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Shoot growth and fruit development of muskmelon under saline and non-saline soil water deficit

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Abstract In irrigated agriculture, the production of biomass and marketable yield depend largely on the quantity and salinity of the irrigation water. The sensitivity of field-grown muskmelon (*Cucumis melo* L. cv. "Galia") to water deficit was compared, using non-saline (EC_i= 1.2 dS m^{-1}) and saline (EC_i=6.3 dS m^{-1}) water. Drip irrigation was applied at 2-day intervals at seven different water application rates for each water quality, including a late water-stress treatment. Neutron scattering measurements showed that the soil layers below the root zone remained dry throughout the experiment, indicating negligible deep percolation. Thus, the sum of the seasonal amount of applied water and the change in soil moisture approximated the cumulative evapotranspiration (ET). Gradual buildup of water and salt stresses resulted in small treatment effects on the size of the vegetative cover and large effects on leaf deterioration and fruit production. Crop responses to salinity may result from an osmotic component of the soil water potential or from other salt effects on the crop physiology. Relating plant data to cumulative ET allowed a distinction to be made between the effect on water availability and specific salinity effects. The relation between fruit fresh weight and ET was not sensitive to EC_i. The slopes for fruit dry weights were also insensitive to EC_i but the intercept was larger for saline treatments. At any given ET saline water increased fruit number, increased fruit dry matter content and decreased fruit netting, in comparison with non-saline water. The combination of salinity and soil-water deficit was detrimental to fruit quality. Saline soil-water deficit decreased the percentage of marketable (netted) fruit and caused an early end to the period of marketable fruit production. Non-saline soil-water deficit increased the percentage of marketable fruit and had no effect on the duration of the production period. Late non-saline water stress caused a pronounced increase in the percentage of marketable fruit.

Introduction

Arid and semi-arid zones are characterized by limited water supply and water of low quality. Melon is an important irrigated crop in such regions (Mendlinger and Pasternak 1992a; Shannon and Francois 1978). Efficient irrigation management of melons requires reliable predictions of the effects of water and alt stresses on the crop's vegetative and reproductive growth.

Water use efficiency (WUE) is defined as production per unit water used by the crop. Water deficit and salinity may affect the biomass and the marketable yield production differently, thereby resulting in different WUEs for biomass (WUE_B) and marketable yield (WUE_Y). When water resources are limited, an important objective may be to achieve a high WUE_Y, which could be the result of higher WUE_B or larger marketable to biomass yield ratio – termed the harvest index (HI) – or both. Contradictory results concerning WUE have been reported for salinity and soil water deficit experiments under controlled environments. In a series of experiments on several crops a gradual increase in soil water deficiency under non-saline conditions caused an initial increase, followed by a decline in WUE_B (McCree 1986; McCree and Richardson 1987; Richardson and McCree 1985). Increased WUE_B under water stress was reported for cowpea (Ismail and Holl 1992). In other experiments substantially decreased WUE_B (Schwarz and Gale 1981; Shone and Gale 1983), although these results were attributed to artifacts (McCree 1986). Salinity, by reducing transpiration, slowed soil drying and thereby decreased water stress and increased the WUE_B (McCree and Richardson 1987; Richardson and McCree 1985).

The sensitivity of a crop to high salinity and to low soil water content may be considered comparable as both factors reduce soil water potential. Calculations of the effects of the two stresses from crop response to the amounts of applied irrigation water (I_W) of different salinities in field studies (Russo 1987; Russo and Bakker 1987) may have been biased by errors caused through deep percolation and the use of stored soil water. A preferable basis for compar-

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ison is water use or evapotranspiration (ET) (Cardon and Letey 1992), which differs from WUE as a result of water loss by evaporation. The intercept of the yield to ET ratio differs from zero as a result of water loss by evaporation or unmeasured biomass such as that in the root system (Ismail and Hall 1992) in the case of WUE_B or unmarketable production in the case of WUE_Y. A linear relationship has generally been found between cumulative biomass and cumulative ET for both non-saline (de Wit 1958) and saline (Childs and Hanks 1975; Shalhevet 1984) conditions. Recent studies indicated that soil water deficit under saline conditions does not cause a significant change in the linear relations between commercial yields and ET for tomato (Peretz and Meiri unpublished data) or cotton (Meiri et al. 1992), as compared with a soil water deficiency under non-saline conditions.

Salt stress generally reduces the number and size of fruit in proportion to its inhibition of vegetative growth (Maas and Hoffman 1977). In melons, salinity reduced the marketable yield more than the total yield, and reduced the fruit weight more than the vegetative weight (Shannon and Francois 1978), and had the least effect on fruit number; it reduced fruit size and fruit netting (Meiri et al. 1981; Mendlinger and Pasternak 1992a, b; Shannon and Francois 1978). Salinity both improved fruit quality by increasing fruit sugar content (Mendlinger and Pasternak 1992a; Shannon and Francois 1978) and impaired fruit quality by reducing netting (Meiri et al. 1981; Meiri et al. 1982; Mendlinger and Pasternak 1992a; Shannon and Francois 1978). The relationship between the components of reproductive growth and ET in the field has been demonstrated to be sensitive to soil moisture deficit (de Wit 1958). The number of flowers, fruit abscission and components of yield quality have been found to depend on the timing, magnitude and duration of soil water deficit (Boote et al. 1982; Mahalakshmi et al. 1988).

Information is needed on how salt stress and soil water deficit interact to affect the quantity and quality of reproductive parts. Irrigation management of saline and non-saline water that increase WUE_Y, could conceivably involve application rates that result in continuous or temporary soil water deficit. Our objective was to compare the effect of saline and non-saline irrigations on the relationship between cumulative ET and components of biomass and yield of muskmelon (cv. "Galia").

Materials and methods

Muskmelon (*Cucumis melo* L., cv. "Galia") was planted after winter wheat at the Ramat Hanegev Field Station in a sandy loess soil having a volumetric field capacity of 25%. The wheat left a dry soil profile, which allowed the detection of deep percolation by observation of any increase in soil water content below the root zone. At the beginning of the experiment the electrical conductivity of the soil saturated paste extract (EC_e) was 1–2 dS m^{-1} to 1.2-m depth. Each experimental plot consisted of three beds, each 12 m long and 1.92 m wide. Soil and plant data were collected in the central bed and the other two served as borders. Drip lines, with emitters having a 4-l h^{-1} discharge rate spaced at 0.5 m along the line, were placed 1.92 m apart, at the centers of the beds. The wetting radius was approximately 0.55 m and provided significant overlapping of the wetting fronts along the lines resulting in a nearly two-dimensional wetting profile. A pre-sowing irrigation of 200 m^3 ha^{-1} (4.8 l per dripper) did not wet the soil below a depth of 0.6 m. On May 14th, seeds were sown along the drip lines and the young seedlings were thinned to eight plants per meter. The application of saline water and irrigation rates that caused soil moisture deficit began 20 days after sowing (DAS). Fresh water was obained from the National Water Carrier (EC_i=1.2 dS m^{-1}) and saline water (EC_i=6.3 dS m^{-1}) was obtained from a local well. Irrigation was supplemented with 25 g m^{-3} N and 20 g m^{-3} P.

Seven levels of water application (I_W) were given with each of the two water qualities (Table 1). At each salinity, water quantities were applied relative to reference treatments (treatments 4 and 11), that were inteded to rewet the soil to field capacity to 0.6 m depth, with no deep percolation. A reference treatment was required for each water quality because salinity suppressed both growth and water uptake. The I_W values of the other experimental treatments were planned to be 0.55, 0.70, 0.85, 1.15 and 1.30 times those of the respective reference treatments. An additional treatment at each salt level (treatments 7 and 14) had the same I_W as treatments 4 and 11, respectively, until 53 DAS and 30% less at later irrigations. The treatment was designed to test the effect of late water stress on the yield of plants that were not stressed during the early vegetative growth stage. The 14 treatments were randomized in four blocks.

There were usually three or four irrigations per week. Two of the four blocks contained three neutron tubes per plot, to measure soil water content weekly by neutron scattering, at 0.1 m from a dripper along the drip line and 0.0, 0.2 and 0.4 m from the drip line. Measurements of soil water content were taken at depths of 0.15, 0.45, 0.75, and 1.05 m. The 12 measurements per plot were assumed to represent a strip volume with a width of 0.55 m and a depth of 1.20 m.

Soil salinity was measured by taking soil samples from every salinized plot at 49 and 109 DAS. Soil samples were also taken from selected non-salinized plots at 119 DAS. Soil samples were taken using an auger at a spot near the drip line and between two drippers along the line. Sampling depths are listed in Table 2.

Fruit were harvested, counted and weighed from a 2.0×9.5 m area in each plot. There were six harvests at 74, 83, 88, 95, 102 and 109 DAS, and an additional harvest from non-saline plots at 119 DAS. Fruit were harvested at full slip or when damaged due to cracking, burning or spoilage. Undamaged fruits were evaluated for netting, which is an indication of maturity and marketable quality. Fruit were considered to be netted if a glabrous area covered less than 50% of the surface. On the final harvest date, all fruit with diameter larger than 5 cm were picked. Fruit dry matter contents were determined at 74 and 83 DAS. Vegetative shoot dry weights were determined for a 1 m^2 area in each plot at 83 DAS, when leaves in the saline treatments had started to show necrotic symptoms and to fall.

The relationships between cumulative ET and the means of the yield components for saline and non-saline waters were interpreted according to a linear model except fruit size in the non-saline treatments and the predictions of the duration of marketable yield production and final netted fruit yields, for which a quadratic model was used. Data from the late-water-stress treatments (6 and 13) and the treatments that might have had some deep percolation (treatments 6 and 13) were excluded from the analysis. The effects of each treatment on the rate and duration of netted fruit production were estimated by fitting a second degree polynomial to the relationship between time of harvest and the cumulative weight of netted fruit.

Results

Increase in amount of applied water (I_W) resulted in increased soil water content in the top soil layers, but the soil layer at 0.9–1.2 m was dry throughout the season in all treatments (Fig. 1). This was the result of applying over 40 small irrigations aimed at restoring soil moisture to field

Fig. 1 Effect of four irrigation regimes on soil water content below the drip line (data represent measurements of one block for treatments 1, 6, 8 and 13. Similar patterns were obtained from another block measured on alternate weeks)

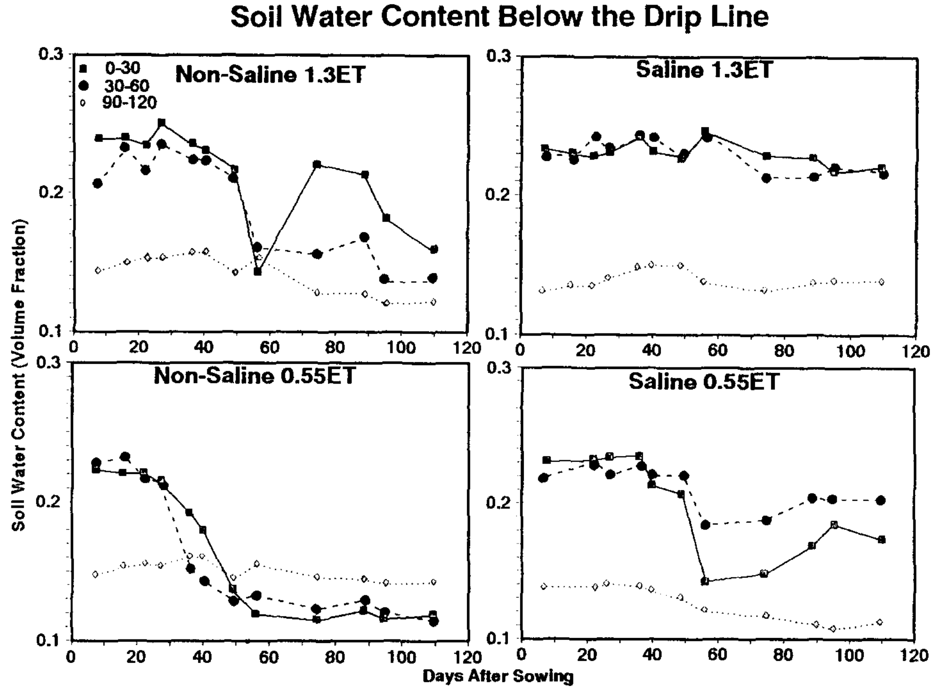

Table 1 Effect of irrigation quantity and salinity of irrigation water (EC_i) on cumulative ET[a]. [a] Cumulative ET from sowing to harvest was calculated as the difference between the irrigation quantity and the change in soil moisture. Class A pan evaporation during the growing period was 125 cm. [b] δS=Change in soil water content from the start to the end of the season. [c] Reference treatment. [d] Late water stress treatments. Until 53 DAS irrigated as the reference treatments 4 and 11, and later as treatments 2 and 9 respectively

Treatment no	Irrigation quantity (cm)	Seasonal δS[b] (cm)	Seasonal ET[a] (cm)
		EC_i=1.2 dS m^{-1}	
1	32.1	-3.3	35.4
2	37.5	-3.2	40.7
3	48.1	-2.5	50.6
4[c]	53.9	-1.4	55.3
5	58.1	-2.4	60.5
6	73.7	-1.6	72.1
7[d]	46.7	-2.4	49.1
		EC_i=6.3 dS m^{-1}	
8	25.2	-2.2	27.4
9	28.1	-1.4	29.5
10	31.7	-1.4	33.1
11[c]	34.2	-0.2	34.4
12	40.7	-0.2	41.1
13	43.6	0.4	43.2
14[d]	30.2	-1.7	31.9

capacity (FC) to a depth of 0.6 m in two treatments, applying less water to other six treatments, and irrigation of four other treatments to result in average deep percolation below 0.6 m of only 0.1–0.3 cm in each irrigation. The actual seepage below 0.6 and 1.2 m was probably much smaller than the calculated as a result of water uptake during infiltration and redistribution (Meiri et al. 1977) into deep dry soil layers with low unsaturated hydraulic conductivity. Because of small deep seepage the cumulative ET could be estimated from I_W and the change in soil water content (δS) (except of treatments 6 and 13, that had positive δS (Table 1) and might have had some deep seepage). Generally, saline treatments showed higher soil water contents and a narrower range across treatments than non-saline ones. This was the result of transpiration reduction due to salinity. The decrease in soil water content in the wet non-saline treatment on 57 DAS was the result of missing one irrigation due to failure of the irrigation controller.

EC_e values at the mid-distance between two emitters are presented in Table 2. The soil solution salinity (EC_{ss}), which for the same EC_e would be higher the drier the treatment, was at least twice as high. The large temporal and spatial variations in salt content does not allow accurate calculation of the effective rootzone salinity and the data in Table 2 can serve only to compare treatments and to indicate trends. Deficit irrigations with saline or fresh water, resulted in progressive salt accumulation in the wetted volume. By 49 DAS, roots were already extracting water at depths of 30–60 cm (Fig. 1); yet salt accumulated mostly at 0–10 cm depth by 49 DAS and at 0–30 cm depth by 109 DAS (Table 2). Salt movement into deeper layers was slow, even in treatments 6, 12 and 13, that show some leaching of the 0–90-cm layers (Table 2). The treatment with the greatest saline water deficit did not reduce soil water content until 58 DAS (Fig. 1); therefore, the detrimental effects of the combination of salinity and soil water deficit would increase with the progress of the growing season.

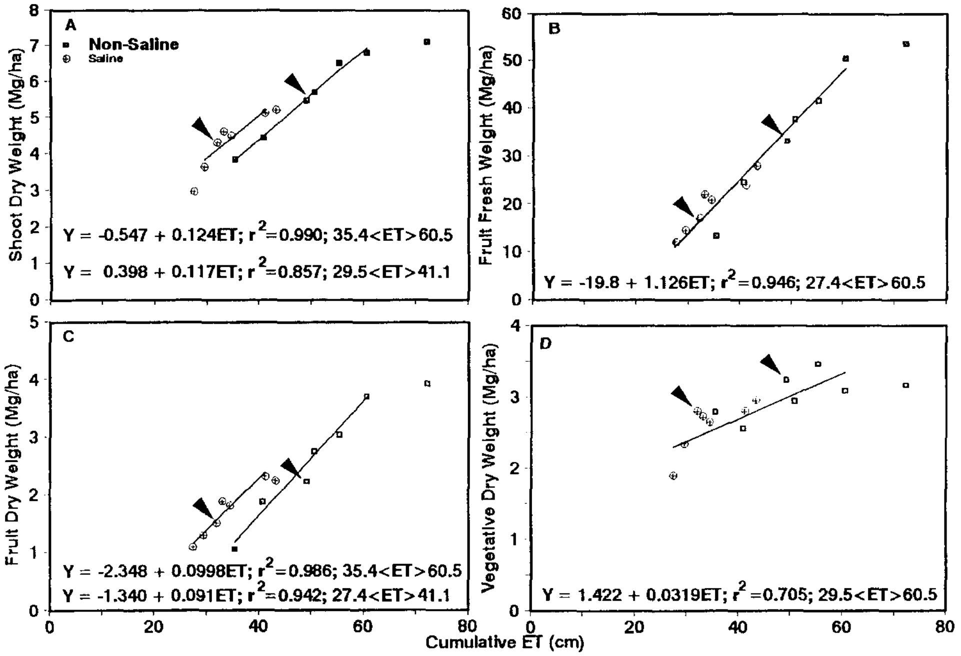

Fig. 2 Effects of water quantity, salinity and late water stress on total shoot dry weight (2a), fresh fruit weight (2b), dry fruit weight (2c) and dry vegetative shoot weight (2d). Arrows point to the results of the late water stress treatments. The upper equation in graphs 2a and 2c is the regression of the means from the non-saline treatments. The lower equation in graphs 2a and 2c is the regression of the means from the saline treatments. The equations in graphs 2b and 2d are the regressions of the means from the non-saline and saline treatments. Late water stress treatments and the treatments that resulted in deep percolation were not included in the analyses

The linear relation between cumulative ET and total (vegetative+fruit yield) above ground dry weight had similar slope and slightly larger intercept in the saline than in the non-saline treatments and was not affected by late water stress (Fig. 2a). Soil-water deficit reduced the total above ground dry weight, primarily by reducing fruit weight (Fig. 2b, c). While a single line describes the fruit fresh weight response to cumulative ET for the two water qualities (Fig. 2b), the saline treatments produced higher fruit dry weights at comparable amounts of ET (Fig. 2c). The fruit dry matter content was not affected by water quantity but was higher in the saline treatments. The mean fruit dry matter content was 0.088±0.002 in all the saline treatments and 0.074±0.001 (w/w) in the non-saline ones. Excluding the driest saline treatment, the vegetative shoot dry weight in all the saline and non-saline treatments showed a common response to cumulative ET. The deviation of the driest saline treatment was mainly the result of leaf drop prior to sampling date (Fig. 2d).

A pronounced effect of saline irrigation water, as compared with non-saline water, was an increase in fruit number at comparable amounts of water use (Fig. 3). Fruit size and maturity depended on the interaction of EC_i with soil water deficit. Non-saline soil water deficit reduced fruit number but had no effect on fruit size except for the driest treatment (Fig. 3). Saline soil water deficit caused a linear decrease in both fruit number and fruit size (Fig. 3).

Saline soil water deficit also reduced, whereas non-saline soil water deficit increased the percentage of mature fruits as indicated by the appearance of a netted surface (Fig. 4). Furthermore, late non-saline soil water deficit substantially increased the percentage of mature fruits (Fig. 4).

The detrimental effects of the combination of saline water and soil water deficit became more apparent as the harvest period progressed. All saline treatments that resulted in soil water deficits (except treatment 13) caused plants to end the production of mature fruit somewhat before the final harvest at 109 DAS (Table 3). The rate of cumulative production for plants treated with non-saline irrigation water diminished only slightly by the final harvest at 119 DAS (Table 3). All saline treatments that resulted in soil water deficit caused necrosis of leaves at the beginning of the harvest period at 74 DAS and of most of the canopy by 109 DAS. Only treatment 3 resulted in a full-cover of non-necrotic leaves by the final harvest, and only treatments 12 and 13 gave detectable rates of transpiration between 102 and 109 DAS (data not shown).

Discussion

Shoot and fruit yield, and yield quality response to water availability, as estimated by ET formed the basis of comparison of salt and water stress effects. The above ground dry biomass was linearly related to cumulative ET, with similar slopes for the two water qualities and a somewhat larger intercept for the saline water. Some fruit parameters showed similar responses to saline and non-saline treatments while others responded differently to the two kinds of treatments. The similar responses are assumed to result from the effects of the total soil water potential (osmotic+matric) while the different responses may indicate salinity-specific effects.

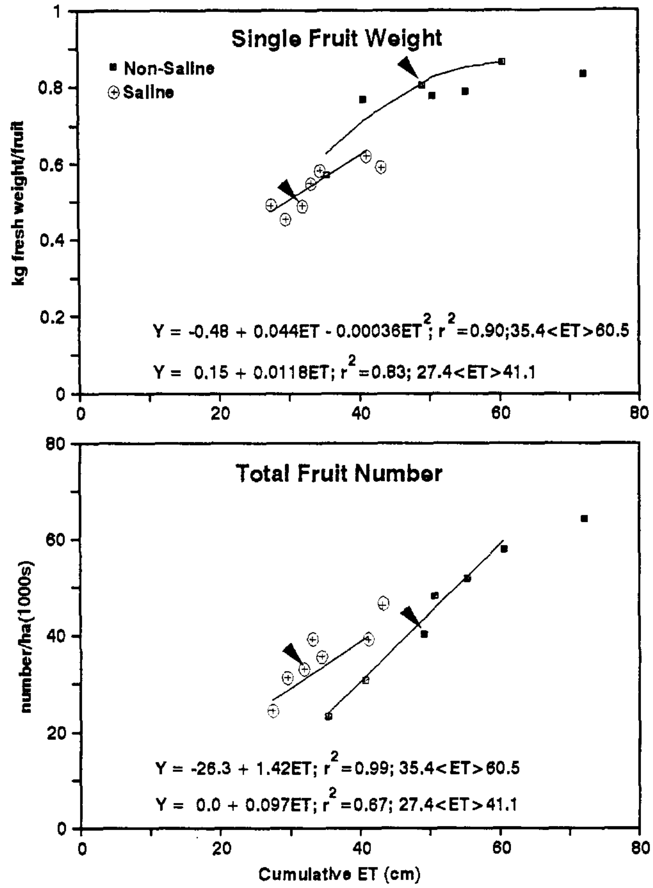

Fig. 3 Effect of water quantity, salinity and late water stress on total fruit number and single fruit weight. Arrows indicate the results of the late water stress treatments. The upper equation in each graph is the regression of the means from the non-saline treatments. The lower equation in each graph is the regression of the means from the saline treatments. Late water stress treatments and the treatment that resulted in deep percolation were not included in the analyses

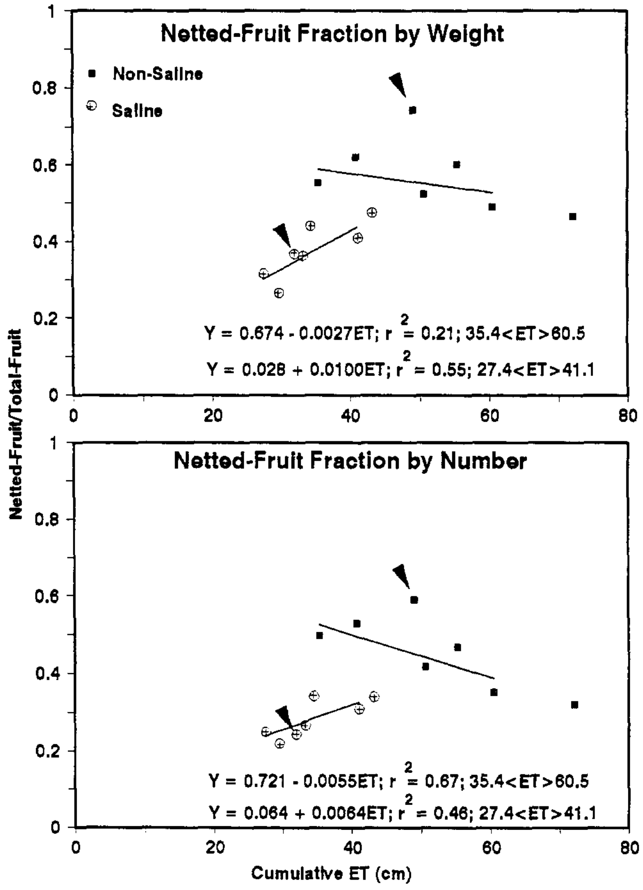

Fig. 4 Effect of water quantity, salinity and late water stress on the percentage of netted fruit (netting is an indication of mature fruit of marketable quality). Fruit was considered netted if a glabrous area covered less than 50% of the surface. Arrows indicate the results of the late water stress treatments. The upper equation in each graph is the regression of the means from the non-saline treatments. The lower equation in each graph is the regression of the means from the saline treatments. Late water stress treatments and the treatments that resulted in deep percolation were not included in the analyses.

The deficit irrigations employed in this study resulted in water and salt stresses which increased with time. Thus, the treatments had small effects on the vegetative growth, which took place mainly in the early growth stages, and larger effects on fruit growth and maturation, which took place later and under greater stress levels. The small effects of the stresses on the vegetative growth and their large effects on the fruits resulted in reduced sink/source ratios for metabolites as the water or salt stresses increased.

Non-saline soil water deficit affected yield, primarily by reducing fruit number. Only the driest non-saline treatments also affected the size of single fruits. This result suggests that water stress reduced the numbers of either flowers or fruits. For similar I_w, fruit number was larger in the saline than in the non-saline treatments. The difference can be related to the smaller water stress (higher soil water content) in the saline treatments (Fig. 1). Non-saline soil water deficit increased the percentage of netted fruit, whereas,

Table 2 Effect of salinity and quantities of irrigation water on mean layer soil salinity at mid-distrance between emitters along the laterals, as electrical conductivity of saturated paste extract (EC_e)±SE, on different sampling dates. [a] Treatment descriptions appear in Table 1

Treat.[a]	49 DAS			109 DAS		
Depth (cm)	0–10	10–30	30–60	0–10	10–30	30–60
			EC_i=6.3 dS m^{-1}			
8	12.3±1.9	6.1±0.4	5.0±0.3	14.3±3.6	4.5±0.5	6.0±1.2
9	14.9±3.0	6.2±0.6	4.7±0.3	21.2±4.2	7.3±0.4	6.6±0.6
10	12.0±2.3	6.1±0.3	5.1±0.1	18.1±2.3	6.3±0.4	5.8±0.6
11	15.7±3.1	6.1±0.4	5.0±0.1	24.9±5.2	6.9±1.1	5.4±0.8
12	11.0±2.9	5.7±0.8	5.4±0.2	12.7±2.9	4.9±0.5	4.9±0.6
13	10.0±2.1	5.4±0.2	5.0±0.2	14.9±0.4	8.5±2.7	5.6±0.5
14	18.8±1.2	6.5±0.8	5.5±0.3	22.6±5.9	5.4±0.7	7.3±1.1
			EC_i=1.2 dS m^{-1}			
2				9.4±2.0	2.7±0.1	2.4±0.6
6				6.6±2.0	2.5±0.7	1.8±0.3

Table 3 Effect of irrigation quantity, salinity and late water stress on the rate and duration of netted-fruit production[a]. (The fitted curves used data of 6 and 7 harvests in the saline and non-saline treatments, respectively. r^2 for all treatments was between 0.97 and 1.00). [a] Rate of production between 74 DAS and the date of the final harvest was estimated according to the equation $Y=A+BX+CX^2$, where Y is the cumulative amount of netted fruit in Mg per ha and "X" is the DAS. [b] Treatment descriptions appear in Table 1. [c] X at $\delta y/\delta x=0$ is the calculated end of netted-fruit production in DAS. [d] Y netted at $\delta y/\delta x=0$ is the calculated final netted-fruit yield in Mg/ha

Treatment[b]	A	B	$C10^{-5}$	X[c]	Y[d]
			$EC_i=1.2$ dS m^{-1}		
1	−16.1	0.292	− 79	186	10.9
2	−55.1	1.139	−467	122	14.4
3	−72.6	1.508	−591	128	23.6
4	−53.1	0.887	−201	220	28.2
5	−102.4	1.947	−740	135	25.7
6	−106.4	1.998	−750	133	26.6
7	−71.7	1.369	−472	145	26.6
			$EC_i=6.3$ dS m^{-1}		
8	−28.3	0.616	−294	105	4.0
9	−33.4	0.726	−353	103	4.0
10	−72.6	1.603	−795	101	8.2
11	−60.0	1.282	−595	108	9.1
12	−83.8	1.776	−842	105	9.9
13	−80.7	1.606	−686	117	12.3
14	−47.5	1.044	−505	103	6.5

saline soil water deficit reduced both fruit size and the fraction of netted fruit. The sink/source relations were important also for fruit netting. Fruit netting improved in the non-saline treatments when the ratio of fruit number to shoot weight decreased. In response to increased I_w fruit number increased more than vegetative yield and fruit netting decreased (Figs. 2–4). The late water stress treatment that resulted in large vegetative shoots and somewhat reduced fruit numbers had the largest fraction of netted fruits. Fruit netting in the saline treatments increased with increasing I_W and the delayed leaf deterioration.

Total fruit fresh weight, an estimate of total fruit volume, showed common positive relation to ET for the two water qualities. We assume that common response for water and salt stresses indicates total soil water potential rather than specific salt effect. All other fruit parameters responded differently to different EC_i indicating specific salinity effects. Increases in melon fruit dry matter contents have been reported under salt (Mendlinger and Pasternak 1992a; Shannon and Francois 1978) or water stresses (Pew and Gardner 1983). In the present study, total fruit dry weight responded primarily to the water availability, or the total potential effect, as seen by the similar slopes for the two water qualities (Figure 2c), but the different intercepts are the result of the additional salinity-specific effect that increased fruit dry matter content. The larger fruit dry matter content in the saline than in the non-saline treatments, with no interaction with water stress, indicates that fruit volume expansion depends more on water availability than on metabolite availability. Salinity has been reported to reduce expansion and increase net photosynthesis of surgarbeet leaves (Heuer and Plaut 1989), while the high sensitivity of volume expansion to water availability is well documented (Hsiao 1993).

The smaller fraction of fruit netting and larger fruit dry matter content in the saline as compared with the non-saline treatments indicates that the two attributes are affected by different mechanisms. They are also determined during different periods of fruit development.

Plants irrigated with saline water produced more fruit of smaller size, with less netting, similar fresh weight and higher dry matter content, as compared with those irrigated with non-saline water that have similar ET. Salinity damage increased with time as a result of damage to the canopy. The combinations of salinity and low amounts of water were detrimental to melons, as indicated by the reduced duration of, and earlier end to the production period, the deterioration of the canopy and reduced fruit netting. Non-deficit irrigation can alleviate part of the damage caused by salinity.

Vegetative and reproductive production depend on the relations between successive development and growth processes. The present study showed that for melons planted in non-saline soil and germinated with fresh water, later water and salt stresses had similar effects on most vegetative growth although salinity accelerated leaf deterioration. The two stresses had similar effects on total fruit fresh weight but different effects on fruit number, size, netting and metabolite content. Understanding of the mechanisms and knowledge of the time when they are most active, should provide the basis for irrigation management in accordance with the quality and quantity of available water. Studies aimed at answering these questions should use a detailed scale of plant development to analyze the effects of the two stresses.

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