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Above and below-ground environmental changes associated with the use of photoselective protective netting to reduce sunburn in apple

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ABSTRACT

Anti-hail (protective) netting was originally developed to protect horticultural crops from hail damage. Netting reduces the amount and modifies the light reaching the orchard canopy. It also has the potential to optimize conditions for canopy and fruit growth and mitigate abiotic stress as climate change leads to increased temperatures. This study measured the effect of different colors of netting on the above and below-ground environment and apple sunburn incidence in a 3-year-old 'Honeycrisp' apple orchard growing in an irrigated desert climate in comparison to a traditional uncovered control. Netting did not affect air temperature or relative humidity within the orchard canopy, but reduced wind speed by 40% compared to the uncovered control. Netting reduced soil temperature and improved soil moisture at 20 and 40 cm depths throughout the study period compared to the uncovered control. Amongst different colors of netting tested in this study, pearl and blue netting significantly reduced soil temperature compared to red netting. Netting also reduced photosynthetically active radiation (PAR) by approximately 20% and strongly reduced fruit surface temperature during hot periods. During full sunlight, differences in maximum fruit surface temperature between the uncovered control and the protective netting were 2.6–4.3 °C under full sun conditions and reduced the incidence and severity of sunburn measured at harvest. As temperatures warm in the future, netting provides a viable option to mitigate some of the negative effects of excessive temperature and light on apple production in hot, dry growing regions.

1. Introduction

The original purpose of protective netting was to protect the crop underneath it from hail (Scott, 1988). However, it has also been shown to modify the underlying environment (Shahak et al., 2004; Bastías et al., 2012; McCaskill et al., 2016) to be more favorable for tree growth and fruit development. This response, however, may vary depending on the regional environment. High light, low rainfall and high temperatures allow for high yields but can also be a source of stress in some commercial apple growing regions, such as central Washington. Such hot, dry conditions limit insect and disease pressure whereas high light increases productivity (Smith, 2000). Under these conditions, excessively high fruit surface temperature can lead to sunburn and other disorders (Wünsche et al., 2002; Schrader et al., 2003; Racsko and Schrader, 2012). In the future, as climate change pushes temperatures higher in traditional apple growing regions (Stöckle et al., 2010), mitigation of the impacts of high temperatures will be critical to maintain orchard productivity and high fruit quality. Even small increases in the average temperature across a region could increase fruit surface temperatures above acceptable thresholds and enhance sunburn susceptibility (Racsko and Schrader, 2012) and negatively affect fruit quality. Under such conditions, sunburn risk will extend to a

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longer duration during the season, requiring ever-increasing management inputs from producers. Cumulative heat stress and earlier fruit maturity may create greater risk and potential loss for commercial apple producers.

In regions where air temperatures frequently exceed 35 °C and light intensity is high, sunburn damage to fruits can result in financial losses for the tree fruit industry. In fact, sunburn is the major source of fruit losses for many warmer growing regions (Smit, 2007; McCaskill et al., 2016). As described in Racsko and Schrader (2012), apple sunburn can manifest itself in one of three ways: sunburn browning, sunburn necrosis and photooxidative sunburn. Sunburn browning is the most common source of apple cullage and is caused by a combination of high light intensity and temperature, and occurs when fruit surface temperatures exceed 46–49 °C (Felicetti and Schrader, 2008). Sunburn necrosis occurs when the fruit surface temperature exceeds 52 °C (Felicetti and Schrader, 2008). Photooxidative sunburn or bleaching occurs when fruit develops in the shade and is suddenly exposed to full sunlight, either through limb removal or in-season fruit movement during fruit growth (Felicetti and Schrader, 2008). Fruit surface temperatures are affected by air temperature, light intensity and wind speed. In high light environments, fruit surface temperature can be approximately 12–15 °C higher than the ambient air temperature (Schrader et al., 2003). Therefore, when air temperatures reach 35 °C, fruit surface temperatures approach or pass the threshold where sunburn browning can occur. Protective netting, including anti-hail nets, can reduce the fruit surface temperature by reducing the amount of light energy reaching the absorptive surface (McCaskill et al., 2016). As climate change pushes the boundaries for continuing to grow fruit in traditionally high-volume and quality fruit growing regions, environmental manipulation to create a more favorable environment will be essential to maintain fruit quality.

In some regions, such as Germany, using anti-hail netting can create shading effects that reduce photosynthesis and plant productivity for apple (Solomakhin and Blanke, 2008). In these areas, light limitation can be a factor that reduces tree performance, fruit yield and quality (Lakso et al., 1999). Therefore, the use of netting may be detrimental to commercial fruit production in those areas. However, in Brazil, Amarante et al. (2011) observed no reductions in plant productivity for 'Fuji' and 'Gala' apples under netting. This may be a function of differences in the ambient light levels in different growing regions. The light saturation point for apple leaves is generally thought to be approximately 1000 μmol m^{-2} s^{-1} (Rom, 1991). This is often well below the light intensity experienced by apple trees grown in desert environments where the maximum daily light intensity exceeds 1800 μmol m^{-2} s^{-1} (Rasko and Schreader, 2012). Excess light energy can be detrimental to trees due to increased photorespiration (Osmond and Grace, 1995; Kozaki and Takeba, 1996), photoinhibition, and photooxidative damage (Cheng et al., 2000) which may reduce net productivity. Another inhibitory factor common to desert environments is direct light which limits light to leaves in the lower canopy. This can negatively affect lower canopy photosynthesis and color development in apples. Protective netting can actually increase the amount of scattered light reaching lower portions of the tree and has the potential to increase net productivity even with overall reductions in light reaching the leaves (Bastías et al., 2012).

This study sought to quantify the impact of anti-hail netting, henceforth referred as protective netting, on the air, soil and tree environment of a commercial apple orchard in a light-saturated, desert environment. The primary focus was to understand the effects of protective nettings of different commercially available colours on wind speed, temperature and humidity in addition to modification of the soil environment. A second objective was to link changes in the environment with sunburn incidence. Environmental manipulation will be essential to create more favorable conditions for growing fruit as climate change challenges the traditional geographic boundaries for temperate zone tree fruit production.

2. Materials and Methods

2.1. Experimental design and field site

The experiment was set up in a commercial, 3-year-old 'Honeycrisp' apple orchard on 'Budagovsky-9′ rootstock located near Quincy, WA (47.23° N, 119.85° W). The orchard is in a desert-like climate with an annual average temperature of 10.3 °C and precipitation of 198 mm. Average daily maximum temperatures are 25.9, 30.4 and 29.9 °C for June, July and August, respectively with a typical precipitation during these months of just 23 mm. This period is the critical time when fruit is the most susceptible to sunburn. In 2013, trees were planted 60 cm apart in the row and 3.7 m between rows (4485 trees/ha) to a V-trellis system. Crabapple (*Malus* spp.) pollinizers were planted every 7.2 m. All trees in the orchard received the same amount of supplemental irrigation using microsprinklers.

In May 2015, after bloom and pollination, three colors of photoselective protective nets were installed at a height of 4 m above the ground and 1 m above the tree canopy over four tree rows; surrounding orchard rows were utilized as uncovered control plots. The netting used was a commercially-available product (Poly Sac Inc., Israel) that reduces light by approximately 20–23%. There were two replications of each treatment. The outside two rows were guard rows and data was not collected from those rows. However, data was collected from trees in the middle two rows of each replicate to limit the effect of the neighboring net treatments and the inner area of the block was considered for data collection leaving south and north ends as in-row guards. To establish an understanding of the variability across the field and because of the limitations in replicates, caliper measurements were made prior to netting deployment at 15 cm above the graft union on 500 trees within two rows of each replicate. 50 trees (5 blocks of 10 trees) were then selected as sample trees for uniformity in tree height and caliper (21–22 mm) so there were no differences in beginning tree size at the time of deployment of the netting treatments. After fruit set, trees were hand thinned in June to a target crop load of 4 fruit cm^{-2} trunk cross-sectional area (16 fruit tree^{-1}) singularizing clusters and remove crop load from the tip.

2.2. Environmental data collection

In June 2015, at three separate locations each in the four experimental treatments, mini weather stations were positioned that included an EM50G datalogger (Decagon Devices, Inc., Pullman, WA) that recorded data every 10 min and transmitted data by cellular signal to a cloud-based server. Sensors at each station included a VP-4 humidity and temperature sensor with a radiation shield (Decagon Devices, Inc., Pullman, WA), a Davis cup anemometer, a photosynthetically active radiation (PAR) sensor (Decagon Devices, Inc., Pullman, WA). These were used to measure, air temperature, relative humidity, wind speed and PAR in each treatment. For measurements that contain more variability, such as in-canopy air temperature and humidity and soil moisture and temperature, four replicate VP-4 sensors for measuring in-canopy air temperature and humidity were placed near the trunk at 1.6 m from the ground in each color of netting. Four 5TM soil moisture and temperature capacitance sensors (Decagon Devices, Inc., Pullman, WA) were installed at dispersed distances within each treatment. The capacitance sensors were installed at depths of 20 and 40 cm to

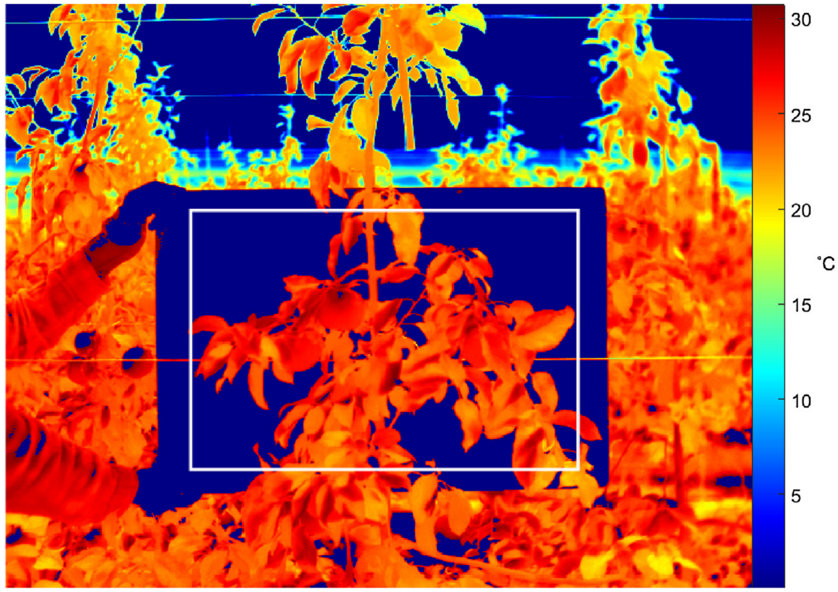

Fig. 1. Pseudocolor thermal image (FLIR) for canopy temperature (°C) of a representative apple tree showing both background and region of interest taken on August 19, 2015 at 12:00.

Table 1
Seasonally averaged (June 9, 2015–August 31, 2015) mean daily maximum photosynthetic photon flux density (PPFD), maximum wind speed, above-canopy air temperature, and relative humidity for pearl, blue and red nets and an uncovered control located in a 3 year-old commercial 'Honeycrisp' apple orchard in Quincy, WA. Different letters denote significant differences between means determined using a Tukey's HSD test ($P < 0.05$).

Treatment	PPFD	Wind Speed	Relative Humidity	Above-Canopy Temperature
	$\mu mol\ m^{-2}\ s^{-1}$	$m\ s^{-1}$	%	°C
Control	1788 [a]	3.27 [a]	39.4 [a]	30.9 [a]
Pearl	1444 [b]	2.26 [b]	38.3 [a]	30.5 [a]
Blue	1386 [bc]	2.23 [b]	38.9 [a]	31.1 [a]
Red	1341 [c]	2.16 [b]	38.6 [a]	30.9 [a]

measure volumetric water content ($cm^3\ cm^{-3}$). Sensor locations were chosen to limit interferences from tree and post shadowing of irrigation microsprinklers and were equidistant from trees within the row. Data was downloaded using DataTrac software (Decagon Devices Inc., Pullman, WA) from the online database on a monthly basis to ensure that sensors were functioning correctly. OriginPro16 (OriginLab, Northampton, MA) was used to perform a one-way ANOVA to compare environmental parameters among netting treatments. Tukey's Honestly Significant Difference (HSD) test was used to separate means ($\alpha = 0.05$).

2.3. Fruit and leaf surface temperature

Fruit and leaf surface temperature was measured by selecting a day when temperatures were forecast to reach 35 °C. A thermal camera (655sc, FLIR Systems Inc., Boston, MA, USA) with spectral band 7.5–14 µm and 640 × 480 image resolution was used for collecting high resolution images. The infrared thermal camera (A655sc, FLIR Systems Inc., Boston, MA, USA) used in this study is a radiometrically calibrated camera that provides pixelated temperature with an accuracy of ±2 °C or ±2% of reading. For validating the camera calibration over time, a blackbody calibrator (Model BB701 infrared calibrator, OMEGA Engineering Inc., Norwalk, CT; working range −18 to 149 °C; target plate diameter 63.5 mm) was also used. Data was collected during solar noon period on August 19, 2015. The ambient air temperature at the time of measurement was 28.8 °C and the light intensity was approximately 1500 $\mu mol\ m^{-2}\ s^{-1}$ in the control and 1200 $\mu mol\ m^{-2}\ s^{-1}$ under the photoselective protective netting treatments. The daily maximum air temperature reached 34.8 °C at 4:00 pm. In each netting treatment, four full trees and four apple fruit were selected randomly from the top of the canopy to limit variability from shading on fruit lower in the canopy. A black board was placed behind each tree or fruit to separate the leaves and fruit from the background. The thermal camera was fixed on a tripod to capture the canopy and the fruit image in the field of view.

The pixel value in each image represents the temperature in that pixel. The images were converted to 'csv' files using ResearchIR software (FLIR Systems Inc., Boston, MA, USA), then imported to Matlab and analyzed using image processing toolbox (The MathWorks Inc. Natick, MA, USA). The region of interest (ROI) was selected from each image to avoid non-canopy or non-fruit area. The average and the maximum temperatures were extracted from each ROI (Figs. 1 and 2). A one-way ANOVA was performed using SAS (Raleigh, NC, USA). Means were separated using a Fisher's LSD test ($P < 0.1$).

2.4. Sunburn assessments

The fruit were harvested on August 26, 2015. Following harvest, all 16 fruit from each tree were individually scored for sunburn using a modified sunburn severity scale of Gala adapted from Schrader et al. (2003) (Fig. 3). The proportions of affected fruit were calculated for each block of 10 trees (80 fruit in each block) and used for the statistical analysis. A one-way ANOVA was performed for the proportion of fruit belonging to each sunburn category with netting treatment as a fixed effect.

3. Results and discussion

3.1. Netting affects the orchard micro-environment

As expected, netting reduced the mean daily maximum light intensity in uncovered rows by approximately 20% (Table 1). The mean daily maximum light intensity in uncovered control plots from June 9, 2015 to August 31, 2015 was 1788 $\mu mol\ m^{-2}\ s^{-1}$ and was significantly greater than all three netting treatments

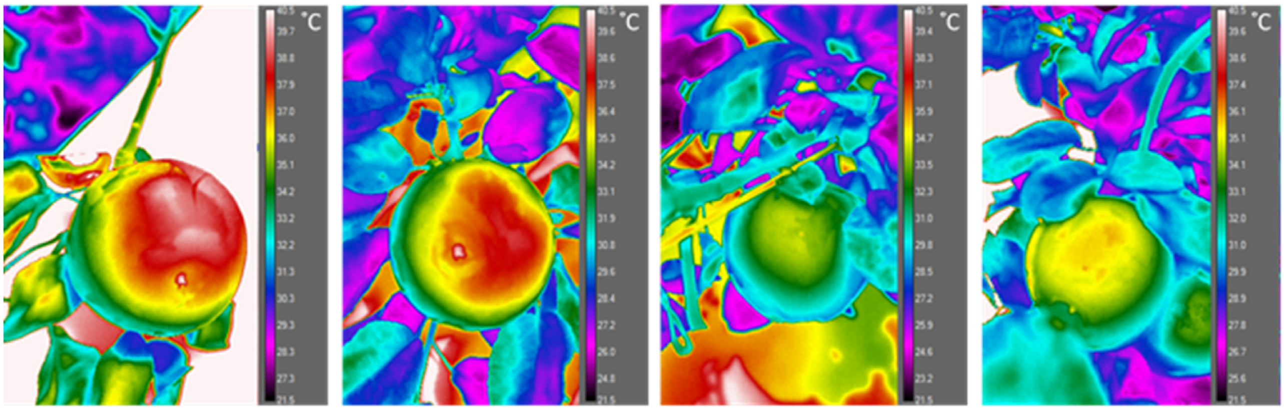

Fig. 2. Pseudocolor thermal image (FLIR) (°C) of representative apples (from left to right: no net control, blue, red and pearl netting treatments taken on August 19, 2015 at 12:00. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Sunburn scales for 'Gala' apple (clean fruit, sunburn Yellow 1 (Y1), yellow 2 (Y2), yellow 3 (Y3), and sunburn Tan) adapted from Schrader et al. (2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

($P < 0.05$). For the netting treatments, the mean daily maximum light intensity under the pearl netting was significantly greater than red netting, whilst light intensity under blue netting did not differ significantly from under the pearl and red netting. The reduced shading effect from pearl netting may be a result of increased light scattering and semi-transparency of the material that has been described for similar netting (Basile et al., 2012; Shahak. 2014). Netting reduced wind speed by approximately 40%. These reductions were consistently observed throughout the measurement period including at times when the wind speed was low. The mean daily maximum wind speed for the uncovered control was 3.27 m s^{-1}. For the three covered netting treatments, the mean daily maximum wind speed ranged from 2.16 to 2.26 m s-1 and were not significantly different from each other. This was similar to other studies measuring wind speed under netting (Middleton and McWaters, 2002; Shahak et al., 2004). The above-canopy mean relative humidity ranged from 38.3 to 39.4% and was not significantly different among treatments. Depending on the year or growing environment, the overall humidity may vary but it would not be expected that the humidity will differ strongly.

Similarly, the mean daily maximum air temperature was not significantly different among treatments. The same was true for mean daily minimum temperatures (data not shown). This is in contrast to other studies that have shown lower temperatures under netting compared to an uncovered control (Iglesias and Alegre, 2006). However, the use of sensors without radiation shields in some previous studies may have confounded the effects of the reduction in light from netting on air temperature. Similar to observations made here where sensors had radiation shields, Middleton and McWaters (2002) reported that netting did not impact overall orchard temperature.

The in-canopy air temperatures were not significantly different under the blue and red netting, but were significantly lower under pearl netting compared to the control (Table 2). Differences between in-canopy air temperatures in control and under the pearl netting was greater when temperatures were between 35 and 40 °C than when temperatures were between 20 and 25 °C. Relative humidity was significantly greater in the canopy of trees under netting compared to the uncovered control (Table 3). As the mean daily temperature increased, the relative humidity decreased. However, the difference in relative humidity between netted trees and uncovered trees was the same across periods when daily temperatures changed.

3.2. Pearl and blue netting decreased soil temperature more than red netting and netting increased volumetric soil water content

Soil temperature was consistently higher throughout the season in the uncovered control than the netted treatments (Fig. 6). Mean soil temperature measured from June 9, 2015 to August 31, 2015 was lower under the netting compared to the uncovered control (Fig. 7). The soil temperature in the control averaged 24.5 and 23.1 °C at 20 and 40 cm soil depth, respectively. The soil temperature under the pearl and blue netting was not significantly different at either 20 or 40 cm soil depths. Soil temperatures under pearl and blue netting was significantly lower compared to the uncovered control and red netting. However, the soil temperature under the red netting was significantly lower than the control at 20 cm but not at 40 cm depth with mean temperatures of 24.1 and 22.9 °C, respectively. Temperature differences during warm periods were magnified between the uncovered control and the netting treatments with soil temperatures exceeding a 1.5 °C difference (Fig. 6). Although less than the control, soil temperatures were greater under red netting compared to blue or pearl. There have not been any reported effects of netting on soil temperature in the literature but the data noted here follow similar trends observed in other energy absorbing surfaces such as leaves and fruit (Gindaba and Wand, 2005; McCaskill et al., 2016). Red net-

Table 2
Seasonally averaged (June 9, 2015–August 31, 2015) daily maximum in-canopy air temperature (±SE, N = 82 days) recorded under blue, pearl, red and control netting and an uncovered control when the maximum daily temperature reached 20–25 °C, 25–30 °C, 30–35 °C and 35–40 °C, respectively. NS indicates no significant difference among treatments within the same temperature range. * indicates a significant difference (P < 0.05) among treatment means separated using a Tukey's HSD test.

Number of Observations	Range	Temperature °C				
		Netting Type				
		Control	Pearl	Blue	Red	
9	20 °C –25 °C	25.2 ± 0.2	25.1 ± 0.2	25.1 ± 0.2	25.5 ± 0.2	NS
27	25 °C –30 °C	29.1 ± 0.2	28.4 ± 0.2	29.1 ± 0.2	29.3 ± 0.2	*
31	30 °C –35 °C	33.5 ± 0.2	32.6 ± 0.2	33.5 ± 0.2	33.8 ± 0.2	*
17	35 °C –40 °C	38.2 ± 0.2	37.5 ± 0.2	38.4 ± 0.2	38.5 ± 0.2	*

Table 3
Seasonally averaged (June 9, 2015–August 31, 2015) daily mean in-canopy relative humidity (±SE, N = 82 days) recorded under blue, pearl, red and control netting and an uncovered control when the maximum daily temperature reached 20–25 °C, 25–30 °C, 30–35 °C and 35–40 °C, respectively. NS indicates no significant difference among treatments within the same temperature range. * indicates a significant difference (P < 0.05) among treatment means separated using a Tukey's HSD test.

Number of Observations	Range	Relative Humidity (%)				
		Netting Type				
		Control	Pearl	Blue	Red	
9	20 °C –25 °C	48 ± 1.4	51 ± 1.4	50 ± .8	51 ± 1.4	*
27	25 °C –30 °C	46 ± 0.7	48 ± 0.7	47 ± 0.7	48 ± 0.7	*
31	30 °C –35 °C	40 ± 0.8	44 ± 0.8	42 ± 0.8	43 ± 0.8	*
17	35 °C –40 °C	37 ± 1.1	39 ± 1.2	38 ± 1.1	39 ± 1.2	NS

ting increases the proportion of red light (600–700 nm) relative to blue light (400–500 nm) (Bastías et al., 2012). There may be other features of its transmittance spectrum that have an impact on soil temperature, but would require further study. Ideally, pigments used within netting should maximise transmittance within the photosynthetically active range (400–700 nm), while minimising the transmittance outside this range because of the deleterious effects of the additional energy on fruit temperature and soil temperature. High soil temperatures have been linked to increased respiration (Boone et al., 1998) and fine root turnover (Pregitzer et al., 2000) in forest trees. In this experiment, daily soil temperatures at times almost reached 30 °C. For apple, these temperatures may represent a substantial stress on the tree.

Soil moisture was consistently greater throughout June, July and August in the netted treatments compared to the uncovered control (Fig. 4). Although all trees received the same amount of supplemental irrigation in this trial, the mean soil moisture content for June 9, 2015 to August 31, 2015 was significantly lower in the uncovered control treatment compared to the three treatments covered with netting (Fig. 5). Soil moisture averaged 12.9, 14.6, 15.3 and 15.0 cm^3 water/cm^3 soil at 20 cm in the control, under pearl, blue and red netting, respectively. At 40 cm, soil moisture was 13.5, 16.8, 15.8, and 16.2 cm^3 water/cm^3 soil in the control and under pearl, blue, and red netting, respectively. Mean soil moisture was greater at 40 cm depth than 20 cm depth for control, pearl and red netting treatments. However, there was no difference in soil moisture between the 20 and 40 cm depth under the blue netting. Soil moisture measurements using capacitance sensors can be affected by soil temperature and can affect measurements (Kizito et al., 2008). However, the temperature differences among treatments in this study were not large enough to explain the observed differences in soil moisture at 20 and 40 cm depth.

The observed differences in soil temperature and moisture could have implication in orchard water-use. Using modeling, McCaskill et al. (2016) reported a 13% reduction in potential evapotranspiration by apple trees under netting compared to apple trees in full sun. This was due to a reduction in wind and solar radiation, while there was an increase in within-canopy relative humidity (McCaskill et al., 2016). In this study, since irrigation was applied equally across the entire orchard, a concomitant increase in soil moisture under netting relative to uncovered control plots could correspond to the predicted change in water-use. Significant reductions in soil temperature and increases in soil moisture observed for netted treatments may improve the conditions for tree growth and improve root health. However, more work is needed to determine the long-term effects on the soil environment from the use of protective netting.

Table 4
Mean and maximum leaf and fruit temperature for pearl, blue and red protective netting and an uncovered control taken at 12:00 pm on August 19, 2015. The air temperature at the time of measurement was 28.8 °C and the light intensity was approximately 1500 $\mu mol\ m^{-2}\ s^{-1}$ in the control and 1200 $\mu mol\ m^{-2}\ s^{-1}$ under the photoselective netting treatments. The daily maximum air temperature reached 34.8 °C at 4:00 pm. Mean/Maximum values with different letters for the same day were significantly different according to a Fisher's LSD test (p < 0.1).

	Leaves		Fruit	
Treatment	Mean (°C)	Maximum (°C)	Mean (°C)	Maximum (°C)
Control	30.2^{a}	36.2^{a}	37.1^{a}	41.5^{a}
Blue	29.3^{ab}	34.7^{abc}	34.5^{ab}	37.0^{b}
Red	29.0^{ab}	34.0^{bc}	32.8^{b}	35.1^{b}
Pearl	28.1^{b}	32.4^{c}	34.1^{ab}	35.9^{b}
LSD	1.34	1.55	3.96	2.93

3.3. Netting reduced leaf and fruit surface temperature

On August 19, 2015, the mean leaf surface temperature was greater in the control compared to pearl netting but was not significantly different from the red and blue netting. Netting significantly reduced mean fruit surface temperature (FST) from 2.6 to 4.3 °C (Table 4). The maximum FST under the uncovered control was 41.5 °C, which was significantly higher than under the blue, red and pearl netting which were 37.0, 35.1 and 35.9 °C respectively. The threshold FST for sunburn browning has been reported to be 46 °C (Racsko and Schrader, 2012). While the FST at the time of measurement was not above this threshold for sunburn, the maximum temperature reached 34.8 °C later in the afternoon. At the time of measurement, the FST was 12.8 °C greater than ambient temperature for the control. This is similar to measurements reported by Li et al. (2014) where surface temperatures were up to 12 °C above ambient air temperature. At peak daily maximum temperature, the

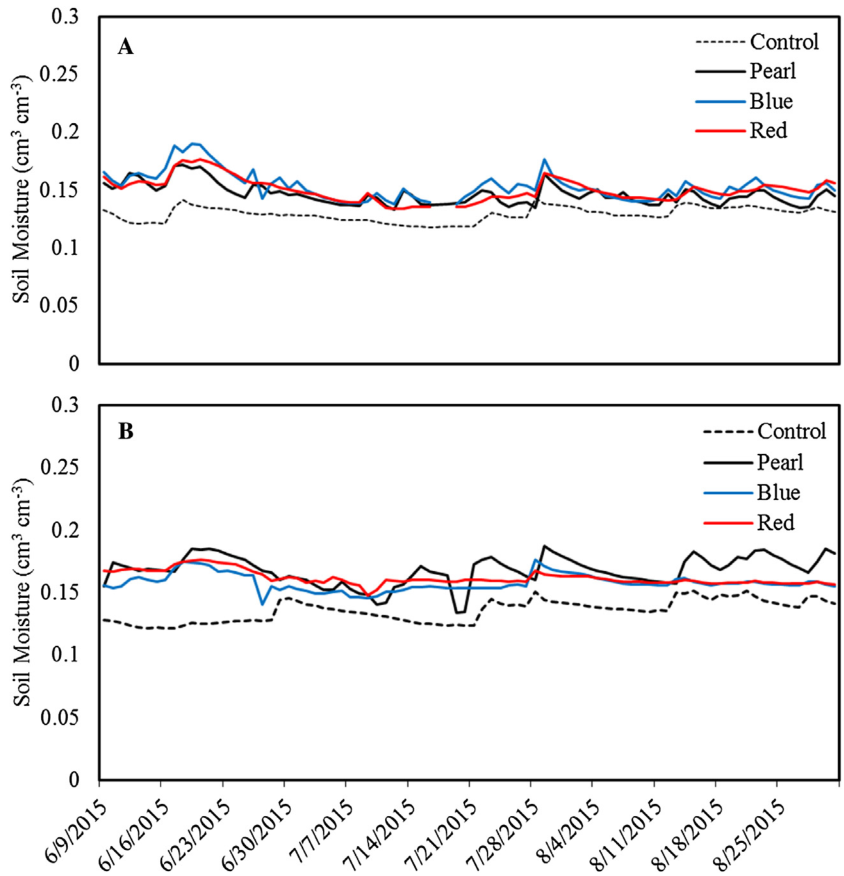

Fig. 4. Mean daily soil moisture (N = 4) at A. 20 cm and B. 40 cm soil depth from June 9, 2015 to August 31, 2015.

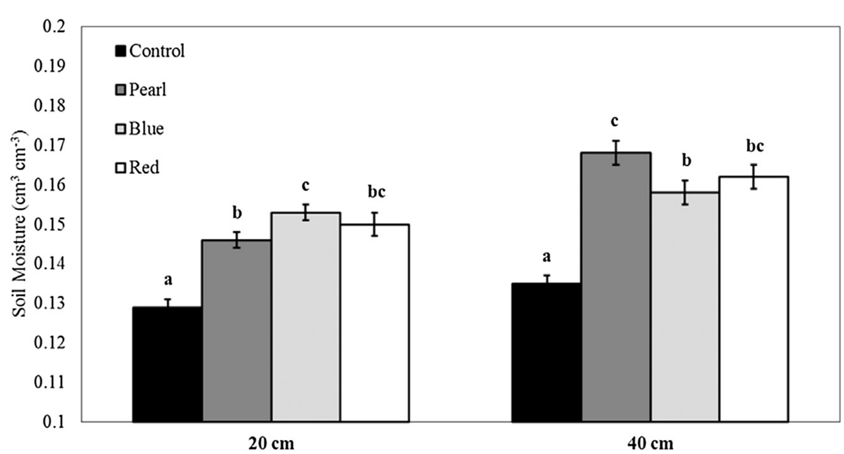

Fig. 5. Mean volumetric soil moisture content ($cm^3\ cm^{-3}$) at 20 and 40 cm depth under pearl, blue and red anti-hail netting compared to an uncovered control in a three year-old 'Honeycrisp' apple orchard in Quincy, WA (47.23° N, 119.85° W). Different letters denote significant differences between means determined using a Tukey's HSD test ($P < 0.05$).

FST in the uncovered control could have surpassed the threshold for sunburn development. However, the fruit surface temperature was only 7–9 °C above the ambient temperature for the netted treatments earlier in the day. Leaf surface temperature was generally lower than FST. Leaves are better able to use or dissipate solar radiation. Leaves also have greater rates of transpiration compared to fruit (Montanaro et al., 2014)) and therefore are better able to thermoregulate surface temperatures than developing fruit. High air temperature or solar radiation in fruits leads to high surface temperature (Racsko and Schrader, 2012). Nets are able to scatter some of the incident solar radiation thereby reducing FST (Gindaba and Wand, 2005). Here, we acknowledge that temperatures were only measured for one day. The temperatures measured using thermal imaging align well with previous measures of fruit surface temperature (Schrader et al., 2003; Racsko and Schraeder, 2012; Li et al., 2014).

3.4. Netting strongly reduced sunburn incidence in apple

In the control, 43.5% of fruit showed sunburn symptoms and the proportion of fruit showing sunburn symptoms was greater in the control than the three netted treatments. (Fig. 8). Pearl netting

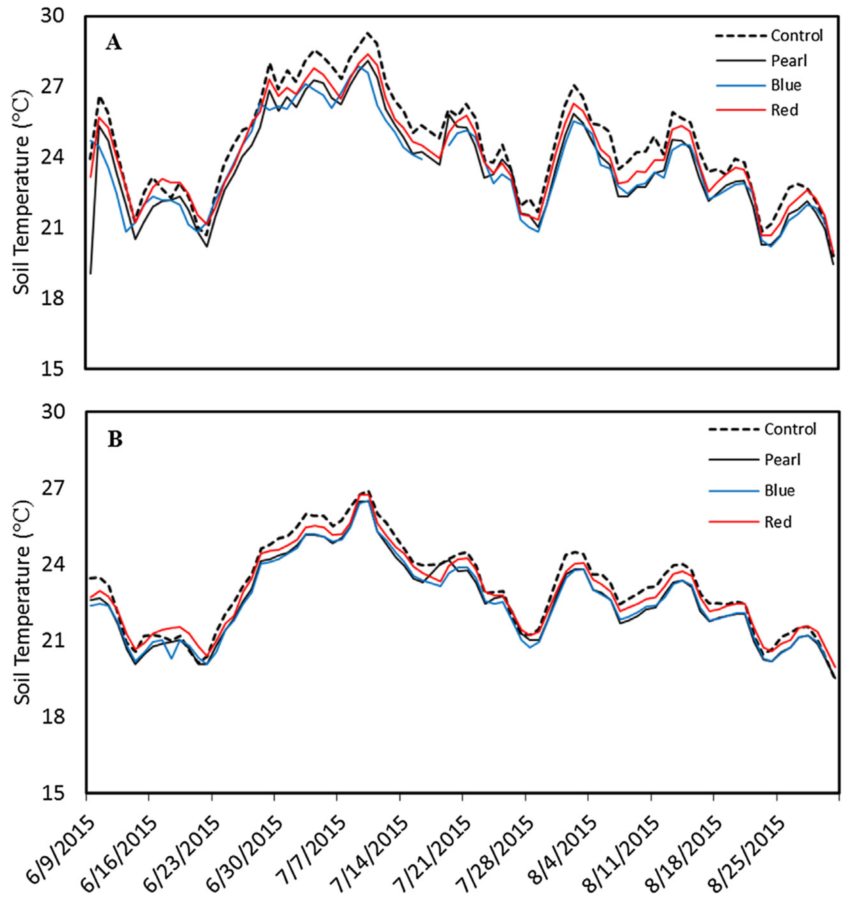

Fig. 6. Mean daily maximum soil temperature (N = 4) at A. 20 cm and B. 40 cm soil depth from June 9, 2015 to August 31, 2015.

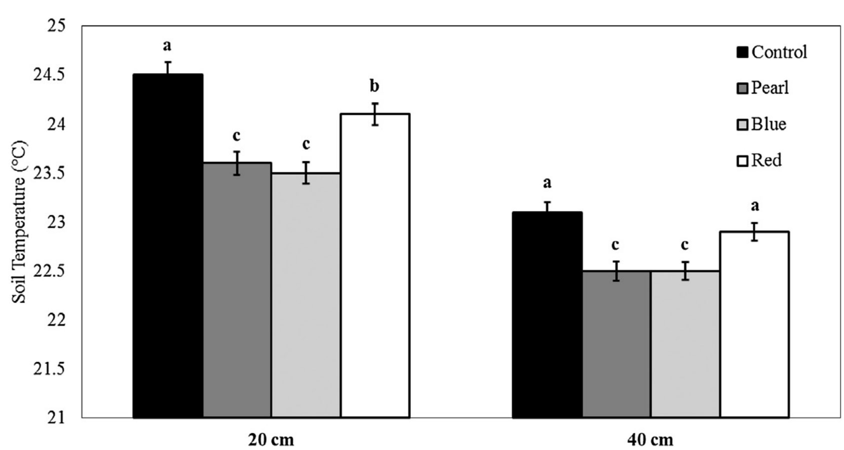

Fig. 7. Mean soil temperature (°C) (±SE, N = 4) at 20 and 40 cm depth under pearl, blue and red protective netting compared to an uncovered control in a three year-old 'Honeycrisp' apple orchard in Quincy, WA (47.23° N, 119.85° W). Different letters denote significant differences between means determined using a Tukey's HSD test ($P < 0.05$).

had more sunburned fruit than blue or red ($P < 0.05$) netting with 72.1, 82.0 and 80.2% of fruit showing no sunburn at all, respectively. Fruit from trees under blue and red netting had a lower proportion of fruit belonging to the Y1 class, i.e. fruit showing minor sunburn, compared to the control and pearl netting. The proportion of fruit belonging to Y1 for the control and under the pearl netting was 14.1 and 14.7%, respectively. Fruit belonging to Y1 is still marketed as high grade fruit and shows no reductions in quality or storability (Schrader et al., 2003; Racsko and Schrader, 2012). There were no differences in the combined proportion of fruit belonging to Y1 sunburn and clean fruit between pearl, blue and red netting ($P < 0.05$).

Fruit harvested from the control had higher proportions of fruit belonging to Y2, Y3 and tan classes. There were no differences among the different colors of protective netting in the proportions of fruit belonging to the Y2, Y3 and tan sunburn classes. Y2 and Y3 fruit are still marketable as second grade fruit but fruit belonging to the tan class is unmarketable and must be discarded (Racsko and Schrader, 2012). In the control, 5.6% of fruit belonged to the tan class. This corresponds with normal estimated losses related to sunburn in Washington State (Racsko and Schrader, 2012). Fruit that experienced necrotic sunburn damage and dropped prematurely from the tree prior to harvest were not included in this data.

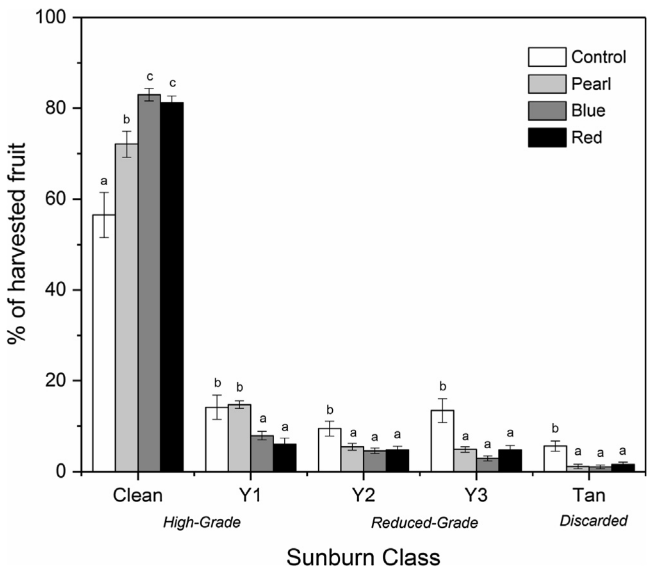

Fig. 8. The proportion of harvested fruit (%) without sunburn (clean), classes with increasing severity of sunburn (Y1, Y2, Y3 and Tan) (See Fig. 3 for sunburn scale) for fruit harvested from under pearl, blue and red protective netting compared to an uncovered control. Error bars denote standard error (n = 10).

This is similar to results reported by McCaskill et al. (2016). Since the amount of necrotic fruit that prematurely dropped was considerably higher in the control than under the protective netting (data not recorded), the estimates of sunburn losses in the non-netted control were less than was actually realized by the grower.

3.5. Conclusions

In regions with high light intensity and air temperatures, there is a fine balance between optimizing growth and quality and overexposing the apple tree or fruit to excess abiotic stress. In the future, as temperatures increase and fruit mature earlier, the risks of heat and light-related stress such as sunburn will increase (Moretti et al., 2010; Stöckle et al., 2010). We anticipate that protected fruit cultivation under nets will play a substantial role in crop protection. Through the reductions in light intensity and wind speed, protective netting has the potential to reduce the amount of stress to which an orchard is exposed and mitigate the impacts of warmer temperatures and better control fruit maturation in these conditions. Furthermore, netting can reduce wind damage to the fruit.

Pertinent to the study area, reductions in air temperatures were not observed in this environment. However, reductions in leaf, fruit and soil temperature was evident and it potentially can reduce above- and below-ground stress on the trees. Such reductions also lead to substantial decreases in fruit sunburn incidence and overall losses from sunburn (Shahak et al., 2004). Protective netting also offers a reduction in potential evapotranspiration associated with the decreases in light intensity and wind speed (McCaskill et al., 2016). In apple growing regions of the world characterized by high light and high temperature conditions, growers may use overhead evaporative cooling to limit sunburn. Although this practice is associated with reducing sunburn, the excess water it brings to the orchard can lead to temporary soil water logging and adverse effects on tree health and fruit quality. In such environments, we anticipate that the use of protective netting might limit the need for overhead cooling. This would present positive environmental impacts by reducing orchard water use. Through the manipulation of light quantity and quality with the use of netting, optimization of light can reduce sunburn incidence in developing fruit as well as reduce abiotic stress factors such as leaf and soil temperature that has positive effects on overall orchard growth and productivity.

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