were more pronounced in 1985 than 1986.

Soil sainity. Generally, crop salt tolerance experiments report crop performance relative to soil salinity expressed as the EC of the saturation extract. Typically, there is a linear relationship between EC_e and EC_b, but EC_b values are lower due to increased resistances in unsaturated soil. In 1985, mean soil EC_b values in the center of plot beds gradually increased with time in the salinity treatment from first-flower; at the last measurement date (4 weeks before harvest) values were about double those of the control at all depths (data not shown).

In 1986, significant salinization at the 30 cm depth in the center of plot beds of the salinity-from-thinning treatment was established at the time the first set of measurements was taken (2 weeks after the treatment was imposed) (Table 3). Mean EC_e values in the salinity-from-first-flower treatment were higher than values in the control treatment at 30 cm 13 weeks after planting. Relative increases in soil salinity in the salinity-from-thinning treatment in 1986 were similar to those observed in the

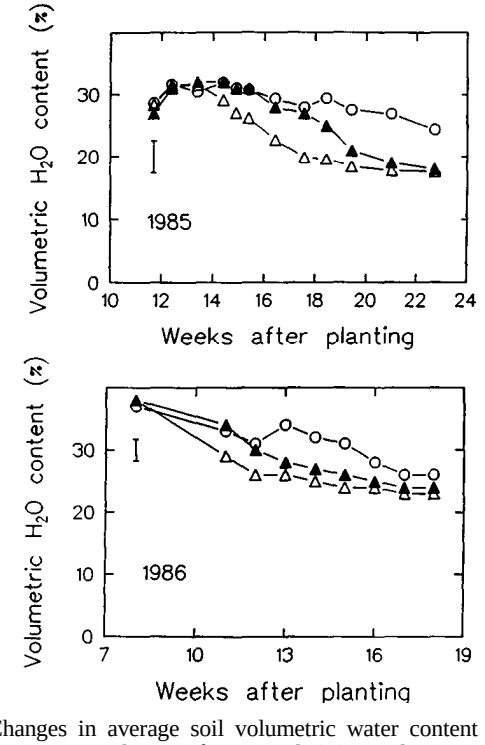

Fig. 1. Changes in average soil volumetric water content (0-120 cm depth) in 1985 and 1986 for control (O), 50-day irrigation cutoff (▲) and 75-day irrigation cutoff (Δ) plots. Each value is a mean of four replications. Vertical bars represent LSD (P = 0.05).

Table 3. Soil electrical conductivity measured in the center of each plot bed (1986).[z,y]

Depth/treatment	Weeks after planting 12	13	14
30 cm			
Control	1.74 b	2.17 c	3.10
Saline from first flower	3.43 b	3.89 b	4.42
Saline from thinning	5.19 a	5.12 a	6.63
60 cm			
Control	0.76	1.16 b	1.77
Saline from first flower	1.25	1.32 b	1.87
Saline from thinning	2.31	2.61 a	4.26
90 cm			
Control	0.36	0.74 b	0.79
Saline from first flower	0.65	0.91 b	1.36
Saline from thinning	1.12	2.02 a	1.92

[z]Values for 12 and 13 weeks after planting are means of four replications and values for 14 weeks after planting are means of two replications. Each value represents a soil salinity probe measurement converted to EC, ($dS \cdot m^{-1}$) using the linear regression equation $EC_e = (2.69)EC_b - 1.93$ ($r = 0.88$).

[y]Mean separation within columns, weeks after planting, and depth by LSD test, $\alpha = 0.05$. No significant differences in columns without letters.

Table 4. Tomato plant biomass production in 2.4 m^2 of treatment plot 2 weeks before final fruit harvest in 1985 and 1 week before final fruit harvest in 1986.[z,y]

Treatment	Total dry wt Plant (g)	Fruit (g)
	1985	
Control	1295 a	498
75-day cutoff	954 b	407
Saline from first flower	1480 a	658
	1986	
Control	1387	712
75-day cutoff	1228	633
Saline from first flower	1456	771
Saline from thinning	1443	763

[z]Values are means of four replications.

[y]Mean separation in columns by LSD test, $P = 0.05$. No significant differences in columns without letters.

Plant growth, fruit development, and marketable yield. Total plant biomass at crop maturity was reduced by the 75-day irrigation cutoff only in 1985, but not by either cutoff in 1986 (Table 4). Saline irrigation did not affect plant growth in either year (Table 4). The harvest index [(fruit dry weight/plant dry weight)100] was unaffected by treatment (38'% to 44% in 1985; 52% to 53% in 1986). Neither irrigation cutoff nor salinity treatments significantly affected fruit set. Percentages of fruit set were 32.0 ± 2.0 for the control, 29.3 ± 1.3 for the 50-day cutoff, 29.8 ± 2.7 for the 75-day cutoff, 30.8 ± 2.4 for the salinity-from-first-flower, and 31.3 ± 2.4 for the salinity-from-thinning treatment. Fruit dry weight production and harvest index were not affected by irrigation cutoff or salinity treatment in either year, and fresh fruit yields were reduced by the 75-day cutoff in both years, but were not affected by either the 50-day cutoff or saline irrigation in either year (Table 5). Fresh fruit yields in the 75-day irrigation treatment were reduced 29% in 1985 and 31% in 1986 relative to the control. Fruit size was reduced in the cutoff treatments in 1986, but not in 1985.

Soluble solids concentration in fruit. In both years the irrigation cutoff treatments had more pronounced effects on the SSC in fruit than the salinity treatments (Table 5). Fruit SSC increased rapidly after irrigations were withheld in comparison to the control and the salinity-from-thinning treatment (Fig. 2). Similar patterns of SSC changes were observed in both cutoff treatments; however, for clarity, only the 75-day cutoff is shown in Fig. 2. Increases in SSC in the cutoff treatments relative to the control were larger in 1986. Salinity increased SSC by ≈8% in both years; however, marketable soluble solids were not significantly affected by either cutoff or salinity (Table 5). Water content in fruit of plants exposed to deficit irrigation was lower than the control throughout development in 1986 and at maturity in 1985, and at maturity by salinity in 1985 (Fig. 3, Table 5).

Fruit sugar, organic acid, and starch contents. At maturity, irrigation cutoff had no effect on the accumulation of hexoses on a dry-weight basis, but significantly increased hexose concentrations on a tissue-water basis relative to the control (Fig. 4). Salinity did not significantly affect hexose accumulation on either a dry-weight or a tissue-water basis. Sucrose concentrations were below detectable levels in all treatments.

Fruit acid concentrations in the control and salinity treatments were similar and declined during the period of fruit development (Fig. 5). The irrigation cutoff treatment increased titratable acidity levels and citrate concentrations during fruit development but not at maturity in 1986. In 1985, acidity was increased at maturity by both water deficit and saline irrigation. Malate accumulation reached levels roughly one-fifth those of citrate, but was unaffected by experimental treatment (data not shown).

The starch content of fruit was unaffected by both the cutoff and salinity treatments throughout development (Fig. 6). At maturity starch levels for all treatments had dropped to ≈1% fruit dry matter.

Fruit inorganic ion accumulation. The 75-day cutoff decreased total cation accumulation (Na^+, K^+, Mg^{+2}, plus Ca^{+2}) per unit dry weight by 5% in mature red fruit in both years (Table 6). Total cation concentration on a fresh-weight basis was increased by 14% and 21% in 1985 and 1986, respectively. The slight decrease in Ca^{+2} accumulation in fruit of the cutoff treatment did not result in increased incidence of blossom-end rot (data not shown). Potassium contributed ≈85% of the total cation accumulation in both years, with concentrations on a tissue-water basis significantly increased by irrigation cutoff. Total anion accumulation (Cl^- plus SO_4^{-2}) per unit dry weight was decreased by 5% in the irrigation cutoff treatment relative to the control in 1986, while concentrations on a tissue water basis were increased by 18%.

Salinity, in contrast, led to an increase in total cation accumulation per unit dry weight of ≈6% to 7% in mature fruit (Table 6). Total cation accumulation on a tissue-water basis was also increased relative to the control by 24% and 12% in 1985 and 1986, respectively. Fruit Ca^{+2} accumulation was either unaffected or increased by the salinity treatments, and in 1986, both K^+ and Cl^- contents were increased under salinity relative to the control.

Discussion

These experiments demonstrate that a moderate irrigation cutoff or irrigation with saline water can significantly improve fruit quality (in terms of SSC and, perhaps, acidity) of field-grown processing tomatoes without depressing marketable yields.

Table 5. Effects of irrigation cutoff and salinity on yields of mature red fruit, fruit size, fruit water content and tomato fruit quality.[z,y]

Treatment	Yield (t·ha^{-1})	Fruit/kg	Fruit water content (%)	Soluble solids concn (°Brix)	Titrable acidity (% citric)	Marketable soluble solids (t·ha^{-1})
			1985			
Control	90.2 a	17.6	94.6 a	4.58 c	0.28 c	4.1 b
50-day cutoff	80.2 a	17.6	94.2 a	5.15 b	0.31 ab	4.1 ab
75-day cutoff	64.0 b	19.7	93.5 c	5.63 a	0.30 b	3.6 b
Saline from first flower	92.6 a	18.4	94.1 b	4.98 b	0.32 a	4.6 a
			1986			
Control	86.2 a	20.1 b	94.5 a	4.60 c	0.34	4.0
50-day cutoff	82.4 a	25.5 a	93.2 b	5.58 ab	0.34	4.6
75-day cutoff	59.8 b	26.0 a	93.3 b	5.88 a	0.33	3.5
Saline from first flower	87.6 a	20.6 b	94.2 a	4.98 bc	0.34	4.4
Saline from thinning	84.2 a	20.1 b	94.3 a	4.95 bc	0.33	4.2

[z]Values are means of four replications.

[y]Mean separation in columns by LSD test, $P = 0.05$. No significant differences in columns without letters.

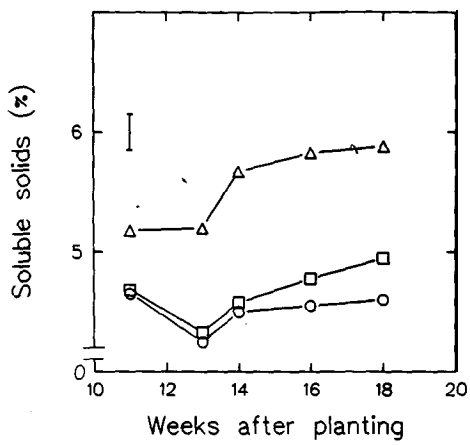

Fig. 2. Changes in soluble solids content (°Brix) throughout development in tomato fruit subjected to control (O), 75-day irrigation cutoff (Δ), and salinity-from-thinning (❑) treatments. Each value is a mean of four replications. Vertical bar represents LSD ($P = 0.05$).

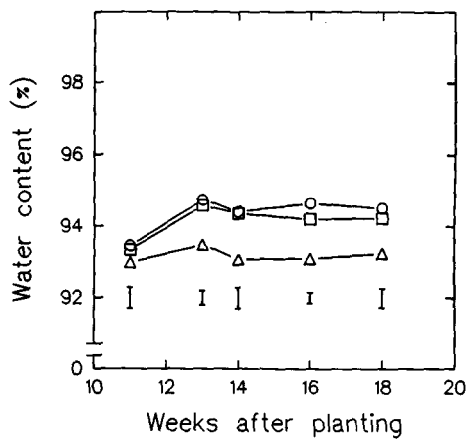

Fig. 3. Developmental changes in water content (%) in tomato fruit subjected to control (O), 75-day cutoff (Δ), and salinity-from-thinning treatments (❑) in 1986. Each value is the mean of four replications. Vertical bars represent LSD ($P = 0.05$) among treatments within a given harvest date.

However, the accumulation of fruit water and the major constituents of fruit dry matter were affected differently by water deficit as opposed to salinity during fruit development. Increases in SSC in fruit grown under soil water deficits are related primarily to decreases in fruit water content and to slight increases in soluble sugar accumulation. Increases in SSC in fruit of salinized plants, in contrast, likely result from the interaction between reduced fruit water content, increased ion content, and maintained hexose accumulation, although reductions in fruit water content were small and only statistically significant in 1985.

These results are in general agreement with our findings from a sand culture experiment (Mitchell et al., 1991). However, considerably higher levels of salt stress were imposed in the sand culture experiment, leading to greater reduction in fruit water and concentration of solutes in the sand culture experiment than those observed in the field.

Fruit set was not impaired by any irrigation treatment. A similar insensitivity of fruit set in tomato under water deficit has been reported by Cannell and Asbell (1974), and, under salinity, by Shalhevet and Yaron (1973). Furthermore, since fruit dry-weight accumulation was also affected little by water deficit, reductions in fruit size and total fresh fruit yields in the irrigation cutoff treatment (Table 5) developed primarily as a result of decreased water import.

Hexose accumulation on a dry-weight basis was unaffected by irrigation cutoff and not salinity relative to the control (Fig. 4A). Ehret and Ho (1986) reported similar results in comparing 2 dS·m^{-1} and 7 dS·m^{-1} salinity treatments. Starch content was statistically unaffected by irrigation treatment. However, during the early stages of fruit development, starch levels appeared to be increased by both irrigation cutoff and salinity in a similar manner to that observed for plants under concentrated macronutrient stress (Ehret and Ho, 1986) and for both water and $Na_2SO_4/CaCl_2$ salinity under greenhouse conditions (Mitchell et al., 1991). The significance of starch accumulation in immature fruit of stressed plants remains unclear. Although fruit osmotic potentials were not measured, indirect evidence that water contents, SSC, and hexose levels in immature fruit of salinized

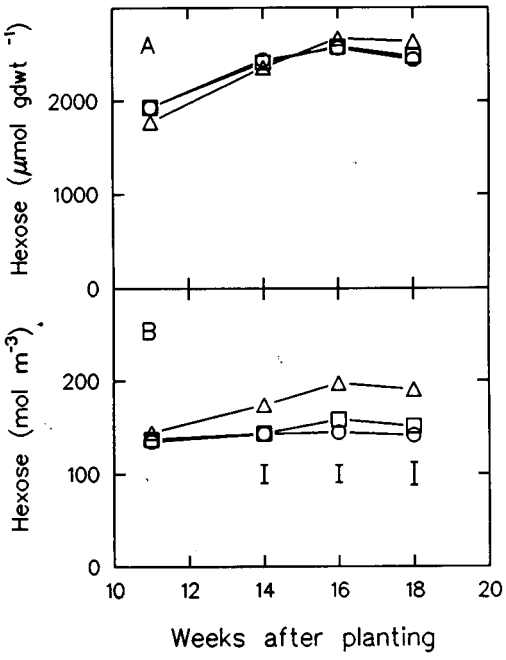

Fig. 4. Changes in tomato fruit hexose levels on a **(A)** dry-weight basis and **(B)** fresh-weight basis throughout development for plants subjected to control (O), 75-day irrigation cutoff (Δ), and salinity-from-thinning (❑) treatments. Each value is the mean of four replications. Vertical bars represent LSD (P = 0.05) among treatments within a given harvest date.

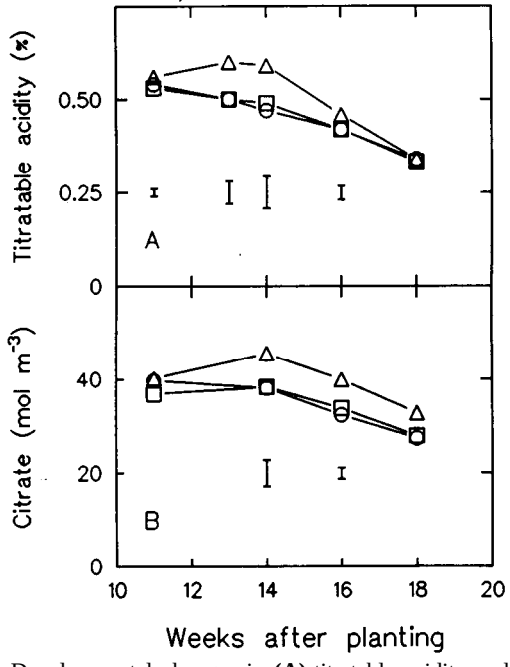

Fig. 5. Developmental changes in **(A)** titratable acidity and **(B)** citrate concentrations of tomato fruit of plants subjected to control (O), 75-day irrigation cutoff (Δ), and salinity-from-thinning treatments (❑), 1986. Each value is the mean of four replications. Vertical bars represent LSD (P = 0.05) among treatments within a given harvest date.

plants were unchanged while starch accumulation increased relative to the control, suggests that increased partitioning of carbon into starch is not an osmotic response, as previously suggested (Yelle et al., 1988), but rather maybe a consequence of a root

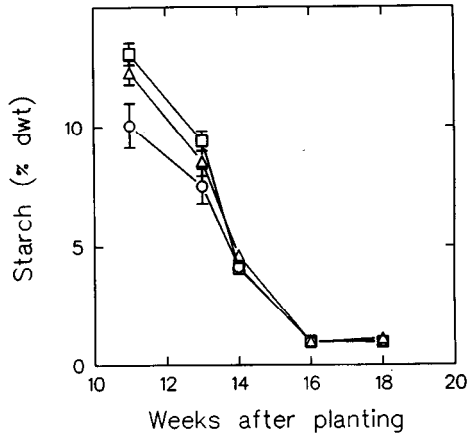

Fig. 6. Starch content (percent dry weight) in tomato fruit from plants subjected to control (O), 75-day irrigation cutoff (Δ), and salinity-from-thinning (❑) treatments at various weeks after planting in 1986. Each value is the mean of four replications. Analysis of variance indicated significant differences among treatments for the first harvest date at P = 0.085. Standard errors of the means are shown when they exceed the height of the symbol.

sensor, perhaps a hormonal trigger, that modifies fruit carbohydrate metabolism under stress (Munns and Termaat, 1986). These results also indicate that high starch levels in immature fruit are not necessarily associated with high SSC in mature fruit, as suggested by Dinar and Stevens (1981), since fruit from water deficit plants had considerably higher SSC than fruit of salinized plants, despite having lower initial starch levels (Figs. 3 and 6).

Increased fruit ion concentrations in water deficit treatments resulted from reduced fruit water content and not from osmotic adjustment due to increased accumulation (Tables 4 and 6). Net ion accumulation was in fact reduced by water deficit. In fruit of salt-treated plants, reduced fruit water content and increased ion import both account for the higher ion concentrations observed (Tables 5 and 6). Interestingly, irrigation with high Na^+ drainage water did not significantly increase fruit Na^+ concentrations, in contrast to results of the greenhouse study (Mitchell et al., 1991), presumably either because the root zone extended beyond the salinized soil volume, or levels were insufficient to overcome exclusion mechanisms. Potassium import by fruit accounted for the major proportion of total fruit ion accumulation in all treatments, but was generally highest in the salinity treatments. Ho et al. (1987) have suggested that K salts regulate the osmotic potential of tomato fruit under high $KNO_3/Ca(NO_3)_2$ salinity since under those conditions, K salts account for 49% of the measured fruit osmotic potential. In contrast, results from both the present field study and our previous greenhouse study (Mitchell et al., 1991) indicate that hexoses are the major component of fruit Y_p under water deficits and $Na_2SO_4/CaC1_2$ salinity (Fig. 4, Table 6). This work does not support the suggestion that increased K^+ transport to fruit is an osmotic response in tomato plants to either of these treatments. Under water deficit, higher concentrations of K^+ in fruit tissue resulted only from reduced fruit water content, not from increased K^+ import into the fruit (Table 6, Mitchell et al., 1991). Under $Na_2SO_4CaCl_2$ salinity, K^+ accumulation on a dry-weight basis was slightly increased in the field, but it was substantially decreased by salinity in the greenhouse study (Mitchell et al., 1991). The osmotic role of K in tomato fruit would thus seem to depend on the specific nature of stress imposed.

Table 6. Tomato fruit inorganic ion accumulation (final harvest) on a dry-weight and a tissue-water basis.[z,y]

Treatment	Na^+	Mg^{+2}	Ca^{+2}	K^+	Total cations	Cl-	SO_4^{-2}	Total (cations–anions)
1985					*μeq·g⁻¹ dry wt*			
Control	41.5	121	48.9 b	841	1059			
75-day cutoff	49.2	112	40.0 b	795	996			
Saline-from-first-flower	68.4	122	60.6 a	870	1120			
					meq·liter⁻¹			
Control	2.4	7.1	3.2	49.5	62.3 c			
75-day cutoff	3.8	8.6	3.1	61.2 a	76.7 a			
Saline from first flower	4.3	7.7	3.9	55.0 b	70.9 b			
1986					*μeq·g⁻¹ dry wt*			
Control	57.9	137 bc	46.9	1040 b	1282 b	238 b	126 bc	918 b
75-day cutoff	51.6	133 c	23.7	1004 b	1212 c	226 b	117 c	871 c
Saline from first flower	63.9	149 a	44.5	1105 a	1362 a	268 a	141 a	953 a
Saline from thinning	71.1	143 ab	43.6	1093 a	1351 a	268 a	136 ab	947 ab
					meq·liter⁻¹			
Control	3.4	8.0 c	2.7	61 c	75.0 c	13.8 b	7.3 c	54.0 b
75-day cutoff	3.8	9.8 a	1.7	74 a	89.3 a	16.3 a	8.6 ab	64.3 a
Saline from first flower	3.9	9.2 ab	2.8	68 b	84.0 ab	16.5 a	9.1 a	58.4 b
Saline from thinning	4.3	8.7 b	2.7	67 b	82.6 b	16.4 a	8.3 b	57.9 b

[z]Values are means of four replications.
[y]Mean separation in columns by LSD test, $P = 0.05$. No significant differences in columns without letters.

There are reports of tomato fruit acidity increasing under both water deficits (Rudich et al., 1977), and salinity (Vinten et al., 1.986). In the field studies reported here, higher fruit acid concentrations resulted from water deficit irrigation in both experiments and from salinity irrigation in 1985, but not at maturity in 1986. The coupling of increased organic acid concentrations with increases in the ratio of inorganic cation : anion uptake has been proposed by Davies (1964) as a means to maintain electro-neutrality in tomato fruit tissue. This relationship is consistent with data from our previous greenhouse experiment (Mitchell et al., 1991); however, it does not account for the ion/acidity interactions of our 1986 field experiment, since fruit acid levels did not increase from salinity irrigation despite higher cation : anion ratios (Table 6).

In summary, the results of these experiments confirm that water deficit and salinity are important factors determining the quality of processing tomato fruit primarily because they affect fruit water accumulation, and not because they promote the synthesis or accumulation of solutes. From a practical point of view, the treatments imposed in this field study represent stresses that can be developed during a single cropping season. The irrigation cutoff treatments that were imposed in this study were selected to provide both moderate and severe water deficits. Irrigation cutoffs that provide optimal yields and fruit quality will need to be determined for specific production conditions. Thus, the results of these experiments may aid in the development of management systems for tomato production in areas facing reduced supplies of good quality water, increased availability of saline drainage water, or increased soil salinization. However, because of the potential hazards salinity may have on the physical structure of the soil, water infiltration, and ultimately on plant production, longer-term studies are required to fully assess the feasibility of using saline agricultural drainage water as a component of an overall irrigation management strategy (Grattan and Rhoades, 1990).

Literature Cited

Aljibury, F.K. and D. May. 1970. Irrigation schedules and production of processing tomatoes on the San Joaquin Valley West side. Calif. Agr. 24(8):10-11.

Beck, L.A. 1984. Case study San Joaquin Valley. Calif. Agr. 41(9, 10):16-17.

California Agricultural Statistical Review for 1984. Calif. Dept. Food and Agr. Sacramento.

Carmen, G.H. and C.W. Asbell. 1974. Irrigation of field tomatoes and measurement of soil water changes by neutron moderation methods. J. Amer. Soc. Hort. Sci. 99(4):304-308.

Davies, J. N. 1964. Effect of nitrogen, phosphorous, and potassium fertilizer on the non-volatile organic acids of tomato fruit. J. Sci. Food. Agr. 15:665-673.

Dinar, M. and M.A. Stevens. 1981. The relationship between starch accumulation and soluble solids content of tomato fruits. J. Amer. Soc. Hort. Sci. 106(4):415418.

Ehret, D.L. and L.C. Ho. 1986. The effects of salinity on dry matter partitioning and fruit growth in tomatoes grown in nutrient film culture. Hort. Sci. 61(3):361-367.

Grattan, S.R. and J.D. Rhoades. 1990. Irrigation with saline groundwater and drainage water, p. 432-449. In: K.K. Tanji (cd.). Agricultural salinity assessment and management manual. Amer. Soc. Civ. Eng. Ann Arbor, Mich.

Ho, L. C., R.I. Grange, and A.J. Pickerr. 1987. An analysis of the accumulation of water and dry matter in tomato fruit. Plant Cell & Env. 10:157-162.

Lapushner, D., R. Frankel, and Y. Fuchs. 1986. Tomato cultivar response to water and salt stress. Acts Hort. 190:247-252.

Martin, P. E., J.C. Lingle, R.M. Hagan, and W.J. Flocker. 1966. Irrigation of tomatoes in a single harvest program. Calif. Agr. (6):13-14.

Mitchell, J. P., C. Sherman, and S.R. Gratton. 1991. Developmental changes in tomato fruit composition in response to water deficit and salinity. Physiol. Plant. (In press.)

Mizrahi, Y., E. Taleisnik, V. Kagan-Zur, Y. Zohar, R. Offenbach, E. Matan, and R. Golan. 1988. A saline irrigation regime for improving tomato fruit quality without reducing yield. J. Amer. Soc. Hort. Sci. 113(2):202-205.

Munns, R. and A. Termaat. 1986. Whole-plant responses to salinity. Austral. J. Plant Physiol. 13:143-160.

Pasternak, D., Y. De Malach, and I. Borovic. 1986. Irrigation with brackish water under desert conditions VII. Effect of time of application of brackish water on production of processing tomatoes *(Lycopersicon esculentum* Mill.). Agr. Water Mgmt. 12:149-158.

Phene, C.J. 1984. Climate-weather relationships for irrigation management. 1985 Annu. Rpt. Westside Field Station, Five Points, CA. Univ. of California.

Rudich, J., D. Kalmar, G. Giezenberg, and S. Harel. 1977. Low water tensions in defined growth stages of processing tomato plants and their effects on yield and quality. J. Hort. Sci. 52:391-399.

Shalhevct, J. and B. Yaron. 1973. Effects of soil and water salinity on tomato growth. Plant and Soil 39:285–292.

Stevens, M.A. and J. Rudich. 1978. Genetic potential for overcoming physiological limitations on adaptability, yield, and quality in the tomato. Hortscience 13(6):673-678.

Vinten, A., J. Shalhevet, A. Meiri, and J. Peretz. 1986. Water and leaching requirements of industrial tomatoes irrigated with brackish water. Irr. Sci. (7):13-25.

Yelle, S., J.D. Hewitt, N.L. Robinson, S. Damon, and A.B. Bennett. 1988. Sink metabolism in tomato fruit. III. Analysis of carbohydrate assimilation in a wild species. Plant Physiol. 87:737-740.