Yield response to regulated deficit irrigation of greenhouse cherry tomatoes

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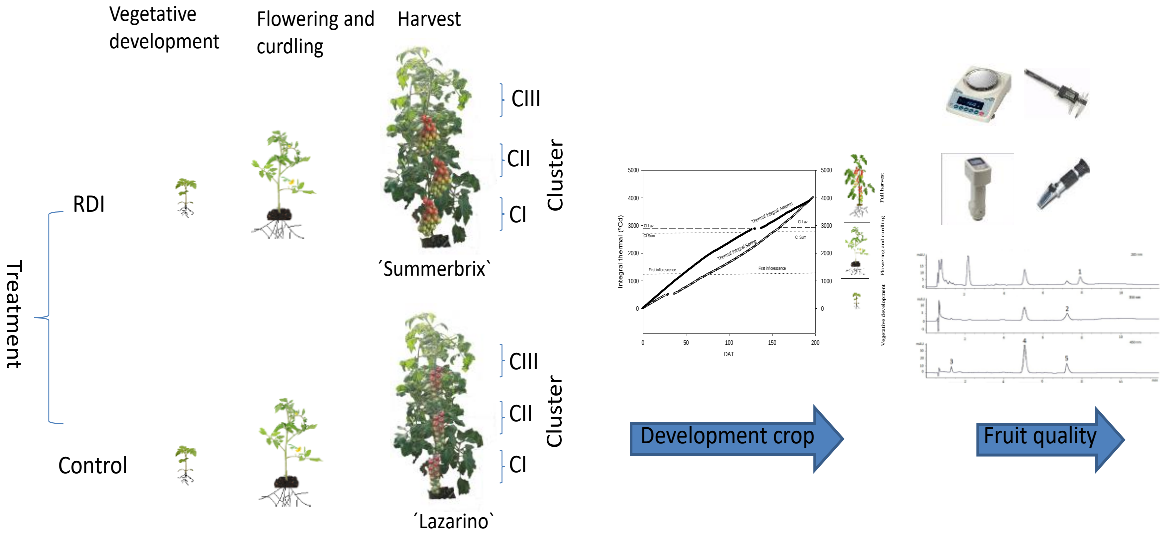
Abstract

Around the world, the tomato is considered the most important vegetable because of the extent of the cultivated area. In addition, it requires vast amounts of irrigation but little is known about the management of deficit irrigation. This study aims to evaluate the effect of regulated deficit irrigation (RDI) on development of crop and fruit quality for cherry tomatoes ('Lazarino' and 'Summerbrix'). Two different cherry cultivars were used during two crop cycles (autumn and spring). RDI was scheduled with an initial period of no water stress and with a period of deficit from the beginning of the flowering, with a threshold of midday leaf water potential of around -1MPa. It was found that the response to the irrigation treatment was affected by the season and even by the cluster considered. During the autumn cycle, there were no clear differences in yield despite water stress being mild but still significant. In the spring cycle, yield reduction peaked with different responses between cultivars. Water stress reduced fruit weight and fruit number per cluster in cv Summerbrix, producing a continuous decrease throughout the harvest period. In cv Lazarino, a yield reduction was detected only at the end of the harvest period and was related to the decrease in fruit weight and the number of inflorescence. The application of RDI reduced water by 85% and increased the content of soluble sugar, carotenoids and total phenols in both cultivars and cycles.

Graphical abstract



***Key words**:* leaf water potential, hydrosustainable foods, deficit irrigation, stress integral

1. INTRODUCTION

The rise in population during recent times implies an increase in agriculture and consequently a greater consumption of water, pushing this resource to its limits (Giuliana, et al, 2011). Moreover, climate change and the location of crops in areas with warm climates that favour production, also limited the availability of water resources (Sepaskhah & Ahmadi, 2010; Mutambara, et al, 2016; Patanè, et al, 2011). The scarcity of water during the development of the crop causes damage which decreases productivity and even the loss of the crop (Xiukang & Yingying, 2016). Regulated deficit irrigation (RDI) it is an irrigation strategy especially used in trees, which tries to ensure an optimal crop water status in phenological phases most sensitive to water stress, and restrict irrigation in most resistant crop phases (Geerts, S., Raes, D., 2009; Galindo et al., 2018). There are few works published in RDI in horticultural crops, tomato has been studied by several authors, and results show yield reduction in many cases and an increase water use efficiency (Yangg et al., 2016; Wang et a., 2015; Bogale et al., 2016; Pulupol et al., 1996). RDI scheduling could improve the irrigation management with null or low yield lost. The management of RDI scheduling is not easy, with particular regards to the level of water stress which could be applied (Chai, et al., 2016). Nevertheless, RDI based on leaf water potential, a water status measurement, could improve the accuracy of this scheduling, because it integrates the soil-water-plant relations system (Corell, et al., 2016).

The application of RDI reduces crop evapotranspiration (ETc) and also leading to improvements in product quality (Chai, et al., 2016; Lahoz, et al., 2016; Carbonell-Barrachina, et al., 2015; Cano-Lamadrid, et al., 2015). Thus, the amount of water supplied to the crop is interdependent on the commercial and functional quality, as well as the environmental and agronomic conditions, leading to a variety of plant responses that can be reflected in leaf water potential, turgor, water content, growth, productivity, fruit size, soluble solids, carotenoid and phenolics content and flavour characteristics (Vinha, et al, 2014; Shao, et al, 2008; Cano-Lamadrid, et al., 2015). These changes in fruits and vegetables grown under a optimum RDI manage provided, in theory, differential products, which are characterised by a high content of bioactive compounds, sensory attributes and high productivity. They are environmentally-friendly and so-called "hydrosustainable" (Cano-Lamadrid, et al., 2015).

Tomato is an important crop and can be found across the entire world, and, it is characterized for large amounts of water (Giuliana, et al, 2011). Actually, there are few studies on RDI in tomato (*Solanum lycopersicum*, L.), and the first studies have focused on the effect on yields related to the application of RDI, in different phenological phases, concluding that the crop establishment and flowering are the most sensitive phenological stage, fruit ripening is a resistant phase, it even improves the organoleptic quality of the fruit (Nangare, et al, 2016; Ripoll, et al, 2016; Zhang, et al, 2013). In tomato grown for processing, the reduction of watering during fruit ripening is standard technique to improve the content of soluble solids (Johnstone et al., 2005). Studies carried out in the south Spain by Fortes et al, specialized in tomato for processing in Extremadura, propose as thresholds: -8MPa as stress level in transplant, flowering and fruit set; and -1MPa for fruit ripening (Fortes et al., 2013).

In tomato cultivars with indeterminate growth the flowering and fruit set occurs at the same time. While the fruits set in the first clusters mature, the fruits of the highest clusters of the plant are setting. The differentiation of the phenolic phases is more difficult. Especially in cherry tomatoes varieties, with numerous fruits per plant. Previous works showed that puntual decrease in leaf water potential in cherry tomatoes to -1MPa (Summerbrix and Lazarino) did not affect greatly the organoleptic quality of common tomatoes and ʿSummerbrixʾ. However, ʿLazarinoʾ was more susceptible to water stress (Coyago-Cruz, et al, 2017a). The aim of this work is scheduling regulated deficit irrigation (RDI) with leaf water potential. And study the effect of the RDI in on the crop development, yield and the fruit quality whilst considering the effect of cluster height in two cherry tomato varieties (Lazarino and Summerbrix).

2. MATERIALS AND METHODS

2.1 Experimental details

The experiment was carried out in two crop cycles during the autumn of 2015 (23rd September to 15th December) and spring 2016 (23rd February to 15th June) at greenhouse at Escuela Técnica Superior de Ingeniería Agronómica (E.T.S.I.A.) located at the Universidad de Sevilla (Seville, south Spain, 37º21'09.71" Lat. N, 5º56'19.13" Long. W, 33 m a.s.l.). The experimental greenhouses were made up of plastic with 75% transmissibility of the radiation, and furthermore they were provided with a ventilation window. The tomato plants were grown in clay loam soil characterized by had 21.5% gross sand; 4.5% fine sand; 42.3% limo and 31.8% clay; pH 8.11; total nitrogen 0.25%; organic matter 2.50%; electric conductivity 1050µS/cm; phosphorus 126mg/Kg; calcium 0.73%; sodium 0.04%, potassium 0.13% and magnesium 0.25%. Some of the weather variables such as temperature, vapour pressure deficit (VPD) and daily radiation were monitored in the greenhouse (Figure 1). The Temperature integral was calculated accumulating the average temperature during the development of the crop.

Two red cherry tomato *Solanum Lycopersicum* L. varieties (ʻLazarino’ and ʻSummerbrix’) with indeterminate growth were studied. The seeds were provided by Fitó (Spain). ʻSummerbrix’ was a small pear cultivar and ʻLazarino’ a round one. These varieties were grown for 30 days in a nursery seedling and they were transplanted into soil when the seedlings had developed three or four true leaves. The dates for transplanting was 22th September during 2015 (autumn season) and 15th January in 2016 (spring season). Harvest periods were from 8th and 19th January (“Summerbrix” and “Lazarino” respectively) to 11th March during 2015 (autumn season) and from 20th and 27th May (“Summerbrix” and “Lazarino” respectively) to 24th June in 2016 (spring season). Flowers were biologically pollinated with bumblebees (BioSur, Spain). Plants were supported at a height of 2m; this was done by pruning especially all secondary stems and leaves, especially the lower leaves to ensure ventilation and an adequate sanitary condition, with the usual tomato crop practices in a greenhouse.

For each cultivar an experimental design was randomized completely blocks with 3 repetition for each irrigation tratments Each elemnentary plot consisted of 30 plants, 3 lines with 10 plants of a single variety, with a density of 2 plants.m^{-2}, with a separation of 50 cm between plants and 1 m between lines. The measurements were taken in 7 central plants of the plot, the rest were considered border.

There were 2 irrigation treatments: Control, no water stress conditions, consisted of a irrigation based on the potential evapotranspiration of the crop (ETc) calculated according to the Penman-Monteith method (Allen, et al, 2006) and which 100% ETc was applied; The second treatment was based on the water status of the crop. This treatment considered two periods: 1) vegetative development (crop establishment basically), in which 100% ETc was applied and 2) RDI: in which an irrigation threshold was maintained at -1MPa a leaf water potential, which is the water stress level recommended for industrial tomatoes (Fortes, et al, 2013). Leaf water potential at midday (Ψw) was measured weekly using a pressure chamber (PMS Instrument Company, USA). Fully developed leaves and sun exposed were measured, on one central plant per plot, at solar midday, weekly. Only the elementary plot was irrigated when the crop reached this threshold (-1MPa). Irrigation amount was applied depending on the distance of the water potential of the leaf of each plot to the said threshold, with a maximum limit of 5mm day^{-1}. ETc maximum estimated for the entire crop. If the reduction was less than 10%, an irrigation dose of 25% of control irrigation was applied. If the reduction was between 10 and 30%, a 50% dose of control treatment was provided. The irrigation of the plants was done by dripping, with 2 drippers per square meter, with two daily irrigations.

In order to describe the accumulative effect of the water deficit, the water stress integral was calculated from the Ψ data (Myers,1988) during the period of water stress (Eq. (1)). Eq. (1) used a reference of −0.2 MPa. The expression used was:

$SI = |\sum(\Psi-(-0.2))*n$

(1) where: SI is the stress integral, Ψ is the average midday stem water potential for any interval, n is the number of the days in the interval.

Soil water content was monitored with an FDR (Frequency Domain Reflectrometry) sensor, ECH2O HS10 (Decagon Devices, USA), plugged into a datalogger (model CR10X with AM 416 multiplexer, Campbell Sci. Ltd., Logan, USA). Measurements from FDR sensors were taken every minute and the datalogger was programmed to report 15-min means. One sensor was installed per plot. In autumn the sensor was installed at a depth of 15 cm (first experiment), and in spring at 25 cm, because 15 cm was too shallow and the roots deepened quickly (Figure 2). To know the profile of the soil moisture gravimetric soil moisture, measurements were made at 20, 40 and 60 cm depth two times per season (Table 1).

2.2 Growth and yield

The measurements were carried out on the experiment: days to flowering and days to fruiting, plant height, inflorescences development during the phenological phases. Inflorescence, buds, open flowers, set fruits and abortions and leaves number, were counted weekly in five plants per plot and production per plant in seven plants per plot. After visually scrutinising the fruit, each block was harvested following commercial practices. 72samples of seven fruits were analyzed from the point of view of commercial quality. One sample per plot comercial mature fruits (about 80 to 100% red stage) representative of seven plants, of three different experimental blocks collected at three clusters (first, third and fifth cluster) in two seasons,

2.3 Physico-chemical analyses

The measurements carried out were in seven fruits per plot in each harvest date: equatorial and longitudinal diameter (cm), fresh weight (W, expressed in grams), soluble solids (SS, expressed as °Brix), firmness (Kg/cm2) and colour parameters (L*, a*, b*) as described by Coyago-Cruz, et al. (2017b). The soluble solids were measured using a Hand-refractometer RHC-200ATC (Huake, China). The fruit firmness was analysed using a PCE-PTR 200 Forge Gauce penetrometer (PCE-Inst., Spain) and the fruit colour was analysed using a CM-700d colorimeter (Minolta, Japan). The whole visible spectrum (380 – 770nm) was recorded with a bandwidth of 1nm for the purpose of this testing. The colour parameters corresponding to the uniform colour space CIELAB were obtained directly from the equipment. Illuminant D65 and 10° observer were considered as references.

Soil humidity was determined using big dry oven (Selecta, Barcelona) with air circulation at 110ºC, to constant weight.

Total carotenoids (TC) and total phenolics (TPC) as a sum of the individual compounds were determined by liquid chromatography on a RRLC and UHPLC respectively, as described by Coyago-Cruz et al. (2018). For this purpose, the sample included a mixture of Sixty-three tomatoes without placenta and seeds. The sample was cut and quickly frozen at -80 ºC, before being freeze-dried with a Cryodos system (Telstar, Japan). For the extraction carotenoids were used approximately 20 mg of homogenized freeze-dried powder, 250 µL of methanol, 500 µL of trichloromethane and 250 µL of MiliQ-water. The mixture was vortexed, sonicated for 2 min and to remove the aqueous phase (colored fraction) was centrifuged at 14 000 ×g for 3 min. The colored fraction was collected and the solid was re-extracted with 500 µL of trichloromethane following the above-mentioned procedure and the times that were necessary until the solid did not show colour. The coloured fractions were evaporated to dryness at a temperature below 30 ºC in a vacuum concentrator and re-dissolved in 40 µL of ethyl acetate prior to their injection on an Agilent 1260 system (RRLC system), equipped with a diode-array detector, C18 Poroshell 120 column (2.7 µm, 5 cm × 4.6 mm) (Agilent Technologies, Palo Alto, Ca. USA). TC were calculated as the sum of phytoene, lutein, licopene and B-carotene. On the other hand, for the extraction phenolics were used 0.5 g of homogenized freeze-dried poweder and 15 mL of acidified methanol 0.1 %. The mixture was vortexed, sonicated for 15 min and to remove the supernatant was centrifuged at 4 190 ×g for 7 min at 4 ºC. The supernatant was collected ant he solid was re-extracted with 5 mL of acidified methanol 0.1%. This process was repeated once again. The supernatant were filtered through Millipore membranes (0.45 µm pore, 15 mm diameter) (Agilent Technologies, Spain) prior to their injection on an Agilent 1290 chromatograph (UHPLC system) equipped with a diode-array detecto, Eclipse Plus C18 column (1.8 µm, 2.1 × 5 mm) (Agilent Technologies, Palo Alto, Ca. USA). TPC were calculated as the sum of p-hydroxibenzoic acid, p-cumárico acid, cafeic acid, chlorogenic acid, gallic acid, quercetin and quercetin.

2.6 Statistical analysis

Data from the experiment were analysed statistically using the STATGRAPHICS Centurion XVII software. Results are provided as the mean + standard deviation. The two cultivars were studied separately, and was analyzed the effect of irrigation treatment, cluster and seasonby simple and factorial ANOVA. The mean separation was made via a Tukey's test with 0.1, 0.01 and 0.001 significant differences, and correlations by Pearson with a 95% confidence level were employed to estimate the possible significance.

3. RESULT AND DISCUSSION

3.1 Climate trend and irrigation variables

Climatic and soil moisture data registered from the beginning of the crop to the end of harvest during autumn and spring are shown in Figure 1. Crop cycles were 172 days in autumn and 127 days in spring. Which are the usual in tomato in our región (Allen et al 2006). The length of each phenological phase was different depending on the cycle analysed. The vegetative phase varied from 40 days in autumn to 74 days in the spring cycle. While the flowering-fruit set was 95 days on average in in the autumn cycle, and 92 days in spring. The Temperature integral varied from 818 and 1670ºC in autumn and spring until the flowering-fruit set phase was reached; 1772 to reach full harvest in in autumn, and 2234ºC in the spring cycle, respectively.

Maximum and minimium temperatures are shown in Fig. 1A. The pattern was clearly different depending on the cycle. Maximum temperature was gradually decreasing in autuum, 25ºC average in november, 22ºC in december, 21ºC in Januay and 23ºC in February. Minimal temperatures showed a similar pattern, decreased gradually: 9ºC average in november, 8ºC in december, 9ºC January and 10ºC in Fabruary. In spring the trend was the opposite, increasing the temperatures gradually since the beginning of the crop cycle, Maximum temperatures: 26ºC average in the days of trial in February, 33ºC in March and 30ºC in April, and mínimum 8ºC, 7ºC and 11ºC respectively. The average temperature inside the greenhouse is shown in Fig. 1-BIn the autumn cycle, the average temperature decreased from around 27ºC in October, 15ºC in November and 13ºC in January. While in the spring cycle, the pattern was the opposite with 15ºC average in the days of trial in February, 18ºC in March and 19ºC in April. Several studies showed that the optimum temperatures in the tomato crop changed between 20 and 24ºC to ensure further development, flowering and fruit ripening (Serrano 2008), and 12ºC and 36ºC would be the growth limit temperatures (Serrano 2009; Rosales, 2008). Our greenhouse is a simple structure, and although we have not always been at the optimum temperatures, we have not been far from the limits. The crop was developed properly. Figure 1C depicts the vapor pressure deficit (VPD) inside the greenhouse. In the autumn cycle, VPD was maximum at the beginning with values around 0.5KPa and decreased from the flowering phase down to values around 0.15KPa. In the spring cycle, VPD values were more changeable, with minimum values until the mid-flowering phase (below 0.2KPa) and with a great increase from this date up to maximum values near 1.2KPa at the end of the cycle.

Figure 1-D is representative of the daily radiation during both cycles. Thus, daily radiation in autumn decreased from the vegetative development (around 20MJ m^{-2} day^{-1}) to the flowering and fruit setting (around 10MJ m^{-2} day^{-1} but the minimum lower than 5MJ m^{-2} day^{-1}), while increasing in full harvest up to values around 15MJ m^{-2} day^{-1}. In the spring cycle, the daily radiation presented an incremental pattern from 10 to 30MJ m^{-2} day^{-1}.

The amount of water supplied in control and RDI treatment in autumn and spring are shown in Table 1. This data showed higher water requirement in both cultivars, in the control treatment during spring (582.7mm) than during autumn (536.7mm) and a greater reduction of irrigation occurs in the RDI treatment for both cycles, with 82.7mm of total water in both cultivars in autumn, because they did not differentiate. And in spring “Summerbrix” receivedand 84mm, and “Lazarino“ 63 mm. . Such reductions agreed with the soil water as shown in Figure 2, section A and B for autumn and spring, respectively. Soil moisture in the control treatment was around field capacity in most of the dates for both cycles. RDI data varied according to the cycle studied; during autumn most of the dates were below the permanent wilting point (17.3%), while in spring there was a continuous decrease until such soil moisture, which was reached around 106 days after transplanting. The low soil moisture values in autumn could be due to where the probe was positioned (15cm from the surface), probably too shallow, and away from the wet bulb, while in spring it was positioned 25cm deep. Gravimetric moisture (Table 1) showed the moisture content throughout the profile. In autumn, the control gravimetric moisture showed 19.5% in the 30 to 50cm depth, while in RDI it was 13.9%. Also in spring, the gravimetric moisture data showed 19.4% in the 30 to 50cm depth, while in RDC it was 14.6% in the 30 to 50cm.

Water potential (Ψw) and stress integral data are presented in Fig 3. The pattern of water potential in the autumn and spring cycles was clearly different, with less significant differences in the former. During the autumn cycle, the pattern of Ψwincreased in both treatments and cultivars because of the evaporative demand (Fig. 1) and it went from -0.6MPa to -0.2MPa. RDI treatments tended to show lower values than the Control in all the cycle for both cultivars with major differences showing only at the beginning of the flowering period (Fig. 3A and B). Ψwdata during the spring cycle were more changeable in both cultivars (Fig. 3-C and D) with lower values than the autumn cycle. During the vegetative development, Ψw was around -0.2MPa in all the plants. The main differences were found during the flowering-fruit setting phase, which showed clearly lower values in the RDI treatments than in the Control ones, most of them significant. This occurred mainly in the Summerbrix cultivar and minimum RDI values of around -1.0MPa were reached in both cultivars. Such differences were also observed during the harvest period, when almost all RDI data in both cultivars were significantly lower than Control, around -0.8MPa. These data are in line with other studies, which suggests that the water requirements in the crop are dependent on the variety, phenological phases and growing season (Serrano, 2014; Patanè, et al, 2011). In addition, the Ψw did not reach the threshold of -1.0MPa in all plots, which means that the crop did not endure severe conditions of water stress, according to Fortes, et al, (2013).

The stress integral in spring was greater than in autumn (Fig 3 E and F). In the two growing cycles, there were significant differences in the total stress integral for both cultivars between irrigation treatments. ʽSummerbrix’ in autumn showed a total stress integral of 13.5 and 21.3MPa·day in Control and RDI, respectively, while ʽLazarino’ showed 11.6 and 15.0MPa·day, respectively. In addition, in spring ʽSummerbrix’ showed a total integral stress of 39.6 and 62.0MPa·day in

Control and RDI, respectively, while ʻLazarino' read 39.9 and 55.0MPa·day, respectively. Such differences were mainly attributed to the stress during the flowering phase. The integral stress shows crop water stress intensity, not only the level that reached the water potential (Hsiao, 1990). There are no references in the tomato bibliography with which to compare but from these results if it can be observed that with an integral stress below 40MPa did not affect the production, while above if differences were observed in sumerbrix, while in lazarino an integral of 50MPa did not affect the production.

3.2 Development of flowering

Flower development in indeterminated tomato cultivar is a continuous process for the plant. Each cluster sprouts at a different height and in a different moment. In addition, there is a developmental period within the cluster. The number of flowers was higher in spring than in autumn, the pattern of open flowers is presented in Figure 4. There were greater numbers of flowers in the cluster V than in the cluster I in both seasons. There were no significant effects of irrigation treatment during the autumn cycle for both cultivars. There was an increase in the number of open flowers between cycles, higher in spring than in autumn, and this change was mainly due to the increase in numbers in clusters III and V. The period of open flowers in each cluster was higher in autumn than in spring but in both cycles, it lasted more than 30 days. The effect of irrigation treatments was almost null during the autumn cycle in both cultivars: only very small significant differences were found in cluster I. On the other hand, there were significant differences in some dates and in all the clusters in the cultivar Summerbrix during the spring cycle, with a reduction greater than 50% in cluster III and V around DAT (day after transplanting) 95. However, the number of fruits set was not significantly affected in any of the cultivars and cycles (data do not show) though RDI tended to lower values than Control in cv Summebrix and the spring cycle. This behavior is similar to that shown by Pulupol et al (1996), with water stress levels of -1.2MPa, and produced a 60% reduction in yield, associated with flower abortion, a very important reduction in the number of flowers was observed.

3.3 Physico-chemical analyses

3.3.1 Commercial quality

Several parameters of yield quality are summarised in Table 2. The fruit weight was significantly affected considering the crop cycle: in cv ‛Lazarino’ it was 23% higher in autumn than in spring, and 21% in ‛Summerbrix’. These results were likely related to the flowers in autumn in comparison with the spring cycle (Figure 4), which probably affected the dry matter partitioning. The decrease in the number of sinks, fruits in the cluster, is likely to improve the growth. The main differences were found in cluster III of the Control plant, where the differences in flowers were the highest (Figure 4). Irrigation treatments also have great impact on the fruit weight. In the autumn cycle, the reduction was lower though significant in both cultivars. In cv Summerbrix, there was an average reduction of around 4% in the fruit weight, mainly in cluster I and III. While in cv Lazarino, the weight reduction was 10% and was greater in cluster III and V (Table 2). During the spring cycle, the greatest reduction in fruit weight was measured in cluster III and V for both cultivars. Such reduction was lower in cv Summerbrix, with an average of 10%, than in Lazarino, with 13%. In the latter, there was a great variability between clusters, with a reduction due to the water restriction in cluster I of around 4% vs a reduction higher than 20% in cluster V (Figure 4). This data was related to other studies that showed a decrease in cherry tomato weight (17.4g in Control and 16.57g in RDI) when a 50% water reduction was applied (Pernice, et al., 2010), and some studies that showed similar results (Patanè, et al, 2011; Favati, et al., 2009; Ozbahce & Tari, 2010). This reduction in fruit weight in spring was likely related to the water status of the crop, since the Ψw decreased in the second half of the flowering to -0.9MPa and accumulated a stress integral of 55MPa·day in ‛Lazarino’ and 62MPa·day in ‛Summerbrix’ (Figure 3). In general, the threshold of -0.8MPa in autumn took on an average decrease of 12% in weight with a water saving of 80%. In general, the ANOVA factorial showed that the weight was influenced by treatment, cluster height and season (Table 2).

Soluble solids (SS) in ‛Lazarino’ were 10% higher in autumn than in spring and 13% for ‛Summerbrix’. These results were similar to previous studies that indicated an increase of the SS with the decrease of the temperature (Wang, et al., 2011; Klaring, et al., 2015). The irrigation treatments showed few significant differences in SS in autumn, with very small differences between Control and RDI, lower than 5%. The effect of the irrigation treatment was clearer during the spring cycle, when SS was significantly higher in all clusters of RDI plants, with increases between 4 and 9%. The decrease of applied water during the harvest causes an increase of the SS described in other works (Quadir, et al., 2006; Beckles, 2012; Nangare, et al., 2016; Patanè, et al., 2011; Lahoz, et al., 2016), which suggested that a water application of 1200 to 2400 $m^3.ha^{-1}$ in cherry varieties in spring did not produce changes in the SS (Pernice, et al., 2010). In general, the ANOVA factorial showed that the SS were influenced by the treatment, cluster height and season. This data correlates with the findings of other authors, who suggested that the SS were influenced by variety, environmental and agronomic conditions (Quadir, et al, 2006).

There were no clear patterns of firmness and colour depending on the season. Irrigation treatments showed slightly differences in both parameters. Only significant differences were found in the spring cycle, cv Lazarino and cluster I with higher firmness in RDI than in Control. Nevertheless, in general, differences were very low in firmness and colour with no clear pattern depending on the irrigation. The lack of results suggest that water stress did not affect the duration of the cycle, and ripening was similar for both irrigation treatments.

3.3.2 Functional quality

The tomato functional quality data (total carotenoids and total phenolics) are summarised in Table 2. The main carotenoids identified in this study were phytoene, lutein, lycopene and β-carotene, with lycopene being the main carotenoid, as noted by other authors (Stinco, et al, 2016; Meléndez-Martínez, et al, 2010; Perveen, et al., 2015. The individual profiles of the carotenoids were published by our group in other work (Coyago-Cruz, et al., 2018). In most cases, the total carotenoids showed higher values in spring than autumn, though the cycle was significant only in Summerbrix. The effect of irrigation was affected by the cycle and cultivar being studied. Summerbrix increased the total carotenoids in RDI plants in the spring cycle, while Lazarino did in autumn cycle, only in cluster I and V. In general, the ANOVA factorial showed changes with the treatment and cluster in ‘Lazarino’, while in ‘Summerbrix’ changes were linked to the treatment and season. This is in line with other authors, who suggested that the total carotenoids change with the variety, climate or geographical location of the crop (Eichholz, et al, 2014; Li, Zhu et al, 2013; Sánchez-Rodríguez, et al., 2011).

The total phenolics content was affected by the cycle. In general, fruits in the spring cycle presented a higher amount of phenolics than autumn fruits, though this effect was more intense in cv Lazarino than cv Summerbrix (Table 2). Such differences between cultivars were also found in the effect of the irrigation treatments. RDI did not affect the total phenolic content in cv Summerbrix. However, irrigation deficit increased the amount of phenolic compounds in cv Lazarino, yet such differences were not always significant. In both cultivars, there were significant effects on the cluster, with an increase with the cluster height, which could reduce the differences between irrigation treatments. Several authors reported that the irrigation restriction increases the total phenolics (Lule & Xia, 2005; Pernice, et al., 2010). The influence of cluster and cycle has been linked to the level of radiation in other works (Minutolo, et al, 2013; Atkinson, et al, 2011; Olsen, et al., 2009; Coyago-Cruz, et al., 2018).

3.4 Yield response

Total and marketable yield showed no statistical differences in autumn in any of the two cultivars (Table 3). Differences were observed in the spring season, RDI resulted in a 38% decrease in ‘Sumerbrix’ and 40% in ‘Lazarino’. Irrigation scheduling clearly reduced the water applied, amount of water was statistically different. the amounts applied in spring and autumn in RDI were similar. If there were clear differences in IWUE, all RDI treatments were significantly different from control ones. Accumulated yield, in both cultivars, was greater in the spring cycle than in the autumn one (Figure 5), while the period of harvest increased in autumn (60 days vs 30 days). However, the pattern of the accumulated yield in the spring cycle was different between cultivars. Important differences were found in cv Summerbrix throughout the harvest period, while in cv Lazarino they were detected only at the end. Although there was no significant reduction in yield during the autumn cycle, RDI treatments tended to produce a lower yield in ‘Summerbrix’, while almost an equal result was noticed in cv Lazarino. There are several authors that reported a yield reduction in RDI scheduling on tomato cultivated in greenhouse, Wang et al (2015) reported reduced yields by 29% with 70%ETTc in cv. 004024. Nangare et al (2016) reported decrease of yield by 20% with 60%ETc at flowering in cv. Ryna®. And Bogale et al (2016) reported reduced yields by 27% in cv Matina and 38% in cv Cochoro with 50%ETc. The slightly non-significant reduction in yield during autumn in cv Summerbrix was not clearly related to any of the parameters measured. Number of flower and fruits were also almost equal between irrigation treatments (Fig.4). Only the fruit weight was significantly affected, but slightly (Table 2) and such reduction did not have a major impact on final yield. Therefore, the water stress level in the autumn cycle could be considered mild (Fig. 2). On the other hand, yield results in the spring cycle showed two different responses to water restriction. Fruit size was affected in the same way in both cultivars (Table 3) but this does not explain the differences in the pattern. The progressive yield decrease in cv Summebrix was related to a significant reduction in the number of open flowers (Fig. 4) which produced a clear trend, but not a significant impact on the fruit setting (Table 3). On the other hand, cv Lazarino showed a reduction in the number of inflorescences at the end of the spring cycle (Fig 3). These results suggest that the irrigation scheduling should be different depending on the cultivars. Summerbrix was likely to be more sensitive to water stress conditions than Lazarino and the threshold value of -1.0MPa was not adequate for RDI scheduling. This cultivar needs an accurate control of the water stress level and, it would appear that values of water potential around -0.8MPa during the period DAT 90-120 were enough to reduce yield. Conversely, cv Lazarino was likely affected by an accumulate stress in a more specific level. The water potential was similar at the end and at the beginning of the spring cycle; subsequently in this case, the stress integral could be a better tool and values slightly lower than 40MPa day could be considered as a threshold in ‘Lazarino’ and 50MPa in ‘Summerbrix’.

4. CONCLUSION

Regulated deficit irrigation can be scheduling with leaf water potential in cherry tomato crop. RDI reduced yield mainly in the spring cycle in both cultivars, 62% in Sumerbrix and 60% in Lazarino. In autumn there was no significant reduction yield but it was observed a drecrease by

20% ’Sumerbirx’ and by 5% ‘Lazarino’. The main effect of the irrigation treatment in the fruit quality was the increase of total carotenoids and phenolics. Although RDI reduced the fruit size in both cycles. The ‘Lazarino’ cultivar was more drought resistant than ‘Summerbrix’. These results strongly suggest that an accurate control of the water stress level could improve the irrigation management in tomato crops.

ABBREVIATIONS USED

E.T.S.I.A., Escuela Técnica Superior de Ingeniería Agronómica; a.s.l., above sea level; RDI, regulated deficit irrigation; ETc, crop evapotranspiration; Eto, reference evapotranspiration; FAO, Food and Agriculture Organization of the United Nations; CI, first cluster; CIII, third cluster; CV, fifth cluster; CIELAB, the Commission International of IEclairage (CIE), defined colour spaces that includes CIE L*a*b*; ºCd, ºC/day; SS, soluble solids, DW, dry weight, Ψw leaf water potential.

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Notes

The authors declare no competing financial interest

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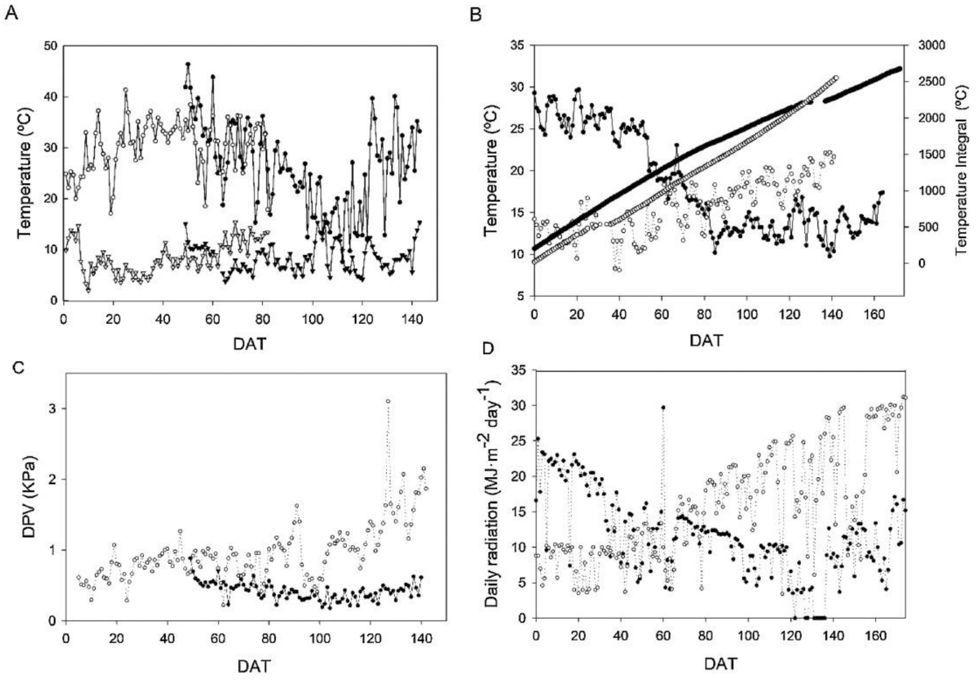


Fig. 1. Environmental factors of the cherry tomato crop in autumn and spring. A shows maximum (circle symbols) and minimum (triangles symbols) temperature in the greenhouse in autumn (black symbols) and spring (symbols); B: shows the Temperature Integral and medium temperature in the greenhouse in autumn and spring; C: vapor pressure deficit (VPD) and D: total daily radiation, in autumn and spring seasons. Symbols: circle empty were spring data, black circles were autumn data. DAT: days after transplant.

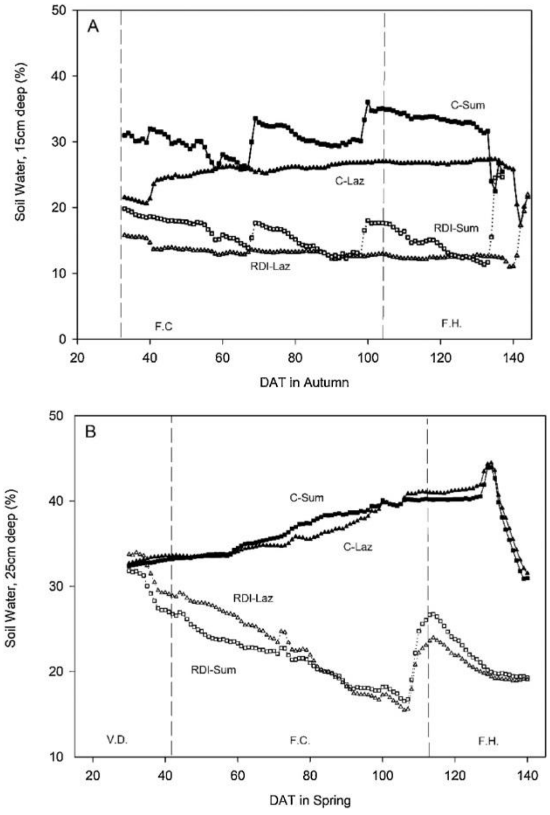


Fig. 2. Soil water content (%) in autumn and spring.

A and B shows the evolution of Soil water content tomato crop autumn (15 cm deep) and spring (25 cm deep) respectively. 'Summerbrix' symbols: square empty RDI plants and blacks control plants; 'Lazarino' symbols: triangles empty RDI plants and blacks control plants. Vertical lines show the separation of phenological phases: vegetative development (VD); flowering and fruit set (FC); full harvest (FH). DAT: days after transplant.

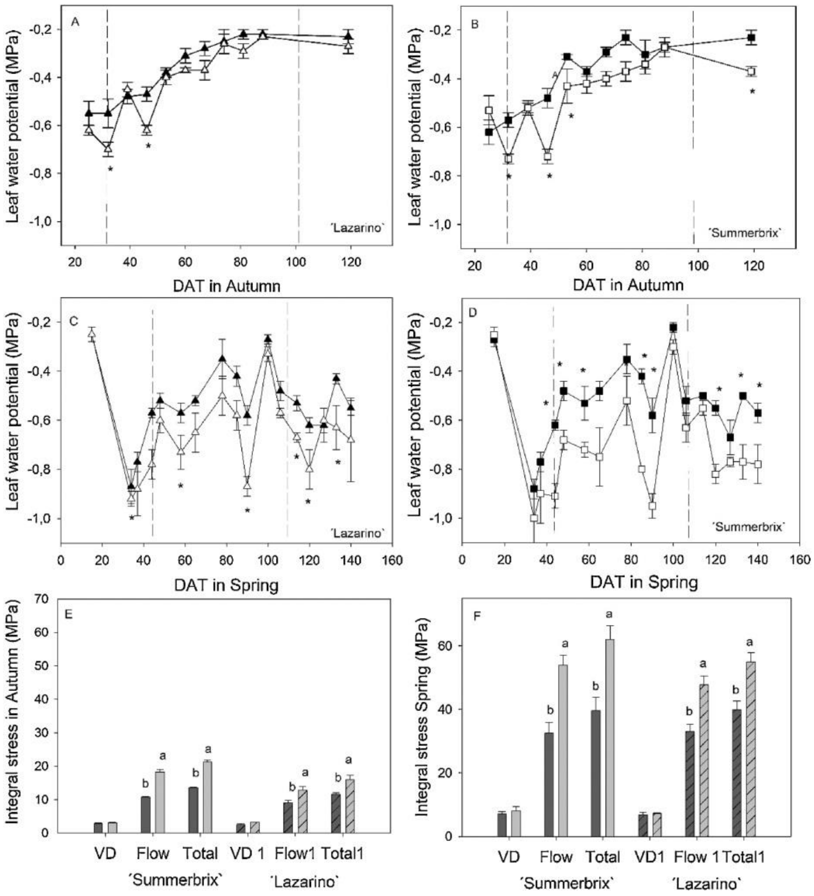
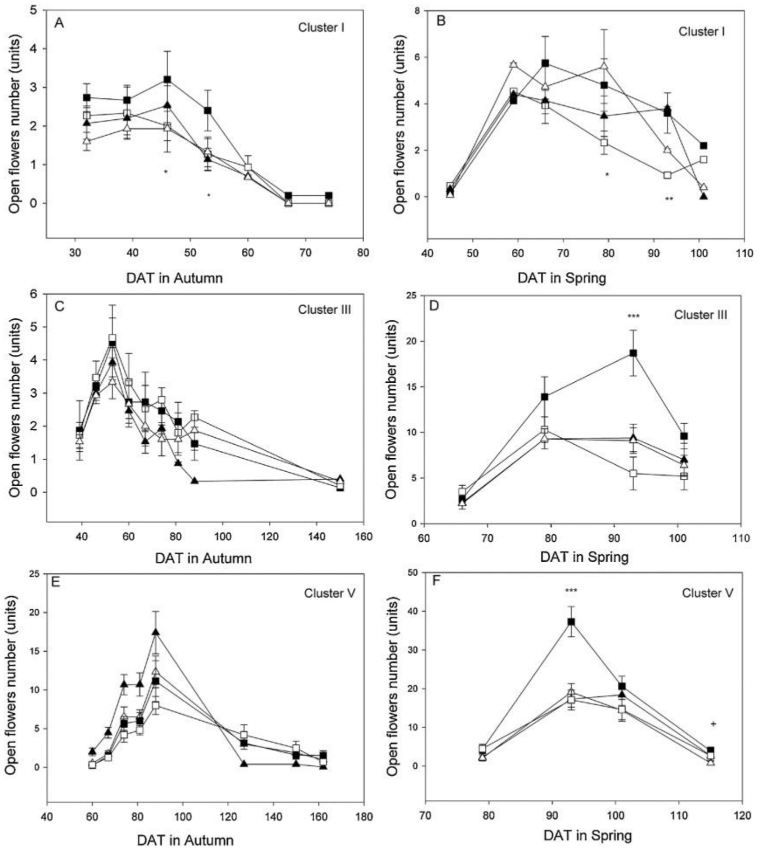


Fig. 3. Leaf water potential and stress integral during the phenological phases of the cherry tomato crop.

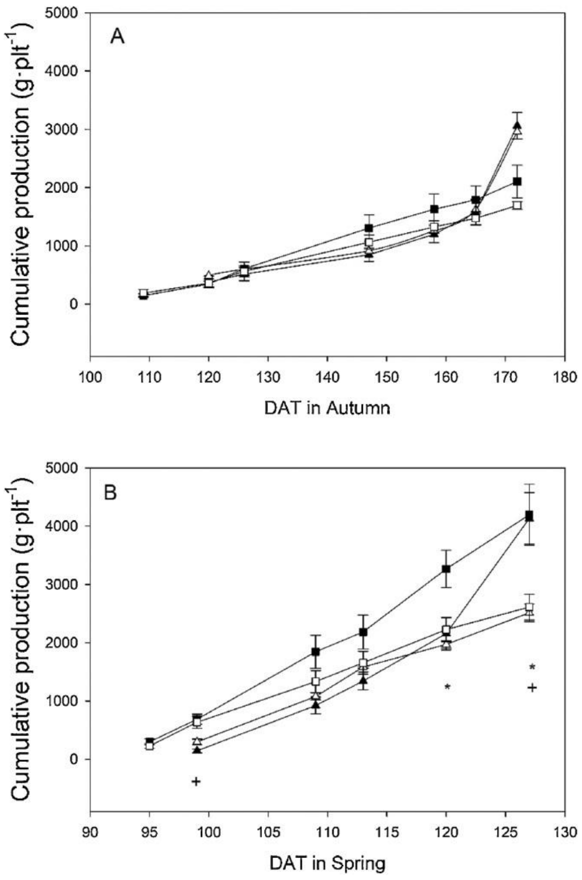
Section A and C shows the leaf water potential of 'Lazarino' in autumn and spring, respectively (symbols: triangles empty RDI plants and blacks triangles control plants), while B and D of 'Summerbrix' (symbols: square empty RDI plants and black square control plants). The section E and F shows the stress integral in the phenological phases (vegetative development (VD), flowering and fruit set (Flow) and total (Total)) in 'Summerbrix' and 'Lazarino'. Vertical lines show the separation of phenological phases: vegetative development (VD); fruit set (FS); full harvest (FH). Significance differences between irrigation treatments acording Tukey is indicated by: *, p < 0.1; **,p < 0.01; ***, p < 0.001. Sections E and F, mean values in the same phenological phase followed by different letters shows significant differences with a confidence level 95%, Tukey. Each point and bar is the average of 3 measurements. Vertical bars represent standard error. DAT: days after transplant

Fig. 4. Development of open flowers in the I, III and V cherry tomato inflorescence in autumn and spring.



Section A, B and C development of inflorescence I, III and V, respectively in autumn; D,E, and F the development of inflorescence I, III and V, respectively in spring 'Summerbrix' symbols: square empty RDI plants and blacks control plants; 'Lazarino' symbols: triangles empty RDI plants and blacks control plants). Significance differences between irrigation treatments is indicated by: *, p < 0.1; **,p < 0.01; ***, p < 0.001 for 'Summerbrix'; +, p < 0.1; ++,p < 0.01; +++, p < 0.001 for 'Lazarino'. Each point and bar is the average of 3 measurements. Vertical bars represent standard error. DAT: days after transplant.

Fig. 5. Cumulative production (g·plant−1) of cherry tomato crop in autumn and spring.



A and B shows the evolution of the cumulative production in the tomato crop autumn and spring respectively. ‘Summerbrix’ symbols: square empty RDI plants and blacks control plants; ‘Lazarino’ symbols: triangles empty RDI plants and blacks control plants). Significance differences between irrigation treatments acording Tukey is indicated by: *, p < 0.1; **,p < 0.01; ***, p < 0.001 for ‘Summerbrix’; +, p < 0.1; ++,p < 0.01; +++, p < 0.001 for ‘Lazarino’. Each point and bar is the average of 3 measurements. Vertical bars represent standard error. DAT: days after transplant.

Table 1

Average accumulate applied water (mm) and soil humidity ($m^3 m^{-3}$) in Control and RDI treatment in the three phenological phases considered in autumn and spring cycles.

	'Summerbrix'						'Lazarino'					
	Phase I		Phase II		Phase III		Phase I		Phase II		Phase III	
	Control	RDI	Control	RDI	Control	RDI	Control	RDI	Control	RDI	Control	RDI
Autumn 2015												
Applied water	66.7	66.7	380.7	82.7	536.7	82.7	66.7	66.7	422.7	82.7	536.7	82.7
Soil humidity (%)												
0 to 10 cm			15.2a	8.4b	22.7a	8.0b			19.3a	8.0b	28.4a	9.5b
10 to 20 cm			13.7a	8.7b	24.7a	10.2b			16.0a	8.3b	26.7a	11.9b
20 to 30 cm			20.3a	12.6b	23.5a	14.1b			19.6a	11.4b	25.9a	13.2b
30 to 40 cm			20.3a	13.5b	18.9a	13.1b			20.4a	11.2b	20.0a	13.3b
40 to 50 cm			19.8a	13.8b	18.9a	14.0b			21.0a	14.7b	19.7a	15.2b
Spring 2016												
Applied water	14.7	4.0	430.7	84	582.7	89.7	14.7	4.0	486.7	60	582.7	63
Soil humidity (%)												
0 to 10 cm			22.0a	7.6b	27.4a	4.7b			22.0a	7.6b	9.7a	3.6b
10 to 20 cm			22.0a	10.1b	24.0a	14.9b			22.0a	10.1b	18.6a	10.3b
20 to 30 cm			20.8a	14.5b	22.1a	14.4b			20.8a	14.5b	22.8a	14.8b
30 to 40 cm			18.4a	14.5b	19.3a	13.0b			18.4a	14.5b	20.4a	12.2b
40 to 50 cm			18.4a	16.6a	19.3a	13.0b			18.4a	16.6a	20.4a	12.2b

Phase I: from transplant to first inflorescence; Phase II: from first inflorescence to harvest; Phase III: harvest period. Different letters indicate significant differences between irrigation treatments ($p < 0.05$, Tukey test).

Table 2

Average values of parameters related to the commercial quality of cherry tomatoes[a].

	CI			CIII			CV		
	Control	RDI	p	Control	RDI	p	Control	RDI	p
Autumn 2015									
'Summerbrix'									
W	23.2 ± 0.6	21.8 ± 0.5	*	28.2 ± 0.7	26.3 ± 0.7	*	21.5 ± 0.9	21.5 ± 0.7	ns
SS	6.9 ± 0.1	7.2 ± 0.1	*	7.0 ± 0.1	7.2 ± 0.1	ns	8.5 ± 0.1	8.6 ± 0.1	ns
F	2.6 ± 0.1	2.4 ± 0.1	ns	2.0 ± 0.1	2.0 ± 0.1	ns	3.0 ± 0.2	3.6 ± 0.1	ns
L^*	34.5 ± 0.3	36.3 ± 2.0	ns	34.9 ± 0.2	35.4 ± 0.3	ns	33.6 ± 0.2	33.6 ± 0.1	ns
C^*_{ab}	22.8 ± 0.5	25.4 ± 1.1	ns	19.6 ± 0.3	22.8 ± 0.4	***	17.1 ± 0.4	18.6 ± 0.6	***
h_{ab}	47.5 ± 0.3	50.9 ± 2.4	ns	48.8 ± 0.2	46.6 ± 0.4	***	53.4 ± 0.2	49.4 ± 0.4	ns
TC	880.6 ± 49.2	1047.3 ± 65.0	***	1008.4 ± 89.2	980.4 ± 61.9	ns	4338.2 ± 315.5	3193.0 ± 228.4	ns
TPC	290.2 ± 9.6	252.1 ± 9.4	**	243.5 ± 6.9	246.3 ± 7.1	ns	894.2 ± 76.0	858.0 ± 70.3	ns
'Lazarino'									
W	27.4 ± 0.6	25.6 ± 0.8	**	31.7 ± 0.6	27.5 ± 0.6	***	27.5 ± 0.7	24.7 ± 0.6	***
SS	6.4 ± 0.1	6.4 ± 0.1	ns	6.8 ± 0.1	6.8 ± 0.1	ns	7.4 ± 0.1	7.8 ± 0.1	***
F	2.6 ± 0.0	2.8 ± 0.1	*	3.6 ± 0.1	3.0 ± 0.1	ns	5.6 ± 0.1	5.6 ± 0.1	ns
L^*	33.7 ± 0.3	33.9 ± 0.3	ns	35.1 ± 0.2	35.7 ± 0.2	*	35.5 ± 0.2	35.6 ± 0.2	ns
C*ab	15.8 ± 0.4	17.1 ± 0.5	ns	16.3 ± 0.4	17.6 ± 0.5	*	19.4 ± 0.4	20.6 ± 0.4	**
hab	55.8 ± 0.3	54.3 ± 0.5	ns	64.6 ± 0.5	62.3 ± 0.2	ns	68.2 ± 0.3	64.5 ± 0.2	ns
TC	441.5 ± 12.7	529.0 ± 4.5	*	1033.5 ± 38.8	1090.0 ± 54.4	ns	1973.0 ± 62.7	2902.3 ± 127.7	*
TPC	237.8 ± 9.3	266.9 ± 12.4	*	306.5 ± 7.8	304.9 ± 12.8	ns	373.6 ± 10.1	385.7 ± 7.4	**
Spring 2016									
'Summerbrix'									
W	18.4 ± 0.6	17.6 ± 0.6	ns	21.4 ± 0.7	18.5 ± 0.5	***	19.7 ± 0.7	17.1 ± 0.7	***
SS	6.4 ± 0.1	6.6 ± 0.1	ns	6.3 ± 0.1	6.6 ± 0.1	***	6.5 ± 0.1	6.9 ± 0.1	*
F	2.8 ± 0.1	2.9 ± 0.1	ns	5.6 ± 0.1	5.6 ± 0.1	ns	3.4 ± 0.1	3.6 ± 0.1	ns
L^*	33.7 ± 0.6	33.2 ± 0.2	ns	33.8 ± 0.2	33.6 ± 0.2	ns	33.6 ± 0.4	34.6 ± 0.2	*
C*ab	21.5 ± 0.3	21.9 ± 0.4	*	23.5 ± 0.4	24.7 ± 0.4	*	27.9 ± 0.3	29.3 ± 0.3	**
hab	47.9 ± 0.2	45.8 ± 0.2	ns	46.7 ± 0.2	44.7 ± 0.3	ns	41.8 ± 0.2	41.6 ± 0.3	*
TC	557.9 ± 14.3	628.0 ± 11.7	*	858.8 ± 15.6	1125.7 ± 41.1	*	1234.8 ± 35.8	2513.0 ± 138.0	*
TPC	312.1 ± 12.8	305.6 ± 10.3	ns	337.8 ± 6.5	337.9 ± 15.6	ns	442.0 ± 15.7	440.1 ± 15.8	ns
'Lazarino'									
W	22.3 ± 1.0	21.5 ± 0.8	ns	23.2 ± 0.4	20.2 ± 0.5	***	22.4 ± 0.6	17.1 ± 0.7	***
SS	6.1 ± 0.1	6.7 ± 0.1	***	6.1 ± 0.1	6.7 ± 0.1	***	5.8 ± 0.1	6.0 ± 0.2	ns
F	2.7 ± 0.2	3.7 ± 0.2	***	2.0 ± 0.1	2.2 ± 0.1	ns	2.0 ± 0.1	1.9 ± 0.1	ns
L^*	36.0 ± 0.4	35.5 ± 0.2	ns	35.7 ± 0.2	35.9 ± 0.2	ns	36.6 ± 0.3	36.9 ± 0.4	ns
C*ab	22.6 ± 1.1	25.2 ± 0.3	**	24.4 ± 0.6	25.5 ± 0.4	ns	25.2 ± 0.7	25.4 ± 0.5	ns
hab	59.2 ± 0.4	52.3 ± 0.3	ns	55.2 ± 0.3	54.3 ± 0.4	ns	56.5 ± 0.4	57.6 ± 0.5	ns
TC	796.3 ± 13.6	736.4 ± 19.2	ns	1401.7 ± 39.8	1219.2 ± 34.6	ns	1769.8 ± 69.7	2368.5 ± 112.3	ns
TPC	491.0 ± 10.3	467.4 ± 13.0	ns	480.4 ± 12.8	585.8 ± 27.5	***	591.2 ± 28.6	601.0 ± 16.9	ns

Weight (W) in g; soluble solid (SS) in °Brix; firmness (F) in kg/cm^2; colour parameters L^*, C^*_{ab} and h_{ab}; TC, total carotenoids in mg.100 g^{-1} tomato dry weight (DW); TPC, total phenolics in mg.100 g^{-1} DW. CI, cluster I; CIII, cluster III; CV, cluster V. [a]Mean values + SD (n = 63). [b]Significance of differences between the RDI and control samples (p); ns, not significant; *,$p < 0.1$; **, $p < 0.01$; ***, $p < 0.001$, Tukey test.

Table 3

Fruit yield and irrigation water use eficiency of cherry tomato in autumn and spring[a].

	'Sumerbrix'			'Lazarino'		
	Control	RDI	p	Control	RDI	p
Autumn 2015						
Applied Water	536.7 a	82.7 b	**	536.7 a	82.7 b	**
Total Yield	4208.1 ± 563	3382.8 ± 134	ns	6120.1 ± 453	5917.9 ± 418	ns
Marketable yield	4192.4 ± 576	3309.7 ± 66	ns	5715.9 ± 404	5780.1 ± 443	ns
IWUE	78.1 ± 11 b	400.4 ± 8 a	***	106.5 ± 8 b	699.2 ± 54 a	***
Spring 2016						
Applied Water	582.7 a	89.7 b	**	582.7 a	63 ± 11	**
Total Yield	8391.1 ± 1057	5223.8 ± 439	*	8261.7 ± 884	5024 ± 304	*
Marketable yield	8087.6 ± 1042	5015.1 ± 479	*	7600.4 ± 825	4665.6 ± 294	*
IWUE	138 ± 18 b	616.9 ± 130 a	**	130.4 ± 14 b	786.6 ± 144 a	**

Applied Water in mm; Total Yield in kg.ha^{-1}; Marketable yield in kg.ha^{-1}; Irrigation water use efficiency (IWUE) in kg.m^{-3}.[a] Mean values + SD (n = 3). [b]Significance of differences between the RDI and control samples (p); ns, not significant; *,$p < 0.1$; **, $p < 0.01$; ***, $p < 0.001$, Tukey test.