Peel Color and Blemishes in ‘Granny Smith’ Apples in Relation to Canopy Light Environment

Jacques R. Fouché, Stephanie C. Roberts, Stephanie J.E. Midgley, and Willem J. Steyn¹

Department of Horticultural Science, University of Stellenbosch, Victoria Street, Stellenbosch, 7600 South Africa

Additional index words. sunburn, red blush, chlorophyll, fruit quality, peel temperature

Abstract. The dark green apple cultivar, Granny Smith (GS), makes up 25% of the South African apple industry. However, production of GS is becoming unprofitable as a result of a high incidence of sunburn, red blush, and pale green fruit that decreases the proportion of Class 1 fruit that is suitable for export to more lucrative markets. This study was conducted to investigate the relationship between canopy position and external fruit quality with the ultimate aim to devise pruning and training strategies to maximize export yield. During early fruit development [26 days after full bloom (DAFB)], chlorophyll concentrations were the highest in fruit from higher light environments. Good green color at harvest relied on exposure of fruit to high irradiance at this stage because 50% shading between 14 and 56 DAFB significantly decreased dark green color at harvest. Exposed fruit from the northern side of east–west rows received the highest irradiance throughout the season [53% of full sun photosynthetic photon flux (PPF)] and had the highest fruit surface temperature (on average 5 °C above ambient). A high proportion of exposed fruit from either side of the row developed red blush. Only 22% to 39% of exposed fruit from the outer canopy did not develop sunburn or red blush. Partially shaded fruit from the southern side of east–west rows received ≈5% of full sunlight and had the highest chlorophyll concentrations and darkest green color at harvest. Deeply shaded inner canopy fruit received ≈2% of full sunlight, had low chlorophyll concentrations, and were lighter green in color. The 10% darkest green fruit received moderately high irradiance (25% to 45% of full sun PPF) during early fruit development (until ≈80 DAFB) but became progressively shaded (3% of full sun PPF) during the latter half of the season. Fruit that developed sunburn and the lightest green fruit were exposed to high (1300 μmol·m⁻²·s⁻¹) and extremely low (50 μmol·m⁻²·s⁻¹) light, respectively, throughout their development. In conclusion, maximum chlorophyll synthesis and dark green color require an open canopy during the first half of fruit development, whereas shading is necessary during the latter half of fruit development to avoid the occurrence of sunburn, red blush, and photothermal destruction of chlorophyll. GS may benefit significantly from the installation of shade netting if combined with rigorous pruning and vigor control.

‘Granny Smith’ (GS) is the most widely planted apple cultivar in South Africa, accounting for 25% of apple plantings in 2008 (Deciduous Fruit Producers’ Trust, 2009).

Received for publication 12 Feb. 2010. Accepted for publication 9 Apr. 2010.

This material is based on work supported by the National Research Foundation under Grant number 2069401, the THRIP programme of the National Department of Trade and Industry, and the South African Apple and Pear Producers’ Association. We thank Oakvalley Estate and Lourensford Estate for provision of trial sites and donation of fruit and Henk Griessel and Coenie Groenewald for their helpful suggestions.

This paper forms part of theses submitted by J.R. Fouché and S.C. Roberts in fulfilling a MScAgric degree requirement.

Any opinions, findings, or conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Research Foundation.

¹To whom reprint requests should be addressed; e-mail wsteyn@sun.ac.za.

However, the total area of GS planted in South Africa has decreased by almost 15% during the last 15 years as a result of competition from more lucrative blushed cultivars. Apart from realizing lower returns, the proportion of Class 1 fruit from GS trees is lower compared with other cultivars as a result of zero tolerance for red blush, sunburn blemishes, and whitening of the peel. Fruit with sunburn or red blush are downgraded to Class 3 and will not pass for export. Although older GS orchards are being replaced with more profitable cultivars, GS will remain an important component of the South African industry for the time being. Hence, ways have to be found to increase the yield of Class 1 fruit.

In South Africa, sunburn and red blush may decrease Class 1 fruit by 35% and 20%, respectively (Griessel, personal communication). These blemishes occur in high light environments (Tustin et al., 1988; Warrington et al., 1996), where high light in combination with low or high temperatures initiates the

synthesis of red anthocyanins or yellow carotenoids, respectively. Sunburn necrosis occurs as a result of thermal death of epidermal and subepidermal cells that leads to formation of a necrotic spot and is caused by extreme fruit surface temperature (52 ± 1 °C), whereas sunburn browning is a result of high fruit surface temperatures (46 to 49 °C) in the presence of light (Schrader et al., 2008). Photo-oxidative browning can occur at much lower peel temperatures (less than 30 °C) when fruit peel is suddenly exposed to high irradiance resulting in photobleaching followed by necrosis (Felicetti and Schrader, 2008). Chlorophyll levels decreased as a result of sunburn in all apple cultivars studied (Felicetti and Schrader, 2009). Red blush in GS is formed when anthocyanin synthesis is stimulated by low night temperature and mild days in combination with high irradiance (Reay, 1999), conditions that occur mostly during early fruit development in spring or during fruit maturation in the fall.

Peel whitening occurs under extremely low irradiance (Hirst et al., 1990) and may decrease Class 1 fruit in South Africa by ≈10% (Griessel, personal communication). The problem usually worsens with storage. A perception is increasing among fruit importers that South African GS is less green than GS of competing countries (Griessel, personal communication). To deal with this problem, fruit are shipped to lower-value markets, which has a negative effect on net profits achieved by producers. There is currently no coordinated effort to develop cultural practices to address this problem. To increase GS Class 1 fruit by decreasing sunburn, red blush, and peel whitening, it is necessary to have a sound understanding of green color development in apple peel and how it is affected by the light environment.

The main objective of this research was to relate GS fruit position in the canopy and the respective light environments to external fruit quality in terms of peel color, sunburn, and red blush development under commercial fruit-growing conditions in South Africa. The peel color of fruit at different canopy positions was measured at regular intervals from fruit set until harvest and related to irradiance level and peel temperature. Our hypothesis was that fruit from partially shaded canopy positions exposed to high levels of diffuse light but with limited exposure to direct sunlight would show less shading-related whitening as well as less high radiation-related yellowing and red blush development during fruit development. We also considered that irradiance level during early fruit development has a major effect on final fruit color. Results obtained would provide a basis from which to reassess the current planting systems used for GS and to devise pruning strategies for improving fruit color and increasing the percentage of Class 1 fruit in existing GS orchards.

Materials and Methods

Trials were conducted in the Mediterranean-type climate Grabouw (latitude: 34°8′

S, long.: 19°3' E) and Somerset West (lat. 34°1' S, long. 18°5' E) regions of the Western Cape province of South Africa.

Canopy position in relation to external fruit quality—2006/2007. Fruit were selected ≈1.5 m from the ground, halfway between the outer canopy and trunk on both sides of the row as well as next to the trunk, on three randomly selected trees in each of four mature north-south row-orientated GS orchards representative of GS in the Grabouw region. One fruit was selected per position per tree. Orchards were of comparable vigor and size and varied in age from 21 and 36 years. Photosynthetic photon flux (PPF) experienced at each canopy position was assessed hourly from 0800 HR to 1800 HR from 18 Feb. [122 d after full bloom (DAFB)] to 31 Mar. 2007 (162 DAFB) with a quantum sensor attached to a light meter (LI-250; LI-COR, Lincoln, NE) held horizontally next to each fruit with the sensor facing upward. Ambient PPF was measured in the middle of the working row in full sunlight.

Fruit were sampled on 6 and 7 Apr. 2007 (during the commercial harvest period ≈170 DAFB) from four randomly selected trees in the same four orchards mentioned previously. A total of 73 fruit was sampled per tree. Twelve fruit were sampled from each side of the row from the outer canopy, and 12 fruit were sampled halfway between the outer canopy and the trunk, also from each side of the row. In addition, 25 fruit were sampled from the inner canopy next to the trunk. Samples were assessed for green color intensity on the visually greenest side of fruit using a color chart (Set A 38; Deciduous Fruit Board, Paarl, South Africa), the occurrence of red blush and sunburn, and chlorophyll concentration of the peel. Lightness values of the visually greenest and least green sides of the fruit were determined with a Minolta chromometer (Model CR-400; Minolta Co. Ltd., Tokyo, Japan). A logarithmic relationship exists between decreasing L values and increasing chlorophyll concentrations (Lancaster et al., 1997).

Chlorophylls were assessed for both the visually greenest and least green sides of fruit. The flesh was scraped off the peel whereafter the peel was frozen in liquid nitrogen, freeze-dried, milled, and kept at -40 °C until pigment analysis. Chlorophylls were extracted from 0.1 g freeze-dried material with 4 mL 100% acetone and constantly stirred for 24 h at 4 °C in the dark. After centrifugation for 15 min at 10,000 × g, the supernatant was decanted and the pellet re-extracted with 4 mL 100% acetone and centrifuged as described previously. The supernatant was added to the first. After filtration through 0.45-μm filters (Millex-HV; Millipore Corporation, Milford, MA), pigments were quantified by spectrophotometry [Cary 50 Bio; Varian Australia (PTY) Ltd., Melbourne, Australia] measuring absorbance at 470, 645, and 670 nm. The extinction coefficients of Lichtenthaler (1987) were used to calculate chlorophyll concentrations, which were then expressed in μg·g⁻¹ dry weight of peel.

Canopy position and external fruit quality—2007/2008. Twenty uniform trees were selected in a vigorous orchard on seedling rootstock in the Grabouw region. Trees were planted in 1983 in an east-west row direction and trained to a free standing central leader form. This orchard is typical of South African GS: 84% of orchards are older than 15 years (Deciduous Fruit Producers' Trust, 2009) and almost all of these orchards were planted on seedling rootstock. One fruit was tagged shortly after fruit set at five canopy positions on each tree, i.e., fully exposed outer canopy on the northern (A) and southern (E) periphery of trees, partially shaded canopy positions on the northern (B) and southern (D) sides of trees, and the shaded inner canopy next to the trunk (C).

PPF directly above each fruit, peel temperature, and peel color were measured every ≈2 weeks on cloudless days from 10 Nov. 2007 (27 DAFB) to 30 Mar. 2008 (162 DAFB) five times daily at 2-h intervals from 0800 HR to 1800 HR. The light sensor was always directed at the sun. This would result in higher but possibly more realistic measurement of irradiance compared with most other studies in which the light sensor is held horizontal. Peel temperature was measured using a high-performance infrared thermometer (Rayner MX4; Raytek Corporation, Santa Cruz, CA) aimed at the position on the fruit facing the current position of the sun. Lightness values were recorded, as described previously, on the side of the fruit receiving the most sun.

Ten representative fruit were sampled on 9 Nov. 2007 (26 DAFB) and again on 14 Apr. 2008 (177 DAFB) (commercial harvest) from each position on each of the 20 selected trees. Hence, a total of 50 fruit per tree were sampled on each date. Lightness was measured on the visually greenest side of fruit harvested on 9 Nov. and the whole fruit was peeled for chlorophyll analysis. Green color intensity, red blush and sunburn incidence, chlorophyll concentration, and lightness values for both sides of the fruit were determined for fruit harvested at maturity.

Effect of early season shading on green color. Fruit from the light-exposed outer

canopy of the western sides of the rows in an orchard planted in 1982 in the Somerset West region on seedling rootstock were enclosed in 40% woven green shade cloth from 14 DAFB (24 Oct. 2007) until 56 DAFB and compared with unshaded fruit from similar positions at 56 DAFB and at commercial harvest (160 DAFB). The two treatments were repeated in five blocks with 20 clusters of fruitlets per block enclosed in the shade cloth. The shade cloth decreased PPF measured with a quantum sensor by ≈50%.

At 56 DAFB, 20 previously shaded and control fruit were sampled for each replicate, peeled for pigment analysis, and lightness was measured on the darkest green side of the fruit. At commercial harvest, previously shaded fruit and unshaded fruit from similar positions were evaluated for the presence of sun bluish (either red blush or sunburn), peel lightness values, and chlorophyll concentrations of the darkest green side of the fruit. Chlorophylls were extracted from 0.3 g fresh peel in 3 mL acetone and expressed as μg·g⁻¹ fresh weight of peel. Analysis of results was carried out using the General Linear Models procedure of SAS 9.1 (SAS Institute Inc., Cary, NC).

Results

Canopy position and external fruit quality—2006/2007. Fruit from inner canopy positions received less light than fruit from partially shaded intermediate positions on the western and eastern sides of rows (Fig. 1). A considerably higher proportion of fruit from outside canopy positions developed sunburn and red blush (Table 1). Sunburn and red blush often occurred on the same fruit. Only 34% to 37% of fruit from the outer canopy were unblemished. There was no appreciable difference between the eastern and western sides of rows in the incidence of sunburn and red blush. Hardly any fruit (1%) from the inner canopy developed sunburn and no fruit developed red blush, whereas 7% to 13% of fruit from partially shaded canopy positions were blemished. Outside fruit were slightly less green, whereas inner and intermediate canopy fruit were similar in color (Table 1).

Fig. 1. Percentage of full sun received by 'Granny Smith' fruit from middle and intermediate canopy positions on an average day during the 2006/2007 season. Values are means ± SE (n = 4).

Table 1. Chlorophyll concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ DW) and lightness values of the visually darkest and lightest green sides as well as green color, incidence of sunburn, and red blush in 'Granny Smith' apples sampled from different canopy positions at commercial harvest (160 d after full bloom) during the 2006/2007 season.^z

Canopy position	Darkest green side		Lightest green side		Green color (chart) ^y	Sunburn (%) ^x	Red blush (%) ^x	Unblemished fruit (%) ^w
	L value	Chlorophyll	L value	Chlorophyll				
Outside (east)	58.0 $\pm$ 0.4	712 $\pm$ 16	60.8 $\pm$ 0.3	594 $\pm$ 36	3.4 $\pm$ 0.1	46.1 $\pm$ 5.6	25.6 $\pm$ 13.3	33.8 $\pm$ 9.2
Intermediate (east)	56.7 $\pm$ 0.4	821 $\pm$ 13	61.0 $\pm$ 0.3	733 $\pm$ 22	3.2 $\pm$ 0.1	11.4 $\pm$ 10.1	1.9 $\pm$ 0.8	86.7 $\pm$ 10.2
Inner	56.4 $\pm$ 0.4	875 $\pm$ 23	61.6 $\pm$ 0.4	749 $\pm$ 13	3.2 $\pm$ 0.2	1.0 $\pm$ 0.7	0.0 $\pm$ 0.0	98.9 $\pm$ 0.8
Intermediate (west)	56.1 $\pm$ 0.5	830 $\pm$ 36	60.4 $\pm$ 0.2	757 $\pm$ 30	3.1 $\pm$ 0.2	5.2 $\pm$ 2.2	2.0 $\pm$ 0.9	92.9 $\pm$ 2.1
Outside (west)	57.4 $\pm$ 0.6	760 $\pm$ 42	60.3 $\pm$ 0.3	592 $\pm$ 46	3.3 $\pm$ 0.3	46.6 $\pm$ 3.9	18.4 $\pm$ 8.8	37.3 $\pm$ 10.7

^zThe values are means $\pm$ SE (n = 4).

^yChart values 1 to 12 in which 1 = green; 12 = pale green/yellow.

^xThe same fruit may have sunburn and red blush.

^wWithout any sunburn and/or red blush.

DW = dry weight.

Lower lightness values and higher chlorophyll concentrations on the visually greenest side of fruit from intermediate and inner canopy positions also indicate their darker green color compared with outer canopy fruit. However, the visually least green sides of inner canopy fruit were slightly lighter in color than the least green sides of outer canopy fruit. There were no appreciable differences between the eastern and western sides of rows in terms of color and chlorophyll concentration.

Canopy position and external fruit quality—2007/2008. Exposed fruit on the northern and southern sides of the east–west row received the highest and second highest irradiance (53% and 31% of full sunlight, respectively) during an average day during the season followed by fruit from intermediate positions on the northern side of rows (12% of full sunlight) (Fig. 2). Fruit from the inner canopy and intermediate positions on the southern side of the row received very little sunlight throughout the day (2% and 5%, respectively). The PPF received by exposed fruit on the southern side of the row decreased by $\approx 60\%$ from the beginning of January to the end of March (Fig. 3). Conversely, light exposure of fruit from intermediate positions on the northern side of rows increased by $\approx 10\%$ from the beginning of February.

Exposed fruit on the northern side of the row had the highest peel temperature throughout the season, $\approx 5^\circ\text{C}$ higher on average than the average ambient air temperature ($\approx 24^\circ\text{C}$) during the season (Fig. 4). The peel temperature of exposed northern fruit reached a maximum of 42°C , 7°C above the air temperature, on 20 Feb. (128 DAFB) (data not shown). Exposed fruit on the southern side of rows and fruit from intermediate positions on the northern side of rows had slightly higher ($\approx 2^\circ\text{C}$) average peel temperatures than ambient. Fruit from the inner canopy and intermediate positions on the southern side of rows did not differ in temperature from ambient.

During early fruit development (26 DAFB), exposed fruit had the lowest lightness values (Table 2; Fig. 5) as well as the highest chlorophyll concentrations together with fruit from intermediate positions on the southern sides of the row (Table 2). Fruit from intermediate canopy positions on the

Fig. 2. Percentage of full sun and average photosynthetic photon flux (PPF; $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) (values shown above columns) received by 'Granny Smith' fruit from different canopy positions during the course of an average day during the 2007/2008 season. (A) Outside and (B) intermediate canopy positions on the northern side of trees planted in east–west rows. (C) Inner canopy position next to the trunk. (D) Intermediate and (E) outside positions on the southern side of trees. Values are means $\pm$ SE (n = 20).

Fig. 3. Average photosynthetic photon flux (PPF) received by 'Granny Smith' fruit from different canopy positions during the 2007/2008 season. (A) Outside and (B) intermediate canopy positions on the northern side of trees planted in east–west rows. (C) Inner canopy position next to the trunk. (D) Intermediate and (E) outside positions on the southern side of trees. Values are means $\pm$ SE (n = 20).

northern and southern sides of the row had similar lightness values with fruit on the southern side of the tree having the same chlorophyll concentration as northern outside fruit. Inner canopy fruit had the highest lightness values as well as the lowest chlorophyll concentrations. Fruit at all canopy positions became lighter in peel color as the season progressed (Fig. 5). Exposed northern fruit were the lightest in color at harvest

followed by inner canopy fruit, northern intermediate fruit, exposed southern fruit, and southern intermediate fruit (Table 3). This corresponds with the visual assessment of color by color chart. The difference in lightness between the on-tree measurements (Fig. 5) and the sampled measurements (Table 3) is because on-tree measurements were not taken on the visually greenest side of the fruit, but on the side facing the sun.

Fig. 4. Ambient air temperature and average surface temperature of 'Granny Smith' fruit from different canopy positions during the 2007/2008 season. (A) Outside and (B) intermediate canopy positions on the northern side of trees planted in east-west rows. (C) Inner canopy position next to the trunk. (D) Intermediate and (E) outside positions on the southern side of trees. The dashed line indicates the average daily air temperature (23.8 °C) that was recorded during fruit development. Values are means $\pm$ SE (n = 20).

Table 2. Peel lightness and chlorophyll concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ DW) of 'Granny Smith' apples sampled from different canopy positions on 9 Nov. 2007 (26 d after full bloom).^a

Canopy position	L value	Chlorophyll
Outside (north)	42.9 $\pm$ 0.7	1352 $\pm$ 29
Intermediate (north)	49.4 $\pm$ 0.4	1284 $\pm$ 30
Inner	51.4 $\pm$ 0.2	1221 $\pm$ 34
Intermediate (south)	49.3 $\pm$ 0.3	1352 $\pm$ 28
Outside (south)	42.7 $\pm$ 0.5	1380 $\pm$ 29

^aThe values are means $\pm$ SE (n = 20).
DW = dry weight.

Fig. 5. Lightness of fruit from different canopy positions during the 2007/2008 season. (A) Outside and (B) intermediate canopy positions on the northern side of trees planted in east-west rows. (C) Inner canopy position next to the trunk. (D) Intermediate and (E) outside positions on the southern side of trees. Values are means $\pm$ SE (n = 20).

Southern intermediate fruit were the darkest green in color with the highest chlorophyll concentrations (Table 3). However, these fruit differed most in color and chlorophyll concentration between their visually greenest and least green sides, indicating a less uniform color over the entire fruit. Southern-exposed fruit were similar to southern intermediate fruit in terms of color and chlorophyll concentration and also showed a considerable

difference in color between the visually greenest and least green sides of the fruit. Exposed northern fruit were the lightest in color with respect to both the greenest and least green sides of the fruit compared with fruit at other canopy positions. These fruit also had the lowest chlorophyll concentrations. However, the difference in color between the greenest and least green sides of exposed northern fruit was less compared with fruit at the southern

and inner canopy positions. Northern intermediate fruit had the most uniform color with respect to their greenest and least green sides. These fruit were darker green on their visually greenest side compared with exposed northern and inner canopy fruit but had similar chlorophyll concentrations as inner canopy fruit on their greenest side. Northern intermediate fruit were darker green on their least green side compared with fruit at other canopy positions. Inner canopy fruit showed a large difference in color between their greenest and least green sides despite having similar chlorophyll concentrations. Chlorophyll concentrations of the visually greenest sides of exposed southern, intermediate northern, and inner canopy fruit were similar. Inner and exposed southern fruit had similar chlorophyll concentrations on the least green sides of the fruit.

The proportion (%) of fruit without sunburn or red blush was considerably higher in all shaded regions of the canopy. Exposed fruit on the northern side of the row had a high prevalence of sunburn and red blush. Many fruit developed both sunburn and red blush. Exposed fruit on the southern side of the row had a high incidence of red blush, but few fruit developed sunburn. Sunburn was first observed on 27 Dec. (70 DAFB) shortly after ambient air temperatures first rose above 35 °C on 22 Dec. (65 DAFB) (Fig. 6).

The 10% fruit with the lowest lightness values (i.e., the darkest green fruit), the 10% fruit with the highest lightness values (i.e., the lightest green fruit), and all the fruit that developed sunburn were compared with regard to the PPF that they received during fruit development (Fig. 6) to further assess the relationship among irradiance, peel color, and sunburn. The darkest green fruit received moderate light ($\approx 35\%$ of full sun PPF) during November and December whereafter they became progressively shaded and received very little light ($\approx 5\%$ of ambient light) in the 2 months before harvest. In contrast, fruit that developed sunburn were exposed to high PPF ($\approx 73\%$ of full sun) throughout their development, but especially during the 2 months before harvest ($\approx 79\%$ of full sun). The lightest green fruit received very little light ($\approx 3\%$ of full sun) throughout their development.

Early season shading. Unshaded control fruit were significantly darker green than shaded fruit at 56 DAFB and at harvest (160 DAFB) (Table 4). Differences in chlorophyll concentrations were only statistically significant ($P < 0.1$) at 56 DAFB and not at harvest. Blemishes caused by excess sunlight were significantly higher at harvest for fruit that had been shaded.

Discussion

PPF decreased with increasing depth in the canopy (Warrington et al., 1996). The western and eastern sides of north-south rows received comparable PPF, whereas the northern side of east-west rows received higher PPF than the southern side. This is the result

Table 3. Chlorophyll concentrations ($\mu\text{g}\cdot\text{g}^{-1}$ DW) and lightness values of the darkest and lightest green sides as well as green color, incidence of sunburn, and red blush in 'Granny Smith' apples sampled from different canopy positions at commercial harvest (177 d after full bloom) in the 2007/2008 season.^z

Canopy position	Darkest green side		Lightest green side		Green color (chart) ^y	Sunburn (%) ^x	Red blush (%) ^x	Unblemished fruit (%) ^w
	L value	Chlorophyll	L value	Chlorophyll				
Outside (north)	62.4 $\pm$ 0.5	379 $\pm$ 13	65.7 $\pm$ 0.4	307 $\pm$ 9	3.4 $\pm$ 0.2	36.0 $\pm$ 2.9	75.5 $\pm$ 4.3	22 $\pm$ 5.5
Intermediate (north)	60.4 $\pm$ 0.3	447 $\pm$ 11	62.4 $\pm$ 0.0	400 $\pm$ 8	2.6 $\pm$ 0.1	1.5 $\pm$ 0.8	14.7 $\pm$ 3.2	85 $\pm$ 3.2
Inner	61.1 $\pm$ 0.2	454 $\pm$ 27	66.3 $\pm$ 0.3	435 $\pm$ 13	3.0 $\pm$ 0.1	0.0	4.2 $\pm$ 2.1	96 $\pm$ 2.0
Intermediate (south)	58.0 $\pm$ 0.3	619 $\pm$ 18	64.4 $\pm$ 0.4	490 $\pm$ 13	2.1 $\pm$ 0.1	0.0	5.6 $\pm$ 1.6	94 $\pm$ 1.6
Outside (south)	59.6 $\pm$ 0.4	479 $\pm$ 15	64.7 $\pm$ 0.3	440 $\pm$ 10	2.5 $\pm$ 0.1	4.0 $\pm$ 1.1	61.4 $\pm$ 5.1	39 $\pm$ 4.9

^zThe values are means $\pm$ SE (n = 20).

^yChart values 1 to 12 in which 1 = green; 12 = pale green/yellow.

^xThe same fruit may have sunburn and red blush.

^wWithout any sunburn and/or red blush.

DW = dry weight.

Fig. 6. Photosynthetic photon flux (PPF) received during the 2007/2008 season by the 10% 'Granny Smith' fruit with the lowest lightness values (i.e., the darkest green fruit), the 10% fruit with the highest lightness values (i.e., the lightest green fruit), and fruit that developed sunburn. Values are means $\pm$ SE (n = 4). First day with maximum temperature exceeding 35 °C was 22 Dec. [65 d after full bloom (DAFB)]. First sunburn was observed on 27 Dec.

Table 4. Peel lightness (L) values and chlorophyll concentrations (in $\mu\text{g}\cdot\text{g}^{-1}$ FW) of 'Granny Smith' apples at 56 DAFB and at commercial harvest (160 DAFB) that were either covered with 40% shade cloth from 14 to 56 DAFB or left unshaded in the 2006/2007 season.^z

Treatment	56 DAFB		160 DAFB		
	L value	Chlorophyll	L value	Sun blemish (%) ^y	Chlorophyll
No shading	55.8 b	214 NS	57.5 b	64 b	228 NS
Shade cloth	58.3 a	172	60.7 a	87 a	185
<i>Pr</i> > <i>F</i>					
Treatment	0.0005	0.0828	0.0273	0.0334	0.2787

^zMeans in columns were separated by LSD (5%).

^ySunburn, blush, or bronzing.

FW = fresh weight; DAFB = days after full bloom; NS = nonsignificant; LSD = least significant difference.

of the maximum zenith angle of 79° that the sun reaches on 21 Dec. at this latitude, causing more sunlight to reach the northern side of the tree, especially during midday (Bergh et al., 1980). Exposed fruit on the southern side of east–west rows and partially shaded fruit on the northern side of the rows received similar PPF during the second half of fruit development. This might be the result of changes in the position of the fruit during the course of the season as branches bend under the weight of fruit (Hirst et al., 1990) thereby increasing the light exposure of inner-canopy fruit on the northern side of rows. Also, the zenith angle of the sun decreases from 79° on 21 Dec. to 56° on 31 Mar., thereby increasing shading on the southern sides of trees. Hence, both the bending of branches and the inclination of

the sun may affect light distribution within the canopy (Bergh et al., 1980). Differences in the irradiance that fruit are exposed to at different canopy positions also results in differences in fruit surface temperature.

Fruit temperature is a function of radiation intensity and air circulation (Bergh et al., 1980). Bright sunlight and low wind velocity can raise fruit temperature in some crops such as grape berries by 10 to 15 °C above air temperature (Smart and Sinclair, 1976). Bergh et al. (1980), Chen et al. (2008), and Parchomchuk and Meheriuk (1996) measured apple peel temperatures in excess of 50 °C on occasions when air temperatures exceeded 30 °C. According to Schrader et al. (2003), sunburn occurs when fruit surface temperature exceeds 45 °C in the presence of

light, which may occur when air temperature exceeds 30 °C. Sunburn was first observed in late December (70 DAFB) on fruit from the northern periphery of trees, soon after air temperatures first exceeded 35 °C. In agreement with Bergh et al. (1980), these fruit received the most sunlight as a result of the sun's inclination and consequently had the highest peel temperatures. As a result of the bending of branches under the weight of fruit and the changing inclination of the sun, outer canopy fruit on the southern side of east–west rows became progressively shaded from February until harvest, thereby significantly decreasing the incidence of sunburn. For the same reason, partially shaded fruit on the northern side of the east–west rows became more exposed to light and developed some sunburn. Sudden exposure of shaded fruit to high light carries a high sunburn risk (Wünsche et al., 2001) as was also evident in the higher incidence of sun blemishes among fruit that were partially shaded from 14 to 56 DAFB. Sunburn only occurred in the northern upper canopy in New Zealand with percentages ranging from 5% to 18% of the total crop (Hirst et al., 1990; Warrington et al., 1996). The very high incidence of sunburn in our results appears to be the result of the unrelenting exposure to high light throughout fruit development usually concurrent with high peel temperatures.

Red blush developed mostly in fruit from the outer canopy and is caused by the synthesis of anthocyanins in response to high irradiance when cold nights are followed by mild, clear days (Curry, 1997; Reay, 1999). Warrington et al. (1996) established that 40% of full sunlight, which is considerably higher than required for red cultivars, is needed for red blush development in GS under New Zealand conditions. In the 2007/2008 season, 60% to 75% of exposed fruit developed red blush. Whereas sunburn developed predominantly on the warmer, exposed northern side of east–west rows, red blush affected fruit on both sides of the row. Red blush evidently contributes significantly to the downgrading of GS fruit.

In north–south rows, chlorophyll concentrations increased and the visually greenest sides of fruit became darker green in color with an increase in within-canopy shading. In the east–west rows, the lightest green fruit were found in the two extreme light environments,

namely the deeply shaded interior canopy and the exposed northern periphery of the tree, whereas partially shaded fruit were darker green in color. Hirst et al. (1990) and Warrington et al. (1996) found the lightest and least green GS fruit in canopy positions exposed to the highest irradiance, whereas Tustin et al. (1988) reported that green color was negatively correlated with percentage light transmission into the canopy. High temperature in combination with high light causes photo-oxidation and photodestruction of chlorophyll in apple peel, although the xanthophyll cycle (carotenoids) and antioxidant systems are upregulated (Chen et al., 2008). White blemishes only occurred on fruit that were subjected to profound shading such as caused by the close proximity of branches, leaves, or neighboring fruit (Hirst et al., 1990; Warrington et al., 1996). The difference in color of inner canopy fruit from north-south and east-west rows is most likely the result of differences in within-canopy light distribution.

At the beginning of the season, the darkest green fruit with the highest chlorophyll concentrations were found in the most exposed canopy positions. This is because chlorophyll synthesis during early fruit development requires light (Gorski and Creasy, 1977). Shading during early fruit development appears to be particularly detrimental to fruit color at harvest. The decline of chlorophyll during fruit development has been well documented (Griessel et al., 1992; Kneen, 1971; Mussini et al., 1985; Reay et al., 1998). During fruit development, chlorophyll concentrations gradually decrease as a result of reduced synthesis and dilution as the fruit expands in surface area with the consequence that fruit gradually become lighter in color. Summer pruning is used to improve fruit bud quality (Mierowska et al., 2002) and red color development in red cultivars (Ferree and Schupp, 2003) by increasing canopy light transmission. However, it may be a potentially risky method to improve green color in GS because it may also increase sunburn (Miller, 1982) and red blush development (Ma and Cheng, 2004). However, if performed during early fruit development (≈ 4 weeks after full bloom at the same time when many producers adjust fruit numbers on the tree by hand thinning), the potential green color development will be maximized. Summer pruning may also, by improving light distribution within the canopy, decrease the difference in lightness between the visually greenest and least green sides of fruit, which was most pronounced (four to five units) in fruit from shaded positions. Early summer pruning could stimulate more regrowth later in the season to provide shade during the latter part of fruit development (Ferree et al., 1984; Miller, 1982) when the risk of sunburn is highest (Li and Cheng, 2008).

Interestingly, the 10% darkest green fruit at harvest experienced comparable *PPF* during early development as fruit that developed sunburn. The difference occurred during the last 2 months of fruit development when dark

green fruit became shaded (as a result of changes in the zenith angle of the sun, bending of branches, or changes in fruit orientation), whereas fruit that developed sunburn remained exposed to high sunlight. Fruit that received very low light ($\approx 3\%$ of ambient) throughout their development were pale in color as a result of lower chlorophyll synthesis. Izso and Larsen (1990) estimated 37% to 70% full sun ($2100 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ *PPF*) as the optimum irradiance level for green color development in GS. These levels would be too high for South African conditions, as indicated by our results. Light appears to be necessary during early fruit development for adequate green color development, whereas continuous high light and associated high peel temperatures or low air temperatures, particularly during the second half of fruit development, result in sunburn and red blush development, respectively. Fruit also become more sensitive to sunburn during fruit development. It may be possible that this increase in sensitivity may relate to the finding of Li and Cheng (2008) that shaded apple peel show a decrease in photoprotective capacity and ability to quench absorbed light through photosynthesis during fruit development.

New apple orchards in South Africa are typically planted in a north-south row direction to maximize light interception. Maximizing light interception may be to the detriment of external fruit quality in GS as a result of the positive correlation between *PPF* and the incidence of sunburn and red blush. Consequently, the standard orchard practices used for red and blushed cultivars, and for green cultivars that are less susceptible to sunburn, may not be ideal for GS. Total light interception of north-south and east-west rows is comparable, but light interception is more evenly spread between the east and west sides of north-south rows (De Jong and Doyle, 1985; Jackson and Palmer, 1972). Sunlight is mainly intercepted on the exposed northern side of east-west rows, which increases sunburn on the northern side while the southern side is shaded from high light conditions (Middleton and McWaters, 2001). We did not find any significant difference in the incidence of red blush and sunburn between the eastern and western sides of north-south rows, whereas sunburn was significantly higher in incidence on the northern side of east-west rows. Because fruit on the southern sides of east-west rows receive less direct sunlight and are therefore much less prone to develop sunburn, it is possible that sunburn may be reduced in east-west compared with north-south orchards where both the east and west sides of rows may have a high incidence of sunburn. However, more red blush develops on the cooler southern sides of east-west rows. In addition, an east-west row direction is generally not recommended for apple because of poor light distribution resulting in lower yields (Middleton and McWaters, 2001). The deficiencies of an east-west row direction become more pronounced with an increase in

tree size and canopy density (Lombard and Westwood, 1977).

Dense and rounded canopies such as found in low-density plantings of open vase trees may increase the proportion of GS fruit without sunburn and red blush. These trees are however less efficient in terms of production (Robinson, 2003). It is also necessary to bear in mind that sufficient light (25% to 50% of full sun, according to our results) is needed in the first half of the season for maximum green color development. Apart from color development, light is also needed to ensure sufficient flower bud development for an optimum return crop (Jackson, 1980). Hence, as suggested by Hirst et al. (1990), an open-textured but leafy environment creating a filtered light environment throughout the season is recommended for GS.

Of various technologies, shade netting is the most effective way to reduce the incidence of sunburn and it may also reduce red blush to less than 1% of total fruit (Gindaba and Wand, 2005). Considering that most of the fruit from the outer canopy is lost to either sunburn or red blush, shade netting should markedly increase the proportion of unblemished fruit in GS. The major drawback to shade netting is the high installation and maintenance costs, but this may be overcome by high yields of Class 1 GS fruit. The increased shading together with increased vigor of shaded trees may increase the proportion pale green fruit. However, rigorous pruning, vigor control, and the use of dwarfing rootstocks to ensure an open canopy for maximum light distribution could negate this problem. In addition, pale green fruit is a minor concern compared with the incidence of sunburn and red blush.

Literature Cited

- Bergh, O., J. Franken, E.J. van Zyl, F. Kloppers, and A. Dempers. 1980. Sunburn on apples—Preliminary results of an investigation conducted during the 1978/79 season. *Decid. Fruit Grow.* 30:8–22.
- Chen, L., P. Li, and L. Cheng. 2008. Effects of high temperature coupled with high light on the balance between photooxidation and photoprotection the sun-exposed peel of apple. *Planta* 228:745–756.
- Curry, E.A. 1997. Temperatures for optimum anthocyanin accumulation in apple tissue. *J. Hort. Sci.* 72:723–729.
- Deciduous Fruit Producers Trust. 2009. Key deciduous fruit statistics 2009. Deciduous Fruit Producers Trust, Paarl, South Africa.
- De Jong, T.M. and J.F. Doyle. 1985. The effect of row orientation on light distribution in hedge-row peach tree canopies. *Acta Hort.* 173:159–166.
- Felicetti, D.A. and L.E. Schrader. 2008. Photooxidative sunburn of apples: Characterization of a third type of apple sunburn. *Int. J. Fruit Sci.* 8:160–172.
- Felicetti, D.A. and L.E. Schrader. 2009. Changes in pigment concentrations associated with sunburn browning of five apple cultivars. I. Chlorophyll and carotenoids. *Plant Sci.* 176:78–83.
- Ferree, D.C., S.C. Myers, C.R. Rom, and B.H. Taylor. 1984. Physiological aspects of summer pruning. *Acta Hort.* 146:243–252.

- Ferree, D.C. and J.R. Schupp. 2003. Pruning and training physiology, p. 319–344. In: Ferree, D.C. and I.J. Warrington (eds.). *Apples: Botany, production and uses*. CABI Publishing, Oxfordshire, UK.
- Gindaba, J. and S.J.E. Wand. 2005. Comparative effects of evaporative cooling, kaolin particle film, and shade net on sunburn and fruit quality in apples. *HortScience* 40:592–596.
- Gorski, P.M. and L.L. Creasy. 1977. Color development in 'Golden Delicious' apples. *J. Amer. Soc. Hort. Sci.* 102:73–75.
- Giessel, H.M., E. Rabe, and D.K. Srydom. 1992. The effect of harvest date on the chlorophyll concentration of 'Granny Smith' apples. *Decid. Fruit Grow.* 42:456–458.
- Hirst, P.M., D.S. Tustin, and I.J. Warrington. 1990. Fruit colour responses of 'Granny Smith' apple to variable light environments. *N. Z. J. Crop Hort. Sci.* 18:205–214.
- Izso, E. and F. Larsen. 1990. Fruit quality development of 'Granny Smith' apples in response to tree canopy light microclimate. *HortScience* 25:1134–1135 (abstract).
- Jackson, J.E. 1980. Light interception and utilization by orchard systems. *Hort. Rev. (Amer. Soc. Hort. Sci.)* 2:208–267.
- Jackson, J.E. and J.W. Palmer. 1972. Interception of light by model hedgegrow orchards in relation to latitude, time of year and hedgerow configuration and orientation. *J. Appl. Ecol.* 9: 341–357.
- Knee, M. 1971. Anthocyanin, carotenoid, and chlorophyll changes in the peels peel of 'Cox's Orange Pippin' apples during the ripening on and off tree. *J. Expt. Bot.* 23:84–96.
- Lancaster, J.E., C.E. Lister, P.F. Reay, and C.M. Triggs. 1997. Influence of pigment composition on skin color in a wide range of fruit and vegetables. *J. Amer. Soc. Hort. Sci.* 122:594–598.
- Li, P. and L. Cheng. 2008. The shaded side of apple fruit becomes more sensitive to photoinhibition with fruit development. *Physiol. Plant.* 134: 282–292.
- Lichtenthaler, H.K. 1987. Chlorophylls and carotenoids: Pigments of photosynthetic biomembranes. *Methods Enzymol.* 148:350–382.
- Lombard, P.B. and M.N. Westwood. 1977. Effect of row orientation on pear fruiting. *Acta Hort.* 69:175–182.
- Ma, F. and L. Cheng. 2004. Exposure of the shaded side of apple fruit to full sun leads to up-regulation of both the xanthophyll cycle and the ascorbate–glutathione cycle. *Plant Sci.* 166: 1479–1486.
- Middleton, S. and A. McWaters. 2001. Increasing the yield and fruit quality of Australian apple orchards. *Horticulture Australia Ltd.*, Sydney, Australia.
- Mierowska, A., N. Keutgen, M. Huysamer, and V. Smith. 2002. Photosynthetic acclimation of apple spur leaves to summer-pruning. *Scientia Hort.* 92:9–27.
- Miller, S.S. 1982. Regrowth, flowering, and fruit quality of 'Delicious' apple trees as influenced by summer pruning. *J. Amer. Soc. Hort. Sci.* 107:975–978.
- Mussini, E., N. Correa, and G. Crespo. 1985. Evolucion de pigmentos en frutos de manzanas 'Granny Smith'. *Phyton.* 45:79–84 (abstract in English).
- Parchomchuk, P. and M. Meheriuk. 1996. Orchard cooling with pulsed overtree irrigation to prevent to solar injury and improve fruit quality of 'Jonagold' apples. *HortScience* 31:802–804.
- Reay, P.F. 1999. The role of low temperatures in the development of the red blush on apple fruit ('Granny Smith'). *Scientia Hort.* 79: 113–119.
- Reay, P.F., R.H. Fletcher, and V.J. Thomas. 1998. Chlorophylls, carotenoids and anthocyanin concentrations in the skin of 'Gala' apples during maturation and the influence of foliar applications of nitrogen and magnesium. *J. Sci. Food Agr.* 76:63–71.
- Robinson, T.L. 2003. Apple-orchard planting systems, p. 345–407. In: Ferree, D.C. and I.J. Warrington (eds.). *Apples: Botany, production and uses*. CABI Publishing, Oxfordshire, UK.
- Schrader, L., J. Zhang, and J. Sunday. 2003. Environmental stresses that can cause sunburn. *Acta Hort.* 618:397–405.
- Schrader, L., J. Sun, J. Zhang, D. Felicetti, and J. Tian. 2008. Heat and light-induced apple skin disorders: Causes and prevention. *Acta Hort.* 772:51–58.
- Smart, R.E. and T.R. Sinclair. 1976. Solar heating of grape berries and other spherical fruits. *Agr. Meteorol.* 17:241–259.
- Tustin, D.S., P.M. Hirst, and I.J. Warrington. 1988. Influence of orientation and position of fruiting laterals on canopy light penetration, yield, and fruit quality of 'Granny Smith' apple. *J. Amer. Soc. Hort. Sci.* 113:693–699.
- Warrington, I.J., C.J. Stanley, D.S. Tustin, P.M. Hirst, and W.M. Cashmore. 1996. Light transmission, yield distribution, and fruit quality in six tree canopy forms of 'Granny Smith' apple. *J. Tree Fruit Prod.* 1:27–54.
- Wünsche, J.N., D.H. Greer, J.W. Palmer, A. Lang, and T. McGhie. 2001. Sunburn—The cost of a high light environment. *Acta Hort.* 557: 349–356.