Water Stress Increases Sunburn in ‘Cripps’ Pink’ Apple

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Abstract. An experiment that entailed the manipulation of irrigation was carried out to assess the effect of water stress on sunburn development in ‘Cripps’ Pink’ apples. Normal irrigation, half irrigation, and no irrigation treatments were applied for 15 days starting on 14 Mar. 2010 (Southern hemisphere). Stem water potential, fruit surface temperature (FST), sunburn incidence, and sunburn severity were measured. Sunburn was also categorized into browning, necrosis, or bleaching sunburn types. Fully exposed fruit without prior sunburn symptoms were tagged for progressive sunburn assessments, whereas sunburn was also assessed at harvest for all fruit per tree. Soil moisture and stem water potential decreased, whereas FST, sunburn incidence, and severity increased linearly with a decrease in irrigation level. Sunburn necrosis increased with increasing water stress. In conclusion, water stress aggravates sunburn development under conditions conducive for its development by increasing FST.

The external appearance of fruit is a crucial factor in consumer preference (Steyn, 2012). Sunburn, a disorder of the fruit peel caused by high temperature in combination with high irradiance (Glenn et al., 2002; Schrader et al., 2003), negatively affects the appearance of apples in warm production areas such as the Western Cape of South Africa. Depending on irradiance level, temperature and the duration of the photothermal stress (Gindaba and Wand, 2007; Schrader et al., 2003) affected fruit show pigment bleaching, a golden bronze sublethal discoloration, or necrosis of the fruit peel (Racsó et al., 2005; Schrader et al., 2003). Losses resulting from sunburn are therefore attributable to the injury and downgraded appearance of the fruit. Sunburn can decrease class one exportable fruit in South Africa by 20% to 50% in the orchard and packhouse and by a further 10% at the export destination (Bergh et al., 1980).

Although excessive heat and high irradiance are the main inductive factors in sunburn

development, indirect factors such as relative humidity, air movement, and various cultural practices such as tree size, canopy structure, pruning, and irrigation may affect the incidence and severity of sunburn (Racsó and Schrader, 2012). Water stress has been reported to exacerbate the development of sunburn (Barber and Sharpe, 1971; Gonda et al., 2006), whereas regular irrigation purportedly decreases the incidence of sunburn, supposedly by facilitating sufficient evaporative cooling in the tree (Van de Ende, 1999). However, little research has been conducted to relate plant water status to sunburn incidence and severity; the link between plant water status and sunburn seems to be based primarily on observations. In a New Zealand study using five three-year-old ‘Braeburn’ trees per treatment, no irrigation did not significantly increase sunburn compared with the control treatment (Wünsche et al., 2001).

Considering the lack of experimental data, we set out to obtain empirical evidence that water stress increases the incidence and severity of sunburn. Hence, the objective of this study was to investigate the effect of water stress on plant water relations and how this affects sunburn development in apples.

Materials and Methods

Plant material. The experiment was conducted during the 2009–10 season at Welgevallen Experimental Farm, Stellenbosch, South Africa (lat. 33°55′ S, long. 18°53′ E) using ‘Cripps’ Pink’ apple planted in 1998 on M793 rootstock. The tree spacing was 4 m × 1.5 m in a northeast by southwest row orientation. The orchard soil was classified as

Oakleaf form, a cambisol with a high clay percentage and a high water-holding capacity. The Western Cape province of South Africa where the experiment was conducted has a Mediterranean-type climate with hot, dry summers that necessitates irrigation.

Treatments and experimental design. Irrigation was manipulated to attain three treatments, i.e., full irrigation, hereinafter called control treatment, half the irrigation amount, hereinafter called half irrigation, and no water for 15 d, hereinafter called no irrigation, starting on 14 Mar. 2010. The normal irrigation at Welgevallen at the onset of the experiment was 6 mm·h⁻¹ delivery for 2.5 h twice weekly emitted by microjet sprayers placed 0.5 m on either side of trees. The half irrigation and no irrigation treatments were attained by exchanging normal spray nozzles (6 mm·h⁻¹) with nozzles that gave half the normal delivery (3 mm·h⁻¹) and stoppers (0 mm·h⁻¹), respectively. Treatments were randomized in eight blocks with three trees per plot and two buffer trees between plots to avoid treatment interference. The blocks were laid out on flat, non-sloping land to avoid the effect of runoff.

Data collection. Hourly air temperature, humidity, rainfall, and irradiance data were obtained from the Helderfontein automatic weather station, ≈4 km from the Welgevallen Experimental Farm. Vapor pressure deficit (VPD) was calculated from the saturated vapor pressure of the air at the relative humidity of the air in the hour that the maximum air temperature was attained.

Measurements of stem water potential, soil water content, and sunburn were taken on Days 0, 8, and 15 (14, 22, and 29 Mar., respectively). To measure stem water potential, two mature inner canopy leaves closer to the trunk were each enclosed in a black polythene bag lined with an outer silver reflective tape for at least 1 h to allow the leaves to reach equilibrium with stem water potential. Still in the bags, the leaves were cut and water potential measured using a pressure bomb (Model 600; PMS Instrument Co., Albany, OR). FST was measured on Day 0 and Day 15 between 1300 HR and 1400 HR using a handheld infrared thermometer (Raynger MX4; Raytek Corporation, Santa Cruz, CA) aimed at the position on the fruit facing the current position of the sun.

Eight sun-exposed fruit without sunburn and without any overshadowing leaves were tagged per tree on the western side of the row at the onset of the experiment and sunburn severity assessed on Days 8 and 15 as well as at harvest using a 0 to 5 scale developed by Schrader and McFerson (Schrader et al., 2003) where 0 represented no sunburn and 5 the most severe form. Tagged fruit were culled to one fruit per cluster. Total sunburn incidence was also assessed on a per-tree basis at harvest. All fruit with sunburn at harvest were further graded into the three sunburn classes, i.e., bronzing, bleaching, and necrosis, according to Schrader et al. (2003).

Relative soil water content (RSWC) was determined gravimetrically by weighing the

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differences between fresh and oven-dried auger-drawn soil samples at a depth of 45 cm on Days 0, 8, and 15. The relative soil water content was expressed as a percentage of the soil weight.

Statistical analysis. Data were subjected to analysis of variance by General Linear Methods using SAS Version 9.1.3 (SAS Institute Inc., Cary, NC). Where significant differences occurred ($P \leq 0.05$), means were separated by the least significant difference. Single df, orthogonal, linear, and quadratic contrasts for irrigation level were fitted.

Results and Discussion

Three levels of RSWC were attained after applying normal, half, or no irrigation for 15 d during March (Southern hemisphere) (Fig. 1A). Rainfall during the 15-d duration of the experiment was insubstantial with 0.5 and 1.9 mm recorded on 26 and 27 Mar., respectively. RSWC markedly declined for the water stress treatments, although significant differences were only apparent at Day 15, possibly as a result of the high water-holding capacity of the soil. Soil from the control and no irrigation treatments had the highest and lowest gravimetric water content, respectively, whereas the half irrigation treatment was intermediate. The decrease in available soil water corresponds to a linear reduction in 'Cripps' Pink' apple tree stem water potential (Fig. 1B). By Day 15, the stem water potentials of the three treatments were significantly different. The control and no irrigation treatment had the highest and lowest water potentials, respectively. Stem water potential is a sensitive and reliable indicator of water stress (Naor, 2006). Comparison with previous research on apple in Israel (Naor et al., 1995) indicates that the no irrigation treatment was severely water stressed by Day 15.

The decrease in stem water potential at lower RSWC corresponds to a considerable difference in FST between treatments measured at Day 15 (Fig. 2). All treatments were significantly different with the no irrigation treatment having the highest average FST of 36.7 °C. The FST of the control and half irrigation treatment were 31.6 and 34.0 °C, respectively. The air temperature during FST measurement on Day 15 was 26.4 °C. FST in sun-exposed apple is reported to exceed air temperature by 5 to 15 °C (Bergh et al., 1980; Racskó and Schrader, 2012, and references therein).

Sunburn incidence among tagged fruit was significantly lower for the control treatment than for the two water stress treatments at Days 8 and 15 and at harvest (Table 1). It seems that the differences in sunburn incidence between treatments were attained within the first 8 d of the treatment. This corresponds with the consistently high air temperatures, VPD, and sunny conditions during the first 8 d compared with the cooler and overcast conditions during the second 7 d of the trial (Table 2). There was a significant linear relationship between irrigation

Fig. 1. The effect of irrigation on (A) soil water content and (B) stem water potential in a 'Cripps' Pink' apple orchard at the Welgevallen Experimental Farm in the 2009–2010 season. The half irrigation and no irrigation treatments were attained by exchanging normal spray nozzles ($6 \text{ mm} \cdot \text{h}^{-1}$) with nozzles that gave half the normal delivery ($3 \text{ mm} \cdot \text{h}^{-1}$) and stoppers ($0 \text{ mm} \cdot \text{h}^{-1}$), respectively, from 14 to 29 Mar. 2010 (Days 0 to 15). ns, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.001, or 0.0001, respectively.

Fig. 2. Effect of irrigation level on average fruit surface temperature measured at midday on fully exposed 'Cripps' Pink' apples at the Welgevallen farm. The half irrigation and no irrigation treatments were attained by exchanging normal spray nozzles ($6 \text{ mm} \cdot \text{h}^{-1}$) with nozzles that gave half the normal delivery ($3 \text{ mm} \cdot \text{h}^{-1}$) and stoppers ($0 \text{ mm} \cdot \text{h}^{-1}$), respectively, from 14 to 29 Mar. 2010 (Days 0 to 15). Air temperature at the time of measurement on Day 0 and Day 15 was 28.4 and 26.1 °C, respectively. ns, *** Nonsignificant or significant at $P \leq 0.0001$, respectively. Treatments with different letters differ significantly at 0.05 level.

level and sunburn incidence. A decrease in irrigation level resulted in an increase in sunburn incidence, but the two water stress treatments did not differ significantly from each other at all three dates. Judging from stem water potentials (Fig. 1B), the half irrigation treatment also experienced significant water stress. For the total fruit at harvest, the same linear trend was observed with the two water stress treatments showing

significantly greater sunburn incidence compared with the control treatment (Table 3). As a result of their much greater exposure to sunlight, tagged fruit on the western sides of trees showed a much higher sunburn incidence (Table 1) compared with the sunburn incidence for the entire tree at harvest (Table 3). The sunburn incidence at harvest for the control treatment is typical for 'Cripps' Pink' apples under South African conditions.

Table 1. Effect of water stress between 14 and 29 Mar. 2010 on sunburn incidence of tagged 'Cripps' Pink' apples at the Welgevallen Experimental Farm.^z

Treatment	Total sunburn (%)			Prevalence of sunburn types at harvest (%)		
	Day 8	Day 15	At harvest	Browning	Necrosis	Bleaching
Control	15 b ^y	30 b	41 b	94 a (39) ^x	5 b (1.6)	3 (1.2)
Half irrigation	42 a	56 a	64 a	92 a (58)	6 b (3.8)	2 (1.3)
No irrigation	45 a	61 a	73 a	75 b (55)	25 a (18)	0
F-test	***	**	**	**	***	NS
Contrasts						
Linear	***	**	**	**	**	NS
Quadratic	*	NS	NS	NS	NS	NS

^yThe half irrigation and no irrigation treatments were attained by exchanging normal spray nozzles (6 mm·h⁻¹) with nozzles that gave half the normal delivery (3 mm·h⁻¹) and stoppers (0 mm·h⁻¹), respectively. Fully exposed fruit without sunburn were tagged on 14 Mar. (Day 0).

^xMeans in the same column followed by the same letter are not significantly different at 0.05 level.

^zFigures in parentheses represent the proportion of sunburn out of the total tagged fruit, whereas those outside parentheses represent the proportion out of total sunburnt fruit.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.001, or 0.0001, respectively.

Table 2. Daily maximum air temperature, vapor pressure deficit (VPD) at the maximum air temperature and the total daily irradiance for 14 to 29 Mar. 2010 from the Helderfontein automatic weather station, 4 km from the Welgevallen Experimental Farm.^z

Date	Daily maximum temp. (°C)	VPD (kPa)	Daily irradiance (MJ·m ⁻²)
14 Mar.	29.8	2.83	23.4
15 Mar.	34.8	4.22	23.0
16 Mar.	30.2	2.79	21.6
17 Mar.	27.2	2.16	22.2
18 Mar.	34.6	4.26	21.8
19 Mar.	34.6	4.06	21.4
20 Mar.	27.7	2.00	15.3
21 Mar.	28.8	2.46	12.2
22 Mar.	30.8	3.04	21.3
23 Mar.	34.8	4.39	21.2
24 Mar.	28.2	2.25	15.8
25 Mar.	24.6	1.58	13.8
26 Mar.	23.1	1.30	7.8
27 Mar.	24.4	1.58	11.6
28 Mar.	26.4	2.17	19.9
29 Mar.	26.1	1.85	20.1

^zThe VPD was calculated from the saturated vapor pressure of the air at the relative humidity of the air in the hour that the maximum air temperature was attained.

Table 3. Effect of water stress from 14 to 29 Mar. 2010 on sunburn incidence (all fruit at harvest) of 'Cripps' Pink' apples at the Welgevallen Experimental Farm.^z

Treatment	Browning (%)	Necrosis (%)	Bleaching (%)	Total sunburn (%)
Control	94 a ^y (8) ^x	5 b (1)	1 (0.1)	9 b
Half irrigation	87 a (13)	12 b (2)	1 (0.0)	15 a
No irrigation	59 b (11)	36 a (7)	5 (0.9)	18 a
F-test	***	***	NS	*
Contrasts				
Linear	***	***	NS	**
Quadratic	*	NS	NS	NS

^yThe half irrigation and no irrigation treatments were attained by exchanging normal spray nozzles (6 mm·h⁻¹) with nozzles that gave half the normal delivery (3 mm·h⁻¹) and stoppers (0 mm·h⁻¹), respectively.

^xMeans in the same column followed by the same letter are not significantly different at 0.05 level.

^zFigures in parentheses represent the proportion of sunburn out of the total tagged fruit, whereas those outside parentheses represent the proportion out of total sunburnt fruit.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.001, or 0.0001, respectively.

Sunburn severity for both tagged fruit and total fruit at harvest showed a linear increase with a decrease in irrigation level (Table 4). For the tagged fruit, sunburn severity did not differ significantly in the two water stress treatments but was significantly greater than the control treatment at Day 8 (Table 4). At Day 15, all three treatments differed significantly in sunburn severity. The control and no irrigation treatments had the least and most severe sunburn,

respectively. Sunburn severity for the tagged fruit at harvest was significantly greater in the no irrigation treatment compared with the half irrigation and control treatments. For all fruit at harvest, the half irrigation treatment did not significantly differ from the control in terms of sunburn severity. However, the no irrigation treatment had a significantly higher sunburn severity.

Sunburn browning was the most predominant sunburn type in all treatments (Tables 1

and 3). There was a significant linear relationship between sunburn browning and sunburn necrosis with irrigation level for tagged fruit and total fruit at harvest (Tables 1 and 3). The percentage sunburn necrosis increased with water stress at the expense of the percentage sunburn browning. Sunburn necrosis for the no irrigation and control treatments was 35.7% and 5.4%, respectively. This indicates a progression in the severity of sunburn in accordance with the increase in FST with an increase in water stress. Sunburn necrosis in apple in Washington State occurs at a threshold temperature of 52 ± 1 °C, whereas sunburn browning requires a lower threshold FST of 46 °C under conditions of high light (Schrader et al., 2003). Daily maximum air temperatures of ≈ 35 °C were reached on four occasions (15, 18, 19, and 23 Mar.) during the trial period (Table 2). It is therefore conceivable that FSTs were elevated to levels conducive to development of sunburn necrosis, particularly in the water-stressed trees. No significant differences were observed between treatments for sunburn bleaching. Photo-oxidative bleaching results when a shaded fruit is suddenly exposed to the sun and can occur at peel temperatures below 30 °C (Felicetti and Schrader, 2008). This sudden exposure can be the result of branch breakages, defoliation, or in response to increased fruit weight as fruit grow. Considering these causative factors of sunburn bleaching, water stress is not expected to increase sunburn bleaching, except if leaf folding exposes shaded fruit to high irradiance.

The obvious question is how water stress results in an increase in FST and thereby in sunburn compared with irrigated trees. Fruit temperature is a function of heat exchange through radiation, evaporation, and convection between the fruit surface and the surrounding plant canopy microclimate (Saudreau et al., 2008; Smart and Sinclair, 1976). First of all, it is possible that leaf folding in response to water stress (Corelli-Grappadelli and Lakso, 2007) could have increased the extent and duration of sun exposure of the fruit, thereby increasing FST. However, although we did not assess leaf folding, FST measurements were done on tagged fruit that were selected based on their full sunlight exposure in the absence of overshadowing leaves.

The increased FST of fully exposed tagged fruit in water-stressed trees implies reduced evaporative and convective heat loss from the fruit surface. Water evaporates from the apple surface through stomata during early fruit development and later through lenticels. As suggested by Van de Ende (1999), the higher FST of apples on water-stressed plants could potentially relate to lower evaporative cooling from lenticels resulting from a reduced VPD between the fruit and the atmosphere. Some indirect evidence of the role of evaporation in FST comes from research on detached and attached peppers (Rabinowitch et al., 1983). Detached fruit became warmer under irradiation than attached fruit at all stages of development leading the authors to speculate on the role of

Table 4. Effect of water stress between 14 and 29 Mar. 2010 on sunburn severity (0–5 sunburn severity scale with 0 having no sunburn and 5 the severest) of tagged fruit (Days 8 and 15) and at harvest in ‘Cripps’ Pink’ apples at the Welgevallen farm.^z

Treatment	Tagged fruit			Total fruit
	Day 8	Day 15	Harvest	Harvest
Control	0.2 b ^y	0.6 c	1.0 b	1.8 b
Half irrigation	0.5 a	1.1 b	1.5 b	2.0 b
No irrigation	0.7 a	1.6 a	2.4 a	3.0 a
F-test	*	**	**	**
Contrasts				
Linear	**	**	**	**
Quadratic	NS	NS	NS	NS

^zThe half irrigation and no irrigation treatments were attained by exchanging normal spray nozzles (6 mm·h⁻¹) with nozzles that gave half the normal delivery (3 mm·h⁻¹) and stoppers (0 mm·h⁻¹), respectively. Fully exposed fruit without sunburn were tagged on 14 Mar. (Day 0).^z Means followed by the same letter in a column are not significantly different at 0.05 level of significance.

^yNonsignificant.

NS, *, ** Nonsignificant or significant at $P \leq 0.05$ or 0.001, respectively.

water movement through the fruit on the fruit heat balance. However, the contribution of evaporation from lenticels to cooling of the apple fruit surface is potentially quite small as a result of a high resistance to water movement in mature apple, although water permeability is considerably greater in developing fruit than in mature fruit (Nobel, 1975). Various fruits show a diurnal growth pattern in that expansion is greater at night, whereas fruit may even shrink during the day as a result of net water loss (Morandi et al., 2007, 2010; Tromp, 1984). Jones and Higgs (1982) reported that shrinkage in apple fruit averaged 31% of net growth in late summer. Tromp (1984) found that only 20% to 35% of the shrinkage could be attributed to evaporation with the remainder attributable to reverse flow of water from fruit to other parts of the tree under conditions of low leaf water potential. Considering that our experiment was conducted ≈ 150 d after full bloom (≈ 40 d before harvest) and that the xylem in apple fruit becomes dysfunctional from 50 to 70 d after full bloom (Dražeta et al., 2004), a contribution of xylem reverse flow to the fruit heat balance was unlikely.

The whole canopy heat load may also potentially affect FST. Because control of leaf temperature under high-energy influx is achieved in large part through evaporative cooling, the availability of ample water is crucial in maintaining optimal leaf temperature (Mahan and Upchurch, 1988). Sepulcre-Cantó et al. (2006) found that well-watered olive trees with a higher water potential had a lower canopy temperature than trees under deficit irrigation with a lower water potential. The higher canopy temperature in water-stressed trees may decrease convective heat exchange from the fruit surface. We unfortunately did not measure canopy temperature.

In conclusion, plant water status seems to play a significant role in sunburn development. In this study, fruit on water-stressed

plants displayed higher fruit surface temperatures with subsequent higher sunburn incidence and severity. The most severe form of sunburn, viz. sunburn necrosis, was highest where irrigation was completely withheld. The tagging of fully exposed fruit without overshadowing leaves excludes leaf folding and therefore increased light exposure of fruit as contributory factor to increased FST and sunburn but points to a direct effect of water stress on sunburn incidence. The respective roles of evaporation and convective heat loss and the interaction of these factors with plant water status in the cooling of the apple fruit surface require further research.

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