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The influence of protective netting on tree physiology and fruit quality of apple: A review

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ABSTRACT

The use of protective netting (also called shade nets or anti-hail nets) is being increasingly adopted in apple (*Malus* × *domestica*) production. Protective netting is mainly used to prevent fruit sunburn and protect trees against hail damage. Netting can also be used for protection against damage from birds, fruit bats, insects, wind and sand storms. In recent times, protective nets have been modified into photoselective nets by incorporating chromatic elements into the netting material. These change the spectral characteristics of the solar radiation reaching the tree canopy below the net and can affect physiological pathways that respond to the altered light spectra. Protective netting primarily modifies light quantity and quality underneath by reducing light intensity by an approximately pre-determined percentage. Protective netting has also been reported to reduce wind speed and soil temperature with minimal impact on canopy temperature and relative humidity. Quantifying the influence of protective netting on tree gas exchange has been difficult due to variations in the environmental conditions at the time of measurement. Reductions in light intensity due to protective netting result in increased leaf area, shoot length, and total shoot fresh weight that increases as the net shading percentage increases. Fruit set, return bloom, and flower induction are all affected by protective netting. Ultimately, fruit quality is the critical factor determining whether protective netting is suitable for apple production. The reported results on the effect of protective netting on fruit quality have not been conclusive. It has been suggested that changes in fruit quality under protective netting are often more influenced by the environmental conditions in that specific growing season than the netting itself. For example, typical shade responses under netting can be exacerbated when the natural overall light intensity is reduced on cloudy days. In conclusion, protective netting provides an alternative to traditional approaches to protecting apple from sunburn, mechanical injury from hail and wind, and abiotic stress that limits tree productivity. However, the inconsistent reported results suggest a targeted approach is needed to identify specific physiological responses of apple under protective netting, and more specifically, photoselective netting as a strategy to protect apple orchards from adverse environmental conditions.

1. Introduction

The use of protective netting (also called anti-hail nets or shade nets) in apple (*Malus* × *domestica*) production is increasing as growers seek to protect both the tree and fruit from excessive solar radiation and hail damage (Do Amarante et al., 2011; Shahak et al., 2004a, 2004b). Excessive solar radiation leads to the development of sunburn in fruit, a physiological disorder that causes huge economic losses for growers (Racsko and Schrader, 2012). Hail damage is common in many apple production regions worldwide and protective netting can help protect the tree and fruit against hail (Iglesias and Alegre, 2006; Middleton and McWaters, 2002). Hail damage not only affects fruit production during the current growing season but also affects fruit yield the following season by damaging flower buds developing during the current season. Protective netting is a viable means to reduce tree stress during weather extremes. For this paper, the term protective netting will be used in the general sense. The terms shade netting, anti-hail netting and photoselective shade netting will be used as specified in original literature.

Protective nets are also used for protection against damage from birds, fruit bats, insects, and strong winds (Arthurs et al., 2013; Shahak

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et al., 2004b; Smit, 2007). In recent years, protective nets have been further developed into photoselective nets by incorporating chromatic elements (Shahak, 2008). Photoselective nets are designed to alter the spectral characteristics of solar radiation by the addition of targeted light dispersive, absorptive and reflective elements into the netting material (Shahak et al., 2008a, 2016). Other benefits of using protective netting in apple production include yield increases, increased income from an increased percentage of clean fruit with no sunburn symptoms (Kalcsits et al., 2017), reduction in irrigation costs from reduced soil water loss (McCaskill et al., 2016), reduced hand thinning costs if protective netting is put up during pollination and reduced spraying costs due to increased spray efficacy (Whitaker and Middleton, 1999).

Protective nets are mostly made of high-density polyethylene (HDPE) (Castellano et al., 2008, 2006). The fibers making up the net are often woven in different ways to improve net flexibility and mechanical resistance to breakage (Castellano et al., 2006). The shading factor is equal to the percentage of incoming radiation that is not transmitted through the protective net (e.g., a 20% protective shade net means that light passing through it is only 80% of full sunlight). The composition of the HDPE, the thread density and weaving style will affect the shading percentage.

Most of the research into the use of protective netting has focused on one or two applied aspects of netting and different environments produce different responses to netting. Therefore, a critical review would be useful to integrate the extensive research detailing the effects of protective netting on apple tree physiology and fruit quality and identify gaps in research that would help clarify contrasting responses and questions that have arisen in past experiments. The aim of this review is to provide a critical appraisal of current research on the use of protective netting in apple production. Here, information on protective netting on the orchard environment, tree physiology, and fruit quality is assembled to identify research gaps that can address future research on the use of protective netting for apple production and other production systems.

2. Environmental conditions under protective netting

One of the primary benefits of protective netting is the reduction in solar radiation reaching the orchard environment underneath it. Protective netting has been reported to modify the orchard environment with respect to light intensity and quality, canopy temperature, relative humidity, and soil temperature (Bastías and Corelli-Grappadelli, 2012; Iglesias and Alegre, 2006; Kalcsits et al., 2017). A summary of the effect of protective netting on the apple orchard environment is given in Table 1 and on light quality in the orchard is given in Table 2.

2.1. Light quantity and quality

The perception of light by plants depends on both the intensity and the spectral signature. Plants utilize light cues at specific wavelengths to regulate processes involved in their growth and development. These light responses include germination, hormone regulation, photomorphogenesis, flowering, shade avoidance, phototropism, stomatal movement and photosynthetic efficiency (De Wit et al., 2016; McDonald, 2003). Through the alteration of the total amount of solar radiation reaching the tree canopy and the quality of light, physiological responses to light cues may change. The changes in light quality through the use of protective netting has been studied in other horticultural species (Stamps, 2009; Basile et al., 2012; Zoratti et al., 2015). However, the most extensive research identifying the impact of colored protective netting on perennial horticultural species has taken place in apple production systems.

For apple production, the shading factor is an important consideration in deciding the type of netting that is suitable for specific growing environments. Protective nets reducing incident photosynthetically active radiation (PAR) by 12%, 15%, 17%, and 30% have been tested in apple (Shahak et al., 2004a), along with some nets being able to reduce up to 90% of the solar radiation (Zibordi et al., 2009). Although protective netting can be designed for specific PAR reduction percentages, 15–30% shading is most commonly used for tree fruit (Shahak, 2014). The age of the net also influences the shading factor. With time, dust particles collect on the shade net affecting light transmission through the net. Blanke (2009) reported a 2% reduction in PAR transmission through the net per year. With time, black and crystal white translucent shade nets become increasingly grey whilst red shade nets become orange because of pigment degradation (Blanke, 2009). Improvements in the quality of thread and pigments used in the manufacturing of protective netting has resulted in potential life-span of 11 years, with the next generation of protective netting having potential life span of up to 15 years (Blanke, 2009). Reduction in PAR under protective netting depends on the type of net, the mesh size, and color of the net (Middleton and McWaters, 2002). The architecture of the net installation may also have an effect on light quality and quantity. Light scattering under a partial angled/louvered netting installation will likely different from a flat structure of the top of the canopy. Other important design characteristics include whether the net is woven or knotted, the number of threads in the net, the thickness of the thread and the material used for the thread (Castellano et al., 2006).

Protective nets change the quality of light passing through them by altering light diffusion, reflectance, transmittance and absorbance (Basile et al., 2008; Ganelevin, 2008). Light scattering contributes to increased diffuse radiation providing a better distribution of light that improves light penetration both vertically and horizontally into the tree canopy (Shahak et al., 2004b). The physical composition of netting can influence spectral transmissivity (Castellano et al., 2006). Protective netting and more specifically, photoselective shade netting can change the light microclimatic conditions in the orchard (Stamps, 2009). Shade nets modify light quality in the ultraviolet (UV) (100–400 nm), photosynthetically active radiation (PAR) (400–700 nm) and near infrared (NIR) (760–1500 nm) wavelength ranges (Castellano et al., 2006). Additionally, the transmission of diffuse radiation is increased under protective netting by 17–170% depending on the physical makeup of the net (Abdel-Ghany and Al-Helal et al., 2010). These changes to light quality can induce physiological responses in the tree (Folta and Carvalho, 2015). Spectral modification by photo selective nets is a more recent technological advancement for protective shade nets that is now being extensively studied.

2.2. Canopy air and soil temperature

Protective netting is a partial physical barrier that reduces both wind speed and the amount of solar radiation passing through it. As a result, the temperature dynamics of canopy air and the soil underneath are inevitably altered. Other factors affecting the measured temperature under protective shade netting include the location of sensor (i.e. above canopy or inside the canopy) and the shading factor (Iglesias and Alegre, 2006). The interactions between these factors may have contributed to the contradicting reported results in how netting affects air temperature. Air temperature under shade nets can either be reduced from reduced radiant heating, i.e. a ‘shade effect’ under nets, or can be increased due to reduced air circulation under shade nets, i.e. a ‘greenhouse effect’ (Iglesias and Alegre, 2006). Air temperature readings from a sensor that is exposed directly to solar radiation have been reported to be 4–6 °C higher than temperature readings from inside a “Stevenson Screen” (Middleton and McWaters, 2002). The use of temperature probes without radiation shields could also explain some of the contrasting results reported in the literature. Elevated air temperatures were reported under 50% red, blue, and pearl shade nets compared to an uncovered control and 50% black shade net (Arthurs et al., 2013). In contrast, a 1–3 °C reduction in air temperature under shade nets has also been reported (Iglesias and Alegre, 2006; Middleton and

Table 1
Influence of protective netting on the orchard environment.

Variable	Net Color (% Shading)	Response	References
Air temperature (°C) (0.8m above ground)	Red-Black (18%), Red-White (14%), Green-Black (20%), White (12%)	↓	(Solomakhin and Blanke, 2010a)
Air temperature (°C) (1 m above ground)	Red (50%), Blue (50%), Pearl (50%)	↑*	(Arthurs et al., 2013)
	Black (50%)	↓*	(Arthurs et al., 2013)
Above canopy air temperature (°C)	Pearl (19%), Blue (22%), Red (22%)	–	(Kalcsits et al., 2017)
Daytime temperatures		↓*	(Middleton and McWaters, 2002, 2000)
Daily maximum in-canopy air temp (range: 25–30 °C, 30–35 °C, 35–40 °C)	Pearl (19%)	↓	(Kalcsits et al., 2017)
Daily maximum in-canopy air temp (range: 25–30 °C, 30–35 °C, 35–40 °C)	Blue (22%), Red (25%)	–	(Kalcsits et al., 2017)
Daily maximum in-canopy air temp (range: 20–25 °C)	Pearl (19%), Blue (22%), Red (25%)	–	(Kalcsits et al., 2017)
Relative humidity (%)	Red (50%), Blue (50%), Black (50%), Pearl (50%)	–	(Arthurs et al., 2013)
	Pearl (19%), Blue (22%), Red (25%)	–	(Kalcsits et al., 2017)
Daily mean in-canopy relative humidity (range: 20–25 °C, 25–30 °C, 30–35 °C)	Pearl (19%), Blue (22%), Red (25%)	↑	(Kalcsits et al., 2017)
Daily mean in-canopy relative humidity (range: 35–40 °C)	Pearl (19%), Blue (22%), Red (25%)	–	(Kalcsits et al., 2017)
Soil temperature (5 cm depth)	Red-black (18%), Green black (24%)	↓*	(Solomakhin and Blanke, 2010a)
Soil temperature (5 cm depth)	Red-white (14%), White (12%)	↑*	(Solomakhin and Blanke, 2010a)
Soil temperature (20 cm depth)	Pearl (19%), Blue (22%), Red (25%)	↓	(Kalcsits et al., 2017)
Soil moisture (20 and 40 cm depth)	Pearl (19%), Blue (22%), Red (25%)	↑	(Kalcsits et al., 2017)
Wind speed ($m\,s^{-1}$)	Pearl (19%), Blue (22%), Red (25%), Red (50%), Blue (50%), Black (50%), Pearl (50%)	↓	(Arthurs et al., 2013; Kalcsits et al., 2017)
Fruit temperature (°C) (not specified)	Red-Black (18%), Red-White (14%), Green-Black (20%), White (12%)	↓	(Solomakhin and Blanke, 2010a)
Leaf temperature (°C) (not specified)	Red-Black (18%), Red-White (14%), Green-Black (20%), White (12%)	↓	(Solomakhin and Blanke, 2010a)
Mean leaf temp (°C)	Blue (22%), Red (25%)	–	(Kalcsits et al., 2017)
	Pearl (19%)	↓	(Kalcsits et al., 2017)
Max leaf temp (°C)	Blue (22%)	–	(Kalcsits et al., 2017)
	Pearl (19%), Red (25%)	↓	

Net Color, or Shading % was left blank in Table 1, if it was not specifically mentioned in the corresponding cited study. Shading percentage number is the given manufacturer's percentage unless PAR measurements were taken to assess the actual shading effect. If actual shading percentage was stated in study, that number was used here.

* Demonstrated an increase or decrease response, but p-values or significance was not indicated in study.

Table 2
[a] Influence of protective netting on light quality.

Net Color	Enhanced Color Spectra	Reduced Color Spectra	Light Diffusion	R/FR[b]	B/R[b]
Red	R + FR	UV + B + G	+ +	↑	↓
Blue	B	UV + R + FR	+ +	↓	↑
Yellow	G + Y + R + FR	UV + B	+ +	–	↓
White	B + G + Y + R + FR	UV	+ +	–	–
Pearl		UV	+ + +	–	–
Grey	–	All	+	–	–
Black	–	All	–	–	–

[a] Table adapted from Rajapakse and Shahak (2007).

[b] Light ratio data sourced from Bastías et al. (2012a) and Shahak et al. (2004b). Ratios are based on direct, not scattered light.

McWaters, 2002; Solomakhin and Blanke, 2010a). Lower air temperature under 50% black shade net when compared to 50% red, blue and pearl shade nets was attributed to different net porosities required to achieve the same shading factor (Iglesias and Alegre, 2006). Kalcsits et al. (2017) found no significant differences in ambient temperature under 22% blue, 19% pearl and 25% red photoselective shade netting compared to an uncovered control. The variable responses reported in the literature suggest there is a need to determine whether shading factor, net porosity, and growing environment may impact the temperature effect of protective netting in the orchard. Further, it would be helpful in future research projects to utilize temperature probes with radiation shields.

2.3. Wind speed

Protective netting reduces wind speed at the tree canopy level. Wind speed was reduced by approximately 47% in an apple orchard in Washington State under 20% pearl, red and blue photoselective shade nets (Kalcsits et al., 2017). This corresponds well with Middleton and McWaters (2000) who reported up to 50% lower wind speeds compared to outside netting in Australian apple orchards. These two examples used 20% protective netting. However, when the shading factor (and netting density) increased, the reported reductions in wind speed also increased. For example, wind speed under 50% red, blue, black and pearl shade nets with the top and sides covered was reduced on average by approximately 89% when compared to an uncovered control (Arthurs et al., 2013). The composition, thread density, and the thread pattern of the protective net can all impact the reduction in wind observed and this must be considered when making comparisons between experimental results reported.

2.4. Relative humidity

Orchard relative humidity is directly related to the relative humidity outside the orchard, wind speed, irrigation and plant density. Depending on the growing environment, the reported effect of netting on the relative humidity in the orchard has been variable. In a more arid environment in Australia, shade nets increased relative humidity by up to 10–15% (Rigden, 2008; Middleton and McWaters, 2002) whilst in a more humid environment in Germany, relative humidity was only reduced by netting from 1 to 3% (Hunsche et al., 2010) and 2–5% (Solomakhin and Blanke, 2010a). Kalcsits et al. (2017) found no changes in orchard relative humidity under photoselective shade nets under arid conditions in Washington State, USA.

Table 3
Influence of protective netting on apple tree physiology.

Variable	Cultivar	Net Color (% Shading)	Response	References
Photosynthesis (mmol CO_2 m^{-2} s^{-1})	'Mondial Gala'	Black (25%)	↑	(Iglesias and Alegre, 2006)
	'Golden Delicious'	Red (55%), Yellow (49%), Blue (52%), Pearl (54%), Grey (46%), Black (48%), Black (33%)	↑*	(Shahak et al., 2004b) (Ebert and Casierra, 2000)
	'Fuji'	Blue (40%)	↑	(Bastías et. al., 2012a)
	'Fuji'	Green-Black (23%)	↓*	(Solomakhin and Blanke, 2008)
	'Royal Gala' 'Cripps Pink'	Black (20%)	↓	(Gindaba and Wand, 2005)
	'Golden Delicious'	Black 33%	↓*	(Ebert and Casierra, 2000)
	'Starkrimson'	Black (55%)	↓	(Romo-Chacon et al., 2007)
	'Golden Delicious'	Black 33%	–*	(Ebert and Casierra, 2000)
	'Starkrimson'	White 40%	–	(Romo-Chacon et al., 2007)
Leaf Chlorophyll Content (SPAD units)	'Gala', 'Fuji'	White (18%)	↑	(Do Amarante et al., 2011)
	'Fuji'	Red-Black (18%), Green-Black (23%)	↑	(Solomakhin and Blanke, 2008)
	'Pinova'	White (12%), Red-White (14%), Red-Black (18%), Green-Black (23%)	↑	(Solomakhin and Blanke, 2008)
	'Fuji'	White (12%), Red-White (14%)	–	(Solomakhin and Blanke, 2008)
Stomatal Conductance (mol m^{-2} s^{-1})	'Fuji' 'Royal Gala', 'Braeburn', 'Cripps' Pink'	Blue (40%), Red (40%), Grey (40%), White (20%) Black (20%)	–	(Bastías et. al., 2012a) (Smit, 2007)
	'Greensleeves' 'Royal Gala', 'Braeburn', 'Cripps' Pink'	Black (50%)	↑	(De Freitas et al., 2013)
		Black (20%)		(Smit, 2007)
Leaf Transpiration/Evapotranspiration (mmol H_2O m^{-2} s^{-1})	'Fuji'	Blue (40%)	↑	(Bastías et. al., 2012a)
	'Fuji'	Green-Black (23%)	↓*	(Solomakhin and Blanke, 2008)
	'Mondial Gala'	Black (25%)	↓*	(Iglesias and Alegre, 2006)
	'Royal Gala', 'Hi Early Red Delicious', 'Red Fuji', 'Granny Smith', 'Pink Lady'	No Colors Given (12-27%)	↓	(Middleton and McWaters, 2002)
Water-use efficiency (mmol mol^{-1})	'Cripps' Pink'	Black (20%)	↑	(Gindaba and Wand, 2007a)
Stem Water Potential (Atm)	'Smoothee Golden Delicious'	Blue (30%), Red (30%), Grey (30%), Pearl (30%), Red-White (18%), White (12%)	↓	(Shahak et al., 2004a)
Shoot Length (cm)	'Fuji'	Red (40%)	↑	(Bastías et al., 2012a)
	'Mondial Gala'	Black (25%)	↑	(Iglesias and Alegre, 2006)
	'Pinova'	Green-Black (23%) Red-Black (18%), Red-White (14%), White (12%)	↑	(Solomakhin and Blanke, 2008)
	'Fuji'	Green-Black (23%) Red-Black (18%), Red-White (14%), White (12%)	–	(Solomakhin and Blanke, 2008)
Vigor – expressed as: Leaf Area (m^2) or No. of Shoots	'Pinova'	Green-Black (23%) Red-Black (18%), Red-White (14%), White (12%)	↑	(Solomakhin and Blanke, 2008)
	'Fuji'	Green-Black (23%)	↑	(Solomakhin and Blanke, 2008)
	'Fuji'	Blue (40%)	↑	(Bastías et. al., 2012a)
	'Fuji'	Red-Black (18%), Red-White (14%), White (12%)	–	(Solomakhin and Blanke, 2008)
	'Mondial Gala'	Black (25%), Crystal (12%)	–	(Iglesias and Alegre, 2006)
Vigor – expressed as: Leaf Area (m^2) or No. of Shoots	'Royal Gala', 'Hi Early Red Delicious', 'Red Fuji', 'Granny Smith', 'Pink Lady'	No Colors Given (12%–27%)	–	(Middleton and McWaters, 2002)
Trunk Cross Sectional Area (TCSA) (cm^2)	'Mondial Gala'	Black (25%)	↑	(Iglesias and Alegre, 2006)
	'Golden Delicious'	Yellow (30%)	↑	(Shahak et al., 2016)
	'Golden Delicious'	Red (30%)	–	(Shahak et al., 2016)
	'Fuji', 'Pinova'	Green-Black (23%) Red-Black (18%), Red-White (14%), White (12%)	–	(Solomakhin and Blanke, 2008)
Specific Leaf Area (cm^2/g)	'Gala', 'Fuji'	White (18%)	↑	(Do Amarante et al., 2011)
Fruit Set (% Flowers Set)	'Smoothee Golden Delicious'	Red-White (18%)	↑	(Shahak et al., 2004a)
	'Smoothee Golden Delicious'	Blue (30%), Red (30%), Grey (30%), Pearl (30%), White (12%)	–	(Shahak et al., 2004a)
	'Topred Red Delicious'	Blue (30%), Red (30%), Grey (30%), Pearl (30%), Red-White (18%), White (12%)	–	(Shahak et al., 2004a)
	'Royal Gala', 'Hi Early Red Delicious', 'Red Fuji', 'Granny Smith', 'Pink Lady'	No Colors Given (12%-27%)	↓	(Middleton and McWaters, 2002)
	'Fuji'	White (18%)	–	(Do Amarante et al., 2011)
	'Gala'	White (18%)	↓	(Do Amarante et al., 2011)

(continued on next page)

Table 3 (*continued*)

Variable	Cultivar	Net Color (% Shading)	Response	References
Return bloom (1 – 9 scale)	'Fuji',	Green-Black (23%), Red-Black (18%), Red-White (14%), White (12%)	↓*	(Solomakhin and Blanke, 2008)
	"Pinova'	Green-Black (23%), Red-Black (18%),	↓*	(Solomakhin and Blanke, 2008)
		Red-White (14%), White (12%)	–*	(Solomakhin and Blanke, 2008)

Cultivar, Net Color, or Shading % was left blank in Table 3, if it was not specifically mentioned in the corresponding cited study. Shading percentage number is the given manufacturer's percentage unless PAR measurements were taken to assess the actual shading effect. If actual shading percentage was stated in study, that number was used here.

* Demonstrated an increase or decrease response, but p-values or significance was not indicated in study.

3. Tree physiology

3.1. Tree gas exchange

There are several factors that can affect leaf photosynthetic rates including plant water status, light levels, and carbohydrate accumulation (Araya et al., 2006; Szymańska et al., 2017). Protective netting has the potential to impact all of these factors (Table 3). Previously, some experiments have been conducted under ambient light conditions while others have occurred under controlled light conditions. Ambient light conditions will capture environmental effects on gas exchange while controlled light conditions will capture inherent physiological differences in leaf function as a response to the different light environments. Generally, when light saturating conditions are not met, netting reduces net photosynthesis. However, when light saturating conditions (or higher) exist, protective netting may have a slightly positive effect on net photosynthesis. The positive effect on photosynthesis under such conditions can be attributed to reduced photoinhibition, which usually occurs during midday at high temperatures (Lebese et al., 2011).

3.1.1. Light intensity

Light saturation for maximal leaf photosynthesis in 'Braeburn', 'Stayman', 'Red Prince Delicious' and 'Tengmu' apples is around 700–800 μmol m^{-2} s^{-1} PAR (Campbell et al., 1992; Husen and Dequan, 2002; Tartachnyk and Blanke, 2004). While light saturation for other cultivars may vary slightly, it can be expected that most cultivars would fall within this range. In many apple growing regions, daily maximum light intensity often exceeds leaf saturating conditions (Bastías et al., 2012a; Gindaba and Wand, 2005; Zibordi et al., 2009). Solomakhin and Blanke (2008) reported that leaf photosynthesis is reduced under protective netting when the amount of light falls below light saturation of 800 μmol m^{-2} s^{-1} PAR. Under saturating light conditions, no differences in photosynthetic rates were observed in 'Fuji' under green-black shade net (2000 μmol m^{-2} s^{-1} PAR) and an uncovered control (2200 μmol m^{-2} s^{-1} PAR) (Solomakhin and Blanke, 2008). Under cloudy conditions, leaf photosynthesis in 'Fuji' was reduced by 21% under green-black shade net (340 μmol m^{-2} s^{-1} PAR) compared to an uncovered control (385 μmol m^{-2} s^{-1} PAR). When light conditions were saturating, Romo-Chacon et al. (2007) reported no significant differences in net photosynthesis of 'Starkrimson' apple for trees under white shade nets (1260 μmol m^{-2} s^{-1} PAR) versus an uncovered control (2000 μmol m^{-2} s^{-1} PAR), but photosynthesis was reduced for trees under black shade nets (900 μmol m^{-2} s^{-1} PAR). Most gas-exchange measurements are typically taken late-morning prior to the effect of photoinhibition. Ebert and Cassiera (2000) observed that net photosynthesis in 'Golden Delicious' under 33% protective shade netting was lower in the morning (08:00) compared to an uncovered control. However, later in the day, net photosynthesis was greater under protective shade netting compared to the uncovered control.

The interaction between high light intensity and ambient temperature on photosynthesis under protective netting is not well understood. Heat stress can cause morphological, physiological and biochemical changes that reduce leaf photosynthetic efficiency (Ashraf and Harris, 2013). In general, when light saturating conditions occur under protective netting, it is expected that the improvement in gas exchange is due to reduced photoinhibition compared to what occurs under the higher light conditions outside the net (Murata et al., 2006; Powles and Critchley, 1980). Mean net photosynthetic rate averaged over three days at high temperature (34–39 °C) and ambient radiation (1700–2100 μmol m^{-2} s^{-1} PAR) in 'Cripps Pink' apple was not different for trees in full sun versus those under 20% black shade net (Gindaba and Wand, 2007a). For 'Royal Gala' net photosynthetic rate measured at air temperatures of 32–36 °C under ambient radiation (1600–2100 μmol m^{-2} s^{-1} PAR) was significantly lower under 20% black protective shade netting compared to an uncovered control for one sampling date but no significant differences were observed on another day (Gindaba and Wand, 2007b).

Stomatal conductance plays an important role in plant gas exchange and plant water relations. The blue and red portion of the light spectrum influence stomatal opening (Sharkey and Raschke, 1981), any changes in these spectra under protective netting has the potential to impact stomatal conductance. Further, stomatal conductance is driven by vapor pressure deficit which is a function of relative humidity and air temperature. Under 50% black shade net, leaf stomatal conductance was significantly increased in 'Greensleeves' apple compared to an uncovered control (air temperature 35.2–36.4 °C) (De Freitas et al., 2013). Similarly, leaf stomatal conductance in 'Royal Gala', 'Braeburn', 'Fuji' and 'Cripps' Pink' was greater under 20% black protective netting compared to an uncovered control at ≈132 days after full bloom(air temperature 30.7–40.7 °C) (Smit, 2007). In contrast, leaf stomatal conductance was significantly reduced under 20% black shade net in "Royal Gala" at two different sampling dates (air temperature 32–36 °C). (Gindaba and Wand, 2007b). Generally, increased stomatal conductance under protective netting on hot days is expected due to the reduced vapor pressure deficit under protective as observed by (Smit, 2007). The divergent results on hot days might explained by other factors e.g. leaf age and protective netting color. Leaf stomatal conductance later in the season as leaves matured at ≈187 days after full bloom and lower ambient temperature (26.6 – 29.2 °C) in 'Royal Gala', 'Braeburn', 'Fuji' and 'Cripps' Pink' was not different under 20% black protective netting compared to an uncovered control (Smit, 2007).

3.1.2. Protective netting color

Black and white colored protective shade nets are the most commonly used types at present. However, the reported physiological responses to each color have been inconsistent. Under sunny conditions, photosynthesis in 'Jonagold' measured under ambient light conditions was significantly lower under white net (1100 $\mu mol\, m^{-2} s^{-1}$ PAR) compared to black net (1000 $\mu mol\, m^{-2} s^{-1}$ PAR) and an uncovered control (1300 $\mu mol\, m^{-2} s^{-1}$ PAR) (Stampar et al., 2001). On the other hand, 'Elstar' had higher net photosynthesis under black shade net compared to control and white shade net under the same conditions (Stampar et al., 2001). This could be a factor of genotypic differences in response to the color of netting.

In a study comparing different protective netting colors, net photosynthesis in 'Fuji' was significantly higher under 46.3% blue and 56.3% grey shade netting compared to 12.5% pearl hail net (Bastías et al., 2011). No significant difference in net photosynthesis was observed between 20.2% red hail net and 41.9% red shade net in the same study. In terms of the diurnal course of leaf gas exchange under different protective net colors, Shahak et al. (2004b) reported that net photosynthesis in 'Golden Delicious' under 30% red and black shade nets had the common morning and afternoon peaks, while in the 30% grey, pearl and blue shade nets had no apparent mid-day depression. In sweet pepper, yellow nets have been shown to reduce photosynthetic rates and lower stomatal conductance (Kong et al., 2012). These results have been explained due to the enriched green light that is transmitted with yellow nets compared to a red net that excludes wavelengths in this region. Green light acts in opposition to red and blue light, and has been linked to reduced leaf size, decreased chloroplast accumulation, a reduction in flowering, inducing shade avoidance growth and inhibiting stomatal conductance. (Folta and Carvalho, 2015).

Bastías et al. (2012a) conducted a study in 'Fuji' comparing 40% blue, red, grey shade nets against a 20% white shade net as a control. This study could not use an uncovered control due to the high risk of hail damage. Net photosynthesis was significantly higher under 40% blue shade net compared to control of 20% neutral white shade net control and 40% red net. No significant differences were obtained between the 40% blue and 40% grey net. Tree net carbon exchange rate calculated from mean leaf photosynthesis and total leaf area per tree was significantly higher in 40% blue shade net compared to 40% grey, 40% red net and 20% white neutral shade net as control (Bastías et al., 2012a). There were no significant differences in stomatal conductance across different net colors, although there was a 25% increase in transpiration under 40% blue net compared to the 20% white net control (Bastías et al., 2012a).

3.1.3. Water use efficiency

Because of the reduced incident solar radiation from protective nets, orchard water use is reduced. McCaskill et al. (2016) estimated potential evapotranspiration to be reduced by 30% under protective netting. With less solar radiation reaching the orchard floor and the tree canopy combined with a reduction in wind speed, water loss from the soil and from evapotranspiration are reduced. Therefore, better water use efficiency (WUE) is exhibited in fruit trees under netting. In apple, Shahak et al. (2004a) concluded that positive increases on fruit size could be due to reduced water stress because the stem water potential (SWP) of trees under protective netting was found to be lower. Gindaba and Wand (2007a) noted increased WUE in 'Cripps' Pink' apples under 20% black shade netting due to reduced transpiration during midday heat peaks. Nicolás et al. (2008) demonstrated similar effects in a lemon grove under 40% protective netting (color not specified), where shaded trees had lower transpiration and higher WUE when compared with unshaded trees. Ultimately, these water-use benefits result from the altered microclimate under the protective net.

3.2. Vegetative growth and leaf morphology

Changes in total solar radiation reaching the tree canopy and changes in leaf gas-exchange under protective netting affects vegetative growth and leaf morphology although these changes are not always consistent. Solomakhin and Blanke (2008) reported increases in mean number of year old shoots per tree, mean length of one year old shoots, and total length of year old shoots in 'Pinova' under 12% white, 14% red-white, 18% red-black and 23% green-black protective netting compared to an uncovered control. In the same study, in 'Fuji', only 23% green black protective netting increased mean number of year old shoots and total length of one year old shoots compared to an uncovered. The length of one year old shoots was not significantly different under 12% white, 14% red-white, 18% red-black and 23% green-black protective netting in 'Fuji' (Solomakhin and Blanke, 2008). In peach, vegetative vigor measured as green pruning was consistently improved under 30% blue, 30% red and 30% yellow, 30% grey, 30% pearl and 12% white nets compared to an uncovered control (Shahak et al., 2004a).

There are several contributing factors that can impact the vegetative growth response for trees under netting. Shade avoidance responses may produce increased vegetative growth, vigor, apical dominance and occurrence of first year shoots under netting (McDonald, 2003; De Wit et al., 2016). Increased vegetative growth typically corresponds to increased shading percentages and darker colors of nets. This is noticeable in the aforementioned 'Fuji' apple trees under the 23% green-black shade net where the largest reduction of PAR was recorded in conjunction with the highest vegetative growth response (total length of one-year old shoots) in the experiment (Solomakhin and Blanke, 2008). Reduced PAR and shading signals a suboptimal light environment for photosynthetically active plants, so the plant will synthesize hormones and allocate resources into extending shoots to "escape" from the shade and into more favorable growing conditions (De Wit et al., 2016).

The capacity of an apple tree to produce fruit can be determined indirectly using trunk cross sectional area (TCSA) (Wright et al., 2006). Changes in TCSA under protective netting could potentially have an influence on tree productivity. The annual increment in TCSA was not affected by 12% white, 14% red-white, 18% red-black, and 23% green black protective netting in 'Pinova', in contrast all the protective netting colors reduced TCSA in 'Fuji in the same study (Solomakhin and Blanke, 2008). Other factors may play a part in trunk growth, influencing the observed changes under protective netting. The strong reduction in trunk growth of 'Fuji' under 20% green-black hailnet could be attributed to alternate bearing as shown by measurements of return bloom (Solomakhin and Blanke, 2010a). Over a three-year period under yellow shade net, TCSA of 'Golden Delicious' apple trees was greater when compared to trees grown in full sun (Shahak et al., 2016). Iglesias and Alegre (2006) reported significantly larger TCSA growth in 'Mondial Gala' trees under 25% black nets when compared to trees under 12% crystal nets (two of five years) or no net at all (three of five years) with no significant differences in the other years. Because of the reduced light and water stress under 25% black nets, they observed an increase in photosynthesis resulting in improved tree vigor (Iglesias and Alegre, 2006).

Shade percentage appears to contribute greatly to the vegetative growth response from netting. However, color has also been reported to affect vigor. Three year-old 'Fuji' apple trees under 40% blue shade net had a significantly larger leaf area (m^2/tree) when compared to a 20% white net control, and a significantly higher total shoot fresh weight (kg/tree) when compared to a 40% grey shade net (Bastías et al., 2012a). There was no significant difference in shoot length across the four netting treatments (40% blue, 40% red, 40% grey and 20% white) (Bastías et al., 2012a). Total above-ground dry matter was 30% higher under blue shade net on average when compared to the red, grey and white shade nets, and was attributed to increased photosynthetic capability of trees under the blue net (Bastías et al., 2012a). In contrast, blue netting has demonstrated reduced vegetative effects including dwarfing, reduced vigor, shorter branches and smaller leaves in ornamentals (Oren-Shamir et al., 2001). The contradictory results from these studies indicate that different plant species may not respond the same to protective netting.

Although the reduction in light quantity by protective shade nets yields a predictable plant response, when different colors are used that alter the quality of light that the plant receives (e.g., blue, red, green, yellow), additional physiological responses may occur. Phytochrome photoreversibility between red (R) and far-red (FR) light signals morphological responses linked to vegetative growth. As the phytochrome (PhyB) perceives FR light, it shifts to the active P_{fr} state, which boosts auxin biosynthesis, leading to increased growth (De Wit et al., 2016). Therefore, with blue nets exhibiting a significantly smaller R/FR ratio (0.87) when compared to other colors like red (0.93), white (0.96), and grey (0.94), this could explain the increased vegetative growth observed in apple and peach under blue nets (Bastías et al., 2012a; Baraldi et al., 1994).

In various plant species, green light exposure has resulted in thin and elongated leaves (Folta and Carvalho, 2015), red light has increased the number of leaves (Naznin et al., 2016), and UV light exposure has led plants to generate wax, trichomes and anthoycyanins in leaves through defense mechanisms (Ben-Yakir and Fereres, 2016). Darker nets containing black thread may also lead to increased chlorophyll synthesis in apple leaves as a compensatory response to the minimal amounts of solar radiation reaching the canopy (Solomakhin and Blanke, 2008). Photoselective nets that alter light quality can impact leaf morphology and vegetative growth leading to practical implications in orchard management such as the need for summer pruning.

The management of vegetative growth in tree fruit production is important to provide optimum light interception for high fruit quality. There are potential applications for using netting to manipulate vegetative growth and serve as a useful management technique in the orchard. In other fruit crops like grapes and kiwifruit, protective netting has been shown to impact vegetative growth and vigor. Grape growers are utilizing 20% yellow photoselective shade net to revitalize old vineyards due to its vigor stimulation effects (Shahak et al., 2016). Basile et al., (2008) evaluated the effects of four different shade nets (blue 20%, grey 22%, red 27%, and white 20%). Kiwifruit vines under the blue net showed significantly reduced vegetative vigor. Photoselective shade netting could then be used to mitigate costly and labor-intensive tasks like pruning. However, under red and grey nets, vegetative growth was stimulated in the vines (Basile et al., 2008). For low-vigor cultivars or rootstocks, netting can be used to increase vigor during orchard establishment and fill the canopy space earlier after planting. The timing of netting deployment could also be a way to manipulate vegetative growth during the growing season. Earlier deployment could increase vigor through environmental stress mitigation, while delayed netting deployment may reduce shoot vigor and limit excess growth. However, more research is needed to determine the optimum deployment time for vigor management in different cultivars.

3.3. Fruit set, flower induction and return bloom

Photoperiod, spectral quality and light intensity can have a significant impact on flowering patterns in plants (McDonald, 2003). As light diffusion increases under protective netting, there is the potential for improved light penetration into the canopy resulting in better flower distribution in the tree. Willaume et al. (2004) demonstrated that increased light interception across a canopy corresponds to increased sugars, hormone production, flower bud development and therefore more consistent regular flowering patterns. Fukuda (2013) and Folta and Maruhnich (2007) demonstrated how different wavelengths of light can alter production of hormones involved in flowering, such as Gibberellic Acid (GA). Phytochrome photoreversibility has been demonstrated to play a crucial role in flowering and other phenological response as well, with red light inducing flowering and far-red light inhibiting it (McDonald, 2003). Therefore, with photoselective nets containing the ability to alter both the intensity and quality of light that the canopy is exposed to, it is important to quantify and understand the specific spectral characteristics of the netting and the associated responses of the tree.

The number of blossom clusters per cm^2 of limb cross-sectional area in 'Gala' and 'Fuji' was significantly reduced under 18.4% white protective netting compared to an uncovered control (Do Amarante et al., 2011). On the other hand, in peach, number of flower clusters per branch under 30% blue, red, and pearl, 18% red-white and 12% white protective was significantly increased compared to an uncovered control (Shahak et al., 2004a). The variability in flowering response under protective netting may be species and protective net color dependent. The effect of protective netting on fruit set in apple has also been variable. Fruit set in 'Fuji' before and after thinning as well as the number of fruit per blossom cluster was not affected under protective netting compared to an uncovered control (Do Amarante et al., 2011). Shahak et al. (2004a) reported no changes in fruit set under 30% blue, red, grey and pearl, 18% red-white and 12% white compared to an uncovered control in 'Topred'. In the same study, similar results were reported in 'Smothee' for all net colors with the exception of 18% red white which had significantly higher fruit set compared to the uncovered control. On the other hand, fruit set in 'Hi Early' was consistently reduced over four growing seasons under black hail net compared to an uncovered control (Middleton and MacWaters, 2000). Protective netting also reduced the number of clusters with multiple fruits in this study. Flower bud development under protective netting could also be hindered in the following season as a result of competition for resources between vegetative and reproductive sinks. Solomakhin and Blanke (2008) reported that return bloom was reduced by up to 13% in 'Pinova' and 30% in 'Fuji' under colored hailnets. This can be explained by a reduction in light transmission into the canopy for flower bud induction to occur (Corelli-Grappadelli et al., 2003).

If timed correctly, the deployment of 90% shade nets at about 30 days after bloom (DAB), when carbon resources are low, can be used as an alternate and nonchemical means of apple fruit thinning (Zibordi et al., 2009). Mcartney et al., (2004) demonstrated a 70% fruit abscission in 'Royal Gala' with the application of an 80% shade net at 20–25 DAB. As noted previously for photosynthesis, the flowering response to netting may be environmentally dependent where flower induction and fruit retention can increase where light intensities are sufficient on the tree or decrease where netting reduces light intensity below the necessary conditions to stimulate flower initiation and fruit set and growth.

4. Apple fruit quality

Fruit quality is represented by several parameters that together determine the long-term storability, consumer satisfaction and repeat purchases, and, ultimately, the economic return to the grower. Consumers purchase visually appealing fruit that has a good coloration and is free from blemishes. Light is important in the formation of anthocyanins that give the bicolor apples their characteristic red color (Espley et al., 2007; Merzlyak and Chivkunova, 2000; Saure, 1990). However, excess light can result in a physiological disorder such as sunburn that makes the fruit less visually appealing (Racsko and Schrader, 2012). In the dark green apple cultivar 'Granny Smith', excess light negatively impacts external fruit quality by producing pale green fruit with undesirable red blush (Fouché et al., 2010). The sum of the effects of netting on fruit quality must produce fruit that have lower disorders, good storability, maintains fruit color, and falls within high value size categories to justify the additional cost of netting infrastructure and maintenance. Often, the overall impact of protective netting on fruit color development compared to an uncovered control is much greater than the impact of one netting color versus another.

4.1. External disorders

Protective netting is an important tool for apple growers to improve external fruit quality and reduce the occurrence of sunburn. In Washington State, apple fruit losses due to sunburn were estimated at 10%, costing the industry about $100 million each year (Schrader et al., 2008, 2003).In addition to protective netting, strategies to control sunburn include overhead cooling and application of sunburn protectant compounds. In Washington State, the percentage of clean fruit with no sunburn in 'Honeycrisp' apple was 56% in an uncovered control compared to 72, 83 and 81% clean fruit under pearl, blue and red photoselective shade nets, respectively (Kalcsits et al., 2017). Do Amarante et al. (2011) reported that shade net significantly reduced sunburn incidence by 12.1% in 'Gala' (18.9% sunburn incidence in an uncovered control). In 'Fuji', sunburn incidence was reduced by 5.2% (28.5% sunburn incidence in control) (Do Amarante et al., 2011). Black and crystal shade nets consistently reduced sunburn incidence by in 'Mondial Gala' over three growing seasons (Iglesias and Alegre, 2006). In all cases, sunburn was strongly reduced by netting. When compared to evaporative cooling and kaolin particle film, 20% black shade net significantly reduced sunburn incidence in both 'Cripps' Pink' and 'Royal Gala' (Gindaba and Wand, 2005). Based on the results from these studies, protective shade netting is a viable sunburn protection tool for apples.

Protective netting also limits the incidence of mechanical injury including hail and wind damage. Protective shade netting reduces wind speed that has been reported to reduce limb rub in apple (Newenhouse, 1991). In a year with hail, damage to fruit was reduced from 10% in an uncovered control to 0% under protective shade netting (Iglesias and Alegre, 2006).

The influence of protective shade netting on the incidence of bitter pit varies by cultivar, net color, shading percentage, net mesh size and timing of deployment relative to full bloom. Do Amarante et al. (2011) observed a 4.8% and 1.7% reduction in bitter pit incidence in 'Gala' and 'Fuji', respectively, for fruit under an 18.4% white net compared to an uncovered control which had bitter pit incidences of 31.4% and 25.8%, respectively. The bitter pit incidence in this study was assessed after four months in regular air cold storage and seven days shelf life. When measured after three months of regular atmosphere cold storage, bitter pit incidence in 'Greensleeves' apples grown under a 50% black net was 42% while it was 0% for fruit grown in the uncovered control (De Freitas et al., 2013). Kelderer et al. (2010) assessed bitter pit incidence in 'Braeburn' apple but rather than disclosing the shading percentage, they noted the actual mesh size of the nets used where a smaller sized hole (e.g., 1 × 1 mm) would result in a larger shading percentage than a larger size hole (e.g., 3 × 8 mm). They found that bitter pit significantly increased to 10.7% under 1 × 1 mm white hail net and 8.4% under 3 × 8 mm black hail net, respectively, compared to 0.8% for the uncovered control when the net was deployed before full bloom. This contrasted with a 1.5% bitter pit incidence under a 2 × 6 mm black hail net deployed after full bloom. The authors ascribed the increase in bitter pit to deploying net before full bloom and the impact it had on reducing fruit set resulting in fruit of larger size.

Protective netting had no effect on russeting severity in 'Gala' and 'Fuji' (Do Amarante et al., 2011), 'Honeycrisp' (Chouinard et al., 2016), and reduced rusting severity in 'Red Fuji', 'Hi Early' and 'Granny Smith' (Middleton and McWaters, 2002). High relative humidity is conducive to the occurrence russeting in apple (Creasy, 1980), high relative humidity during the growing season is not likely to be a problem under protective shade netting in the more arid growing regions like Washington State USA, Western Cape South Africa and Chile. However, management decisions can impact the relative humidity in the tree canopy. In Washington State, orchard practices such as overhead irrigation for sunburn reduction can lead to high relative humidity and may increase disease incidence (Kim and Xiao, 2010). In environments with high summer rainfall (e.g., parts of Germany, New York and Maine), netting could present postharvest problems in apples. Moran et al. (2009) noted that soft scald incidence of 'Honeycrisp' in Maine, USA was strongly related to the number of hours when relative humidity was greater than 85%.

4.2. Yield and fruit size

Elfving and Schechter (1993) noted that the sink strength of an apple crop influences fruit size and it is proportional to the number of fruit per tree. Yield and fruit size depend upon environmental conditions and the genetic potential of a cultivar (De Silva et al., 2000; Naor et al., 2008). Fruit length, width and weight in 'Delicious' was linearly related to the percentage of full sunlight trees were exposed to (Robinson et al., 1983). The change in environmental conditions under protective shade netting could potentially affect yield and fruit size. In environments where trees are not stressed and light limitation is possible because of shading, protective netting has the potential to reduce fruit size from reduced tree photosynthesis. However, in regions where trees regularly experience abiotic stress due to excessive solar radiation, netting may have a positive effect on fruit size through the mitigation of some of the effects of stress by maintaining higher photosynthetic rates later in the day, especially, when compared to trees in full sun that may be experiencing photoinhibition.

Four year total yield average of 'Golden Delicious' was significantly higher under 30% pearl, 30% red, and 15% white protective netting, whilst 30% blue, grey and black protective netting was not different from the control (Shahak et al., 2008b). Yield per tree under white and black shade netting (% shading factor not disclosed) was not significantly different in 'Elstar' from an uncovered control (Stampar et al., 2001). However, in 'Jonagold' yield per tree was significantly higher in black shade net, but not white shade net. No changes in yield per tree were observed under 25% black shade and 12% crystal shade net over four growing seasons in 'Mondial Gala' compared to an uncovered control; similar results were obtained for fruit weight, except for one growing season where 25% black shade net significantly reduced fruit size (Iglesias and Alegre, 2006). Do Amarante et al. (2011) also observed no changes in yield in both 'Gala' and 'Fuji' under 18.4% white shade net compared to an uncovered control, although fruit size was greater for both cultivars. Bastías et al. (2012a) reported increased fruit size for fruit grown under blue (27%) and grey (37%) shade nets when compared to white (20%) (control) and red (27%) shade nets. For trees in the trial, they noted that crop load was set at 5 fruits/TCSA (cm^2) so that crop load between experimental treatments would be uniform and not influence fruit size. The larger fruit weight that they observed under blue and grey nets was the result of accelerated fruit growth throughout the season attributed to increased net photosynthesis (Bastías et al., 2012a). Another hypothesis to possibly explain the increased fruit size under blue nets is due to the increase in the B:R light ratio of light the leaves are exposed to. Enhanced blue light exposure is linked to the enhancement of photosystem II, dry matter (DM) production and increased stomatal conductance (Goins et al., 1997; Matsuda et al., 2004). This enrichment of the blue light spectra may lead to an increase of assimilated carbon to support fruit growth.

4.3. Fruit skin coloration

Apple fruit skin coloration is affected by light exposure for both green and bi-color or blushed cultivars. Red skin coloration is used as an external quality criteria in bi-colored apples, the more red coloration usually resulting in a greater economic return for the grower. Red color development in bi-colored apple cultivars requires exposure to sunlight closer to harvest, whilst green colored fruit (e.g., ‘Granny Smith’) require high light exposure earlier in the growing season to achieve optimal coloration (Fouché et al., 2010; Hirst et al., 1990; Siegelman and Hendricks, 1958). Apple fruit in the periphery of the canopy that is exposed to higher light levels is usually redder in color when compared to shaded fruit in the interior of the canopy (Jackson and Sharples, 1971). Protective netting reduces light levels for fruit over the entire growing season and, if too much shading results, there is the potential to adversely affect fruit color in both green and bi-colored cultivars. For ‘Mondial Gala’, Iglesias and Alegre (2006) compared fruit red coloration under black shade net and full sun. In three out of four growing seasons, they noted that fruit under black shade nets had significantly poorer red coloration than fruit from trees exposed to full sun.

Anthocyanin pigments accumulate under light stress conditions and they are more stable under these conditions when compared to chlorophyll. In the apple peel, anthocyanins protect against both light-induced stress and damage to fruit peel by trapping light in the chlorophyll absorption gap (green-orange part of light spectrum). Solomakhin and Blanke (2010b) reported that the peel of apples under colored hail nets contained more chlorophyll but 4–5 fold less anthocyanin. During fruit maturation, the combination of cool temperatures combined with high light intensity induces rapid accumulation of anthocyanin pigmentation in the apple peel (Blankenship, 1987; Gouws and Steyn, 2014; Iglesias and Alegre, 2006). For non-red cultivars, shading during early fruit development reduced green color in ‘Granny Smith’, the degree of loss of green skin coloration increased with the duration of shading (Hirst et al., 1990). Fouché et al. (2010) also reported that good green color at harvest in ‘Granny Smith’ relied on exposure of fruit to high irradiance during the early phase of fruit development. Blanke (2009) recommended black shade nets for single-colored green or bi-colored apple cultivars with good coloration. More research is necessary to definitively say what net color and shade percentage is best to promote ideal coloration of any hard-to-color apple cultivars.

4.4. Fruit internal quality

Internal quality influences consumer acceptance and determines storability of fruit. Important internal fruit quality parameters in apples include total soluble solids (TSS), total acidity (TA), TSS:TA ratio, starch breakdown, dry matter accumulation and firmness (Table 4). Changes in internal fruit quality under protective netting are often more influenced by the environmental conditions in a specific growing season than a result of different net colors (Stampar et al., 2002).

Starch is hydrolyzed into soluble carbohydrates during apple ripening and the resultant sugars are used for respiration and enhance sweetness (Doerflinger et al., 2015). The conversion of starch to soluble carbohydrates is used as a maturity indicator in apples where more starch being hydrolyzed corresponds to more advanced maturity. Starch breakdown was reduced by protective shade netting in both ‘Fuji’ and ‘Pinova’ under 12% white, 14% red-white, 18% red-black and 20% green-black shade nets compared to an uncovered control (Solomakhin and Blanke, 2010b). Do Amarante et al. (2011) reported increased starch breakdown at harvest under 18.4% white shade net in ‘Gala’, whilst starch breakdown was not affected in ‘Fuji’ under the net. Starch breakdown in ‘Cripps’ Pink’ and ‘Royal Gala’ was not affected by 20% black shade net (Gindaba and Wand, 2005). In this same study, the effect of 25% black and 12% crystal shade net on starch conversion was inconsistent over a four-year period where it was delayed for two years in both colors but was not affected in the other two years.

Sweetness is one of the main drivers of consumer preference for apples and TSS is used as an estimate of sweetness (Aprea et al., 2017). TSS from outer canopy ‘Starking’, ‘Golden Delicious’ and ‘Granny Smith’ fruit was consistently higher over two growing seasons than from inner canopy fruit (Hamadziripi et al., 2014a). Inner canopy fruit are exposed to different microclimatic conditions with lower temperature and light intensity which is a similar effect to what is experienced by fruit under protective netting. Black shade net (25%) significantly reduced TSS in three growing seasons compared to a 12% crystal shade net and uncovered control in ‘Mondial Gala’, whilst in another growing season, no differences were found in amongst the three treatments (Iglesias and Alegre, 2006). TSS in ‘Elstar’ was reduced by both white and black shade net (shading factor not disclosed) compared to a control without netting, whilst in ‘Jonagold’ only black shade net reduced TSS (Stampar et al., 2001). TSS in fruit from under 18.4% white shade net was significantly reduced in ‘Gala’ but not ‘Fuji’ at harvest (Do Amarante et al., 2011). When was assessed after four months in regular atmosphere cold storage and seven days shelf life at room temperature, TSS was significantly reduced in ‘Gala’ under 18.4% white shade compared to an uncovered controls (Do Amarante et al., 2011). In contrast, TSS was significantly increased in ‘Fuji’ after regular atmosphere cold storage and shelf life in the same study (Do Amarante et al., 2011).

Fruit acidity affects the perception of taste and is therefore an important component of organoleptic quality in apple (Etienne et al., 2013; Khan et al., 2013). Fruit acidity is also used as an indicator of postharvest storability. The exposure of fruit to full sunlight in terms of canopy position affects TA, however this effect is not consistent. Malic acid, which is the predominant organic acid in apple, was significantly higher in the flesh of outer canopy ‘Mutsu’ fruit compared to fruit from the inner canopy, however, there were no malic acid differences observed for ‘McIntosh’ and ‘Gala’ fruit (Feng et al., 2014). On the other hand, inner canopy ‘Starking’, ‘Golden Delicious’ and ‘Granny Smith’ fruit had higher TA compared to fruit in the outer canopy during one growing season, with no differences being observed between the two canopy positions in another year (Hamadziripi et al., 2014a). The change in environmental conditions under protective netting has the potential to affect TA in apple fruit. TA in ‘Mondial Gala’ under 25% black and 12% black was not affected by protective netting in three out of four years, but in the fourth year, 25% black shade net increased TA compared to an uncovered control (Iglesias and Alegre, 2006). Malic acid content was significantly increased by white net in ‘Elstar’ compared to an uncovered control, whilst black net was not significantly different from the control (Stampar et al., 2001). In the same study, no differences in malic acid content were observed in ‘Jonagold’ when the uncovered control was compared to black and white shade nets.

The position of apple fruit in the canopy influences its’ firmness where fruit from the outer canopy tend to be firmer in texture when compared to shaded fruit in the interior of the canopy. This can be explained by poor cell wall formation and a greater influx of water into cells forming the flesh under low light conditions (Loreti et al., 1993).

Table 4
Influence of protective shade netting on apple fruit quality.

Variable	Cultivar	Net color and % shading	Response	References
Total Soluble Solids Concentration (TSS)	'Fuji', 'Pinova', 'Mondial Gala' 'Jonagold' 'Cripps' Pink'	Green-Black (20%), White (12%), Red-White (14%), Red-Black (18%), Black (25%, 20%)	↓	(Solomakhin and Blanke, 2010b) (Iglesias and Alegre, 2006) (Gindaba and Wand, 2005)
	'Mondial Gala' 'Royal Gala'	Black (25%, 20%), Crystal	–	(Iglesias and Alegre, 2006) (Gindaba and Wand, 2005)
	'Elstar'	Black, White	↑	(Stampar et al., 2001)
Titratable Acidity (TA)	'Fuji', 'Pinova'	Green-Black (20%), White (12%), Red-White (14%), Red-Black (18%)	↓	(Solomakhin and Blanke, 2010b)
	'Mondial Gala'	Crystal (12%)	–	(Iglesias and Alegre, 2006)
	'Mondial Gala'	Crystal (12%)	↑	(Iglesias and Alegre, 2006)
Starch Conversion	'Cripp's Pink' 'Royal Gala'	Black (20%)	–	(Gindaba and Wand, 2005)
Fruit Weight	'Fuji', 'Pinova', 'Mondial Gala'	Green-Black (20%), White (12%), Red-White (14%), Red-Black (18%), Black (25%)	↓	(Solomakhin and Blanke, 2010b) (Iglesias and Alegre, 2006)
	'Mondial Gala' 'Cripps' Pink' 'Royal Gala'	Black (20%), Crystal (12%)	–	(Iglesias and Alegre, 2006) (Gindaba and Wand, 2005)
Average Fruit Firmness	'Pinova' 'Fuji"	Green-Black (20%), White (12%), Red-White (14%), Red-Black (18%)	↓	(Solomakhin and Blanke, 2010b)
	'Fuji', 'Mondial Gala'	White (12%), Red-White (14%), black (25%), Crystal (12%)	–	(Solomakhin and Blanke, 2010b) (Iglesias and Alegre, 2006)
Sun Exposed-side Firmness	'Cripp's Pink'	Black (20%)	↓	(Gindaba and Wand, 2005)
	'Royal Gala'	Black (20%)	–	(Gindaba and Wand, 2005)
Shade Exposed- side Firmness	'Cripp's Pink' 'Royal Gala'	Black (20%)	–	(Gindaba and Wand, 2005)
Fruit Density	'Fuji'	White (18.4%)	↓	(Do Amarante et al., 2011)
	'Gala'	White (18.4%)	–	(Do Amarante et al., 2011)
Fruit Diameter				
< 70 mm and 70–80 mm	'Mondial Gala'	Black (25%), Crystal (12%)	–	(Iglesias and Alegre, 2006)
(> 80 mm)	'Mondial Gala'	Black (25%), Crystal (12%)	↑	(Iglesias and Alegre, 2006)
(> 80 mm)	'Mondial Gala'	Black (25%), Crystal (12%)	–	(Iglesias and Alegre, 2006)
Sunburn	'Mondial Gala' 'Gala' 'Honeycrisp' 'Royal Gala'	Black (25%), Crystal (12%), White (18.4%), Red (22%), Blue (22%), Pearl (19%)	↓	(Iglesias and Alegre, 2006) (Do Amarante et al., 2011) (Kalcsits et al., 2017), (Gindaba and Wand, 2005)
	'Mondial Gala' 'Fuji'	Black (25%), Crystal (12%), White (18.4%)	–	(Iglesias and Alegre, 2006) (Do Amarante et al., 2011)
Fruit Cracking	'Mondial Gala'	Black (25%), Crystal (12%)	–	(Iglesias and Alegre, 2006)
	'Mondial Gala'	Black (25%)	↓	(Iglesias and Alegre, 2006)
Hail Damage	'Mondial Gala'	Black (25%), Crystal (12%)	↓	(Iglesias and Alegre, 2006)
Russeting				
Severity	'Gala', 'Fuji'	White (18.4%)	–	(Do Amarante et al., 2011)
Bitter Pit (%)	'Gala', 'Fuji'	White (18.4%)	↓	(Do Amarante et al., 2011)
Apple Scab (%)	'Gala'	White (18.4%)	–	(Do Amarante et al., 2011)
	'Fuji'	White (18.4%)	↓	(Do Amarante et al., 2011)
Watercore (%)	'Fuji'	White (18.4%)	–	(Do Amarante et al., 2011)
Fruit Fly Damage (%)	'Gala"	White (18.4%)	↓	(Do Amarante et al., 2011)
Fruit Puncture Severity	'Gala'	White (18.4%)	↓	(Do Amarante et al., 2011)
Blush Coverage	'Gala', 'Fuji'	White (18.4%)	–	(Do Amarante et al., 2011)
Moldy Core (%)	'Fuji'	White (18.4%)	–	(Do Amarante et al., 2011)
Decay After Cold Storage (%)	'Fuji"	White (18.4%)	↓	(Do Amarante et al., 2011)

Cultivar, Net Color, or Shading % was left blank in Table 4, if it was not specifically mentioned in the corresponding cited study. Shading percentage number is the given manufacturer's percentage unless PAR measurements were taken to assess the actual shading effect. If actual shading percentage was stated in study, that number was used here.

Hamadziripi et al. (2014b) reported lower fruit firmness in inner canopy fruit of 'Golden Delicious' compared to outer canopy fruit over two consecutive years with no differences observed in 'Starking' over the same period. Minor inconsistent changes were observed in fruit firmness of 'Granny Smith', 'Fyriki', 'Fuji Kiku 8′ and 'Imperial Double Red Delicious' from upper, middle and lower sun exposed and shaded canopy positions (Drogoudi and Pantelidis, 2011). Fruit firmness in 'Fuji' was increased under 15% black shade compared to an uncovered, whilst 55% black shade net reduced fruit firmness compared to an uncovered control in the same experiment (Dussi et al., 2005). Black and crystal shade net had no effect on fruit firmness at commercial harvest over four growing seasons in 'Mondial Gala' (Iglesias and Alegre, 2006). Apple fruit firmness varied across different shade cloth colors, with 'Fuji' and 'Pinova' apples grown under green-black and red-black netting being softer than those grown under red-white, with the uncovered control fruit yielding the firmest fruit (Solomakhin and Blanke, 2010b). White shade netting (18.4%) significantly reduced fruit flesh firmness at harvest in 'Gala' but not in 'Fuji' (Do Amarante et al., 2011). Fruit fresh firmness after four months in regular atmosphere cold storage and seven days shelf life was significantly reduced under 18.4% white shade net in both 'Fuji' and 'Gala' compared to an uncovered controls (Do Amarante et al., 2011).

4.5. Fruit nutritional and nutraceutical quality

Fruit contain a variety of antioxidants which are useful to scavenge free radicals and helps to prevent cancer and cardiovascular diseases (Zampini et al., 2011). Vitamin C is an antioxidant involved in many biological activities in the human body, 90% of vitamin C in human diet is supplied by fruits and vegetables (Lee and Kader, 2000). Polyphenols in apple also have antioxidant properties, they protects cells from damaging effects of free radicals and also inhibit the oxidation of low density lipoproteins (Rana and Bhushan, 2016). Apple fruit are a rich source polyphenols, examples of polyphenols are dihydrochalcones, flavanols, flavonols, anthocyanins and phenolic acids (Rana and Bhushan, 2016). Environmental factors and canopy microclimate influences fruit nutritional and nutraceutical quality in apple (Hamadziripi et al., 2014a; Musacchi and Serra, 2017). Peel anthocyanin concentration, vitamin C, total phenolics and antioxidant capacity was significantly higher in the outer canopy compared to the inner canopy fruit in 'Granny Smith', 'Starking' and 'Golden Delicious' (Hamadziripi et al., 2014a,). The same study also reported significantly higher total phenolics and antioxidant capacity in the flesh of outer canopy fruit compared to inner canopy fruit for 'Granny Smith', 'Starking' and 'Golden Delicious'. Bastías et al. (2012b) reported that the apple peel under 22% red hail net, red shade net (≈38%), blue shade net (≈41%) net and 43% pearl shade net contained on 2–6 fold less anthocyanins than the uncovered control. Vitamin C content was 31% less under 20% green-black shade net, 42% less under 18% red-black hailnet, 10% less under 14% red-white hailnet compared to an uncovered control, whilst under 12% white hailnet it was 5% more than the uncovered control (Solomakhin and Blanke, 2010b). Reflective ground covers improve light utilization under protective netting by reflecting more light back into the tree canopy. Solomakhin and Blanke (2007) reported that reflective ground covers under hailnet had a pronounced effect on fruit quality in the lower canopy with higher vitamin C content and anthocyanins compared to control which had a grass cover. Considering that protective netting will become more necessary in the future due to climate change, more research into reflective ground covers will be needed to negate the effect of protective netting on nutritional quality of apple.

5. Future research

As protective netting use increases, more research is needed to provide reliable information that is specific for the different cultivars and geographic/climatic regions. Arid climates, such as Washington State with high light intensities and long days, may have a different optimal shading factor for protective netting compared to European conditions where protective netting is mainly used as anti-hail protection. Research also needs to be conducted on establishing trees under protective netting and how the increased vegetative growth can be used to fill canopy space and enter production earlier. For cultivars with low vigor, this can have a significant economic impact. Environmentally, as climate change puts increased pressure on water resources, the potential and real water savings under protective nets from reduced evapotranspiration needs to be quantified. The resulting data can be used to develop new irrigation strategies under protective netting. More research is also required to tease apart the effects of different colors of protective netting on color development in different cultivars. This research could include products/cultural practices that can counteract limited color development in certain environments under protective netting. Several options exist to do this including using reflective fabrics, sprays to improve fruit color, sprays to slow the ripening processes to allow the fruit more time on the tree to reach optimal color and overhead cooling to reduce fruit surface temperature and enhance anthocyanin pigment development in the skin. A better understanding of how different cultivars respond to netting in the same environment is required to better develop management strategies for apples with different growth habits under protective netting. Protective netting will continue to be used in regions that experience conditions that can negatively affect tree growth, yield, fruit size, or quality. It is important to understand the interactions between growing environment, cultivar and protective netting strategy to provide the most complete information on the response of apple to protective netting.

6. Conclusion

Overall, protective netting is a resilient innovation that can be used to buffer climactic extremes like intense heat, light and wind stresses so the canopy may remain healthier, photosynthetically active for longer periods of time, and more efficient in water usage. Protective shade netting provides an alternative to traditional approaches to protect apple from sunburn, mechanical injury from hail and wind, and abiotic stress that limits tree establishment, productivity, and health in many growing regions that frequently experience hot and dry conditions. Here, it is evident that the impact of protective shade netting compared to none at all is much greater than the relatively small differences among the many color options available commercially. However, netting color may provide niche opportunities to increase productivity or quality on a system or in cultivar-specific situations. In the future, research is needed to tease out these small differences to maximize productivity in all orchard systems and cultivars.

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