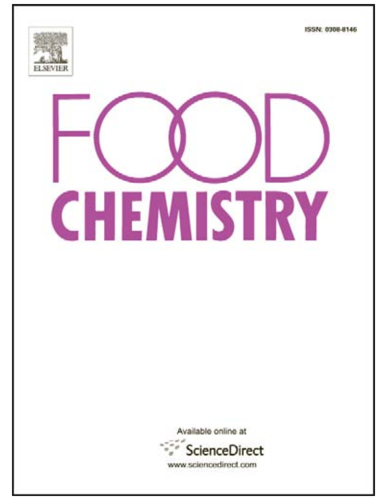
Food Chemistry, Volume 122, Issue 4, 15 October 2010, Pages 1020-1026

Accepted Manuscript



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PII: S0308-8146(10)00337-7
DOI: 10.1016/j.foodchem.2010.03.060
Reference: FOCH 9452

To appear in: *Food Chemistry*

Received Date: 30 June 2009
Revised Date: 8 February 2010
Accepted Date: 15 March 2010

Please cite this article as: Bordonaba, J.G., Terry, L.A., Manipulating the taste-related composition of strawberry fruits (*Fragaria* x *ananassa*) from different cultivars using deficit irrigation, *Food Chemistry* (2010), doi: 10.1016/j.foodchem.2010.03.060

Manipulating the taste-related composition of strawberry fruits (*Fragaria* x *ananassa*) from different cultivars using deficit irrigation

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ABSTRACT

Demand and, consequently, production of strawberry fruits has increased over the past few years and, as a result, the water abstractions for cultivation of this fruit have risen considerably. To limit the amounts of water used for several horticultural crops, water deficit irrigation (DI) has been seen as a potential alternative for new cultivation systems. DI in strawberry fruits is generally associated with reduction in berry size and yield; however, a recent study demonstrated that DI on strawberry can increase the concentration of some taste- and health-related compounds in fruits from cv. Elsanta. Hence, the aim of the present study was to further corroborate such findings and to assess the response (and variability) among different strawberry cultivars (namely Christine, Elsanta, Florence, Sonata and Symphony) to imposed water-DI conditions. Water-DI affected both fruit physiology and biochemistry. Nevertheless, the response to drought stress was different for each of the cultivars tested. Plants from cvs. Elsanta, Sonata and Symphony showed a greater reduction in berry size, accompanied by a significant increase in dry matter content for fruit harvested from DI-treated plants. Concomitant to this, and where dry matter was increased, the concentrations of sugars and some

acids were generally higher in DI-derived fruit. In contrast, cvs. Florence and Christine did not show significant variations in berry weight or any of the target analytes measured when grown under the conditions imposed in this study. The results presented herein suggest that reducing water irrigation between flower initiation and fruit harvest may be a viable technique for increasing the concentrations of taste-related compounds in cvs. Elsanta, Sonata and Symphony and it may not have a negative impact on overall fruit size of cvs. Christine and Florence.

Keywords: Berry size, dry matter, organic acids, sugars, sweetness

1. Introduction

Demand for and availability of strawberries (*Fragaria* x *ananassa* Duch.) have increased substantially during recent years, driven in part, by the highly desired taste of the fruit, along with its known health-promoting properties (Wang, Feng, Lu, Bowman & Ding, 2005). To satisfy this demand, over 250,000 ha are currently designated for strawberry cultivation worldwide (FAOSTAT, 2007). Strawberry production is generally irrigated, as it is known that strawberry plants are very sensitive to drought stress during flowering and fruit ripening (Krüger, Schmidt & Brückner, 1999). Nowadays, however, concerns are arising due to the high water abstractions used for some horticultural purposes, especially in some areas where water resources are already scarce or threatened. Growers are under increasing pressure to demonstrate that their water abstractions for irrigation are reasonable, justified and environmentally sustainable (Fereres & Soriano, 2007; Terry, Chope & Giné Bordonaba, 2007a; Leathes, Knox, Kay, Trawick & Rodríguez-Diaz, 2008). To ease pressure on existing water resources, water deficit irrigation (DI) has been seen as a potential alternative for new cultivation systems which could not only considerably reduce water usage but also increase water use efficiency in several horticultural crops (Topcu, Kirda, Dasgan, Kaman, Cetin, Yazici & Bacon, 2007). DI, also known as regulated deficit irrigation (RDI), is an irrigation technique whereby crops are exposed to lower amounts of water and the minor stress experienced by the plant is expected to have a minimal effect on the yield (English & Raja, 1996). In strawberry plants, however, this technique (DI) is generally associated with reduction in fruit size and yield (Blatt, 1984; Serrano, Carbonell, Savé, Marfà & Peñuelas, 1992; Krüger et al., 1999; Liu, Savić, Jensen, Shahnazari, Jacobsen, Stikić & Andersen, 2007). Nevertheless, a recent study demonstrated that DI of strawberry cv. Elsanta plants can markedly increase the concentration of some taste- and health-related compounds in both primary and secondary ripe fruit (Terry *et al*., 2007a). Indeed, despite berry size being detrimentally affected by DI, monosaccharides, and more importantly the sugar/acid ratio, were generally much greater in DI-treated fruits. In this context, the ratio between sugar and acids in strawberries and other berries can act as an important indicator of fruit taste (Terry, White & Tigwell, 2005; Giné Bordonaba & Terry, 2008), fruit ripeness (Pérez, Olías, Espada, Olías & Sanz, 1997) or even as an index of consumer acceptability (Keutgen & Pawelzik, 2007a).

Most of the studies conducted thus far, which have endeavoured to elucidate the effect of DI on strawberry fruit, have been focused on a single cultivar, rather than evaluating the response of different genotypes to imposed water deficit conditions. It is known that different strawberry cultivars respond differently to imposed stress conditions. For instance, cvs. Elsanta and Korona responded differently when grown in enriched ozone atmospheres (Keutgen & Pawelzik, 2008a) or under long term salt stress (Keutgen & Pawelzik, 2008b). It is therefore plausible to speculate that strawberry cultivars will respond differently to imposed DI conditions. Hence, the aim of the present study was to assess the response (and variability) among five different strawberry cultivars (namely Christine, Elsanta, Florence, Sonata and Symphony) to imposed water-DI conditions. Specific emphasis was given to quantifying sugars and organic acids as the main indicators of strawberry fruit quality and taste.

2. Materials and methods

2.1. Plant materials and experimental design

Five different maiden year cold-stored strawberry cultivars were grown in a glasshouse during 2007 (April to July) in 1 l capacity pots containing compost. The total nitrogen concentration of the compost substrate was 8.88 g N kg^{-1}, as determined by Kjeldahl analysis. A completely randomised design was adopted with each of 4 blocks containing 30 plants (5 cvs. x 3 replicates x 2 treatments = 30 x 4 blocks = 120). Water treatments started when most of the primary fruits from the primary truss were at flower initiation stage. Plants were irrigated with either 50 or 200 ml day^{-1} over an eight-week periods, daily (*ca*. 09:00 h). Prior to commencing water treatments, plants were kept at or near field capacity (*ca*. 0.8 m^3 of water per m^3 of soil) for approximately four weeks. Plants were treated to prevent incidence of spider mites (*Tetranychus* spp.) and powdery mildew (*Podosphaera aphanis*, formerly *Sphaerotheca macularis* (Wallr.: Fr) Jacz f sp. *fragariae* Peries), as described elsewhere (Terry & Joyce, 2000; Terry *et al*., 2007a). Flowers were hand-pollinated with a sable paintbrush to minimise the occurrence of misshapen fruit.

2.2. Soil moisture content and environmental monitoring

Soil moisture content (m^3 water per m^3 of growing media) was measured daily (*ca*. 16.00h) by time-domain-reflectometry (TDR), using a Thetaprobe (ThetaKit type TK3, Delta-T devices, Cambs., UK). The water-holding characteristics of the soil media were determined as described by Terry et al. (2007a). Hourly temperatures within the glasshouse were recorded by means of four Tiny Tag Ultra 2 data loggers (Gemini Data Logger, Sussex, UK), each shielded from solar radiation by a polystyrene cup and placed in each block. Mean temperature inside the glasshouse during the growing period was 21 ºC.

2.3. Fruit sampling

From each plant, both of the secondary fruits from the primary truss were harvested according to developmental stage. All fruits were harvested at the red stage, which was considered as optimum ripeness. Days after anthesis (DAA) was monitored for primary and secondary fruits from the primary truss by tagging of flowers (n = 360) at anthesis (Terry & Joyce, 2000). The objective colour of each fruit was measured using a Minolta CR-400 colorimeter and a DP-400 data processor (Minolta Co. Ltd., Japan) with an 8 mm light-path aperture. The instrument was calibrated with a Minolta standard white tile CR-400 (Y = 93.5, x = 0.3114, y = 0.3190). The mean of three readings at 3 equidistant points around the equatorial axis of the fruits were recorded and the lightness (L*), chroma (colour saturation; C*) and hue angle (H°) automatically calculated (Terry, Ilkenhans, Poulston, Rowsell & Smith, 2007b). Berry weight, with and without calyx, was measured and recorded. Strawberry secondary fruits without calyces were cut in half vertically, immediately snap-frozen in liquid nitrogen and stored briefly at -40°C before being freeze-dried in an Edwards Modulyo freeze-drier (W. Sussex, UK) for 3 days at 0.015kPa. Lyophilized samples were then ground in a pestle and mortar, weighed and returned to the freezer prior to use. All reagents were purchased from Sigma (Dorset, UK) unless otherwise stated.

2.4.Extraction and quantification of sugars

Sugars were extracted using 62.5% (v/v) aqueous methanol, as described elsewhere (Terry et al., 2007a). Sugar content in strawberry extracts was determined using an Agilent 1200 series HPLC binary pump system (Agilent, Berks., UK), equipped with an Agilent refractive index detector (RID) G1362A. Strawberry extracts (20 µl) were diluted (1:10), and injected into a Rezex RCM monosaccharide Ca+ (8%) column of 300 mm x 7.8 mm diameter (Phenomenex, CA, USA; Part no. 00H-0130-K0) with a Carbo-Ca^{2+} guard column of 4 mm x 3 mm diameter (Phenomenex,; Part no.

AJ0-4493). Temperature of the column was set at 80ºC, using a G1316A thermostatted column compartment. The mobile phase used was HPLC grade water at a flow rate of 0.6 ml min^{-1} (Terry et al., 2007a; Giné Bordonaba & Terry, 2008). Temperature of the optical unit in the detector was set up at 30ºC and temperature of the autosampler at 4ºC using an Agilent cooled autosampler G1330B. The presence and abundance of fructose, glucose and sucrose were automatically calculated by comparing sample peak area to standards (0.025-2.5 mg ml^{-1}) using ChemStation Rev. B.02.01.

2.5.Extraction and quantification of non-volatile organic acids

Extracts for organic acids determination were prepared as described elsewhere (Terry et al., 2007a; Giné Bordonaba & Terry, 2008). Briefly, freeze-dried strawberry extracts (50 mg) were dissolved in 3 ml of HPLC grade water. Samples were kept at room temperature (25ºC) for 10 min and then filtered through a 0.2 µm syringe filter. L-ascorbic, citric, and malic acid contents in extracts were detected at 210 nm, using the same HPLC system, as described above, equipped with an Agilent DAD G1315B/G1365B photodiode array with multiple wavelength detector. Extracts (20 µl) were injected into an Alltech Prevail Organic Acid column 250 mm x 4.6 mm diameter, 5 µm particle size (Alltech, CA, USA; Part no. 88645) with an Alltech Prevail Organic Acid guard column of 7.5 mm x 4.6 mm diameter (Alltech; Part no. 96429). The mobile phase was analytical grade degassed 0.2% (w/v) metaphosphoric acid in H_2O (Giné Bordonaba and Terry, 2008). The flow rate of the mobile phase was 1.0 ml min^{-1} under isocratic conditions and the column temperature was set at 35 ºC. Temperature of the autosampler was set at 4ºC. The presence and quantity of each acid was calculated by comparing the peak area obtained with standards (0.02-2.0 mg ml^{-1}), using ChemStation Rev. B.02.01.

2.6. Estimation of strawberry taste parameters

Sweetness index (SI) for the different cultivars analysed was calculated as previously described (Keutgen & Pawelzik, 2007a). Briefly, the contribution of each major sugar found in strawberry fruits was calculated, considering that fructose and sucrose are 2.3 and 1.35 times sweeter than glucose, respectively. Accordingly, SI = 1.0 [Glucose] + 1.35 [Sucrose] + 2.3 [fructose].

2.7. Data analysis

All statistical analyses were carried out using Genstat for Windows, Version 10 (VSN International Ltd., Herts., UK). Data were subjected to analysis of variance (ANOVA) tests, based on a completely randomised design within blocks. Least significant difference values (LSD; $P = 0.05$) were calculated for mean separations, using critical values of t for two-tailed tests. Correlations between experimental variables were made using Spearman's rank correlations and, if required, presented as Spearman's correlation coefficient (r) and P value, based on a two-tailed test. Unless otherwise stated, significant differences were $P < 0.05$.

3. Results and discussion

3.1. Soil water status

Soil water content values of the growing media differed between treatments, but also between cultivars when submitted to DI conditions, indicating the existence of genotypic differences in the response of strawberry plants to drought stress, as well as differences in water usage between different cultivars. Values for non-DI-treated plants were consistent between cultivars, ranging from 0.73 to 0.85 m^3 of water per m^3 of growing media (Figure 1). Similar water contents were observed by Terry et al. (2007a) when assessing water deficit irrigation in cv. Elsanta fruits grown under comparable conditions. Greater differences between water content of soils from water-stressed plants and plants kept at or near field capacity were observed for cv. Elsanta during the whole duration of the study (Figure 1). Elsanta plants grown under drought stress conditions used more water (up to 20% more) from the growing medium during the first days after commencing water treatments than did the rest of cultivars. Water usage of DI-treated plants for cvs. Sonata and Symphony were similar throughout the trial as was also observed for cvs. Florence and Christine. Higher water uptake for Elsanta plants may be the result of either the increase in root growth or root hydraulic conductivity or even greater water usage as compared to other cvs. (Savić, Stikić, Radović, Bogičević, Jovanović & Šukalović, 2008). Overall, water content in the growing media of DI-treated plants declined, following water-soil dynamics similar to those previously described (Liu et al., 2007; Terry et al., 2007a; Savic et al., 2008).

3.2. Effect of DI on fruit physiology

The response of fruit physiology to water stress was dependent on the genotype. Differences in fruit physiology among cultivars may be accounted for by differences in abscisic acid (ABA) or other hormone metabolism in plants exposed to drought stress. For instance, the plant hormone ABA regulates various physiological reactions in plants and its role in the response to drought stress is well documented for many horticultural crops (Seki, Umezawa, Urano & Shinozaki, 2007). In strawberry plants (cv. Elsanta), grown under comparable DI conditions, ABA was greater than that of fully irrigated plants (Terry et al., 2007a). In the present study, berry weight from secondary strawberry fruits was significantly reduced (approximately 1/3 lower) by DI in cvs. Symphony, Elsanta and Sonata (Figure 2a). However, both cvs. Christine and Florence showed similar weights, for both water-stressed and non water-stressed plants. Concomitant with this, and in those cultivars where berry size was reduced, dry matter, as a proportion of fresh weight, was considerably greater in fruits from water-stressed plants than from plants kept at or near field capacity (Figure 2b). Previous studies also showed that fruit from strawberry plants that received full irrigation had a higher water content and greater berry fresh weight than had fruit from plants grown under reduced irrigation (Blatt, 1984; Serrano *et al*., 1992; Krüger *et al*., 1999; Kirnak, Kaya, Higgs & Gercek, 2001; Kirnak, Kaya, Higgs, Bolat, Simsek & Ikinci, 2003; Liu *et al*., 2007; Terry *et al*., 2007a). Fruits from cv. Elsanta showed the greatest increase (1.24-fold higher) in dry matter content as a proportion of fresh weight in response to reduced water supply. These findings were in agreement with Terry et al. (2007a), since strawberry fruits (cv. Elsanta) from DI-treated plants also showed 25% more dry matter than did non-water stressed plants. Similarly, Kirnak et al. (2003) reported higher soluble dry matter contents for cvs. Oso Grande and Camarosa fruits submitted to DI in trials conducted in the field. Plant responses to either water or salt stress have been reported to have much in common (Munns, 2002). For instance, salinity reduces the capacity of plants to take up water, which may result in reduced growth rate and metabolic changes similar to those observed in plants grown under water stress. In this context, strawberry plants grown under high salinity conditions had either higher (Awang & Atherton, 1995) or lower (Keutgen & Pawelzik, 2008b) dry matter contents. The greater dry matter content observed in the results presented herein suggests a concentration effect by either limitation of water uptake and/or enhanced import of solutes into the fruit. In this study, dry matter content from other parts of the plants were not investigated and therefore, it is difficult to conclude whether or not the increased dry matter may be the result of a trade off in resource allocation within the plant (e.g. vegetative and root growth versus fruit growth). This said, the dilution effect observed in plants that received more water was limited to certain cultivars since fruits from cv. Christine and/or Florence showed similar dry matter contents between DI-treated and non-water-stressed plants (Figure 2b).

Anthesis occurred significantly ($P < 0.05$) later in water-stressed plants for cvs. Elsanta, Florence and Christine and was generally reduced for the other cultivars investigated. In a similar manner, fruit maturation was also slower for some water-stressed cvs. (*viz*. Elsanta and Christine) taking 33 days after anthesis for plants treated with 50 ml of water per day in comparison to 31 days for plants receiving 200 ml per day (data not shown). Time from anthesis to harvest for all other cvs. was not affected by DI. Terry et al. (2007a) also found that fruit maturation was slower (not significantly) in Elsanta fruit grown under drought stress conditions. Indeed, it has been shown that, for certain crops, drought stress may result in considerable increase of the time to anthesis and to physiological maturity (Geerts, Raes, Garcia, Mendoza & Huanca, 2008).

3.3. Effect of DI on taste-related compounds and overall fruit quality

Colour of strawberries is without doubt one of the main attributes which governs consumer perception and therefore their acceptability (Francis, 1995). Objective colour of each fruit was measured when fruit was adjudged to be at optimum ripeness (when fully red) and significant differences were encountered between the different cultivars investigated (Table 1). Similarly, significant differences in objective colour have been reported by others when studying different cultivars (Sacks & Shaw, 1994; Capocasa, Scalzo, Mezzetti & Battino, 2008; Hernanz, Recamales, Meléndez-Martínez, González-Miret & Heredia, 2008; Giné Bordonaba and Terry, 2009) or between fruits from plants grown under different conditions (Hernanz et al., 2008). Generally, no significant differences were observed for colour (L*, C*, H°) parameters among secondary fruits within a cultivar. Nonetheless, even if all fruit were picked at the full red stage, significant differences were encountered for C* values among fruits from Elsanta. Accordingly, previous work carried out by Terry et al. (2007a) also found significant differences in the objective colour of strawberry cv. Elsanta fruits when picked at optimum harvest. Generally, DI had a considerable effect on objective fruit colour. Plants receiving 50 ml of water per day showed lower C* values than did non-water-stressed plants (Table 1). These differences were especially highlighted for cvs. Elsanta, Sonata and Florence ($P < 0.05$). The effect of DI on L* and Hº values was dependent on the cultivar. Some cultivars (namely Elsanta and Symphony) showed higher values for lightness (L*) and lower redness (higher Hº) for plants receiving 50 ml per day than did non-water-stressed plants. The remaining cultivars tended to show lower L* and H° values for DI-treated plants (Table 1). Likewise, Terry et al. (2007a) also found higher Hue angles in cv. Elsanta fruits treated with 50 ml day^{-1} than with plants receiving either 100 or 200 ml day^{-1}. Strawberry fruit colour is due, in part, to anthocyanins, which account for the red colour of the fruits. It will be expected, therefore, that if lower red coloration (higher Hº) is reported for water-stressed plants, lower anthocyanin contents will also be encountered in the fruit. However, in the study carried out by Terry et al. (2007a), DI resulted in lower redness but higher concentration of pelargonidin-3-glucoside and derivatives of this anthocyanin on a FW basis. In view of that, the authors suggested that the lower redness in smaller fruits was most probably an artefact of the objective colorimeter measurement since shorter distances between achenes will exist in smaller fruits, resulting in lower recorded redness.

Little information is available which describes the effect of DI on the taste-related attributes (namely sugars and acids) of strawberries (Terry et al., 2007a). In contrast, ample data are available on the effect of either cultivation practices or other stress conditions (namely ozone exposure, salinity) on strawberry fruit quality (Wang, Zheng & Galletta, 2002; Davik, Bakken, Holte & Blomhoff, 2006; Keutgen & Pawelzik, 2007a and 2007b; Hargreaves, Adl, Warman & Rupasinghe, 2008; Keutgen & Pawelzik, 2008b; Hargreaves, Adl & Warman, 2009). In strawberry fruits, non-structural carbohydrates are the main components of dry matter. Independent of the water treatment applied, results showed that sugars accounted for 6 to 8% of the total fresh matter. Similar proportions have been reported by others (Cordenunsi, do Nascimento, Genovese & Lajolo, 2002; Ménager, Jost & Aubert, 2004; Terry et al., 2007a; Keutgen & Pawelzik, 2008b). Fructose, glucose and sucrose were the three main sugars found in the different strawberry genotypes studied, and concentrations differed significantly among cultivars and water treatments (Table 2). Variations in sugar content between different cultivars are not unusual and have been extensively reported (Wang *et al*., 2002; Skupien & Oszmiański, 2004; Davik *et al*., 2006; Keutgen & Pawelzik, 2008a). The relative concentrations of sugars were similar between cvs. (Table 2); however, fruit from cv. Sonata, had a greater sucrose content than had other cultivars studied. Overall, values were in the range of previously reported studies (Wang *et al*., 2002; Skupien & Oszmiański, 2004; Davik *et al*., 2006; Keutgen & Pawelzik, 2008; Giné Bordonaba and Terry, 2009). This said, greater amounts of sucrose were encountered herein and can only really be comparable to the results from Terry et al. (2007a), given that the same extraction method was used. Along these lines, fructose and glucose or sucrose are nearly twice or three times more soluble in methanol-based solvents than in aqueous-based solvents (Davis, Terry, Chope & Faul, 2007) and therefore the methanol-based extraction used herein may have enhanced the solubility of these sugars, especially sucrose. Consequently, it is clear that comparison of sugar contents in strawberry fruits from different studies should be treated with some caution.

Both on a DW and FW basis, Florence and Sonata were the cvs. showing higher sugar content for non-water-stressed plants (70.8 and 68.8 mg g^{-1} FW, respectively). Nevertheless, cvs. Elsanta and Sonata fruits had the greater sugar content (82.34 and 81.57 mg g^{-1} FW, respectively) when subjected to DI. Fructose contents in cvs. Elsanta and Sonata plants, as well as glucose content in Elsanta, were the only sugar contents significantly greater in DI-treated plants than in plants kept at or near field capacity (Table 2). Previous studies (Terry et al., 2007a) also highlighted that, although sucrose was not affected by DI, monossacharide contents (glucose and fructose) were significantly higher in DI plants. The authors concluded that lower concentrations of sugars in fruits that received more water were most probably due to a dilution effect. Despite total soluble solids not always being well correlated with sugar content in strawberry fruits (Perez et al., 1997; Terry et al., 2005), in the study by Awang et al. (1995), higher soluble solids content in cv. Rapella, grown under salinity stress, was associated with restricted vegetative growth and shift of photoassimilates to fruits. In both of these cases, the results from this study may support such findings. Although no evidence exists for strawberry fruits, it is well documented that plants grown under water stress undergo a process of osmotic adjustment (Mahajan & Tuteja, 2005). Thereby, the greater sugar content in DI-treated plants may be an attempt by the plant to reduce osmotic potential by the accumulation of solutes.

Sweetness of strawberry fruits is an important factor which can characterise the acceptance of the fruits by consumers. Considering that fructose is *ca*. 1.8 times sweeter than sucrose, and the sweetness of glucose is 60% that of sucrose, DI resulted in generally sweeter berries, as determined by the sweetness index (Figure 3a). Fruits from Elsanta plants subjected to drought stress showed as much as one third higher sweetness than fruits from plants kept at or near field capacity. A significant increase in the sweetness index of Sonata was also observed for DI-treated plants.

Taste in strawberry fruits is not, however, only just influenced by sugars. Acids and volatile compounds are also important contributors to strawberry taste and flavour (Cordenunsi et al., 2002). In the present study, and in earlier reports (Perez et al., 1992; Keutgen & Pawelzik, 2007; Terry et al., 2007a), three major acids were found within the cultivars, corresponding to citric, malic and ascorbic acids. Citric acid was the major acid found in the different cultivars investigated herein, accounting for approximately 1% of the total fresh matter, in agreement with that found in the literature (Terry et al., 2007a; Keutgen & Pawelzik, 2008b; Giné Bordonaba & Terry, 2009). Malic and ascorbic acid were also identified in all cultivars at lower concentrations, up to 4.49 and 0.78 mg g^{-1} FW, respectively. Drought stress also affected acid composition (Table 3). On a DW basis, plants kept at or near field capacity tended to have greater acid contents than did those exposed to drought stress. Christine and Florence were the only cvs. where DI resulted in higher acid contents. However, considering the results on a FW basis, DI resulted in greater acid content for Symphony and Florence whilst it did not significantly affect acid content for the rest of the cvs. In an ealier study, DI resulted in lower ascorbic, citric and malic acid contents on a DW basis for Elsanta plants (Terry et al., 2007a); however, it is clear that, in the present study, DI had a genotype-dependent effect on acid metabolism. As indicated by differences in fruit physiology, it may be plausible to speculate that DI resulted in different respiratory metabolisms among cultivars and hence different utilisations of respiratory substrates such as organic acids. Strawberry fruits are an important source of ascorbic acid (AsA). This vitamin, in combination with other phytochemicals (namely anthocyanins and phenolic acids) found in strawberry has been reported to be responsible for the numerous health benefits associated with these berries. In this context, strawberries were recently ranked as one of the most important sources of cellular antioxidant activity in the North American diet (Wolfe, Kang, He, Dong, Zhang & Liu, 2008). In the present study, the concentration of AsA ranged from 0.42 (DI treated cv. Elsanta) to 0.73 (DI treated cv. Florence) mg g^{-1} FW and was dependent on the water regime and cultivar. Values were in agreement with those previously reported (Perez et al., 1992; Davik et al., 2006; Terry et al., 2007a). DI resulted in significantly lower and higher concentration of AsA only for cultivars Elsanta and Florence (Table 3). DI had the greatest effect in cultivar Florence which showed a 1.3-fold higher AsA concentration in fruits from water stressed plants, and hence perhaps resulting in more healthful berries. This said, Keutgen and Pawelzik (2007b), testing strawberry fruits from plants grown under other environmental stress conditions, observed that the content of ascorbic acid was reduced in fruits from cvs. Elsanta and Korona plants subjected to moderate salt stress.

The balances between sugars and acids in strawberries and other berries are important indicators of fruit taste (Terry et al., 2005 & 2007a; Giné Bordonaba & Terry, 2008). Additionally, the ratio can be used as an indicator of fruit ripeness (Pérez et al., 1997) or even as an index of consumer acceptability (Keutgen & Pawelzik, 2007a). Recently, Terry et al. (2007a) showed that sugar/ acid ratios were significantly greater in DI-treated plants than in non-water-stressed plants. The results from this study show that, although sugar/acid ratios for DI-treated were substantially higher in Symphony, Elsanta and Sonata, significant differences between treatments ($P < 0.05$) were only encountered in fruits from Sonata (Figure 3b). Water DI did not have a significant effect on the sugar / acid ratio of either Christine or Florence, and comparable values were observed for both irrigation regimes. Cordenunsi et al. (2002) reported that good quality strawberry fruits were those with a ratio higher than 5.3. However, such information must be accepted with caution as values will directly depend on the nature of the measurements. Plants kept at or near field capacity (for all the cultivars except Symphony) had sugar acid ratios higher than 5 (e.g. Elsanta and Christine with values of 5.9). As a result of DI, the quality of strawberries was significantly and substantially higher in Sonata and Elsanta with values of 6.2 and 6.9, respectively.

4. Conclusions

It is known that DI on strawberry plants can reduce berry size and yield. However, the results presented herein, and previous findings by Terry et al. (2007a), showed that DI can have a considerable effect on the concentrations of certain compounds linked to taste and consumer preference. This study showed, for the first time, that differences exist in the way different cultivars respond to drought stress resulting in different fruit compositions. Despite the detrimental effect that DI can have on berry size, reducing water irrigation by a quarter from flower initiation to fruit harvest, resulted in better water use efficiency, as well as enhanced fruit quality and taste (greater sweetness and sugar/acid ratio) in cvs. Elsanta, Sonata and Symphony. In addition, results indicated that, for certain cultivars (namely Christine and Florence), water savings by means of DI, can be achieved without having a negative effect on overall strawberry fruit quality.

Acknowledgements

The authors thank the Horticultural Development Company (HDC; CP_43), The Perry Foundation and GlaxoSmithKline for financial support. Rosie Burns, Balwinder Cook and Allen Hilton are thanked for their technical assistance and Charles Marshall is thanked for statistical advice.

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Table captions

Table 1 Effects of water deficit irrigation (DI: 50 ml day^{-1}) or full irrigation (FI: 200 ml day^{-1}) on objective colour (L* is lightness, C* is chroma, and Hº is the hue angle) of secondary strawberry fruits from the primary trusses of five different cultivars. Cultivars are arranged in descending order of Hº values for fully irrigated plants

Table 2 Effects of water deficit irrigation (DI: 50 ml day^{-1}) or full irrigation (FI: 200 ml day^{-1}) on concentration of main sugars of secondary strawberry fruits from the primary trusses of five different cultivars. Cultivars are arranged in descending order of total sugar concentrations for fully irrigated plants on a DW basis

Table 3 Effects of water deficit irrigation (DI: 50 ml day^{-1}) or full irrigation (FI: 200 ml day^{-1}) on main non-volatile organic acids of secondary strawberry fruits from the primary trusses of five different cultivars. Cultivars are arranged in descending order of total acid concentrations for fully irrigated plants on a DW basis

Figure captions

Figure 1 Water volume of the growing medium of five different strawberry cultivars (Symphony (-○-), Elsanta (-▼-), Sonata (-Δ-), Florence (-■-) and Christine (-□-)) grown under deficit irrigation (50 ml day^{-1}) conditions. Water volumes of growing media from fully irrigated (-●- 200 ml day-^{1}) plants were similar among cultivars and values are presented as the mean per day of the five cultivars. Error bars indicate LSD (P < 0.05) values for the daily interaction cultivar*water treatment. LSD (P < 0.05) value for the overall interaction days*cultivar*water treatment was 0.182

Figure 2 Effects of water deficit irrigation (▬ DI; 50 ml day^{-1}) or full irrigation (▬ FI; 200 ml day^{-1}) on weight characteristics of secondary fruits from the primary trusses of five different strawberry cultivars; (**A**) Weight (g) and (**B**) Dry matter as a proportion of fresh weight (g 100 g^{-1} FW). Cultivars are arranged in descending order of berry weight for fully irrigated plants. Error bar indicates LSD value (P < 0.05)

Figure 3 Effects of water deficit irrigation (▬ DI; 50 ml day^{-1}) or full irrigation (▬ FI; 200 ml day^{-1}) on taste-related attributes of secondary fruits from the primary trusses (**A**: Sugar/acid ratio; **B**: calculated sweetness) of five different strawberry cultivars. Cultivars are arranged in descending order for calculated sweetness of DI-treated plants. Error bar indicates LSD value (P < 0.05)

Table 1 Giné Bordonaba and Terry

Cultivar	L*		C*		H°	
	DI	**FI**	**DI**	**FI**	**DI**	**FI**
Christine	44.85	46.87	51.92	52.78	42.6	43.09
Sonata	44.73	46.08	51.69	53.84	43.42	42.98
Elsanta	44.91	44.12	47.49	49.56	46.68	41.84
Symphony	41.76	39.89	46.21	46.65	43.2	38.15
Florence	36.49	40.77	38.06	44.27	36.22	37.12
LSD ($P < 0.05$)	1.857		2.486		2.310	

Table 2 Giné Bordonaba and Terry

Cultivar	mg g^{-1} DW								mg g^{-1} FW							
	Sucrose		**Fructose**		**Glucose**		**Total sugars**		**Sucrose**		**Fructose**		**Glucose**		**Total sugars**	
	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI
Sonata	252	291	143	139	150	169	545	599	39.0	33.5	20.8	16.0	21.8	19.3	81.6	68.8
Florence	202	243	141	156	144	165	487	565	27.3	30.7	19.7	19.4	20.1	20.7	67.1	70.8
Elsanta	191	223	183	158	188	169	562	550	28.0	24.0	26.9	16.8	27.5	17.9	82.3	58.6
Symphony	187	173	145	154	150	171	482	497	23.3	16.7	17.6	14.7	18.3	16.2	59.3	47.6
Christine	188	161	158	148	168	150	514	458	22.9	19.6	19.3	18.2	20.4	18.3	62.5	56.1
LSD ($P < 0.05$)	49.3		21.1		24.2		50.8		7.20		3.78		4.26		8.74	

Table 3: Giné Bordonaba and Terry

Cultivar	mg g^{-1} DW								mg g^{-1} FW							
	Ascorbic		**Malic**		**Citric**		**Total Acids**		**Ascorbic**		**Malic**		**Citric**		**Total Acids**	
	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI	DI	FI
Symphony	90.5	99.1	25.2	35.1	4.86	5.68	121	140	11.1	9.45	3.10	3.35	0.59	0.54	14.8	13.3
Sonata	62.1	83.6	29.5	39.0	3.50	4.13	95.1	127	8.59	9.67	4.13	4.49	0.47	0.47	13.2	14.6
Florence	82.4	80.3	21.4	23.4	5.33	4.31	109	108	11.4	10.1	2.91	2.97	0.73	0.54	15.1	13.6
Christine	80.4	66.2	29.1	21.5	5.09	5.10	115	92.8	9.63	7.87	3.46	2.55	0.60	0.61	13.7	11.0
Elsanta	64.7	63.6	16.4	22.2	3.07	5.22	84.2	91.0	9.22	6.88	2.36	2.43	0.42	0.57	12.0	9.88
LSD ($P < 0.05$)	1.26		7.11		17.0		20.3		0.143		0.876		2.12		2.81	

FIGURES

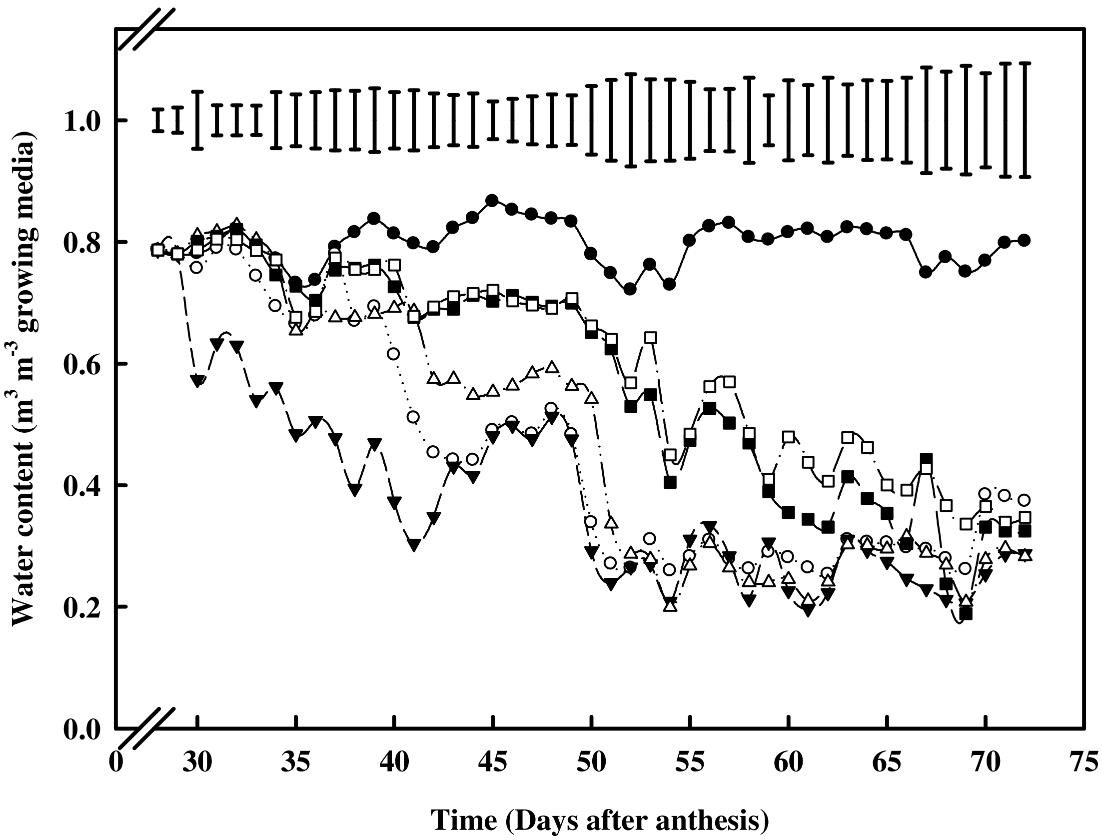

Figure 1 Giné Bordonaba and Terry

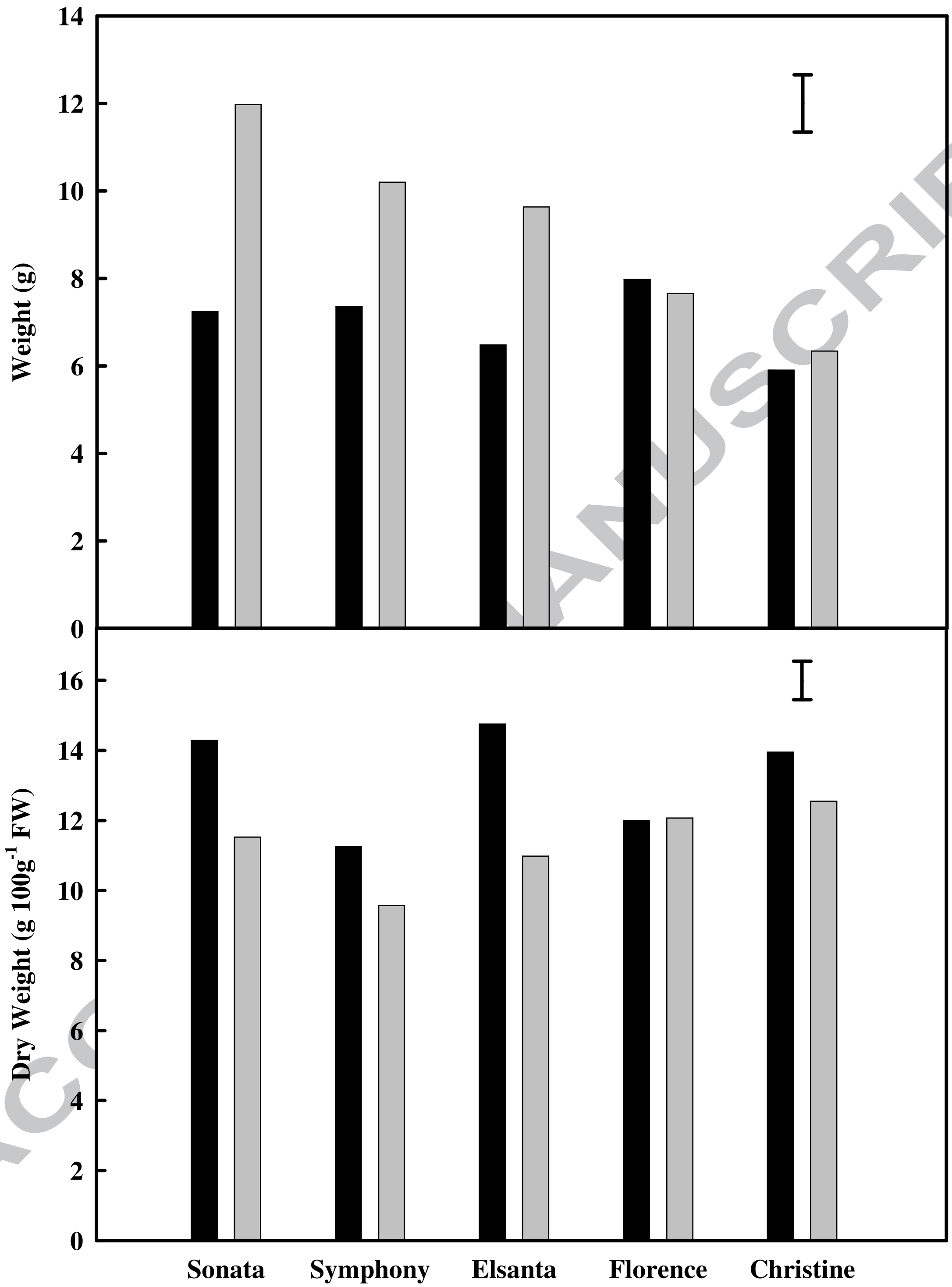

Figure 2 Giné Bordonaba and Terry

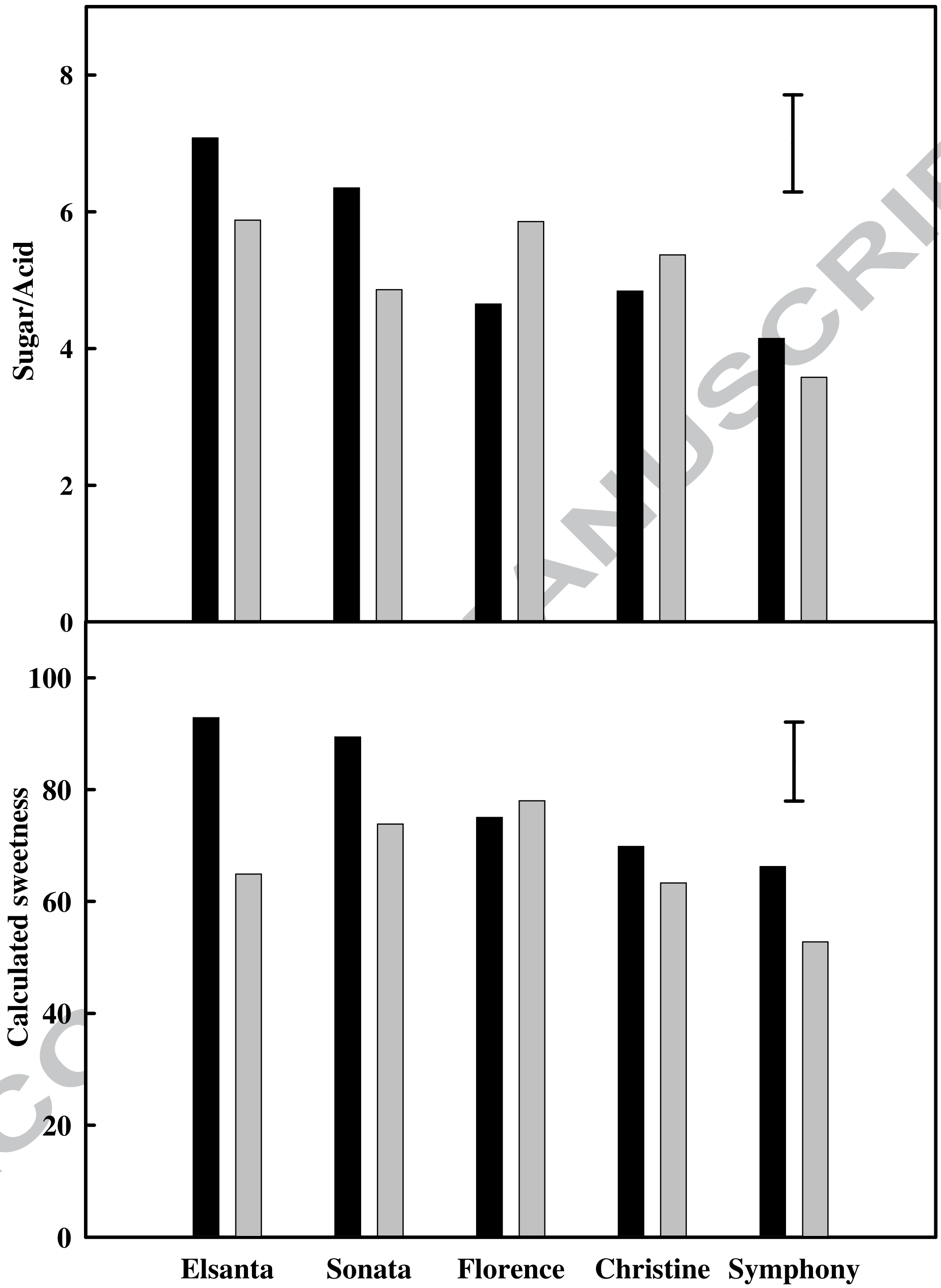

Figure 3 Giné Bordonaba and Terry