Yield, Mineral Composition, Water Relations, and Water Use Efficiency of Grafted Mini-watermelon Plants Under Deficit Irrigation

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Abstract. Limited water supply in the Mediterranean region is a major problem in irrigated agriculture. Grafting may enhance drought resistance, plant water use efficiency, and plant growth. An experiment was conducted in two consecutive growing seasons to determine yield, plant growth, fruit quality, leaf gas exchange, water relations, macroelements content in fruits and leaves, and water use efficiency of mini-watermelon plants [*Citrullus lanatus* (Thunb.) Matsum. and Nakai cv. Ingrid], either ungrafted or grafted onto the commercial rootstock ‘PS 1313’ (*Cucurbita maxima* Duchesne × *Cucurbita moschata* Duchesne), under open field conditions. Irrigation treatments were 1.0, 0.75, and 0.5 evapotranspiration rates. In both years (2006 and 2007), marketable yield decreased linearly in response to an increase in water stress. When averaged over year and irrigation rate, the total and marketable yields were higher by 115% and 61% in grafted than in ungrafted plants, respectively. The fruit quality parameters of grafted mini-watermelons such as fruit dry matter and total soluble solids content were similar in comparison with those of ungrafted plants, whereas titratable acidity, K, and Mg concentrations improved significantly. In both grafting combinations, yield water use efficiency (WUE_y) increased under water stress conditions with higher WUE values recorded in grafted than ungrafted plants. The concentration of N, K, and Mg in leaves was higher by 7.4%, 25.6%, and 38.8%, respectively, in grafted than in ungrafted plants. The net assimilation of CO₂, stomatal conductance, relative water content, leaf, and osmotic potential decreased under water stress conditions. The sensitivity to water stress was similar between grafted and ungrafted plants, and the higher marketable yield from grafted plants was mainly the result of an improvement in nutritional status and higher CO₂ assimilation and water uptake from the soil.

Water is fast becoming an economically scarce resource in many areas of the world, especially in arid and semiarid regions such as the Mediterranean basin. The increased competition for water among agricultural, industrial, and urban consumers creates the need for continuous improvement of irrigation practices in commercial vegetable production in this region. Crop growth in arid and semiarid regions usually depends on irrigation, but inappropriate irrigation practice can result in water stress. The reduction in plant growth and yield caused by water stress has been well documented (Hartz, 1997; Jaimez et al., 1999; Kirmak et al., 2002; Şimşek et al., 2004). Moreover, when water supply is limited, plant structure is modified by increasing the root:shoot ratio

(Atkinson et al., 1999; Chaves et al., 2003). Limitation of leaf growth and an increase in stomatal resistance to gas exchanges are associated with a decrease of water and mineral nutrition flow from roots, which affects net assimilation, thereby decreasing the production and allocation of carbohydrates to the epigeous plant parts, including the fruits (Atkinson et al., 1999; Shaw et al., 2002).

In recent years, it has become clear that the maintenance of a slight water deficit can improve the partitioning of carbohydrates to reproductive structures such as fruit and also control excessive vegetative growth (Chalmers et al., 1981), carrying out what was called “regulated deficit irrigation” (RDI) by Chalmers et al. (1986). In this technique (RDI), irrigation input is removed or reduced for specific periods during the growth cycle of crops as described in eggplant (*Solanum melongena* L.; Kirmak et al., 2002) or watermelon (Şimşek et al., 2004). This technique is widely used in the horticultural

industry, because it results in more efficient use of irrigation water and often improves product quality (Turner, 2001).

Another way to reduce losses in production and to improve water use efficiency under drought conditions in high-yielding genotypes would be to graft them onto rootstocks capable of reducing the effect of water stress on the shoot as observed in tree crops (García-Sánchez et al., 2007; Satisha et al., 2007). In the past, grafting was used widely in vegetable crops to limit the effects of soil pathogens (Lee, 1994), but the reasons for grafting as well as the species of vegetables grafted have increased over the years. Grafts have been used to induce resistance against low (Bulder et al., 1990) and high (Rivero et al., 2003) temperatures and against iron chlorosis in calcareous soils (Romera et al., 1991) and to enhance nutrient uptake and mineral nutrition (Pulgar et al., 2000; Ruiz et al., 1997), increase synthesis of endogenous hormones (Proebsting et al., 1992), reduce uptake of persistent organic pollutants from agricultural soils (Otani and Seike, 2006), raise salt and flooding tolerance (Estañ et al., 2005; Yetisir et al., 2006), and limit the negative effect of boron and copper toxicity (Edelstein et al., 2005, 2007; Rouphael et al., 2007). Nevertheless, no published data are available concerning the effects of water stress on agronomical and physiological responses of grafted mini-watermelon [*Citrullus lanatus* (Thunb.) Matsum. and Nakai]. Our hypothesis is that grafting may enhance drought resistance, plant water use efficiency, and plant growth. To verify this hypothesis, watermelon plants were grown in two consecutive growing seasons under full and deficit irrigation regimes. Grafted and ungrafted plants were compared in terms of yield, plant growth, fruit quality parameters, leaf gas exchange, water relations, macroelement content in fruits and leaves, and water use efficiency.

Materials and Methods

Experimental site and climatic data. An experiment was conducted in two consecutive growing seasons, one in 2006 (Season 1) and another in 2007 (Season 2) in an experimental station located in Viterbo, central Italy (lat. 42°25′N, long. 12°08′E, alt. 310 m above sea level). The soil was a sandy loam soil of volcanic origin (bulk density 1.1 g·cm⁻³, pH 7.1, organic matter 1.8%, available P 21 mg·kg⁻¹, exchangeable K 3380 mg·kg⁻¹ with a textural analysis of 67% sand, 18% silt, and 15% clay). The measured field capacity (−0.33 bar) and permanent wilting point (−15 bar) averaged 22.3% and 16.3% by weight. Table 1 summarizes the monthly climate data during the two growing seasons compared with the long-run means.

Crop management, experimental design, and irrigation treatments. In both growing seasons, watermelon plants [*Citrullus lanatus* (Thunb.) Matsum. and Nakai], cultivar Ingrid (Taki, Japan), which was selected as a representative mini-watermelon hybrid cultivated

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Table 1. Climatic parameters prevailed during the two growing seasons (2006 and 2007) compared with the long run data.

Climatic parameters	May	June	July	August
		<i>Long run data (1984–2004)</i>		
Minimum air temp. (°C)	8.5	12.0	14.7	15.4
Maximum air temp. (°C)	21.1	25.3	29.3	29.5
Rainfall (mm)	56.2	53.9	31.2	53.1
Relative humidity (%)	65.0	55.1	50.9	63.7
Wind speed (m·s ⁻¹)	1.1	1.2	1.2	1.3
ET _o (mm) ²	130.1	143.8	169.9	139.2
		2006		
Minimum air temp. (°C)	9.6	12.9	18.6	15.7
Maximum air temp. (°C)	23.7	27.2	32.3	27.9
Rainfall (mm)	5.4	23.8	18.2	88.2
Relative humidity (%)	66.3	52.7	52.2	66.5
Wind speed (m·s ⁻¹)	1.1	1.4	1.4	1.2
ET _o (mm)	132.0	148.4	178.7	133.2
		2007		
Minimum air temp. (°C)	10.7	14.1	15.6	16.4
Maximum air temp. (°C)	23.8	27.7	31.2	29.0
Rainfall (mm)	70.2	46.0	0.8	25.1
Relative humidity (%)	68.8	66.9	50.2	59.6
Wind speed (m·s ⁻¹)	1.1	1.1	1.2	1.3
ET _o (mm)	123.4	142.2	170.4	145.5

²ET_o reference evapotranspiration calculated according to Penman-Monteith equation.

in Italy, was used as a scion and the commercial and widely used hybrids rootstock PS 1313 (*Cucurbita moschata* Duchesne × *Cucurbita maxima* Duchesne; Petoseed Company, Parma, Italy) was used as a rootstock. Seeds of the hybrid Ingrid were sowed 3 d before than the *Cucurbita* rootstock seeds to ensure uniformity in hypocotyl diameter of both the scion and rootstock. The “tongue approach” (Lee, 1994) was used for grafting the scion Ingrid onto the commercial rootstock. Grafted (‘PS 1313’/‘Ingrid’) and ungrafted (‘Ingrid’) watermelon plants were transplanted on 26 May 2006 (Season 1) and on 26 May 2007 (Season 2) after a wheat crop. The 3-year rotations included wheat, watermelon, and processing tomato. In both seasons, preplant fertilizer was broadcast (kg·ha⁻¹; 130N–52P–141K–12 Mg) and incorporated into the soil. Additional fertilizer (kg·ha⁻¹; 61N–78K) was applied through the drip system weekly for 5 weeks using KNO₃ and NH₄NO₃ as sources of N and K, respectively. In both growing seasons, powdery mildew, caused by the fungi *Erysiphe cichoracearum* and *Sphaerotheca fuliginea*, was controlled by two foliar treatments of penconazole (Topas 10EC; Syngenta, Milano, Italy) + dinocap (Karathane FN; Dow Agrosciences, Bologna, Italy) at the labeled rate, whereas copper-based products (Coprantol WG; Syngenta) were used twice to control downy mildew (*Pseudoperonospora cubensis*); aphids and spider mites were controlled with one foliar treatment of imidacloprid (Confidor 200 SL; Bayer CropScience, Milano, Italy) and two foliar treatments of fenpiroximate (Miro; Bayer CropScience), respectively. In both seasons, weeds were controlled with hand hoeing.

Treatments were defined by a factorial combination of three irrigation levels based on evapotranspiration (ET) rates (1.0, 0.75, and 0.5 ET) and two grafting treatments (ungrafted ‘Ingrid’ and grafted ‘PS 1313’/‘Ingrid’). Each experimental unit consisted

of three rows, 7 m in length, with 2-m row spacing and 1-m in-row spacing containing 21 plants, giving a theoretical plant population of 5000 plants/ha. The treatments were arranged in a randomized complete block design with three replicates per treatment.

Drip lines, with in-line emitters located 0.30 m apart and an emitter flow rate of 3.4 L·h⁻¹, were placed 10 cm away from the plants and were spaced with a 2-m distance between each lateral. All treatments were given uniform optimal irrigation (1.0 ET) for 3 weeks after transplanting to promote root system establishment without water stress. The water supply was based on the actual water requirements (I), which was calculated as follows: $I = (ET_o \times K_c)$ where ET_o is the potential ET from micrometeorological data using the FAO Penman-Monteith method (Allen et al., 1998) and K_c the crop coefficient that was estimated by the percentage groundcover by foliage development measured weekly with a digital camera pointed straight upward beneath the canopy.

Yield, fruit quality, and plant biomass measurements. In both seasons, fully mature fruits were harvest on 3 Aug. 2006 (70 d after transplanting, Season 1) and on 6 Aug. 2007 (73 d after transplanting, Season 2). Fruits that were cracked, badly misshapen, and weighed less than 1.8 kg were considered unmarketable. The number of fruits, mean fruit mass, and total and marketable yields were determined. The total yield and marketable yield were expressed in t·ha⁻¹.

In both seasons, six representative marketable fruits per treatment were analyzed for fruit quality parameters. Immediately after harvest, fruit shape index (SI), defined as the ratio of equatorial and longitudinal lengths, was measured. From the liquid extract obtained from liquefying and filtering the mesocarp of each fruit, total soluble solids (TSS) content in juice was determined by an Atago N1 refractometer (Atago Co. Ltd., Tokyo) and expressed in °Brix at 20 °C.

Acidity was determined by potentiometric titration with 0.1 M NaOH up to pH 8.1 using 15 mL of juice. Results were expressed as percentage malic acid in the juice. Fruits were dried in a forced-air oven at 80 °C for 72 h and weighed to determine the fruit dry matter (DM).

At final harvest, 70 and 73 d after transplanting in 2006 and 2007, respectively, seven plants per plot were separated into stems, and leaves and their tissues were dried in a forced-air oven at 80 °C for 72 h for biomass determination. Shoot dry biomass was equal to the sum of aerial vegetative plant parts (leaves + stems) and was expressed in t·ha⁻¹.

Seasonal evapotranspiration and water use efficiency. Evapotranspiration (for each treatment) was estimated according to the water balance approach (James, 1988).

$$ET = I + P - D_r - R_f \pm \Delta_s \quad (1)$$

where ET is the seasonal crop ET, I is the applied irrigation water during the growth period, P is the effective rainfall during the growth period, D_r is the amount of deep percolation, R_f is the amount of runoff, and Δ_s is the change in the soil water content determined by gravimetric sampling. All terms in Eq. (1) are expressed in millimeters. Rainfall below 5.0 mm was assumed to be lost by evaporation and therefore ineffective; it was treated as zero rainfall contribution.

To determine ET, soil moisture at 0 to 30, 30 to 60, and 60 to 90 cm depth was measured gravimetrically before each irrigation and at harvest. Because there was no observed runoff during the experiments and the water table was at 6 m depth, capillary flow to the root zone and runoff flow were assumed to be negligible in the calculation of ET. Drainage below 90 cm, after a number of soil–water content measurements, was considered negligible. So the previous equation was reduced to $ET = I + P \pm \Delta_s$. Yield water use efficiency (WUE_y) was calculated as the marketable fruit yield divided by the seasonal crop evapotranspiration (Baille, 2001), whereas biomass water use efficiency (WUE_b) was calculated as the aboveground dry biomass divided by the seasonal crop evapotranspiration. WUE_y and WUE_b were expressed in kg·m⁻³.

Mineral analysis. For the 2006 growing season only, dried plant tissues (leaf and fruit) were ground separately in a Wiley mill (Thomas Scientific, Swedesboro, NJ) to pass through a 20-mesh screen; then 0.5 g of the dried plant tissues were analyzed for the following macronutrients: N, P, K, Ca, and Mg for leaves and P, K, Ca, and Mg for fruits. Nitrogen concentration in the leaf tissue was determined after mineralization with sulfuric acid by “Regular Kjeldahl method” (Bremner, 1965), P, K, Ca, and Mg concentrations were determined by dry ashing at 400 °C for 24 h, dissolving the ash in 1:25 HCl, and assaying the solution obtained using an inductively coupled plasma emission

spectrophotometer (ICP Iris; Thermo Optek, Milano, Italy) (Karla, 1998).

Leaf gas exchange and water potential measurements. Sixty days after transplanting (for the 2006 growing season), leaf gas exchange [the net assimilation of CO₂ (ACO₂; μmol CO₂/m²·s⁻¹) and stomatal conductance (g_s; mol·m⁻²·s⁻¹)] were measured using a portable photosynthetic open system (LI-6200; LI-COR, Lincoln, NE). Those measurements were made on the most recent fully expanded leaves using six replicate leaves per treatment. The LI-6200 was equipped with a well-stirred 2.5 × 10⁻⁵ m³ leaf chamber with constant area inserts (1.2 × 10⁻³ m²) and fitted with a variable intensity red source (Model QB1205LI-670; Quantum Devices, Barneveld, WI) (Tennessen et al., 1994). Leaf temperature within the chamber was 30 ± 2 °C, vapor pressure difference between the leaf and air was 2.6 ± 0.3 °C, and CO₂ concentration was 365 ± 10 μA·L⁻¹. All gas exchange measurements were made between 1000 and 1200 HR on clear sky days (photosynthetically active radiation greater than 1500 μmol·m⁻²·s⁻¹).

Leaf relative water content (RWC) was measured on the fully opened fourth or fifth leaf from the top of the plant of six plants per replicate. Five leaf discs of 10 mm diameter were excised from the interveinal areas of each plant. For each replicate, 30 discs were pooled and their fresh weight (FW) was determined. They were floated in distilled water in petri dishes for 4 h in the dark to regain turgidity, and then thawed and reweighed [turgid weight (TW)]. The samples were dried at 80 °C for 24 h to determine the dry weight (DW). Tests showed that complete hydration of the leaf discs occurred within 4 h. RWC was calculated using the following formula (Jones and Turner, 1978):

$$RWC\% = \frac{FW - DW}{TW - DW} \times 100 \quad (2)$$

The water potential components of leaves were measured psychrometrically using C52 sample chambers in conjunction with a HR-33T Dew point microvoltmeter (Wescor, Logan, UT) previously calibrated by a gradient series of standard KCl solutions on saturated discs of filter paper placed in the C52 chamber. A Peltier cooling current of 5 mA was applied for 15 s, and the microvolt output was recorded with a strip chart recorder. Leaf water potential (Ψ_w) was measured between 1100 and 1400 HR on tissue discs punched from fully expanded, healthy, and sun-exposed leaf. Leaf disc samples (0.5 cm diameter) were rapidly sealed inside the chamber in less than 8 s. An equilibration period of 2 to 3 h was required to obtain stable readings of Ψ_w. For osmotic potential (Ψ_π), leaf discs taken from the same leaves were wrapped in aluminum foil and rapidly frozen at -35 °C on dry ice. When thawed, Ψ_π was determined after 30 min equilibration in the same C52 sample chambers. Turgor potential (Ψ_p) was derived as the difference between Ψ_w and Ψ_π.

Statistical analysis. Analysis of variance of the treatment effects on measured traits was performed using the GLM procedure of SPSS software package (SPSS 10 for Windows, 2001). Combined analysis of variance over 2 years was performed for yield, fruit yield components, aboveground dry biomass, and fruit quality [SI, DM, TSS, and titratable acidity (TA)] of mini-watermelon plants. In this analysis, year was considered a random variable. All parameters were analyzed by two-way analyses of variance within each year. In both seasons, orthogonal contrasts were used to compare irrigation rate effects (Gomez and Gomez, 1983) on selected parameters.

Results

Fruit yield and biomass production. Total yield, marketable yield, mean fruit mass, fruit number, and shoot dry biomass of watermelons were significantly influenced by irrigation rate (I) and grafting combination (G), whereas no significant differences were observed on year (Y, except for fruit mean mass), Y × I, Y × G, I × G, and Y × I × G interactions (Table 2). In 2006 and 2007, in both grafted and ungrafted plants, total yield and marketable yield decreased linearly in response to an increase in water stress (Table 2). When averaged over year and irrigation rate, the total and marketable yields were higher by 115% and 61% in grafted than in ungrafted plants, respectively. The lowest marketable yield of ungrafted plants was attributed to a reduction in both mean fruit mass and numbers of fruits per plant (Table 2).

Similar to fruit yield, the shoot dry biomass of grafted and ungrafted plants in both seasons decreased linearly in response to an increase in water stress. When averaged over year and irrigation rate, the shoot biomass was significantly higher in grafted than in ungrafted plants (Table 2).

Fruit quality. No significant differences among treatments were observed for SI, fruit DM, and TSS contents (Table 3). Moreover, the (TA) was significantly affected by grafting combination but not by year, irrigation rate, or Y × I × G interaction (Table 3). When averaged over year and irrigation rate, the TA was higher in grafted than in ungrafted plants.

Concerning the fruit mineral composition, no significant difference among treatments were observed for P (average 1.66 mg·g⁻¹ dry wt) and Ca (average 1.90 mg·g⁻¹ dry wt) concentrations, whereas K and Mg concentrations were significantly affected by both irrigation rate and grafting combination with no significant irrigation × grafting interaction (Table 4). Across the grafting combination, the K and Mg concentrations increased quadratically and linearly, respectively, as the irrigation rate decreased from 1.0 to 0.5 ET. Moreover, when averaged over the irrigation rate treatments, the concentration of K and Mg in grafted plants was significantly higher by 13.0% and 23.8%, respectively, than those recorded in ungrafted plants.

Seasonal evapotranspiration and water use efficiency. In both growing seasons, the seasonal ET of grafted and ungrafted plants decreased with increasing water deficit, whereas both yield and biomass water use efficiency increased under water stress conditions (Table 5). When averaged over years, the reduction in water use in ungrafted plants at 0.75 ET and 0.5 ET treatments was 15.1% and 32.5%, respectively, compared with 1.0 ET, whereas the reduction in water use in grafted plants at 0.75 ET and 0.5 ET treatments was 15.7%, and 30.5%, respectively, compared with 1.0 ET (Table 5). The WUE_y in grafted and ungrafted plants grown at 0.5 ET increased by 10% and 7%, respectively, compared with those grown under a full irrigation regime (Table 5). Similar to WUE_y, the WUE_b of grafted and ungrafted plants in

Table 2. Main effects of year, deficit irrigation based on evapotranspiration (ET) rates, and grafting combination on total yield (t·ha⁻¹), marketable yield (t·ha⁻¹), fruit mean mass (kg/fruit), fruit number (no./plant), and aboveground dry biomass (t·ha⁻¹) of mini-watermelon plants.

Treatment	Yield		Marketable fruit		Dry biomass
	Total	Marketable	Mean mass	Number	
Year					
2006	37.0	25.0	3.21	1.54	1.32
2007	35.8	24.1	2.86	1.65	1.42
Irrigation rate					
1.0 ET	45.5	29.5	3.24	1.82	1.50
0.75 ET	38.3	26.0	3.09	1.68	1.41
0.5 ET	25.9	22.1	2.78	1.59	1.21
Graft combination					
Ungrafted	23.2	19.8	2.86	1.39	1.04
Grafted	49.9	31.9	3.21	2.00	1.70
Significance ²					
Year (Y)	NS	NS	**	NS	NS
Irrigation (I)	L**	L***	L**	L**	L**
Graft combination (G)	***	***	**	***	*
Y × I	NS	NS	NS	NS	NS
Y × G	NS	NS	NS	NS	NS
I × G	NS	NS	NS	NS	NS
Y × I × G	NS	NS	NS	NS	NS

²L = linear.

NS, *, **, ***Nonsignificant or significant at *P* < 0.05, 0.01, or 0.001, respectively.

Table 3. Main effects of year, deficit irrigation based on evapotranspiration (ET) rates, and grafting combination on shape index, dry matter, total soluble solids contents, and titratable acidity of mini-watermelon fruits.

Treatment	Shape index	Fruit dry matter (%)	Total soluble solids (°Brix)	Titratable acidity (%)
Year				
2006	0.80	8.32	8.55	0.09
2007	0.86	8.48	8.86	0.09
Irrigation rate				
1.0 ET	0.85	8.17	8.72	0.09
0.75 ET	0.82	8.37	8.44	0.09
0.5 ET	0.83	8.62	9.02	0.08
Graft combination				
Ungrafted	0.85	8.57	8.65	0.08
Grafted	0.82	8.31	8.71	0.11
Significance ²				
Year (Y)	NS	NS	NS	NS
Irrigation (I)	NS	NS	NS	NS
Graft combination (G)	NS	NS	NS	*
Y × I	NS	NS	NS	NS
Y × G	NS	NS	NS	NS
I × G	NS	NS	NS	NS
Y × I × G	NS	NS	NS	NS

²NS, *Nonsignificant or significant at $P < 0.05$, respectively.

Table 4. Main effects of deficit irrigation based on evapotranspiration (ET) rates and grafting combination on macroelements content in fruit of mini-watermelons grown in 2006.

Treatment	Mineral elements (mg·g ⁻¹ dry wt)			
	P	K	Ca	Mg
Irrigation rate				
1.0 ET	1.6	15.3	1.7	2.2
0.75 ET	1.6	18.8	2.1	2.4
0.5 ET	1.8	17.5	2.0	2.6
Graft combination				
Ungrafted	1.6	16.1	2.0	2.1
Grafted	1.7	18.3	1.8	2.7
Significance ²				
Irrigation (I)	NS	Q*	NS	L*
Graft combination (G)	NS	*	NS	*
I × G	NS	NS	NS	NS

²L = linear; Q = quadratic.

NS, *Nonsignificant or significant at $P < 0.05$, respectively.

Table 5. Effects of deficit irrigation based on evapotranspiration (ET) rates and grafting combination on evapotranspiration (ET), yield water use efficiency (WUE_y), and biomass water use efficiency (WUE_b) of mini-watermelon plants grown in 2006 and 2007.

Irrigation rate	Graft combination	ET (mm)		WUE _y (kg·m ⁻³)		WUE _b (kg·m ⁻³)	
		2006	2007	2006	2007	2006	2007
1.0 ET	Ungrafted	238.4	248.3	9.2	9.5	0.47	0.49
	Grafted	270.7	273.9	12.9	13.6	0.64	0.69
0.75 ET	Ungrafted	205.7	207.2	9.3	9.9	0.50	0.53
	Grafted	232.5	227.3	13.5	14.4	0.73	0.81
0.5 ET	Ungrafted	162.1	165.9	9.8	10.5	0.53	0.55
	Grafted	189.5	189.0	14.1	15.0	0.78	0.83

both seasons increased in response to an increase in water stress.

Leaf mineral composition. The macroelements concentration in watermelon leaves as a function of the grafting combination and irrigation rate are displayed in Table 5. When averaged over grafting combination, the concentration of N, P, and K decreased linearly in response to an increase in water stress, whereas an opposite trend was observed for Mg concentration (Table 6). The results also indicate that the concentration of N, K, and Mg in leaves was significantly higher by 7.4%, 25.6%, and 38.8%, respectively, in grafted than in ungrafted plants (Table 6). Finally, no significant difference among treat-

ments was observed for the Ca (average 27.5 mg·g⁻¹ dry wt) concentration.

Leaf gas exchange and water relations. Net assimilation of CO₂ (A_{CO₂}) and g_s were measured for leaves to study gas exchange. A_{CO₂} and g_s were significantly affected by irrigation rate ($P < 0.01$), grafting combination ($P < 0.05$), and irrigation × grafting interaction ($P < 0.05$). In both grafted and ungrafted plants, A_{CO₂} and g_s decreased quadratically in response to an increase in water stress. However, under severe water stress, the reduction in A_{CO₂} and g_s was more in ungrafted than in grafted plants (Fig. 1).

Relative water content, Ψ_w, Ψ_π, and Ψ_p were significantly affected by irrigation rate

but not by the grafting combination and the irrigation × grafting interaction (Table 7). In both grafted and ungrafted plants, RWC, Ψ_w, Ψ_π, and Ψ_p decreased linearly in response to an increase in water stress.

Discussion

Agronomical responses. It is well established that crop growth and yield decrease with increasing water stress (Chaves et al., 2003). Mini-watermelon marketable yield decreased with increasing water stress (Table 2) in agreement with many open-field studies on muskmelon (*Cucumis melo* L.; Fabeiro et al., 2002), eggplant (Kirmak et al., 2002), watermelon (Leskovar et al., 2004; Şimşek et al., 2004), cucumber (*Cucumis sativus* L.; Ertek et al., 2006), bell pepper (*Capsicum annuum* L.; Sezen et al., 2006), and tomato (*Lycopersicon esculentum* L.; Topcu et al., 2007). The higher yield of mini-watermelon from grafted plants observed in this study has been reported earlier on tomato (Fernández-García et al., 2004) and melon (Ruiz et al., 1997; Ruiz and Romero, 1999). The lowest marketable yield recorded in ungrafted plants was associated with reduction in mean fruit mass and number of fruits per plant (Table 2). Those results are consistent with the findings of Salam et al. (2002) and Yetisir and Sari (2003) who found that grafting watermelon onto bottle gourd rootstock enhances production by increasing both mean fruit mass and number.

It was demonstrated that grafting directly affects plant yield (Nielsen and Kappel, 1996; Rivero et al., 2003) by interactions of some or all of the following processes: increase of water and nutrient uptake resulting from the vigorous root system of the rootstock (Lee, 1994; Ruiz et al., 1997), enhanced production of endogenous hormones (Zijlstra et al., 1994), or enhancement of scion vigor (Leoni et al., 1990). The joint action of some or all of these processes could explain the higher yield in mini-watermelon from grafted plants observed in the current study.

In general, water stress reduces the yield of vegetable crops, but in many cases improves their quality. In the present study, the fruit quality aspects were slightly affected by the water stress. Our results indicate that under water stress conditions, a higher concentrations of K and Mg was observed (Table 4), which is interesting from a nutritional point of view because fruits and vegetables usually contribute 35% and 24%, respectively, of the total K and Mg to the dietary intake of humans (Levander, 1990). Moreover, no numerical differences were found in fruit DM and TSS contents (Table 3). Those results are consistent with the findings of Leskovar et al. (2004) who reported for diploid and triploid watermelon cultivars that increasing deficit irrigation based on ET rate did not significantly change the soluble solids content.

Many investigations have provided evidence that certain *Cucurbita* rootstocks may

Table 6. Main effects of deficit irrigation based on evapotranspiration (ET) rates and grafting combination on leaf macroelements content of mini-watermelon plants grown in 2006.

Treatment	Mineral elements (mg·g ⁻¹ dry wt)				
	N	P	K	Ca	Mg
Irrigation rate					
1.0 ET	34.0	1.2	13.5	26.4	5.0
0.75 ET	32.5	1.1	12.1	28.1	5.9
0.5 ET	30.5	0.9	11.3	28.0	6.6
Graft combination					
Ungrafted	31.2	1.0	10.9	27.9	5.07
Grafted	33.5	1.1	13.7	27.1	5.40
Significance ^z					
Irrigation (I)	L***	L*	L**	NS	L**
Graft combination (G)	**	NS	**	NS	***
I × G	NS	NS	NS	NS	NS

^zL = linear.

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

Fig. 1. Effects of deficit irrigation based on evapotranspiration (ET_c) rates and grafting combination on net assimilation CO₂ (A_{CO₂}), and stomatal conductance (g_s) of mini-watermelon plants.

significantly deteriorate fruit quality (Lee, 1994; Lee and Oda, 2003). In the present study, quality characteristics such as fruit DM and TSS content of grafted mini-watermelon were similar to those of the plants grown on their own roots, whereas TA and K

and Mg concentrations improved significantly. Therefore, the use of watermelons grafted onto 'PS 1313' rootstock would be a potential strategy in increasing marketable yield without detrimental effects on fruit quality.

Water use efficiency. When averaged over years, the seasonal crop ET of ungrafted and grafted mini-watermelon totaled 243 and 272 mm, respectively (Table 5). Şimşek et al. (2004), who measured crop ET by water balance under open-field conditions, reported that total seasonal ET of 'Crimson' watermelon grown in the semiarid zone of Turkey was 647 mm and this value was 166% and 138% (for ungrafted and grafted plants, respectively) higher than the values recorded in this study. Explanations for this difference could be the different environments in which the plants were grown; the central region of Italy is characterized by a mild summers with maximum air temperature up to 32 °C and ET_o from May to July equal to 448 mm, whereas the Harran plain has a well-defined hot and dry season from May to September with air temperature up to 47 °C, relative humidity averaging ≈34%, and the total class A pan evaporation from May to July equal to 1046 mm. Another reason for this disagreement was the different watermelon cultivars used in these studies, the widely grown 'Crimson' cultivar (mean fruit weight 7 to 9 kg) used by Şimşek et al. (2004), whereas the 'Ingrid' mini-watermelon is characterized by a very early maturity stage, small fruit size

(fruit mean weight of 3 to 4 kg), and limited vegetative growth.

In this study, we found that the relationship between ET and yield was modified by water supply. As a mean of both years, the yield WUE_y of ungrafted plants amounted to 9.3, 9.6, and 10.1 kg·m⁻³ for control, moderate, and severe drought, respectively, whereas the WUE of grafted plants amounted to 13.2, 13.9, and 14.5 kg·m⁻³ for control, moderate, and severe drought, respectively (Table 5). Increased WUE values under water stress conditions were also found in eggplant (Kırnak et al., 2002), bell pepper (Dalla Costa and Gianquinto, 2002), and watermelon (Şimşek et al., 2004). The higher efficiency of water use under stress is because drought-stressed plants wilt far more than unstressed plants and wilting invariably occurs in times when the saturation deficit of the atmosphere is large. Therefore, the plant assimilates only when the saturation deficit is small and hence loses less water for every carbon molecule fixed (Bloch et al., 2006; Clover et al., 2001). Grafted plants obtained higher marketable yield in all treatments and hence used the water more efficiently than ungrafted plants.

Nutrient uptake. The low macronutrient concentration (N, P, and K) recorded in the current study under water stress conditions could be attributed to a decrease in soil moisture content in the root zone (Table 6). Those results are consistent with the findings of Simonne et al. (1998), Kırnak et al. (2001, 2002), and Kaya et al. (2003) who reported for several vegetable crops that water stress has a wider role in reducing leaf macronutrient concentrations.

The plants grafted onto 'PS 1313' showed a high capacity for N, K, and Mg assimilation with respect to the ungrafted ones (Table 6). In early studies, influence of rootstocks on plant nutrient uptakes was principally attributed to physical characteristics such as lateral and vertical development of roots that promoted the uptake of water and inorganic nutrients (Castle and Krezdorn, 1975). Besides, the vigorous root system of rootstocks is often capable of absorbing plant nutrients more efficiently than scion roots (Pulgar et al., 2000; Ruiz and Romero, 1999) and serves as a good supplier of endogenous hormones (Jang, 1992; Kato and Lou, 1989). This result confirms our hypothesis that grafted plants on vigorous rootstocks can improve mineral nutrition and nutrient uptake with respect to ungrafted plants.

Physiological response. Severe drought stress significantly reduced yield and biomass production of both ungrafted and grafted mini-watermelon plants. These reductions were associated with changes in various parameters of photosynthesis and leaf water status. A decline in the photosynthetic rate under water stress conditions could be attributed either to a decrease in g_s or to nonstomatal limitations (Cornic and Massacci, 1996; Jones, 1992). The parallel changes of photosynthetic rate and g_s provide evidence that the maintenance of the photosynthetic rate could be mainly attributed to the maintenance

Table 7. Main effects of deficit irrigation based on evapotranspiration (ET) rates and grafting combination on relative water content (RWC), leaf water potential (Ψ_w), leaf osmotic potential (Ψ_π), and leaf turgor (Ψ_p) potential of mini-watermelon plants grown in 2006.

Treatment	RWC (%)	Ψ _w (MPa)	Ψ _π (MPa)	Ψ _p (MPa)
Irrigation rate				
1.0 ET	91.8	-0.57	-0.79	0.23
0.75 ET	82.6	-0.67	-0.86	0.19
0.5 ET	72.4	-0.78	-0.91	0.14
Graft combination				
Ungrafted	80.9	-0.67	-0.86	0.18
Grafted	83.7	-0.66	-0.85	0.18
Significance ^z				
Irrigation (I)	L***	L**	L**	L*
Graft combination (G)	NS	NS	NS	NS
I × G	NS	NS	NS	NS

^zL = linear.

NS, *, **, ***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

of g_s (Fig. 1). Moreover, decrease of soil water moisture in the root zone can lead to an osmotic adjustment (lowering of leaf Ψ_π) that is generally accepted as an important adaptation to drought. The decrease of Ψ_π would compensate the drought-induced lowering of Ψ_w , helping to maintain turgor pressure and cell functions under adverse water conditions (Table 7). Finally, the similar physiological responses (RWC and leaf water status) between the grafted and ungrafted watermelon plants may explain the similarity in response to drought and confirm that the higher marketable yield recorded with grafting was the result of a better nutritional status and higher CO_2 assimilation and water uptake from the soil.

Conclusions

Water deficit has been shown to adversely affect yield, biomass production, leaf mineral composition, and leaf water status of watermelon, but reduced water use and increased the WUE. Our results also indicate that grafted plants exhibited higher marketable yield, improved nutritional status (higher N, K, and Mg concentration in leaf tissue), fruit quality parameters (higher K and Mg), and WUE than in ungrafted plants, whereas no significant difference was observed in gas exchange and leaf water relations. Sensitivity to water stress was similar between grafted and ungrafted plants and the higher marketable yield recorded with grafting can be associated with a higher nutrient and water uptake ability of their roots and CO_2 assimilation of leaves. Finally, because of the higher crop performance of watermelon plants grafted onto *Cucurbita* rootstock 'PS 1313', we suggest the use of grafted plants under both full and deficit irrigation regimes.

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