Low Tunnel Covering and Microclimate, Fruit Yield, and Quality in an Organic Strawberry Production System

Heidi C. Anderson¹, Mary A. Rogers¹, and Emily E. Hoover¹

ADDITIONAL INDEX WORDS. controlled-environment agriculture, *Fragaria* × *ananassa*, high tunnels, ultraviolet light

SUMMARY. Consumer demand for local and organic strawberries (*Fragaria* × *ananassa*) is increasing. Growers who can meet this demand have a competitive edge in the direct-to-consumer market. Innovations in strawberry production for northern climates offer new opportunities for growers to meet the demand for local organic strawberries. Typically adopted for season extension, the use of poly-covered tunnels for crop protection provides other benefits including protection from adverse weather. Low tunnels are easy to install, low cost, temporary protective structures that are well-adapted for annual day-neutral strawberry production, and they are more space efficient than high tunnels for these low-stature crops. A range of specialty tunnel plastics that modify and diffuse light are available, but there is little information on how these influence strawberry plant growth and performance in the field. Our objectives were to determine the effects of experimental ultraviolet blocking and transmitting plastics on light and microclimate in low tunnel environments and assess differences in fruit yield and quality in the day-neutral strawberry cultivar Albion in an organic production system. This research was conducted on U.S. Department of Agriculture-certified organic land over 2 years, in 2016 and 2017. We found that ultraviolet intensity and daily light integral (DLI) were lower in covered plots than in the open field. Maximum daily temperatures were slightly higher in covered plots. Both ultraviolet-blocking and ultraviolet-transmitting plastics improved marketable fruit yield compared with the open-field control. Strawberries grown in the open-field treatment were lower in chroma than covered plots in 2017, and there was no difference in total soluble solids between treatments in either year. Low tunnel systems allow for increased environmental control and improved fruit quality and are well-adapted for day-neutral organic strawberry production systems.

Strawberries are among the most popular fruit in the United States based on total crop value and fresh sales at grocery stores

Received for publication 19 Feb. 2019. Accepted for publication 17 May 2019.

Published online 7 August 2019.

¹Department of Horticultural Science, University of Minnesota, 1970 Folwell Avenue, St. Paul, MN 55108

We thank Jared Rubinstein, Nathan Hecht, Dr. Andrew Petran, Ignasi Riera Vila, Matthew Gullikson, Aimee Foster, Truong Nguyen, Samantha Vilella, Connor Mikre, and Sadie Green for laboratory and field support; Steve Poppe for field preparation and for low tunnel installation; Dr. William D. Hutchison for providing guidance and reviewing this work; Dr. Kathy Demchak, Dr. Eric Hanson, and the Tunnel Berries research team for materials, advice, and support; and Dr. Daniel Peck of BioWorks and Dr. H. Brett Highland of Certis USA for providing me with biopesticide samples. Funding for this research was provided by the U.S. Department of Agriculture Specialty Crops Research Initiative, award number 2014-51181-22380.

M.A.R. is the corresponding author. E-mail: roge0168@umn.edu.

This is an open access article distributed under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

<https://doi.org/10.21273/HORTTECH04319-19>

[Produce Marketing Association, 2018; U.S. Department of Agriculture (USDA), 2017]. Most strawberry acreage in the United States is conventional, but demand for organic strawberries is on the rise (Daugaard, 1999; Gu et al., 2017; Hoover et al., 2014). The high value placed on local agriculture, organic production, and direct market sales (Tourte et al., 2016) has led to increasing demand

around the country for locally produced fruits and vegetables (Howard and Allen, 2010; Jensen and Malter, 1995; Tourte et al., 2016). Currently, the U.S. strawberry industry is concentrated in California and Florida (USDA, 2017). Growers who are able to supply local and organic strawberries in other parts of the country have a competitive edge in the direct-to-consumer market (Kadir et al., 2006a; Petran et al., 2017).

Climate plays a major role in determining regional and site suitability for strawberry production (Rysin et al., 2015). Depending on the cultivar, strawberry can be sensitive to variables such as late spring frosts, low winter minimum temperatures, and short growing seasons. There are two types of commercially produced strawberry cultivars: June-bearing and day-neutral (Darrow and Waldo, 1933; Gu et al., 2017). Nationally, most commercial strawberry producers use day-neutral cultivars for their longer season and higher yield potential compared with June-bearing cultivars, but historically, day-neutral cultivars have not performed well in northern regions of the United States (Darrow and Waldo, 1933; Petran et al., 2017). However, recent developments in breeding and protected environment agriculture have created new opportunities for producing day-neutral strawberries as annuals in some regions of the United States where conditions have traditionally been considered unsuitable (Hoover et al., 2014; Petran et al., 2017; Solomon et al., 2001).

Growing strawberries under protection can have many benefits. Shielded from rain and hail, fruit sustain less damage under high tunnels than in open fields (Jett, 2007).

Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil(s)	mm	39.3701
28.3495	oz	g	0.0353
33.9057	oz/yd ²	g·m ⁻²	0.0295
1	ppm	mg·kg ⁻¹	1
6.8948	psi	kPa	0.1450
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Berries are also cleaner with less surface moisture at harvest (Karlsson and Werner, 2011), and tunnels can increase the length of time during which strawberries can be harvested (Kadir et al., 2006a; Rowley et al., 2011). High tunnel strawberry production has also been shown to promote earlier flowering and fruiting when compared with open-field production (Kadir et al., 2006a). The more diffuse light conditions under tunnels may result in better light penetration to lower leaves, thereby increasing photosynthesis (Baeza and López, 2012; Demchak, 2009). One of the most important benefits of tunnels is disease management due to the lack of moisture accumulation on leaves in a sheltered environment (Burlakoti et al., 2014; Daugaard, 1999; Demchak, 2009).

Low tunnels are similar to high tunnels but relatively unexplored as a strawberry protected environment tool. In the low tunnel system, strawberries are grown on raised beds with plastic mulch. Steel hoops spaced evenly down the length of a bed support a plastic covering roughly 2 ft above the raised bed (Demchak and Hanson, 2013; Gu et al., 2017; Hoashi-Erhardt et al., 2013; Kadir et al., 2006a; Lewers et al., 2017). Low tunnels offer some unique advantages over high tunnels. Long-term high tunnel growers have identified soil compaction and quality as an issue in their systems (Demchak and Hanson, 2013). Low tunnels, which are not permanent structures, can easily be moved to new fields annually, reducing the risk of soil compaction. This also gives growers more flexibility in adjusting the scale of production from year to year. Soil-borne diseases are problematic in strawberry production, and having the ability to rotate the planting area can improve the sustainability of strawberry production systems. This is especially true in organic systems where synthetic soil fumigants cannot be used for disease management (Rysin et al., 2015). Other problems growers have observed with high tunnels include building and maintenance costs (Lewers et al., 2017), difficulties with temperature management, and loss of tunnels in extreme weather (e.g., severe winds and excessive snow) (Demchak and Hanson, 2013). Low tunnel materials may be expensive initially, but the hoops can

be reused year after year, and actual tunnel construction is relatively simple. Temperature management is fairly easy as low tunnels do not require complex venting schemes—the sides can be opened and closed manually, and some tunnel plastics incorporate ventilation holes that run the length of the plastic. Air circulation, coupled with protection from rain, ensures that foliage, flowers, and fruit remain dry for longer periods of time, which can reduce the duration and frequency of disease infection periods (Karlsson and Werner, 2011).

For growers interested in low tunnels, new plastics designed for specific light absorption and transmission characteristics are now commercially available (Karlsson and Werner, 2011). In northern climates with short growing seasons, nontraditional plastic materials that operate as photo-selective barriers could improve crop performance or even aid in pest and disease control in a tunnel system (Baeza and López, 2012; Karlsson and Werner, 2011; Krizek et al., 2005; Paul et al., 2005). These plastic films selectively block or absorb wavelengths of light in the IR or ultraviolet ranges, or diffuse incoming direct beam solar radiation without inhibiting necessary transmission of photosynthetically active radiation (*PAR*). *PAR* includes both visible light and the spectral range important for photosynthesis, 400–700 nm (Björn, 2015). The standard films most commonly used in horticultural production transmit lower levels of ultraviolet light, allowing little or no transmission of ultraviolet-B (280–315 nm) and reduced transmission of ultraviolet-A (315–400 nm), but there are now other films that are completely opaque to ultraviolet light (Krizek et al., 2005; Paul et al., 2005).

Changing levels of light exposure can influence many aspects of crop morphology and chemistry (Ballaré et al., 2011, 2012). Total soluble solid content may be affected by the amount and quality of light a plant receives (Perkins-Veazie, 1995). Some studies have shown that fruit color and plant growth may be negatively affected by restricted ultraviolet exposure (Elfadly et al., 2012; Tsormpatsidis et al., 2011). And there is evidence suggesting that exposure to ultraviolet light improves

crop resilience in the face of environmental stressors by way of photoreceptors that trigger critical defense mechanisms (Ballaré et al., 2012; Wargent et al., 2011). At the same time, restricting ultraviolet light can reduce the spread of diseases that affect strawberry fruit quality (Baeza and López, 2012; Karlsson and Werner, 2011; Krizek et al., 2005). Although it is generally understood that ultraviolet exposure can be harmful in some ways and helpful in other ways for plants, it is unknown how changing levels of ultraviolet exposure could affect overall growth and performance of strawberry plants under low tunnels.

The objectives of this study were to evaluate the effects of ultraviolet-blocking and ultraviolet-transmitting plastics on the light and microclimate in low tunnel environments and on fruit yield and quality. We evaluated these questions in the context of an organic field production scenario as we were primarily interested in practical applications for a strawberry grower producing for local organic markets. The broader context of this study is about improving the availability and quality of strawberries and sustainable production in a cold climate to help growers meet the demand for more local strawberries.

Materials and methods

EXPERIMENTAL DESIGN AND MAINTENANCE. This research was conducted at the Minnesota Agricultural Experiment Station (MAES) in St. Paul (lat. 44.996°N, long. 93.185°W) on USDA-certified organic land in 2016 and 2017. In both years of the experiment, organic-approved practices were followed. Dormant, bare root ‘Albion’ strawberry plants were purchased and shipped from Nourse Farms (Whately, MA) before site preparation. The plants were stored in a cooler at 38 °F for 4–5 weeks until planting. Extra plants were potted in plastic pots 5 inches deep and placed in cold frames for later replacement of plants that died in the field within 2 weeks of the first planting. The potting soil was a 50/50 mix of commercially available peat-based germination media (Seed Starter Mix; Purple Cow Organics, Middleton, WI) and potting mix (Black Gold Potting Mix; Sun

Gro Horticulture, Agawam, MA), both approved for organic systems.

Soil characteristics of the planting sites were evaluated in preplanting soil tests conducted by the University of Minnesota Research Analytical Laboratory (St. Paul). Results of the soil tests are shown in Table 1. Fields were rotovated before planting with a Howard Rotovator (type R500 B-255S-R; Kongskilde Agriculture, Hudson, IL). Raised beds were made with a bed shaper (model 2121-D; Buckeye Tractor Co., Columbus Grove, OH), and plastic mulch and drip tape (two lines per bed) were laid with a mulch layer (model 2133; Buckeye Tractor Co.). Each raised bed had 1-mil-thick white-on-black embossed plastic mulch (Berry Plastics, Detroit Lakes, MN) 4 ft wide for two rows of plants staggered 12 inches apart within and 14 inches between rows, with 64 plants total within a row. A 2- to 3-ft walkway between raised beds was covered with 3-oz./yard², 300 × 3-ft black landscape fabric (Boulder Ridge Spunbound Landscape Fabric; Central Landscape Supply, St. Cloud, MN). Planting took place on 17–18 May in 2016 and 15 May in 2017. We constructed tunnels from the TunnelFlex Retractable Low Tunnel System (Dubois Agrinovation, Saint-Remi, QC, Canada). Galvanized steel hoops, 71 cm wide by 100 cm tall, were placed every 6 ft down the length of each plot.

We used a completely randomized design with two low tunnel treatments. Two experimental plastics (Lumisol, BPI Visqueen, Stevenson, UK) were used as low tunnel coverings. These plastics were 7.9 mil thick and varied in absorbance/transmittance properties. One of these was

designed to block most light in the ultraviolet A and B ranges (ultraviolet-blocking/UVB) and the other was designed to transmit low amounts of light in the ultraviolet A and B ranges (ultraviolet-transmitting/UVT). These were compared with an open-plot control and replicated four times per treatment for a total of 12 discrete independent plots. Because of manufacturing limitations and shortfalls in the supply of experimental plastics, new film was not available for use. Consequently, we sourced plastics from Michigan State University in East Lansing, where plastics had previously been used on high tunnels for 1 year. These plastics are manufactured to last for a minimum of seven years and were physically sound without visual defects. Plastic was not reused between 2016 and 2017. Yield data were collected on 32 plants in each plot.

The low tunnel plastic coverings were held in place on top of the steel hoops with bungee cords and were tied off on each end to steel anchors in the ground. For most of the season, the sides of each tunnel were partially raised ~12 inches to allow for ventilation while maintaining full coverage above the plants. In October, as night temperatures began to drop below 40 °F, the tunnel sides were fully lowered to a height of ~6 inches above the ground.

Irrigation was turned on as needed up to once per week for as long as 2 h at a time at a rate of 10 psi. Through mid-September, a liquid fish-based 2N–1.3P–0.8K fertilizer (Organic Fish and Seaweed Fertilizer; Neptune's Harvest, Gloucester, MA) was delivered to the plants up to once per week at 5 lb/acre nitrogen (80 mL) through a 2-gal fertilizer injector (EZ-FLO Injection Systems;

DripWorks, Willits, CA) connected to the drip irrigation system. This rate was based on local recommendations (Hoover et al., 2014). Weeding was performed by hand as needed. Flowers and stolons were removed from the young plants up until 1 July each year to promote vegetative growth. For pest management, two-spotted spider mites (*Tetranychus urticae*) and lygus bugs (*Lygus* sp.) were monitored weekly and certified organic spinosad (Entrust SC; Dow AgroSciences, Indianapolis, IN) was sprayed as needed, following the label rate.

LIGHT AND MICROCLIMATE. Data on temperature, relative humidity, and light intensity in the *PAR* range were collected using photosynthetic light smart sensors (S-LIA-M003), temperature/relative humidity sensors (S-THB-M008), and a remote monitoring station data logger (HOBO RX3000) (all Onset Computer Corp, Bourne, MA). Temperature/humidity sensors were installed at planting and placed in the center of two plots (two replicates) of each treatment type. One *PAR* sensor was placed in the center of a single plot (one replicate) of each treatment at the plant canopy and unobstructed by foliage, placed ~2 ft below the plastic cover. The *PAR* sensors had a measurement range of 0–2500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ over wavelengths from 400 to 700 nm. Data were logged every 30 min from the beginning of the season until after the last harvest. *PAR* data were converted to DLI by summing the daily *PAR* readings and multiplying by the time interval in seconds between measurements and are reported as moles per square meter per day. A ultraviolet meter (Light Scout; Spectrum Technologies, Aurora, IL) was used to gather data on the intensity of light in the ultraviolet range reaching the plants. The device reported intensity of ultraviolet light in the wavelength range of 250–400 nm in units of micromoles per square meter per second. These data were gathered weekly, within an hour of solar noon. At each sampling, the ultraviolet meter was placed in a cup to hold it upright and perpendicular to the ground and set in the center of each raised bed for a 2-min recording period. During that time, the ultraviolet intensity reading was recorded every 30 s and

Table 1. Soil characteristics of planting sites for day-neutral ‘Albion’ strawberry in 2016 and 2017. The two sites were ~100 m (328.1 ft) apart in the same field area on USDA-certified organic land in St. Paul, MN.

	Yr	
	2016	2017
Soil texture	Medium (silty loam)	
Soil organic matter	7.4%	5.7%
pH	7.2	6.8
Bray 1 phosphorus (ppm) ^a	100+ (very high)	
Potassium (ppm)	300+ (very high)	
Previous crop	Edible bean (<i>Phaseolus vulgaris</i>)	

^a1 ppm = 1 mg·kg⁻¹.

averaged. Because ultraviolet intensity data could not be collected simultaneously from each plot, the data were collected from each plot in a randomly assigned order on each sample date.

YIELD AND GRADE. Harvesting took place in the mornings between 9:00 AM and noon. In 2016, harvest began on 21 July (65 d after planting) and was carried out twice per week during peak production until 23 Sept., when it was reduced to once per week. In 2017, harvest began on 17 July (63 d after planting) and was carried out twice per week until 14 Sept., when it was reduced to once per week. Harvesting ceased after the first frost that killed most of the strawberry flowers, on 8 Nov. 2016 and 23 Oct. 2017. At each harvest, all fully ripe fruit were picked. Yield was recorded on a per-plot basis as the total weight in grams of harvested fruit. The total number of living plants in the experimental units of each plot was also recorded for the purpose of calculating mean yield per plant. The total yield of fruit was sorted and weighed by grade at eight different harvest periods in 2016 (during peak production). In 2017, grade data were collected throughout the season at one harvest per week for a total of 16 times. USDA standards were used to group fruit into U.S. No. 1 or U.S. No. 2, based on size and uniformity and all else (designated as low grade or unmarketable in this study) (USDA, n.d.). For the purposes of this experiment, USDA grade U.S. No. 1 and U.S. No. 2 together constituted the “marketable quality” fruit category; however, not all fruit designated as low grade or unmarketable were discarded. In many cases, this fruit was still salable for local, direct market. In 2017, verticillium wilt (*Verticillium* sp.) infection was detected and confirmed in leaf tissue analyses conducted by the University of Minnesota’s plant pathology laboratory (St. Paul), affecting 12.5% of the plants at random over the entire field area. No other diseases were detected. Dead plants were removed, and yield data were corrected for missing plants by calculating average yield per living plant in each plot at each harvest.

FRUIT COLOR AND TOTAL SOLUBLE SOLIDS. Fruit color was

measured with a colorimeter (Chroma Meter CR-400; Konica Minolta Sensing, Ramsey, NJ). Measurements were taken from a subsample of eight ripe, marketable fruit per plot. In 2016, sampling dates were 29 Aug. and 16 Sept. In 2017, sampling dates were 17 and 24 Aug., 7 and 14 Sept., and 9 and 23 Oct. Measurements were taken on the surface of each berry at the point of widest diameter and recorded in terms of the Munsell color system. The Munsell color system is based on a three-dimensional model, which assigns color values for three different attributes: hue, value, and chroma. On a three-dimensional chart, a central vertical axis represents the change in value from white at the top to black at the bottom. Radial planes leading from this axis correspond each to a particular hue, which describes the color itself (e.g., red). And chroma, which describes the intensity or saturation of hue, is measured by the perpendicular distance from any point to the vertical axis (Munsell, 1912).

Total soluble solids were measured with a digital handheld refractometer (Spectrum Technologies). Measurements were taken from a subsample of eight ripe, marketable fruit per plot. In 2016, sampling dates were 5, 12, 18, and 29 Aug. and 13 Sept. In 2017, sampling dates were 10, 24, and 31 Aug., 7 Sept., and 9 and 23 Oct. In cases where there were not eight marketable grade berries available for measuring color or total soluble solids, the next highest quality, lower grade berries were used.

STATISTICAL ANALYSES. All analyses were performed with R statistical software version 3.3.3 (R Core Team, 2013). Analysis of variance (ANOVA) was conducted with each measured factor as a function of the covering treatment (UVT, UVB, and open) to determine the presence of significant treatment differences at $P < 0.05$. Square-root transformations were performed on ultraviolet intensity data that did not fit the assumptions of normality. Untransformed means are reported in tables. Pairwise comparisons were conducted using Tukey’s honestly significant difference post hoc test, significance at $P < 0.05$.

Results

LIGHT AND MICROCLIMATE. In both years of the experiment, ultraviolet light (250–400 nm) intensity was significantly different across treatments (Table 2). Open plots were exposed to the most ultraviolet light followed by UVT plots, with UVB plots exposed to the least amount. Open and UVT plots experienced the highest ultraviolet intensity, whereas UVB plots experienced lower ultraviolet intensity. Open plots experienced the highest DLI compared with UVT and UVB plots (Table 2). The UVT and UVB plastics transmitted different levels of ultraviolet light, but similar DLI across both years. General trends in DLI showed that light decreased as the season progressed from midsummer to fall, but always remained higher in open-field environments (data not shown).

Significant differences in temperature were observed across treatments in 2016 but not in 2017. In 2016, UVT and UVB plots had the highest maximum daily temperatures, followed by open plots, but this trend was not observed in 2017 (Table 3). Mean maximum daily temperatures varied by less than 3 °C across treatments in both years. Differences in maximum daily temperatures were more pronounced later in the season when tunnels were closed (Fig. 1). Maximum daily relative humidity levels were different across treatments in both years, but differences were only significant in 2017. In 2016, UVB plots had the highest maximum daily relative humidity levels, but in 2017, open plots had the highest maximum daily relative humidity levels (Table 3). In both years, mean values of maximum daily relative humidity differed by less than 3.5% across treatments. As with temperature, differences were more pronounced late in the season when tunnels were closed.

YIELD AND GRADE. Cumulative yield per plant was similar across all treatments in both years, averaging 520–667 g/plant (Table 4). UVT/UVB plots produced significantly higher percentage marketable yield than open plots in both years (Table 4). In 2016, the difference in the percent marketable yield between UVT and UVB plots was also significant, with UVT plots producing

Table 2. Average ultraviolet (UV) light intensity and average daily light integral (DLI) measured from strawberry planting date through the last harvest under open-field and two covering treatments, UV transmitting (UVT) and UV blocking (UVB), in 2016 and 2017.

Treatment	Mean ultraviolet intensity [mean $\pm$ SE ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)] ^z	Mean DLI [mean $\pm$ SE ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)] ^y
2016		
Open	89.1 $\pm$ 7.8 a ^x	32.7 $\pm$ 1.1 a
UVT	59.1 $\pm$ 5.2 b	22.0 $\pm$ 0.9 b
UVB	4.8 $\pm$ 0.3 c	22.7 $\pm$ 1.0 b
<i>P</i> > <i>F</i>	0.0001	0.0001
2017		
Open	101.8 $\pm$ 4.2 a	31.5 $\pm$ 1.3 a
UVT	59.5 $\pm$ 2.9 b	22.0 $\pm$ 1.0 b
UVB	8.2 $\pm$ 0.5 c	21.8 $\pm$ 1.0 b
<i>P</i> > <i>F</i>	0.0001	0.0001

^zUV light measurements were obtained at weekly intervals.

^yDaily instantaneous *PAR* readings were obtained at 30-min intervals from planting through the last harvest and converted to DLI.

^xLetters denote statistically significant differences within columns within years by Tukey's post hoc test at *P* < 0.05.

Table 3. Maximum daily temperature and daily percent relative humidity (RH) calculated from measurements collected every 30 min from strawberry planting date through the last harvest in six plots under open-field and two covering treatments, ultraviolet transmitting (UVT) and ultraviolet blocking (UVB), in 2016 and 2017.

Treatment	Maximum daily temp [mean $\pm$ SE ($^{\circ}\text{C}$)] ^z	Mean maximum daily RH [mean $\pm$ SE (%)]
2016		
Open	26.6 $\pm$ 0.4 b ^y	95.5 $\pm$ 0.3
UVT	29.2 $\pm$ 0.4 a	95.8 $\pm$ 0.2
UVB	28.8 $\pm$ 0.4 a	96.3 $\pm$ 0.2
<i>P</i> > <i>F</i>	0.0001	0.0598
2017		
Open	26.3 $\pm$ 0.4	95.9 $\pm$ 0.3 a
UVT	26.8 $\pm$ 0.4	92.4 $\pm$ 0.4 b
UVB	27.1 $\pm$ 0.4	93.6 $\pm$ 0.3 b
<i>P</i> > <i>F</i>	0.3270	0.0001

^z(1.8 $\times$ $^{\circ}\text{C}$) + 32 = $^{\circ}\text{F}$.

^yDifferent letters denote statistically significant differences within columns within years by Tukey's post hoc test at *P* < 0.05.

a higher percentage of marketable yield than UVB plots. Differences in marketable yield across treatments were less pronounced in 2017 than in 2016, and overall, all treatments produced higher percent marketable yield in 2017 than in 2016. In 2016, marketable yield averaged 218.4 g/plant in open plots, 474.7 g/plant in UVT plots, and 313.6 g/plant in UVB plots. In 2017, marketable yield averaged 373.3 g/plant in open plots, 471.2 g/plant in UVT plots, and 510.4 g/plant in UVB plots. Yield accumulated at different rates over the course of each season in 2016 and 2017 (Fig. 2). In 2017, yield accumulated quickly early in the season, whereas in 2016, the greatest gains in yield did not occur until $\approx$ 120 d after planting.

FRUIT COLOR AND TOTAL SOLUBLE SOLIDS. In 2016, no statistically significant differences in color hue (*P* = 0.554), value (*P* = 0.404), or

chroma (*P* = 0.164) were found (data not shown). In 2017, the fruit color chroma differed significantly by treatment (Table 5), with color chroma being lowest in open plots. Total soluble solids did not differ significantly by treatment in either 2016 (*P* = 0.58) or 2017 (*P* = 0.773) (data not shown).

Discussion

PAR and ultraviolet intensities differed across treatments as expected, but it was somewhat surprising to find only small and mostly insignificant differences in mean daily temperature and humidity levels. This was probably because the tunnel sides remained fully open for most of the season. Had the tunnel sides been lowered to some midpoint between closed and open, we may have observed higher temperatures and humidity levels under UVT and UVB plots than open plots.

However, day-neutral strawberry cultivars are sensitive to extreme heat because of shallow root systems, and increasing temperatures could have been detrimental (Hoover et al., 2016; Kadir et al., 2006b). Strawberry plants are capable of flowering and producing fruit within a wide range of temperatures, but 29 $^{\circ}\text{C}$ is considered the upper limit at which they will initiate flowers (Hoover et al., 2016). This upper limit was reached in 2016 as the mean maximum daily temperature over the course of the season was 29.2 $^{\circ}\text{C}$ in UVT plots and 28.8 $^{\circ}\text{C}$ in UVB plots. Kadir et al. (2006b) have shown that temperatures above 30 $^{\circ}\text{C}$ reduce the photosynthetic rate in strawberry, and so it is unlikely that adjusting tunnel sides to increase daily temperatures would have produced any benefits beyond those benefits already achieved by covering plots.

Fig. 1. Maximum daily temperature in six plots under open-field and two covering treatments, ultraviolet transmitting (UVT) and ultraviolet blocking (UVB), in (A) 2016 and (B) 2017. Points on the graph indicate daily maximum readings averaged between two replicates of each covering type; lines displayed are local regression trend lines; $(1.8 \times ^\circ\text{C}) + 32 = ^\circ\text{F}$.

Table 4. Season total strawberry fruit yield per plant and percent marketable strawberry fruit yield under open-field and two covering treatments, ultraviolet transmitting (UVT) and ultraviolet blocking (UVB), in 2016 and 2017.

Total fruit yield [mean $\pm$ SE (g)] ^z		Marketable yield [mean $\pm$ SE (%)]
Treatment		2016
Open	519.9 $\pm$ 31.3 b ^y	42 $\pm$ 2 c
UVT	668.6 $\pm$ 25.4 a	71 $\pm$ 1 a
UVB	570.1 $\pm$ 36.6 b	55 $\pm$ 2 b
<i>P</i> > F	0.0058	<0.0001
		2017
Open	557.1 $\pm$ 27.6	67 $\pm$ 2 b
UVT	604.1 $\pm$ 33.8	78 $\pm$ 2 a
UVB	654.4 $\pm$ 32.7	78 $\pm$ 1 a
<i>P</i> > F	0.1030	<0.0001

^a1 g = 0.0353 oz.

^yDifferent letters denote statistically significant differences within columns within years by Tukey's post hoc test at $P < 0.05$.

There are many factors that may have contributed to the differences in fruit yield and marketability observed in this study. Overall, total yields in this study were higher than yields previously reported for 'Albion' strawberry plants grown on

plasticulture in the same experiment station in St. Paul, MN. In a previous study conducted in 2013 and 2014, yields were reported to range from an average 290 g/plant when low tunnels were not used to 480 g/plant when low tunnels were used (Petran

et al., 2017). In our study, the yield averages ranged from 520 to 667 g/plant. In comparison, 'Albion' yields are typically much higher in Watsonville, CA, where yields can reach up to 1000 g/plant (Samtani et al., 2011). This likely is due to differences in field or weather conditions. Yield may have peaked at different points in the season each year because of differences in weather conditions early on. In 2016, the month of June was drier and cooler, with 2.13 cm of rainfall and a mean temperature of 19.6 °C, than 2017, with 10.7 cm of rainfall and a mean temperature of 21.9 °C (National Weather Service, 2017). Although the DLI was lower in UVT/UVB plots than open plots, fruit yield and marketability were still higher in UVT/UVB plots in both years, indicating that the lower threshold for light intensity necessary for plant growth and functioning was still met by conditions in UVT/UVB plots. Leaf-level photosynthetic measurements taken on strawberry plants in both open and covered production systems in Maryland showed that 90% of the light-saturated photosynthetic rate occurred at a PAR of 800 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Condori et al., 2017). In our study, the maximum daily PAR intensity far exceeded that level across all treatments and DLI was within sufficient ranges reported for the vegetative growth of strawberry (Miyazawa et al., 2009).

UVT plots produced higher yields and a higher percent marketable yield compared with UVB plots in 2016, but not in 2017. de Lima Nechet et al. (2015) found that differences in ultraviolet intensity did not promote changes in strawberry fruit production or quality in studies in Brazil. However, increases in ultraviolet can increase sporulation for certain fungal diseases, which can negatively affect both yield and quality (de Lima Nechet et al., 2015; West et al., 2000).

Sugar content in strawberries may be affected by the amount and quality of light a plant receives (Perkins-Veazie, 1995), but the different light environments created by the treatments in this study did not result in significant differences in fruit sugar content. This is in contrast to a study by Palmieri et al. (2017), which found increases in sugar content at lower levels of ultraviolet radiation. Overall,

Fig. 2. Mean cumulative strawberry fruit yield in 12 plots under open-field and two covering treatments, ultraviolet transmitting (UVT) and ultraviolet blocking (UVB), in (A) 2016 and (B) 2017. Each point is the mean cumulative yield per plant at that point in time (days after planting), calculated from total yields per plot divided by total number of living plants per plot; 1 g = 0.0353 oz.

Table 5. Strawberry fruit color value and chroma, as described by the Munsell scale, in 12 plots under open-field and two covering treatments, ultraviolet transmitting (UVT) and ultraviolet blocking (UVB), analyzed across six sampling dates in 2017. Value can range from 1 (black) to 10 (white). Chroma can range from 0 (no saturation) to 12 (maximum saturation).

Covering		Color value (mean $\pm$ SE)		Color chroma (mean $\pm$ SE)	
Open		3.2 $\pm$ 0.03		7.5 $\pm$ 0.08 b ^z	
UVT		3.3 $\pm$ 0.03		7.7 $\pm$ 0.08 ab	
UVB		3.4 $\pm$ 0.05		7.8 $\pm$ 0.09 a	
ANOVA	Df	F	P	F	P
	2	2.904	0.0565	4.332	0.014

^zDifferent letters denote statistically significant differences within columns within years by Tukey's post hoc test at $P < 0.05$.

the total soluble solid levels observed in our study ranged from 5% to 11%, comparable to levels reported in our location by Petran et al. (2017) who evaluated total soluble solids in 'Albion' under various cultural practices.

The lack of significant differences found in fruit color in 2016 may have simply been due to the small sample size that year, when color

measurements were taken on just two separate dates. In 2017, when color measurements were taken on six separate dates, fruit color chroma and value were significantly higher in fruit from UVB plots than fruit from open plots, but not compared with UVT plots. Visual attributes are perceived by consumers as among one of the strongest determinants of purchasing

choice (Moser et al., 2011), but the color differences observed in our study, although statistically significant, were small and possibly indiscernible to the naked eye. In addition, without further analyses, we do not know whether these color differences reflected significant differences in nutritional value or other quality parameters. In at least one study, ultraviolet radiation was found to speed the rate of color development, which was also correlated with an increase in fruit anthocyanin, flavonoid, and phenolic contents at harvesting (Tsormpatzidis et al., 2011). Temperature may also play a role. Kadir et al. (2006b) found that keeping strawberry plants at low temperatures (below 20 °C) increased redness of the fruit; however, this effect was not observed in all cultivars and is contrary to our findings where the highest strawberry chroma was observed in the UVB plots, which tended to be warmer than open-field plots for 'Albion'.

Low tunnels can improve organic strawberry production systems in cold climates by increasing yields and fruit quality, but we found no clear advantages or disadvantages to using a ultraviolet-blocking vs. a ultraviolet-transmitting plastic covering. 'Albion' day-neutral strawberry produced higher yields and higher percent of marketable fruit in UVT/UVB covered plots than open control plots, but it is unclear whether the differences in ultraviolet transmission through the plastic coverings influenced these measured variables. Shielded from rain and wind, fruit were better protected under the tunnels and less likely to sit with surface moisture after heavy rain events, and these were likely important factors that led to higher percent marketable fruit harvested from covered plots, and corroborate a previous study (Petran et al., 2017). In this study, fruit color was minimally affected by the type of covering and fruit total soluble solid content was unaffected. We were able to assess fruit quality based on a few parameters, but to more fully assess the effects of light on the fruit, it would be useful to evaluate more cultivars and levels of secondary metabolites, as well as consumer sensory panels. Differences in ultraviolet transmission through plastics might have variable effects on plant growth and production from

year to year depending on weather conditions. To better understand how *PAR* or ultraviolet transmission through plastic covering affects strawberry plant growth and production, evaluating ultraviolet and *PAR* intensity at different wavelengths within the *PAR* and ultraviolet spectral ranges might allow for additional information. Presently, use of plastic coverings to selectively block ultraviolet light in protected cropping systems may be most relevant at higher altitudes or closer to the equator where ambient ultraviolet intensity is highest. However, in the future, large-scale shifts in environmental conditions due to climate changes that alter cloud cover and snow cover, a weakening ozone layer, and various land-use intensifications may increase ambient ultraviolet intensity around the world (Ballaré et al., 2011; Gigahertz-Optik Inc., 2008; Paul et al., 2005).

Conclusions

Our research on the effects of ultraviolet-blocking and transmitting plastics in day-neutral strawberry production systems showed differences in ultraviolet light quality between treatments, with less ultraviolet light transmitted in blocking plastics. The open-field plots experienced higher DLI levels than the covered plots, which experienced similar levels. Differences in light quality translated into differences in total yield between treatments in 2016, with ultraviolet-transmitting plastic plots producing more overall fruit than the ultraviolet-blocking plastic and the open-field plots. However, no treatment effect was observed in 2017. Percent marketable strawberry fruit was higher in both years under covered treatments vs. open-field plots. Our research shows that low tunnel systems can improve marketable fruit yield of day-neutral strawberry systems; however, advantages of ultraviolet-blocking and transmitting plastics remain unclear.

Literature cited

- Baeza, E. and J.C. López. 2012. Light transmission through greenhouse covers. *Acta Hort.* 956:425–440.
- Ballaré, C.L., M.M. Caldwell, S.D. Flint, S.A. Robinson, and J.F. Bornman. 2011. Effects of solar ultraviolet radiation on terrestrial ecosystems. *Patterns, mechanisms, and interactions with climate change. Photochem. Photobiol. Sci.* 10:226–241.
- Ballaré, C.L., C.A. Mazza, A.T. Austin, and R. Pierik. 2012. Canopy light and plant health. *Plant Physiol.* 160:145–155.
- Björn, L.O. (ed.). 2015. *Photobiology: The science of light and life*. 3rd ed. Springer, New York, NY.
- Burlakoti, R.R., J. Zandstra, and K. Jackson. 2014. Evaluation of epidemics and weather-based fungicide application programmes in controlling anthracnose fruit rot of day-neutral strawberry in outdoor field and protected cultivation systems. *Can. J. Plant Pathol.* 36:64–72.
- Condori, B., D.H. Fleisher, and K. Lewers. 2017. Relationship of strawberry yield with microclimate factors in open and covered raised-bed production. *Trans. Amer. Soc. Agr. Biol. Eng.* 60:1511–1525.
- Darrow, G.M. and G.F. Waldo. 1933. Photoperiodism as a cause of the rest period in strawberries. *Science* 77:353–354.
- Daugaard, H. 1999. Cultural methods for controlling *Botrytis cinerea* Pers. in strawberry. *Biol. Agr. Hort.* 16:351–361.
- de Lima Nechet, K., D.W. Heck, D. Terao, and B. de Almeida Halfeld-Vieira. 2015. Effect of the increase of UV-B radiation on strawberry fruit quality. *Scientia Hort.* 193:7–12.
- Demchak, K. 2009. Small fruit production in high tunnels. *HortTechnology* 19:44–49.
- Demchak, K. and E.J. Hanson. 2013. Small fruit production in high tunnels. *Acta Hort.* 987:41–44.
- Elfadly, E.M., J.J. Wargent, W. Sobeih, J.P. Moore, and N.D. Paul. 2012. UV radiation as an exploitable and diverse tool in the regulation of crop quality and yield. *Acta Hort.* 956:67–74.
- Gigahertz-Optik Inc. 2008. Plant physiology. 15 Nov. 2017. <<https://light-measurement.com/plant-physiology/>>.
- Gu, S., W. Guan, and J.E. Beck. 2017. Strawberry cultivar evaluation under high-tunnel and organic management in North Carolina. *HortTechnology* 27:84–92.
- Hoashi-Erhardt, W., P. Moore, D. Collins, A. Bary, and C. Cogger. 2013. Evaluation of day-neutral cultivars for organic strawberry production in Washington. *Acta Hort.* 1001:167–174.
- Hoover, E., S. Wold-Burkness, S. Poppe, A. Petran, E. Jordan, and P. Hugunin. 2014. Cold climate strawberry farming. 31 May 2019. <<http://hdl.handle.net/11299/164095>>.
- Hoover, E., C. Rosen, J. Luby, and S. Wold-Burkness. 2016. Day-neutral strawberry production in Minnesota. 31 May 2019. <<http://hdl.handle.net/11299/197960>>.
- Howard, P.H. and P. Allen. 2010. Beyond organic and fair trade? An analysis of ecolabel preferences in the United States. *Rural Sociol.* 75:244–269.
- Jensen, M.H. and A.J. Malter. 1995. Protected agriculture: A global review. World Bank Tech. Paper No. 253.
- Jett, L.W. 2007. Growing strawberries in high tunnels in Missouri. 18 Dec. 2017. <<https://www.hort.vt.edu/ghvegetables/documents/High%20Tunnel%20Construction%20and%20Crop%20Production/High%20Tunnel%20Strawberries%20by%20Lewis%20Jett.pdf>>.
- Kadir, S., E. Carey, and S. Ennahli. 2006a. Influence of high tunnel and field conditions on strawberry growth and development. *HortScience* 41:329–335.
- Kadir, S., G. Sidhu, and K. Al-Khatib. 2006b. Strawberry (*Fragaria ×ananassa* Duch.) growth and productivity as affected by temperature. *HortScience* 41:1423–1430.
- Karlsson, M.G. and J.W. Werner. 2011. High tunnel covering materials for northern field production. *Acta Hort.* 893:1333–1340.
- Krizek, D.T., H.D. Clark, and R.M. Mirecki. 2005. Spectral properties of selected UV-blocking and UV-transmitting covering materials with application for production of high-value crops in high tunnels. *Photochem. Photobiol.* 81:1047–1051.
- Lewers, K.S., D.H. Fleisher, and C.S.T. Daughtry. 2017. Low tunnels as a strawberry breeding tool and season-extending production system. *Intl. J. Fruit Sci.* 17:233–258.
- Miyazawa, Y., S. Hikosaka, E. Goto, and T. Aoki. 2009. Effects of light conditions and air temperature on the growth of everbearing strawberry during the vegetative stage. *Acta Hort.* 842:817–820.
- Moser, R., R. Raffaelli, and D. Thilmany-McFadden. 2011. Consumer preferences for fruit and vegetables with credence-based attributes: A review. *Intl. Food Agribus. Mgt. Rev.* 14:121–142.
- Munsell, A.H. 1912. A pigment color system and notation. *Amer. J. Psychol.* 23:236–244.

- National Weather Service. 2017. Weather information for the Twin Cities. 1 Jan. 2018. <<https://www.weather.gov/mpx/mspcimate>>.
- Palmieri, L., D. Masuero, P. Martinatti, G. Baratto, S. Martens, and U. Vrhovsek. 2017. Genotype-by-environment effect on bioactive compounds in strawberry (*Fragaria × ananassa* Duch.). *J. Sci. Food Agr.* 97:4180–4189.
- Paul, N.D., R.J. Jacobson, A. Taylor, J.J. Wargent, and J.P. Moore. 2005. The use of wavelength-selective plastic cladding materials in horticulture: Understanding of crop and fungal responses through the assessment of biological spectral weighting functions. *Photochem. Photobiol.* 81:1052–1060.
- Perkins-Veazie, P. 1995. Growth and ripening of strawberry fruit. *Hort. Rev.* 17:267–297.
- Petran, A., E. Hoover, L. Hayes, and S. Poppe. 2017. Yield and quality characteristics of day-neutral strawberry in the United States upper Midwest using organic practices. *Biol. Agr. Hort.* 33:73–88.
- Produce Marketing Association. 2018. Top 20 fruits and vegetables sold in the U.S. 19 Dec. 2018. <<https://www.pma.com/content/articles/2017/05/top-20-fruits-and-vegetables-sold-in-the-us>>.
- R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rowley, D., B.L. Black, and D. Drost. 2011. Late-season strawberry production using day-neutral cultivars in high-elevation high tunnels. *HortScience* 46:1480–1485.
- Rysin, O., A. McWhirt, G. Fernandez, F.J. Louws, and M. Schroeder-Moreno. 2015. Economic viability and environmental impact assessment of three different strawberry production systems in the southeastern United States. *HortTechnology* 25:585–594.
- Samtani, J.B., H.A. Ajwa, J.B. Weber, G.T. Browne, S. Klose, J. Hunzie, and S.A. Fennimore. 2011. Evaluation of non-fumigant alternatives to methyl bromide for weed control and crop yield in California strawberries (*Fragaria ananassa* L.). *Crop Prot.* 30:45–51.
- Solomon, M.G., C.N. Jay, P.J. Innocenzi, J.D. Fitzgerald, D. Crook, A.M. Crook, M.A. Easterbrook, and J.V. Cross. 2001. Review: Natural enemies and biocontrol of pests of strawberry in northern and central Europe. *Biocontrol Sci. Technol.* 11:165–216.
- Tourte, L., M. Bolda, and K. Klonsky. 2016. The evolving fresh market berry industry in Santa Cruz and Monterey counties. *Calif. Agr.* 70(3):107–115.
- Tsormpatsidis, E., M. Ordidge, R.G.C. Henbest, A. Wagstaffe, N.H. Battey, and P. Hadley. 2011. Harvesting fruit of equivalent chronological age and fruit position shows individual effects of UV radiation on aspects of the strawberry ripening process. *Environ. Exp. Bot.* 74:178–185.
- U.S. Department of Agriculture. n.d. Strawberries grades and standards. 2 July 2016. <<https://www.ams.usda.gov/grades-standards/strawberries-grades-and-standards>>.
- U.S. Department of Agriculture. 2017. Noncitrus fruits and nuts: 2016 Summary. 9 Jan. 2018. <https://www.nass.usda.gov/Publications/Todays_Reports/reports/ncit0617.pdf>.
- Wargent, J.J., E.M. Elfadly, J.P. Moore, and N.D. Paul. 2011. Increased exposure to UV-B radiation during early development leads to enhanced photoprotection and improved long-term performance in *Lactuca sativa*. *Plant Cell Environ.* 34:1401–1413.
- West, J.S., S. Pearson, P. Hadley, A.E. Wheldon, F.J. Davis, A. Gilbert, and R.G.C. Henbest. 2000. Spectral filters for the control of *Botrytis cinerea*. *Ann. Appl. Biol.* 136:115–120.