Cultivar Selection and Placement of Shadecloth on Midwest High Tunnels Affects Colored Bell Pepper Yield, Fruit Quality, and Plant Growth

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Abstract. Growing colored bell peppers in high tunnels enhances fruit quality and accelerates ripening. While there are benefits to high tunnel pepper production, increased heat inside the structures can lead to plant stress, blossom drop, sunscald, and reduced marketable yields. The objective of this study was to test shadecloth treatments placed on high tunnels to mitigate heat stress and improve colored bell pepper yield and fruit quality, while also identifying cultivars that perform well within Midwest high tunnel systems. Research was conducted at the Iowa State University Horticulture Research Station (Ames, IA) from 11 May to 11 Oct. in 2017 and 3 May to 9 Oct. in 2018. Six single-poly passively ventilated Quonset high tunnels were used for the experiment. The shade treatments (no shadecloth, 30% light-reducing shadecloth, and 50% light-reducing shadecloth) were applied in June of each season. Within each shade treatment, there were three randomized complete blocks of the seven colored bell pepper cultivars (Archimedes, Delirio, Flavorburst, Red Knight, Sirius, Summer Sweet, and Tequila). Data were collected on yield, fruit quality, and plant growth characteristics. Environmental parameters were monitored throughout the growing season. Both the 30% and 50% shadecloth treatments reduced monthly average and maximum air temperatures within high tunnels, with the largest differences occurring in the months of July and August. The use of a shadecloth reduced the incidence of sunscald by 59% between no shade and 50% shadecloth treatments. While there was no difference between 30% and 50% shade treatments, the use of 50% shadecloth caused a decrease in both marketable number (32%) and weight (29%) of pepper fruit compared with the control. ‘Tequila’, ‘Delirio’, and ‘Flavorburst’ had more marketable fruit per plant. Shade treatments did not affect fruit soluble solids content (SSC), pH, or total titratable acidity (TTA). Shade treatments had no effect on Soil Plant Analysis Development (SPAD) readings, shoot biomass, the number of leaves per plant or the total leaf area per plant; however, plant height increased by an average 14.5 cm for plants under shadecloth treatments. Average leaf size was 11.2 cm² larger on plants grown under the 50% shadecloth, compared with the control. Several cultivar differences existed for each fruit quality and plant growth parameter. While differences in fruit quality and plant growth parameters were limited among shade treatments, decreasing marketable yield is concerning. Our research suggests that Midwest growers should not exceed 30% light-reducing shadecloth on their high tunnels for colored bell pepper production.

Colored sweet bell peppers (*Capsicum annuum*) are a category of large, blocky peppers that are horticulturally mature when green, but continue to ripen to physiological maturity in colors including red, yellow, orange, purple, white, brown, or black (Simonne et al., 1997). Fresh bell peppers are an important source of ascorbic acid and provitamin A, with green, red, and orange peppers having the highest concentrations of these antioxidants (Simonne et al., 1997). While green bell peppers still

dominate consumer preferences, markets exist for colored bell peppers, particularly orange, red, and yellow (Frank et al., 2001), and fresh market demand for colored peppers has been increasing (Jovicich et al., 2005).

Colored bell peppers are usually priced two to three times higher than their green counterparts (Jovicich et al., 2005), which compensates for the increased time needed for peppers to go through the period of coloring that lengthens crop exposure to adverse

environmental conditions that can damage the fruit and lead to reduced yield and quality (Day, 2010). Jovicich et al. (2005) found greenhouse-grown colored bell peppers were worth up to five times more than those produced in open field conditions, which may explain why colored bell pepper production takes place extensively under protection (Lopez-Marin et al., 2012). Peppers are among the top five most common crops grown in Midwest high tunnels (Knewton et al., 2010a); and though more recent data are needed on production trends, the underlying assumption is that high tunnel production of colored bell peppers in the Midwest is increasing.

A high tunnel is a solar-heated, passively ventilated, plastic-covered structure that is used to produce high-value specialty crops (Jett, 2017; Lamont, 2009), and small-scale growers serving local markets are the primary users of high tunnels (Carey et al., 2009; Zheng et al., 2019). In the Midwest, high tunnels are an especially important tool for growing solanaceous crops (Carey et al., 2009; Lamont, 2009) because they extend the growing season substantially (Lamont, 2009; Reeve and Drost, 2012) while increasing yield (Waterer, 2003) and improving fruit quality (O’Connell et al., 2012). These improvements in crop production are achieved, in large part, because of the protection afforded by the high tunnel from adverse weather including rain, wind, and hail (Lamont, 2009).

High tunnels maintain a higher soil temperature throughout the duration of the growing season, which improves crop growth (Gent, 1992; Knewton et al., 2010b), and air temperatures within high tunnels increase the total number of growing degree days (GDD) and the rate at which GDD accumulate (Both et al., 2007; Waterer and Bantle, 2000). Increased GDD accumulation accelerates solanaceous crop growth, development, and ripening (Both et al., 2007; O’Connell et al., 2012; Waterer and Bantle, 2000), and harvest from high tunnel crops can occur 2 to 5 weeks ahead of crops grown in open-field conditions (Kaiser and Ernst, 2012). This acceleration of growth becomes especially important for colored bell pepper production because the development of mature fruit color can take an additional 20 to 30 d after the fruit has reached the mature green stage (Vidigal et al., 2011).

While high tunnels are an important production tool for solanaceous crops, farmers continue to struggle with management challenges within high tunnels, as recently reported by Bruce et al. (2019). Challenges within high tunnel production systems are wide-ranging (Bruce et al., 2019; Zheng et al., 2019), but they include management of heat-related stress (Díaz-Pérez and Smith, 2017). Excess heat can increase bell pepper flower and fruit abortion (Bosland and Votava, 2000; Deli and Tiessen, 1969) as well as increase the incidence of physiological disorders including sunscald (Barber and Sharpe, 1971) and blossom-end rot (BER) (Olle and Bender, 2009).

Bell peppers are adapted to average growing temperatures between 18 and 29 °C (Swiader

and Ware, 2002). Night and daytime temperatures above 24 and 32 °C, respectively, lead to flower abortion and stalled fruit set (Bosland and Votava, 2000; Swiader and Ware, 2002). Unfortunately, flower abortion and fruit loss of bell peppers because of high temperatures are common problems in the United States (Bosland and Votava, 2000). The term “sunscald” has been used to define a general category of fruit tissue injury that results from direct exposure to solar radiation, and the physiological disorder can cause economically important losses in bell pepper production (Barber and Sharpe, 1971). BER is a symptom of a localized calcium deficiency, commonly seen in fruit of tomatoes and peppers (Taylor and Locascio, 2004); and several factors, including genetics, growth rate, irrigation regime, and relative humidity, have been shown to have an effect on BER incidence on fruit (Coolong et al., 2019; Taylor and Locascio, 2004). The presence of BER makes fruit unmarketable, and losses because of BER have been reported as high as 35% in the southeastern United States (Coolong et al., 2019). While a large-scale field producer may be able to absorb a larger percentage loss without economic impact, small-scale growers who have the added expense of the high tunnel must work to optimize production and avoid losses related to excess heat.

In temperate climates, producers experience heat-related crop challenges within high tunnels in the summer production months (Díaz-Pérez and Smith, 2017). Techniques to manage excess heat within high tunnels include the use of either forced or natural ventilation (Zheng et al., 2019), whitewashing of the high tunnel (Díaz-Pérez and Smith, 2017), and shade cloth (shade netting) (Díaz-Pérez and Smith, 2017; Drost and Maughan, 2018).

While ventilation including gables, fans, and roof vents have been identified as important tools for heat management in high tunnels (Zheng et al., 2019), these may be cost-prohibitive for many small-scale growers. The use of shade cloth may be the most economically feasible option on many farms (Díaz-Pérez, 2014; Drost and Maughan, 2018).

Shade cloth (or shade netting) is typically made of woven or knitted plastic materials such as high-density polyethylene or polypropylene (Castellano et al., 2008) and is commonly black (Stamps, 2009). Shade cloth has been shown to improve yield (Ambrózy et al., 2016; Elad et al., 2007; Selahle et al., 2015) and postharvest quality of sweet bell peppers (Ambrózy et al., 2016; Kong et al., 2013; Mashabela et al., 2015; Selahle et al., 2015).

Shade cloth is cited as a tool to manage excess heat and solar radiation (Stamps, 2009), but the recommendations for level of light reduction and color of shade cloth vary. Many recent studies of the effects of shading on colored bell pepper production have been conducted outside of the United States (Ambrózy et al., 2016; Díaz-Pérez and Smith, 2017; Elad et al., 2007; Kong et al., 2013; Mashabela et al., 2015; Selahle et al., 2015) or in regions excluding the Midwest (Day, 2010; Díaz-Pérez 2013, 2014). Furthermore, many studies are conducted in open-field conditions (Ambrózy et al., 2016; Day, 2010; Díaz-Pérez, 2013, 2014; Kong et al., 2013), which makes it more difficult to predict plant performance under shade within high tunnel production systems. Research from the Southeast region using shade structures in open-field conditions suggests the optimum shade level to improve bell pepper plant health and yield is between 30% and 47% (Díaz-Pérez, 2013, 2014); however, shade recommendations for Midwest high tunnel pepper production are unknown.

The purpose of the present research was to define responses of colored pepper production to high tunnel shade cloth use in the Midwest. Our objectives were to 1) test black shade cloth with light-reduction levels that were within the ideal (30%) as well as the upper limit (50%) of the current recommendations, and 2) evaluate the performance of seven commercially available bell pepper cultivars with four different colors at maturity—orange, purple, red, and yellow—while assessing their response to the shade treatments.

Materials and Methods

Site description. Research was conducted March to October in both 2017 and 2018 at the Iowa State University Horticulture Research Station in Ames, IA. Six Quonset-style GrowSpan Round Premium High Tunnels (PB01662R4; FarmTek, Dyersville, IA) with dimensions 4.3 m wide × 10.9 m long × 3.2 m tall were used for both seasons, and the length of the high tunnels were oriented north to south. All high tunnels had a single layer of 6-mil polyethylene film and had manual roll-up sides. Three of the high tunnels were constructed prior in 2011, and new polyethylene film was placed on the high tunnels in 2015 (Tufflite® IV Clear; Berry Global Inc., Evansville, IN). The additional three high tunnels were constructed in Spring 2017. For purposes of the study, the tunnels constructed in 2011 were considered block 1 (B1) and the tunnels constructed in 2017 were considered block 2

(B2). Blocking of the high tunnels was used to account for differences between the two sets with respect to soil properties, irrigation source, and age of polyethylene film.

The B1 high tunnels were used to grow crops of colored bell peppers (*Capsicum annuum*) during the 2015 and 2016 seasons. The soils within the B1 and B2 high tunnels were Clarion loam and Webster clay loam, respectively. Soil samples were taken at time of planting in both 2017 and 2018, and the results are summarized in Table 1. Irrigation water applied via drip irrigation was sourced from rural municipal water for B1 high tunnels and was pumped from a pond located at the research station for B2 high tunnels.

Transplant production. Seven colored bell pepper cultivars used in this study were representative of four unique colors at maturity (Fig. 1). Red cultivars were ‘Archimedes’ (Seedway, LLC, Hall, NY) and ‘Red Knight’ (Seedway, LLC). Yellow cultivars included ‘Flavorburst’ (Seedway, LLC), ‘Summer Sweet’ (Harris Seeds™, Rochester, NY), and ‘Sirius’ (Siegers Seed Company, Holland, MI). Finally, ‘Delirio’ (Seedway, LLC) and ‘Tequila’ (Seedway, LLC) represented orange and purple cultivars, respectively. All transplants were grown in the Iowa State University Department of Horticulture greenhouse maintained at 20 to 22 °C from 0600 to 2200 hr and 17 to 19 °C from 2200 to 0600 hr. Supplemental irradiance was provided during 0600 to 2200 hr with 1000 W, high-pressure sodium lamps.

On 26 Mar. 2017 and 13 Mar. 2018, seeds were sown in 72-cell propagation trays filled with a soilless potting mix (Metro Mix 360; Sun Gro Horticulture, Agawam, MA). Seedlings were watered as needed and fertilized uniformly across all cultivars. Application of fertilizer to seedlings occurred five times in 2017 [17, 22, 31, 35, and 40 d after seeding (DAS)] and eight times in 2018 (18, 27, 31, 35, 41, 43, 45, and 48 DAS). A water-soluble 15–5–15 Peters Excel Multi-Purpose and Cal-Mag (Everris International, Geldermalsen, The Netherlands) with N at 150 mg·L⁻¹ concentration was used.

Field design and management. This 2-year study was a factorial experiment with shade as the whole-plot factor and cultivar as the subplot. Shade treatment (no shade, 30%, and 50%) was applied to one of three tunnels within each of the two high tunnel blocks (B1 and B2). The placement of shade treatments was randomized among the tunnels each year. Within each shade treatment, there were three randomized complete blocks of the seven colored bell pepper cultivars for a total of 21 experimental units (126 plants) in each high tunnel and 126 experimental units (756 plants) in each year.

Each season, before planting, fertilizer applications were made as follows. In 2017, B1 high tunnels each received a broadcast application of Sustane 4–6–4 All Natural Granulated Slow Release Nitrogen Fertilizer (Sustane Natural Fertilizer, Inc., Cannon Falls, MN) at a rate of 134.5 kg·ha⁻¹ N. To build soil organic matter in the B2 high tunnels, each

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Table 1. Results of soil tests from samples collected at time of planting in 2017 and 2018 for six high tunnels at the Iowa State University Horticulture Research Station, Ames, IA.^z

High tunnel	Organic matter (%)	CEC (meq/100 g)	pH	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
Block 1 ^y				2017			
No shade	4.5	21.9	7.5	111	334	3,183	611
30% shade	4.7	20.5	7.4	108	328	2,952	591
50% shade	4.7	21.4	7.3	100	294	3,162	583
Block 2							
No shade	3.8	17.8	7.1	41	193	2,741	437
30% shade	3.2	16.4	7.2	33	143	2,474	442
50% shade	3.1	16.9	7.4	31	140	2,582	430
Block 1				2018			
No shade	4.0	25.9	7.3	164	377	4,063	830
30% shade	4.7	26.9	7.2	211	497	4,195	840
50% shade	4.7	28.3	7.1	241	523	4,351	914
Block 2							
No shade	3.0	21.2	7.2	69	224	3,362	687
30% shade	3.8	22.0	7.2	84	293	3,536	666
50% shade	3.8	21.5	7.2	79	211	3,354	730

^zSoil cores were collected to a depth of 15.2 cm and were a composite of five samples within each high tunnel.

^yBlock 1 high tunnels were constructed in 2011 and block 2 high tunnels were constructed in 2017.

Fig. 1. Marketable colored bell peppers sorted by color after grading on 17 Aug. 2017. (A) Red cultivars included in the study were Red Knight and Archimedes. (B) Yellow cultivars included Flavorburst, Summer Sweet, and Sirius. (C) Purple and (D) orange cultivars were Tequila and Delirio, respectively. As the season progressed, 'Tequila' included orange and red hues in addition to purple. Fruit were harvested when at least 80% of the surface had changed from green to the mature color.

tunnel received a broadcast application of dairy compost from the Iowa State University Compost Facility. The N analysis of the dairy manure-based compost was 1.1% N, and compost was applied at a target rate of 134.5 kg·ha⁻¹ N. Amendments were broadcast across the entire soil surface and incorporated using a tractor-mounted rotary tiller inside each high tunnel.

In 2018, Healthy Grow 10-3-2 with Holganix (Pearl Valley Organix, Inc., Pearl City, IL) was applied in all six high tunnels. Five of the six tunnels received an application of 134.5 kg·ha⁻¹ N, whereas the sixth tunnel

had a lower organic matter value, therefore warranting an application of 156.9 kg·ha⁻¹. Additionally, two high tunnels in B2 were lower in K, and received supplemental applications of potassium chloride (0-0-60; Key Cooperative, Story City, IA) at rates of 58 kg·ha⁻¹ K and 81.5 kg·ha⁻¹ K, respectively. Amendments were applied and incorporated by hand, following three passes that were made in each planting row with a walk-behind rotary tiller to prepare the planting bed.

Peppers were transplanted into the high tunnels on 11 May 2017 and 3 May 2018. Within each high tunnel there were three beds

of peppers with a 1.2 m center-to-center distance between beds. Each bed contained two rows of peppers 0.4 m apart, and the entire bed was equally divided into seven twin-row sections. Each section contained one cultivar (subplot), with six plants in staggered double-rows, with 0.3 m within-row spacing. There was a 0.2 m buffer between sections within a row. Two single row beds, one on each outside edge of the high tunnel, served as non-data guard rows. Major field operations and data collection after transplanting are summarized in Table 2. Plants were supported using 1.5 m tall wooden stakes and tomato twine (Professional Grade Tomato Twine; Berry Hill Irrigation, Inc., Buffalo Junction, VA) to keep peppers contained within double rows and avoid breaking shoots. To suppress weed growth, each high tunnel was mulched to a depth of 15 cm with dried switchgrass (*Panicum virgatum*) after planting each season.

Drip tape was installed in both seasons to apply irrigation at a volume of up to 66,214 L·ha⁻¹ per week within each high tunnel. Irrigation volume was held constant among all high tunnels. During the season, fertilizer was provided with a Dosatron Injector (Model D14MZ2; Dosatron International, Clearwater, FL) using Nature's Source Professional Plant Food 10-4-3 (Ball DPF, LLC, Sherman, TX) to provide N ranging from 125 to 600 mg·L⁻¹ concentration on the dates listed in Table 2. Fertilizer applications were always held constant within either block of high tunnels.

On 6 June 2017, magnesium deficiency was noted in the B2 high tunnels. Corrective action was taken by using two additional fertilizer products. On 12 June, Cal Mag Special 17-5-17 Plus with 4% Ca and 1% Mg (Plant Marvel Laboratories, Inc., Chicago Heights, IL) was applied at a rate of 200 mg·L⁻¹ in 1252.7 L of water per high tunnel. Additionally, MgSO₄·7H₂O (9.8% Mg and 12.9% S; PQ Corporation, Malvern, PA) was used, applied as follows. On 13 June and 10 July, MgSO₄·7H₂O was foliar applied at a rate of 0.1 kg MgSO₄·7H₂O per L in 7.6 L of water. On 20 and 29 June and 10 July, 1.4 kg

Table 2. Schedule of major field operations and data collection events for bell peppers transplanted into high tunnels on 11 May 2017 and 3 May 2018 in Ames, IA.^z

Event	2017	2018
	Days after transplanting	
Fertilizer applications ^y	20, 21, 33, 49, 50, 60, 74, 90, 104	12, 18, 26, 40, 45, 52, 80
Placement of shadecloth	34	47
Insecticide applications ^x	51	71, 75, 110
Harvest	55, 62, 69, 76, 83, 90, 97, 104, 111, 118, 125, 132, 139, 146, 153	56, 70, 77, 84, 91, 98, 105, 112, 119, 126, 133, 140, 147, 154
SPAD data collection	64, 120, 153	49, 77, 105, 139, 153
Fruit collected for SSC, pH, and TTA analysis	111	112
Plant height measured ^w	154, 159	159
Sample collection for leaf area and biomass measurements ^w	153, 154, 158, 159	159, 160

^zBell pepper cultivars in the study were Archimedes, Delirio, Flavorburst, Red Knight, Sirius, Summer Sweet, and Tequila.

^yNature's Source Professional Plant Food 10-4-3. Additional fertilizer applications to correct Mg deficiency are not included here but are detailed in the text.

^xDiPel PRO DF (*Bacillus thuringiensis* subspecies *kurstaki*, strain ABTS-351).

^wSample collection occurred over several days within two individual blocks of high tunnel (shadecloth) treatments.

Table 3. Mean irradiance reduction (%) for no shadecloth treatment, 30% shade, and 50% shadecloth treatments as compared with full-sun, outdoor conditions. Data were recorded 12 July to 23 Sept. 2017 and 2018 for high tunnel production of bell peppers in Ames, IA.^z

Shade treatment	Irradiance reduction (%) ^y	
	2017	2018
No shade	16.2 b ^x	17.5 b
30% shade	53.3 a	45.9 a
50% shade	65.3 a	63.9 a

^zBell pepper cultivars in the study were Archimedes, Delirio, Flavorburst, Red Knight, Sirius, Summer Sweet, and Tequila.

^yIrradiance was measured at 100 cm above the soil and recorded every 1 h.

^xMeans within the same column followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

of $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ was applied via drip irrigation in 757.1 L of water within each high tunnel. In 2018, minor symptoms of Mg deficiency began to appear, so $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ was applied in 757.1 L of water within each high tunnel at rates of 1.4 and 0.7 kg $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ on 29 May and 12 June, respectively.

Crops were scouted weekly for signs of insect pests and diseases. Other than Mg deficiency, no disease or environmental issues were observed in either season. Tobacco hornworms (*Manduca sexta*) were managed through the use of *Bacillus thuringiensis* subspecies *kurstaki*, strain ABTS-351 (DiPel PRO DF; Valent U.S.A. Corp., Walnut Creek, CA), which was sprayed once in 2017 and three times in 2018 (Table 2) at a rate of 1.1 kg·ha⁻¹ a.i.

Shadecloth treatments were placed over the polyethylene film of the high tunnels on 14 June 2017 and 19 June 2018 (Table 2). Within B1 and B2, the three treatments applied were as follows: no shadecloth (control), 30% light-reducing shadecloth, and 50% light-reducing shadecloth. Each shadecloth was black-knitted, ultraviolet stabilized polypropylene [CS3K2672 (30%) and GSC5026 (50%); Nolt's Produce Supply, Charles City, IA] and was held in place using Clip-its (GSC10; Nolt's Produce Supply) and nylon rope tied to the baseboards of the high tunnel. The shadecloth covered the high tunnel down to each hip-board along

the sides, and there was a 0.5-m overhang on each end wall. After placement, each shadecloth remained on the high tunnel throughout the entire growing season.

Environmental monitoring. To monitor ambient air temperature and irradiance, two data loggers (Hobo Pendant Temperature/Light data loggers UA-002-8; Onset Computer Corporation, Bourne, MA) were placed within each high tunnel as well as outside each block of high tunnels. Data loggers were secured on top of posts 100 cm above the soil line and were programmed to collect data every 1 h. Additionally, two data loggers [Hobo Pendant Temperature/Alarm (waterproof) data loggers UA-001-08, Onset Computer Corporation] were buried 15.24 cm below the soil surface to collect soil temperature data every 1 h.

Harvest. Harvest took place 15 times between 5 July to 11 Oct. 2017 and 14 times between 28 June to 4 Oct. 2018. Plants were checked once a week, and fruit was harvested once 80% of the fruit surface had changed color based on visual observation. Nonmarketable bell peppers were categorized as fruit that were small (<5 cm in diameter); severely misshapen; damaged from sunscald, BER, insects, or rodents; or other biotic surface defects. Fruit count and weight was recorded for all categories of fruit for each harvest.

SSC, pH, and TTA. Once all cultivars were consistently producing fruit within each shade treatment, samples were collected for SSC, pH, and TTA analysis. Sample collection occurred on 30 Aug. 2017 and 23 Aug. 2018. Marketable fruit were brought back to a laboratory, stored in a refrigerator at 6 °C for 5 d, and processed for analysis at room temperature (21 °C) on day six. One whole fruit from each subplot was selected for analysis ($n = 126$).

Analysis of SSC, pH, and TTA used a similar protocol to methods used by Mashabela et al. (2015) and is summarized as follows. Samples were prepared by slicing the fruit into quarters to remove the calyx and seeds, with the four quarters remaining together as one sample for processing and analysis. Each sample was blended in a food processor (Black + Decker FP1700B; Towson, MD) for 1 min, strained through six layers of cheesecloth into a clean weigh boat, and 1 mL of the extract was transferred to a digital refractometer

(Pocket Pal-1 refractometer; Atago, Tokyo, Japan). Three 1-mL sub-samples from each fruit were analyzed, and the refractometer was cleaned and calibrated between each treatment using deionized water.

The same fruit extract used for SSC was used to analyze pH and TTA. In 2017, processed samples were stored in 30-mL Nalgene bottles and stored frozen at -20 °C until the time of the pH and TTA analysis; and in 2018, samples were stored at 6 °C for 7 d until analyzed. Using an automatic titrator (HI 84532 Minititrator; Hanna Instruments Inc., Woonsocket, RI), the initial pH was recorded, and TTA in terms of percent malic acid milliequivalents was determined by potentiometric titration of 5 mL of pepper juice diluted with 45 mL of deionized water to an endpoint of pH = 8.1 with sodium hydroxide.

Leaf chlorophyll concentration. An indirect estimate of leaf chlorophyll concentration was measured during each growing season using a SPAD-502 Plus chlorophyll meter (Konica Minolta Sensing America Inc., Ramsey, NJ). After placement of shadecloth treatments, SPAD measurements were collected three times in 2017 and five times in 2018 (Table 2). Five readings were collected on the first fully developed leaf of each plant, and measurements were averaged to obtain one value per plant. This routine was repeated on each of the six plants for each cultivar within the plot ($n = 756$).

Plant growth. Several measurements were taken at the end of each growing season to assess plant growth, including final plant height, total plant leaf count and area, and shoot biomass. The growing season was ended on 11 Oct. and 9 Oct. in 2017 and 2018, respectively. Data collection occurred within B1 and B2 across several days (Table 2). Plant height was measured from the soil line to the growing point of each plant ($n = 756$). One representative plant from each subplot was sampled destructively for shoot biomass by cutting the stem at the soil surface ($n = 126$). Each biomass sample was collected in a brown paper bag and transported to the Iowa State University Agronomy Research Farm to be dried at 67 °C in forced-air drying rooms for 4 d. Dried tissue was weighed using a 4000-g scale (Scout Pro SPE4001; Ohaus Corporation, Parsippany, NJ).

Table 4. Mean minimum, average, and maximum air and soil temperature (°C) for outdoor and no shade cloth treatment, 30% shade, and 50% shade cloth treatments on high tunnels for colored bell pepper production. Data were recorded 12 July to 23 Sept. 2017 and 2018 in Ames, IA.^z

Month/shade treatment	2017						2018					
	Air temp (°C) ^y			Soil temp (°C) ^x			Air temp (°C)			Soil temp (°C)		
	Min.	Avg	Max.	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max.
July												
Outside	17.8 b ^w	27.8 ab	43.3 ab	23.2 a	24.9 a	26.5 a	15.7 b	26.5 b	44.4 a	23.7 a	25.3 a	27.1 a
No shade	18.1 a	28.6 a	44.8 a	21.5 b	21.8 b	22.1 b	16.2 a	27.6 a	45.6 a	22.0 b	22.6 b	23.2 b
30% shade	18.2 a	27.2 bc	40.3 bc	21.4 b	21.7 b	21.6 b	16.1 ab	26.1 b	41.3 b	21.5 bc	21.9 b	22.4 b
50% shade	18.1 a	26.7 c	38.5 c	20.9 b	21.2 b	22.0 b	16.2 a	25.2 c	38.7 c	20.8 c	21.3 b	21.9 b
August												
Outside	13.4 b	23.3 ab	39.3 ab	19.8 a	21.4 a	22.9 a	16.3 b	24.9 b	39.5 b	22.4 a	23.5 a	24.8 a
No shade	13.8 a	24.3 a	41.7 a	19.8 a	20.1 ab	20.4 ab	16.6 a	25.8 a	41.1 a	21.1 b	21.6 b	22.1 b
30% shade	13.9 a	22.8 b	36.5 bc	19.2 a	19.5 b	19.8 b	16.6 a	24.8 b	37.6 c	20.7 bc	21.2 bc	21.6 bc
50% shade	13.8 a	22.2 b	34.2 c	19.9 a	20.1 ab	20.4 ab	16.6 a	24.0 c	35.5 d	20.1 c	20.5 c	21.0 c
September												
Outside	13.0 a	22.8 ab	39.2 ab	18.1 a	19.4 a	20.8 a	14.7 b	22.5 b	36.7 b	20.6 a	21.6 a	22.9 a
No shade	12.9 a	24.1 a	43.1 a	18.7 a	19.0 a	19.3 a	15.1 a	23.5 a	38.6 a	20.1 b	20.5 b	20.9 b
30% shade	13.1 a	22.6 ab	37.8 ab	18.2 a	18.5 a	18.8 a	15.1 a	22.4 b	34.9 c	19.9 b	20.2 bc	20.6 b
50% shade	13.1 a	21.8 b	34.2 b	18.3 a	19.1 a	19.4 a	15.1 a	21.7 c	32.4 d	19.3 c	19.6 c	20.1 b

^zBell pepper cultivars in the study were Archimedes, Delirio, Flavorburst, Red Knight, Sirius, Summer Sweet, and Tequila.

^yAir temperature (°C) was measured 100 cm above the soil and recorded every 1 h.

^xSoil temperature (°C) was recorded every 1 h with data loggers buried 15.24 cm below the soil surface.

^wMeans within the same column and month followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

Table 5. Effects of shade and cultivar on mean marketable fruit per plant (number and weight) and mean total fruit per plant (weight) from seven bell pepper cultivars grown with no shade cloth treatment, 30% shade, and 50% shade cloth, Ames, IA, 2017–18.^{z,y}

Treatment	Marketable fruit per plant		Total fruit per plant
	no. of fruit	wt (kg)	wt (kg)
Shade			
No shade	7.7 a ^x	1.4 a	2.7 a
30% shade	5.9 ab	1.1 ab	2.0 ab
50% shade	5.2 b	1.0 b	1.8 b
Cultivar			
Archimedes	5.1 c	1.2 a	2.2 a
Delirio	6.0 bc	1.1 a	2.1 a
Flavorburst	6.4 b	1.1 a	2.1 a
Red Knight	5.0 c	1.1 a	2.1 a
Sirius	4.8 c	1.1 a	2.1 a
Summer Sweet	4.8 c	1.0 a	2.1 a
Tequila	11.6 a	1.3 a	2.3 a

^zData were pooled across years as there were no significant shade (S) × year (Y), cultivar (C) × Y, or C × S × Y interactions ($P \leq 0.05$) for marketable fruit per plant, (number and weight), or total fruit per plant (weight). For all previously stated variables, there were also no S × C interactions ($P \leq 0.05$).

^yHarvest occurred 15 times 5 July to 11 Oct. 2017 and 14 times 28 June to 4 Oct. 2018.

^xMeans within the same column and treatment followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

Plant leaf count and leaf area data were collected by selecting one representative plant from each subplot ($n = 126$). All individual leaves were counted as they were removed from the plant and placed into a labeled plastic trash bag. All samples were stored in a 6 °C refrigerator until the time of the total plant leaf area measurement. Total plant leaf area was measured using a LI-COR Leaf Area Meter (3100; LI-COR Inc., Lincoln, NE). Each individual leaf was passed through the meter, and total leaf area was recorded.

Data analysis. Analysis of variance (ANOVA) and mean separation were conducted using the GLIMMIX procedure in SAS (version 9.4; SAS Institute, Cary, NC). For initial analysis, the year, cultivar, and shade were fixed effects to test for interactions among the variables, with the exceptions of irradiance reduction, air temperature, and soil temperature. There were two restrictions on random-

ization: high tunnel (B1 and B2), and three replicated blocks nested in year, high tunnel, and shade. Both blocking factors and all interactions with fixed effects were considered random terms in the linear model. When there was not an interaction with year, the term year and all interactions with year were set as random terms in the model to test the fixed effects of shade and cultivar. To test irradiance reduction, air temperature, and soil temperature, the model terms were tunnel (random), shade (fixed), and block (nested in tunnel).

Conditional residuals were analyzed for each response variable, and data transformation was used if there was deviation from homogeneity or normality assumptions. SSC, pH, TTA, SSC:TTA, and shoot biomass data were log-transformed to satisfy the homogeneity of variance and normality assumptions of ANOVA, and data were back-transformed for presentation of means. During all of the analysis described previously, if variance for

a random term was zero, the term was dropped from the model and variance pooled to residual error. To account for field variability while avoiding type II errors, all treatment means were separated using the unrestricted least significant difference procedure ($\alpha = 0.05$).

Results

Environmental conditions. Within each year, the shade cloth treatments caused a reduction in the irradiance (recorded in LUX) reaching the plant canopy (Table 3). The reduction in average light levels under 30% shade cloth was 53.3% in 2017 and 45.9% in 2018, while the 50% shade cloth reduced average light levels by 65.3% in 2017 and 63.9% in 2018 (Table 3). Light levels were lower than the control under both the 30% and 50% shade cloth treatments, but there was no difference in light reduction between the 30% and 50% shade cloth treatments (Table 3).

In 2017, the minimum air temperature did not vary among shade cloth treatments in any month (Table 4). In both July and Aug. of 2017, the average and maximum air temperatures were highest in tunnels without shade cloth. Both average and maximum air temperatures decreased with the use of 30% and 50% shade cloth (Table 4). In Sept. 2017, the average and maximum air temperatures decreased between no shade and 50% shade cloth treatments (Table 4). In each month of 2017, soil minimum, average, and maximum temperatures were unaffected by shade cloth (Table 4).

The minimum air temperature was unaffected by shade cloth treatments for any month in 2018 (Table 4). Shade cloth treatments incrementally reduced both average and maximum air temperatures in July, Aug., and Sept. 2018. Averaged over the 2018 season, the use of 30% and 50% shade cloth reduced average air temperatures by 1.2 and 2 °C, respectively.

Table 6. Effect of cultivar by shade treatment on mean total fruit per plant (number) and mean percent marketable fruit [number (%)] from bell pepper cultivars grown in high tunnels with no shade cloth treatment, 30% shade, and 50% shade cloth, Ames, IA, 2017–18.^{z,y}

Cultivar	Total fruit per plant (no. of fruit)			Percent marketable fruit [no. (%)] ^x		
	No shade	30% shade	50% shade	No shade	30% shade	50% shade
Archimedes	10.4 b ^w	7.8 b	6.6 c	62.5 ab	64.6 a	62.5 a
Delirio	11.6 b	9.0 b	7.3 bc	67.2 ab	68.6 a	57.8 a
Flavorburst	11.0 b	9.3 b	7.9 b	70.6 a	61.9 a	71.0 a
Red Knight	9.5 b	7.1 b	5.7 c	68.7 ab	70.1 a	70.2 a
Sirius	9.6 b	8.0 b	7.0 bc	59.0 ab	62.3 a	60.6 a
Summer Sweet	10.3 b	7.9 b	5.8 c	53.1 b	64.9 a	62.1 a
Tequila	23.8 a	18.7 a	15.3 a	61.2 ab	58.5 a	66.4 a

^zData were pooled across years as there were no significant shade (S) × year (Y), cultivar (C) × Y, or C × S × Y interactions ($P \leq 0.05$) for total fruit per plant (number) or percent marketable fruit number. There was a significant S × C interaction for total fruit per plant (number) ($P = 0.0135$) and percent marketable fruit number ($P = 0.0501$).

^yHarvest occurred 15 times 5 July to 11 Oct. 2017 and 14 times 28 June to 4 Oct. 2018.

^xPercent marketable fruit [number (%)] = number of marketable fruit per plant/total number of fruit per plant.

^wMeans within the same column followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

Table 7. Effect of cultivar and shade treatments by year on mean percent marketable bell pepper fruit [weight (%)] grown in high tunnels with no shade cloth treatment, 30% shade, and 50% shade cloth, Ames, IA, 2017–18.^{z,y}

Treatment	Percent marketable fruit [wt (%)] ^x	
	2017	2018
Shade		
No shade	42.3 a ^w	71.3 a
30% shade	42.6 a	75.0 a
50% shade	43.3 a	73.2 a
Cultivar		
Archimedes	41.4 a	71.2 abc
Delirio	43.6 a	73.0 abc
Flavorburst	42.4 a	76.3 ab
Red Knight	44.9 a	78.4 ab
Sirius	41.0 a	67.7 bc
Summer Sweet	44.4 a	63.7 c
Tequila	41.2 a	82.0 a

^zThe year (Y) × cultivar (C) interaction was significant ($P = 0.0494$); however, there was no C × shade (S) interaction within either Y ($P \leq 0.05$).

^yHarvest occurred 15 times 5 July to 11 Oct. 2017 and 14 times 28 June to 4 Oct. 2018.

^xPercent marketable fruit [weight (%)] = weight of marketable fruit per plant/total weight of fruit per plant.

^wMeans within the same column and treatment followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

The 30% and 50% shade cloth treatments reduced maximum air temperatures by 3.8 and 6.2 °C, respectively, compared with the control (Table 4). In July 2018, the minimum soil temperature was reduced between the control and 50% shade cloth treatments (Table 4). Minimum, average, and maximum soil temperatures were reduced slightly between no shade and 50% shade cloth treatments in Aug. 2018 (Table 4). In Sept. 2018, the minimum soil temperature was reduced under 50% shade cloth as compared with the control and 30% shade cloth, and the average soil temperature was reduced between the control and 50% shade cloth (Table 4).

Marketable yield. There were no interactions among year, shade, or cultivar for the number of marketable fruit or weight per plant (as well as total fruit weight per plant), so analysis focused on the main effects of shade and cultivar across both years (Table 5). Over-

all, plants grown under the 50% shade cloth treatment had a reduced number of marketable fruit and decreased marketable fruit weight compared with plants grown in high tunnels without shade cloth. There was a 2.5 fruit and 0.4 kg fruit weight decrease between no shade and 50% shade cloth treatments (Table 5). The use of 30% shade cloth did not reduce the number or weight of fruit per plant as compared with the control treatment (Table 5). The 50% shade cloth caused a reduction in total fruit weight compared with the no shade cloth treatment. There were no differences among cultivars for marketable or total fruit weight per plant; however, ‘Tequila’ and ‘Flavorburst’ had a higher number of marketable fruit per plant at 11.6 and 6.4, respectively, while the remaining cultivars averaged 4.8 to 6 fruit per plant (Table 5).

There were no interactions with year for total fruit number per plant or percent marketable fruit number, but there was a shade by cultivar interaction for each variable. Data were analyzed for the shade by cultivar interaction across both years (Table 6). Within the control and 30% shade cloth treatments, the total fruit per plant was the same among all cultivars except Tequila, which had an increased fruit number (Table 6). Under the 50% shade cloth, ‘Tequila’ and ‘Flavorburst’ had higher fruit yields than the other cultivars (Table 6). The percent marketable fruit number was unaffected among cultivars under the 30% or 50% shade cloth treatments. Under no shade cloth, the percent marketable fruit number was highest for ‘Flavorburst’ (70.6%) and lowest for ‘Summer Sweet’ (53.1%), which was the only difference among the cultivars (Table 6).

There was a year by cultivar interaction for the percent marketable fruit weight, so data were analyzed as the interaction of year with shade and cultivar, respectively (Table 7). The use of shade cloth did not affect the percent marketable fruit weight within either year. There were also no differences among cultivars in 2017. In 2018 cultivar differences were present: ‘Tequila’, ‘Flavorburst’ and ‘Red Knight’ had marketable fruit weight ranging from 76% to 82%, while ‘Summer Sweet’ had the lowest marketable fruit weight at 64% (Table 7).

Sunscald and BER. There were no interactions among year, shade, or cultivar for incidence of sunscald, so analysis focused on the main effects of shade and cultivar across both years (Table 8). There was no difference between the control and 30% shade cloth, or 30% and 50% shade cloth treatments, but there was a 59% reduction in the incidence of sunscald between the control and 50% shade cloth treatments (Table 8). There were no differences among cultivars with respect to incidence of sunscald damage on fruit (Table 8).

When examining the incidence of BER on fruit, there were no interactions with year, but there was a shade by cultivar interaction, and data were analyzed accordingly (Table 9). There was a general trend of decreased BER with increased shade cloth percentage, but cultivar differences were only present in the control and 30% shade treatments (Table 9). Under no shade cloth, ‘Sirius’ had 16.8% incidence of BER, while ‘Archimedes’, ‘Flavorburst’, ‘Red Knight’, and ‘Tequila’ were within the range of 2.1% to 6.0% BER (Table 9). Under 30% shade cloth, fruit with BER dropped to 8.2% for the cultivar Sirius, which was only different as compared with ‘Tequila’ at 1.2% BER (Table 9).

Fruit size. Marketable fruit size data were analyzed to reflect the shade by cultivar interaction, and no interactions with year were found (Table 10). Within each shade treatment ‘Tequila’ had the smallest fruit size, and ‘Archimedes’, ‘Red Knight’, and ‘Sirius’ consistently had the largest fruit sizes (Table 10). Overall, fruit size increased with the addition of shade cloth treatments with the exceptions of ‘Archimedes’, ‘Flavorburst’, and ‘Sirius’, which had the lowest marketable fruit sizes under 30% shade cloth (Table 10).

SSC, pH, TTA, and SSC:TTA ratio. There were no interactions among year, shade, or cultivar for SSC, pH, TTA, or SSC:TTA ratio, so analysis focused on the main effects of shade and cultivar across both years (Table 11). The use of shade cloth did not cause any changes in fruit SSC, pH, or TTA. Subtle differences in SSC and TTA resulted in a decreased SSC:TTA ratio under the 30% shade cloth treatment as compared with the control (Table 11).

Table 8. Mean incidence (%) of sunscald and blossom end rot (BER) on pepper fruit as affected by cultivar and shade treatments applied to high tunnels, Ames, IA, 2017–18.^{z,y}

Treatment	Sunscald (%) ^x
Shade	
No shade	2.9 a ^w
30% shade	2.2 ab
50% shade	1.2 b
Cultivar	
Archimedes	2.6 a
Delirio	2.3 a
Flavorburst	2.4 a
Red Knight	1.8 a
Sirius	2.6 a
Summer Sweet	2.3 a
Tequila	1.0 a

^zData were pooled across years as there were no significant shade (S) × year (Y), cultivar (C) × Y, or C × S × Y interactions ($P \leq 0.05$). There was also no S × C interaction ($P \leq 0.05$).

^yHarvest occurred 15 times 5 July to 11 Oct. 2017 and 14 times 28 June to 4 Oct. 2018.

^xSunscald incidence (%) = number of fruit with sunscald/total number of fruit.

^wMeans within the same column and treatment followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

Table 9. Effect of cultivar by shade treatment on mean incidence (%) of blossom end rot (BER) on fruit collected from bell pepper cultivars grown in high tunnels with no shadecloth treatment, 30% shade, and 50% shadecloth, Ames, IA, 2017–18.^{z,y}

Cultivar	BER (%) ^x		
	No shade	30% shade	50% shade
Archimedes	6.0 b ^w	3.2 ab	5.0 a
Delirio	10.7 ab	5.3 ab	4.4 a
Flavorburst	2.7 b	4.4 ab	3.0 a
Red Knight	4.9 b	4.3 ab	6.3 a
Sirius	16.8 a	8.2 a	8.6 a
Summer Sweet	11.2 ab	3.9 ab	6.0 a
Tequila	2.1 b	1.2 b	1.0 a

^zData were pooled across years as there were no significant shade (S) × year (Y), cultivar (C) × Y, or C × S × Y interaction ($P \leq 0.05$). There was a significant S × C interaction ($P = 0.0180$).

^yHarvest occurred 15 times 5 July to 11 Oct. 2017 and 14 times 28 June to 4 Oct. 2018.

^xBER incidence (%) = number of fruit with BER/total number of fruit.

^wMeans within the same column followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

The cultivar Summer Sweet had fruit with the highest SSC at 8.4, but the pH and TTA were similar to several other cultivars (Table 11). Fruit from ‘Archimedes’ also had a high SSC value, but the pH was lower than the other cultivars; however, the TTA was the highest of all the cultivars with a value of 0.27% malic acid (Table 11). ‘Tequila’ had the lowest SSC at 4.3, but it also had the highest pH value. ‘Tequila’ had the lowest TTA value at 0.10%, which resulted in the cultivar having the highest SSC:TTA ratio at 41.5. ‘Summer Sweet’ and ‘Sirius’ had the second and third highest SSC:TTA ratios at 35.8 and 33, respectively. The remaining

four cultivars had SSC:TTA ratios ranging from 28.8 to 30 (Table 11).

Leaf chlorophyll concentration. Within each year, there were no cultivar by shade interactions for the estimated leaf chlorophyll concentration as determined by SPAD values (Table 12). The shadecloth treatments did not affect SPAD values on any date in either year, but cultivar differences in SPAD values were present on each sample date within each year (Table 12).

Plant growth. There were no interactions among year, cultivar, or shade for plant height, shoot biomass, the number of leaves per plant, total leaf area per plant, or the average leaf size, so analysis focused on the effects of shade and cultivar across both years (Table 13). Plants grown under the 30% and 50% shadecloth treatments were taller than plants grown without shade, with an average height increase between 12.5 to 16.4 cm (Table 13). The use of shadecloth did not affect shoot biomass, the number of leaves per plant, or the total leaf area per plant; however, there were some general trends. Total leaf area was lowest under the 30% shade and highest under the 50% shadecloth, but the number of leaves per plant decreased incrementally with the addition of shadecloth treatments. These two trends explain an increase in individual leaf size between no shade and 50% shade treatments, with the average leaf size increasing from 33.7 to 44.9 cm² with the addition of 50% shadecloth (Table 13).

Differences among the cultivars existed for all plant growth variables (Table 13). ‘Summer Sweet’ had the tallest average plant height at 114.9 cm, while ‘Red Knight’ was the shortest averaging 96.5 cm. ‘Archimedes’, ‘Sirius’, and ‘Summer Sweet’ had larger biomass compared with the other cultivars (Table 13). The number of leaves per plant was highest for ‘Tequila’, with ‘Red Knight’ and ‘Summer Sweet’ having the fewest leaves per plant (Table 13). ‘Archimedes’ and ‘Sirius’ had the highest total leaf area per plant, while ‘Summer Sweet’ had the lowest leaf area per plant compared with the other cultivars (Table 13). These patterns resulted in ‘Archimedes’ having the largest individual leaves, followed by ‘Sirius’, with ‘Flavorburst’ and ‘Tequila’ having the smallest leaves (Table 13).

Discussion

Our research provides new insights into bell pepper performance in Midwest high tunnels covered with shadecloth. Using a 50% shadecloth proved detrimental to plant yield, and the value of using a 30% shadecloth remains debatable as demonstrated by our data. There were limited differences in fruit quality or plant growth parameters under the three shade treatments, but differences among cultivars were common. Our research serves as a caution against the use of shadecloth that is 30% or greater; however, several interactions between shade and cultivar effects demonstrate that some cultivars may

perform better than others under different shade regimes.

Actual shade factors may differ considerably from the target values attributed to the shadecloth (Stamps, 2009), which we also observed in our study. The average light reduction within the unshaded high tunnels was 17%, compared with outdoor conditions. The average reduction in light intensity under 30% and 50% shadecloth averaged 50% and 65%, respectively, compared with outdoor conditions. Our findings demonstrate the combined effect of the high tunnel’s polyethylene film covering and shadecloth at reducing light levels in the plant canopy. In Georgia, Díaz-Pérez (2014) found a quadratic response of bell pepper yield and quality that was optimized between 30% and 47% shade. Light reduction in our study of 50% and 65% under 30% and 50% shadecloth treatments, respectively, exceeded these recommended values, and this may be a large reason for the negative yield and fruit quality responses we observed.

During each growing season, the average temperature within all three high tunnels remained between 21.7 and 28.6 °C, which is within the desired temperature range for pepper production (Swiader and Ware, 2002). High tunnel temperatures were highest in the month of July for each season, indicating that shadecloth placement during this month may have been the most beneficial. Average maximum air temperatures within high tunnels exceeded 32 °C in both seasons, creating favorable conditions for flower abortion and delayed fruit set (Bosland and Votava, 2000; Swiader and Ware, 2002) regardless of shadecloth application. However, it is likely that the use of both the 30% and 50% shadecloth decreased the frequency and length of time that air temperatures were above a detrimental threshold (Díaz-Pérez, 2013; Stamps, 2009). The decrease in average air temperatures under 30% and 50% shadecloth would have contributed to decreased GDD accumulation, which explains the general trend we observed (although, data were not shown) that harvest of ripened fruit began ≈1 week earlier in high tunnels without shadecloth (Both et al., 2007; O’Connell et al., 2012; Waterer and Bantle, 2000). It is reasonable that the use of shadecloth had no effect on minimum air temperature because of the role of shadecloth in reducing solar radiation as the primary factor in temperature regulation (Stamps, 2009).

In general, shadecloth did not result in decreased soil temperature, which is contrary to the findings of Díaz-Pérez (2013). The use of switchgrass mulch for weed suppression within all high tunnels likely reduced absorption of solar radiation by the soil, regulating temperature differences. Our findings may also be because of the environmental differences of the high tunnel vs. open field conditions and may also be attributed to the role of plant canopy cover in shielding the soil from solar radiation (Díaz-Pérez, 2013).

In both years of the study, the shadecloths were placed on the high tunnels in June and remained through September, when the growing season ended. Removal of the shadecloth earlier in the season (mid to late

Table 10. Mean size of marketable bell pepper fruit as affected by cultivar and shade treatment interactions when grown in high tunnels with no shade cloth treatment, 30% shade, and 50% shade cloth, Ames, IA, 2017–18.^{z,y}

Cultivar	Size of marketable fruit (g) ^x		
	No shade	30% shade	50% shade
Archimedes	231.8 a ^w	213.4 ab	243.1 a
Delirio	178.9 c	186.3 bc	189.2 bc
Flavorburst	181.6 bc	166.8 c	178.4 c
Red Knight	221.3 a	231.5 a	237.7 a
Sirius	217.7 a	212.8 ab	228.8 ab
Summer Sweet	207.0 ab	221.0 a	198.0 abc
Tequila	106.3 d	108.6 d	115.3 d

^zData were pooled across years as there were no significant shade (S) × year (Y), cultivar (C) × Y, or C × S × Y interaction ($P \leq 0.05$). There was a significant S × C interaction ($P = 0.036$).

^yHarvest occurred 15 times 5 July to 11 Oct. 2017 and 14 times 28 June to 4 Oct. 2018.

^xSize = weight of marketable fruit/number of marketable fruit.

^wMeans within the same column followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

Table 11. Effect of cultivar and shade treatments on mean soluble solids concentration (SSC), pH, total titratable acidity (TTA), and SSC:TTA of bell pepper fruit, Ames, IA, 2017–18.^{z,y}

Treatment	SSC (%)	pH	TTA (% malic acid)	SSC:TTA (ratio)
Shade				
No shade	6.9 a ^x	5.1 a	0.22 a	33.0 a
30% shade	7.0 a	5.2 a	0.23 a	31.5 b
50% shade	7.1 a	5.1 a	0.22 a	33.1 ab
Cultivar				
Archimedes	8.0 ab	4.9 c	0.27 a	30.0 c
Delirio	7.2 cd	5.0 bc	0.24 bc	29.7 c
Flavorburst	7.4 bc	5.0 bc	0.26 ab	28.9 c
Red Knight	7.1 cd	5.0 bc	0.25 abc	28.8 c
Sirius	6.8 d	5.1 b	0.21 d	33.0 b
Summer Sweet	8.4 a	5.1 b	0.24 c	35.8 b
Tequila	4.3 e	5.8 a	0.10 e	41.5 a

^zSSC, pH, TTA, and SSC:TTA data were log-transformed to satisfy the homogeneity of variance and normality assumptions of ANOVA. Data were back-transformed for presentation of means. Data were pooled across years as there were no significant shade (S) × year (Y), cultivar (C) × Y, or C × S × Y interactions ($P \leq 0.05$) for SSC, pH, TTA, or SSC:TTA. For all previously stated variables, there were also no S × C interactions ($P \leq 0.05$).

^yFully ripe fruit were harvested 111 d after transplanting (DAT) in 2017 and 112 DAT in 2018, and one marketable fruit per plot was selected for analysis ($n = 126$).

^xMeans within the same column and treatment followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

August) would likely have improved the yield response of the crop, especially as outdoor temperatures dropped and daylength decreased. Future research on the timing of shade cloth placement and removal could be especially beneficial for growers in the northern United States.

The number and weight of marketable fruit per plant we found was lower than expected when compared with other recent data from Midwest high tunnel production systems (Loewen, 2018). A decrease of between and within-row plant spacing from 0.5 to 0.2 m has been shown to reduce the number of marketable fruit by 63% (Cushman and Horgan, 2001). While adjusting planting spacing within all high tunnels may have improved yield across treatments, the number of cultivars within the study and our desire to achieve three replications per tunnel was a constraint on plant spacing.

The decrease in marketable fruit yield and weight between no shade and 50% shade treatments aligns with the findings of Díaz-Pérez (2014), who proposed that shade should not exceed 47% to maximize bell pepper yield in open field conditions. Our

finding of no yield increase between the no shade and 30% shade cloth treatments is in contrast to both Díaz-Pérez (2014) and Day (2010), who found greatly improved yield responses under 30% shade cloth compared with unshaded conditions. However, these studies were conducted in open-field conditions, and as discussed earlier, the additive effect of the high tunnel covering plus the shade cloth must be considered when examining our results.

The cultivars Delirio, Flavorburst, and Tequila had the highest marketable yield per plant, indicating that ‘Flavorburst’ may be a better option compared with the other two yellow peppers in the study (‘Sirius’ and ‘Summer Sweet’). While ‘Tequila’ produced more fruit, the fruit were much smaller than those of the other cultivars. When considering the total number of fruit per plant, differences among cultivars became more widespread under the 50% shade cloth treatment, indicating that some cultivars may be more resilient under low light conditions.

While the purpose of this study was to use shade to decrease damage from solar radiation and increased temperatures, the effect of the high tunnel plus the shade cloth resulted in

increases in plant shading that may have been detrimental for flowering and fruit formation. Aloni et al. (1996) found that rate of abscission increased as light was reduced between 86% to 100% for three of the five cultivars they tested. More recent work conducted by Marcelis et al. (2004) showed that an increased plant density increased flower abortion, and that shading of plants had the greatest effect on abortion rate when it occurred a few days before anthesis up to 2 weeks after anthesis (Marcelis et al., 2004).

Under the 30% shade cloth, the marketability ranged from 59% to 70%, which is higher than the range of 30% to 52% reported by Selahle et al. (2015) or 50% reported by Mashabela et al. (2015) for colored bell peppers grown under a 25% shade cloth within a high tunnel in South Africa. Both of those studies were comparing yield response under 25% black shade cloth to other colors of shade cloth (pearl, red, and yellow), the results of which had fruit marketability ranges from 45% to 95% (Selahle et al., 2015) and 70% to 83% (Mashabela et al., 2015).

While the use of 50% shade cloth greatly reduced the incidence of sunscald on fruit compared with the no shade treatment, the rate of sunscald did not exceed 3% for any shade treatment, thus limiting possible economic impact. Damage from sunscald may be more critical in open field conditions, with losses from sunscald that were shown to be as high as 49% on red bell peppers (Day, 2010). Both Day (2010) and Díaz-Pérez (2014) have demonstrated the role of shade cloth in reducing sunscald incidence on colored bell peppers grown in open field conditions. The shading afforded by the polyethylene film of a high tunnel may offer enough reduction in irradiance to keep the overall incidence of sunscald low. Additionally, the incidence of sunscald will likely remain low when plant health is maintained to provide adequate foliage cover (Coolong et al., 2019).

Losses because of BER in our study ranged from 1% to 17% compared with values reported by Coolong et al. (2019), who observed losses because of BER from 9% to 27% in sweet bell peppers harvested at the mature green stage in open field conditions. Although there was an interaction between shade and cultivar rates of BER that averaged 8%, 4%, and 5% under no, 30%, and 50% shade cloth, respectively. The slight increase in BER incidence between 30% and 50% shade cloth may be attributed to preferential accumulation of Ca by leaves compared with fruit, because of increased canopy growth (Taylor and Locascio, 2004) resulting from decreased light levels from shade treatments. Marcelis and Ho (1999) reported that BER was positively correlated to growth rate of pepper; however, our results did not align with this finding, as plant growth trended down with increased shading; but BER was highest under the no shade cloth treatment. The use of shade cloth may have aided in reducing leaf transpiration and water loss, which has been shown to result in more balanced distribution of Ca between fruit and leaves under shaded treatments

Table 12. Effect of cultivar and shade treatments on mean SPAD readings collected from bell peppers grown in high tunnels 64, 120, and 153 d after transplanting (DAT) in 2017 and 49, 77, 105, 139, and 153 DAT in 2018, Ames, IA.^{z,y}

Treatment	DAT in 2017			DAT in 2018				
	64	120	153	49	77	105	139	153
Shade								
No shade	52.9 a ^x	52.2 a	53.4 a	54.7 a	51.2 a	52.4 a	58.5 a	54.6 a
30% shade	52.7 a	52.1 a	53.3 a	55.8 a	52.5 a	54.6 a	57.2 a	58.1 a
50% shade	50.2 a	51.8 a	53.3 a	54.2 a	50.7 a	52.0 a	57.0 a	57.4 a
Cultivar								
Archimedes	53.9 a	54.0 ab	55.7 ab	52.7 c	52.0 bc	53.9 b	58.6 b	58.8 ab
Delirio	51.0 ab	51.9 bc	53.4 bc	53.9 bc	51.5 bcd	51.6 bc	56.3 c	57.1 ab
Flavorburst	49.7 ab	51.2 c	51.8 c	55.8 b	49.9 de	52.4 b	56.8 bc	56.5 ab
Red Knight	55.4 a	54.3 a	57.9 a	60.3 a	54.8 a	56.8 a	60.9 a	59.8 a
Sirius	53.1 ab	52.2 abc	52.6 bc	54.0 bc	52.8 b	53.5 b	57.6 bc	54.9 b
Summer Sweet	52.7 ab	52.1 abc	54.3 abc	54.8 bc	50.6 cde	53.6 b	59.1 ab	59.5 a
Tequila	47.7 b	48.5 d	47.7 d	53.0 bc	48.8 e	49.3 c	53.6 d	50.2 c

^zThere were no cultivar $\times$ shade interaction for any response variables ($P \leq 0.05$).

^yAll six plants in each experimental unit were used for SPAD data collection ($n = 756$). Data were an average of five readings collected on the first, fully mature leaf on each plant.

^xMeans within the same column and treatment followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

Table 13. Effect of cultivar and shade treatments on mean plant height, shoot biomass, number of leaves per plant, leaf area per plant, and leaf size of seven colored bell pepper cultivars grown in high tunnels with no shadecloth treatment, 30% shade, and 50% shadecloth, Ames, IA, 2017–18.^{z,y}

Treatment	Plant ht (cm)	Shoot biomass (g)	No. of leaves per plant	Total leaf area per plant (cm ²)	Leaf size (cm ²) ^x
Shade					
No shade	94.9 b ^w	95.2 a	250 a	8,377 a	33.7 b
30% shade	107.4 a	89.9 a	218 a	7,921 a	36.9 ab
50% shade	111.3 a	108.8 a	207 a	9,341 a	44.9 a
Cultivar					
Archimedes	107.0 b	117.4 a	223 ab	9,763 a	44.8 a
Delirio	104.8 b	87.0 bc	226 ab	7,967 ab	37.0 bc
Flavorburst	99.5 bc	83.0 c	232 ab	8,001 ab	34.0 c
Red Knight	96.5 c	86.8 bc	205 b	8,029 ab	38.6 bc
Sirius	107.1 ab	108.7 a	231 ab	9,588 a	41.2 ab
Summer Sweet	114.9 a	104.1 a	202 b	7,678 b	39.6 abc
Tequila	101.8 bc	98.7 ab	257 a	8,799 ab	34.6 c

^zBiomass data were log-transformed to satisfy the homogeneity of variance and normality assumptions of ANOVA. Data were back-transformed for presentation of means. Data were pooled across years as there were no significant shade (S) $\times$ year (Y), cultivar (C) $\times$ Y, or C $\times$ S $\times$ Y interactions ($\alpha \leq 0.05$) for plant height, shoot biomass, number of leaves per plant, leaf area per plant, or leaf size. For all previously stated variables, there were also no S $\times$ C interactions ($\alpha \leq 0.05$).

^y11 Oct. 2017 and 9 Oct. 2018 were the conclusion of the research period for each season. End of season plant height, shoot biomass, and leaf area were collected over several days at the end of each season.

^xLeaf size (cm²) = total leaf area per plant (cm²)/number of leaves per plant.

^wMeans within the same column and treatment followed by the same letter are not different according to the unrestricted least significant difference procedure ($\alpha = 0.05$).

(Möller and Assouline, 2007), thus reducing BER. Management of BER in Midwest bell pepper production should focus on irrigation, fertility management, and cultivar selection, which can be more cost-effective alternatives to shadecloth application. In general, the cultivar Sirius had a high incidence of BER, which may be a consideration for growers who have previously struggled with calcium management in pepper production.

For several pepper cultivars, fruit size was lowest under the 30% shade treatments. This observation is in contradiction with Díaz-Pérez (2014), who observed an improved fruit weight under shade conditions up to 47%, with a plateau in the response curve with additional shading. Fruit size observed by Díaz-Pérez (2014) did not exceed 150 g, while all the cultivars in our study, except for ‘Tequila’, had average weights over 178 g regardless of shade treatment.

The fruit SSC values found in our study were higher than those observed by Díaz-Pérez (2014) or Mashabela et al. (2015), but they were similar to values found by Kong et al. (2013) in bell peppers that were red or yellow in color. Selahle et al. (2015) observed SSC values that were similar to ours in red

peppers, but they reported lower SSC values for the yellow peppers in their study; Díaz-Pérez (2014) did not see a clear divide in SSC by pepper color between yellow and red. SSC was unaffected by shade in our research, but Díaz-Pérez (2014) observed a linear decrease in SSC of fruit as shade level increased. Kong et al. (2013) compared the effect of 35% pearl shadecloth vs. 35% black shadecloth and found no effect on SSC; however, as the harvest season progressed, TTA was higher in fruit grown under black vs. pearl shadecloth. The TTA values we observed were like those found by both Mashabela et al. (2015) and Selahle et al. (2015); however, we did not observe any differences in TTA among shadecloth treatments. In terms of cultivars, our findings align with those of Díaz-Pérez (2014); it appears cultivar differences in SSC and TTA may not be directly linked to the color of the fruit. In our study the SSC:TTA ratio was higher under no shade conditions compared with fruit grown under 30% shadecloth. Mashabela et al. (2015) found an SSC:TTA ratio of 25 in fruit grown under 25% black shadecloth, which was lower than any of the SSC:TTA ratios found in our study regardless of shade or cultivar effects.

Chlorophyll indices (SPAD readings) are used as an indirect estimate of leaf chlorophyll and N concentrations (Díaz-Pérez, 2013). There was no difference in SPAD readings among shade treatments on any sampling date within either year of our research, and this result is contrary to those obtained by Díaz-Pérez (2013), who saw a linear decrease in SPAD readings with increasing shade values. However, Díaz-Pérez (2013) also demonstrated the role that leaf thickness may play in the outcome of SPAD readings, because plants grown under shaded conditions generally have larger but thinner leaves. When SPAD readings are normalized using their specific leaf weight, the values increase slightly as shade level increases Díaz-Pérez (2013).

Plants grown under low light conditions undergo morphological adaptations such as greater foliage surface area, increased specific leaf area (leaf dry weight/leaf area), thinner leaves, and taller stems (Larcher, 1995). These responses were demonstrated in peppers by Díaz-Pérez in 2013, who showed an increase in plant height, plant leaf area, and individual leaf area with increase shading and a linear decrease in the number of leaves per plant with increased shading. Day (2010) also found a

decrease in the number of leaves per plant and increased plant leaf area and individual leaf area under 30% shade cloth compared with open field conditions. Our results were somewhat contradictory to these two studies, as we did see an increase in plant height and individual leaf area under increased shading but found that shoot biomass, the number of leaves per plant, and the total leaf area per plant were not different. The lack of a response to shade treatments may be attributed to the low number of replications and the high amount of plant variability within treatments. Cultivar differences existed for all plant growth response variables, with Sirius and Archimedes having increased shoot biomass and total leaf area, and Summer Sweet having increased shoot biomass and plant height compared with the other cultivars—indicating that plant spacing and staking should be considered to optimize production of these cultivars.

Conclusions

Management of excess heat within high tunnels will remain a challenge for producers, but tools used to manage high temperatures should not come at the sacrifice of yield or fruit quality. Our study demonstrates that the use of black shade cloth above 30% light reduction is not appropriate in Midwest production systems. The use of lower light reduction (10% or 20% shade cloth) should be examined; however, it is also important to assess if the level of damage from sunscald, BER, or other biotic disorders is high enough to warrant action. Our study helps form research-based recommendations for shade cloth use on Midwest high tunnels for colored bell pepper production, and future research should 1) examine lower levels of light reduction, 2) test photo-selective shade cloths as an alternative to black, and 3) identify the optimum time of year or temperature threshold for shade cloth placement and removal.

Literature Cited

- Aloni, B., L. Karni, Z. Zaidman, and A.A. Schaffer. 1996. Changes of carbohydrates in pepper (*Capsicum annuum* L.) flowers in relation to their abscission under different shading regimes. *Ann. Bot.* 78(2):163–168.
- Ambrózy, Z., H. Daoud, Z. Nagy, H. D. Ledó, and L. Helyes. 2016. Effect of net shading technology and harvest times on yield and fruit quality of sweet pepper. *Appl. Ecol. Environ. Res.* 14:99–109.
- Barber, H.N. and P.J.H. Sharpe. 1971. Genetics and physiology of sunscald of fruits. *Agr. Meteorol.* 8:175–191.
- Bosland, P.W. and E.J. Votava. 2000. *Peppers: Vegetables and spice capsicums*. CABI Publishing, New York.
- Both, A.J., E. Reiss, J.F. Sudal, K.E. Holmstrom, C.A. Wyenandt, W.L. Kline, and S.A. Garrison. 2007. Evaluation of a manual energy curtain for tomato production in high tunnels. *HortTechnology* 17:467–472.
- Bruce, A.B., E.T. Maynard, and J.R. Farmer. 2019. Farmers' perspectives on challenges and opportunities associated with using high tunnels for specialty crops. *HortTechnology* 29:290–299.
- Carey, E.E., L. Jett, W.J. Lamont, T.T. Nennich, M.D. Orzolek, and K.A. Williams. 2009. Horticultural crop production in high tunnels in the United States: A snapshot. *HortTechnology* 19:37–43.
- Castellano, S., G.S. Mugnozza, G. Russo, D. Briassoulis, A. Mistriotis, S. Hemming, and D. Waaijenberg. 2008. Plastic nets in agriculture: A general review of types and applications. *Appl. Eng. Agr.* 24:799–808.
- Coolong, T., A.L.B.R. da Silva, and J. Shealey. 2019. Fertilizer program impacts yield and blossom end rot in bell pepper. *HortTechnology* 29:163–169.
- Cushman, K.E. and T.E. Horgan. 2001. Plant population affects bell pepper yield. Annual report of the North Mississippi Research and Extension Center. Miss. Agr. Experimental Station Info. Bul. 375:294–295.
- Day, S. 2010. Biological and mechanical approaches to sunscald management in bell pepper production. Utah State Univ., Logan, M.S. Thesis.
- Deli, J. and H. Tiessen. 1969. Interaction of temperature and light intensity on flowering of *Capsicum frutescens* var. *grossum* cv. California Wonder. *J. Amer. Soc. Hort. Sci.* 40:493–497.
- Díaz-Pérez, J.C. 2013. Bell pepper (*Capsicum annuum* L.) crop as affected by shade level: Microenvironment, plant growth, leaf gas exchange, and leaf mineral nutrient concentration. *HortScience* 48:175–182.
- Díaz-Pérez, J.C. 2014. Bell pepper (*Capsicum annuum* L.) crop as affected by shade level: Fruit yield, quality, and postharvest attributes, and incidence of Phytophthora blight (caused by *Phytophthora capsici* Leon.). *HortScience* 49:891–900.
- Díaz-Pérez, J.C. and E. Smith. 2017. Training of growers and extension agents in the Dominican Republic on managing heat stress of bell pepper (*Capsicum annuum* L.) grown in high tunnels. *HortScience* 52:1148–1150.
- Drost, D. and T. Maughan. 2018. Constructing shade structures: Small area vegetable and fruit production. Utah State Univ. Extension Publication 2018-04.
- Elad, Y., Y. Messika, M. Brand, D.R. David, and A. Szejnberg. 2007. Effect of colored shade nets on pepper powdery mildew (*Leveillula taurica*). *Phytoparasitica* 35:285–299.
- Frank, C.A., R.G. Nelson, E.H. Simonne, B.K. Behe, and A.H. Simonne. 2001. Consumer preferences for color, price, and vitamin C content of bell peppers. *HortScience* 36:795–800.
- Gent, M.P.N. 1992. Effect of planting date, ventilation and soil temperature on growth and nutrition of tomato in high tunnels. *Plant Soil* 145:81–91.
- Jett, L.W. 2017. 6—High tunnels, p. 107–116. In: M.D. Orzolek (ed.). *A guide to the manufacture, performance, and potential of plastics in agriculture*. Elsevier, Cambridge, MA.
- Jovicich, E., J.J. VanSickle, D.J. Cantliffe, and P.J. Stoffella. 2005. Greenhouse-grown colored peppers: A profitable alternative for vegetable production in Florida? *HortTechnology* 15:355–369.
- Kaiser, C. and M. Ernst. 2012. High tunnel tomatoes. University of Kentucky College of Agriculture, Food and Environment Cooperative Extension Service, Lexington.
- Knewton, S.J.B., E.E. Carey, and M.B. Kirkham. 2010a. Management practices of growers using high tunnels in the central Great Plains of the United States. *HortTechnology* 20:639–645.
- Knewton, S.J.B., R. Janke, M.B. Kirkham, K.A. Williams, and E.E. Carey. 2010b. Trends in soil quality under high tunnels. *HortScience* 45:1534–1538.
- Kong, Y., L. Avraham, Y. Perzelan, S. Alkalai-Tuvia, K. Ratner, Y. Shahak, and E. Fallik. 2013. Pearl netting affects postharvest fruit quality in 'Ver-gasa' sweet pepper via light environment manipulation. *Scientia Hort.* 150:290–298.
- Lamont, W.J. 2009. Overview of the use of high tunnels worldwide. *HortTechnology* 19:25–29.
- Larcher, W. 1995. *Physiological plant ecology. Ecophysiological and stress physiology of functional groups*. Springer, Berlin, Germany.
- Loewen, D. 2018. Tomato and pepper grafting for high tunnel production: Effects on yield, compatibility, and plant morphology. Kansas State Univ., Manhattan, M.S. Thesis.
- Lopez-Marin, J., A. Galvez, A. Gonzalez, C. Egea-Gilabert, and J.A. Fernandez. 2012. Effect of shade on yield, quality and photosynthesis-related parameters of sweet pepper plants. VII International Symposium on Light in Horticultural Systems 956:545–552.
- Marcelis, L.F.M., E. Heuvelink, L.R. Baan Hofman-Eijer, J. Den Bakker, and L.B. Xue. 2004. Flower and fruit abortion in sweet pepper in relation to source and sink strength. *J. Expt. Bot.* 55(406):2261–2268.
- Marcelis, L.F.M. and L.C. Ho. 1999. Blossom-end rot in relation to growth rate and calcium content in fruits of sweet pepper (*Capsicum annuum* L.). *J. Expt. Bot.* 50:357–363.
- Mashabela, M.N., K.M. Selahle, P. Soundy, K.M. Crosby, and D. Sivakumar. 2015. Bioactive compounds and fruit quality of green sweet pepper grown under different colored shade netting during postharvest storage. *J. Food Sci.* 80(11):H2612–H2618.
- Möller, M. and S. Assouline. 2007. Effects of a shading screen on microclimate and crop water requirements. *Irr. Sci.* 25:171–181.
- O'Connell, S., C. Rivard, M.M. Peet, C. Harlow, and F. Louws. 2012. High tunnel and field production of organic heirloom tomatoes: Yield, fruit quality, disease, and microclimate. *HortScience* 47:1283–1290.
- Olle, M. and I. Bender. 2009. Causes and control of calcium deficiency disorders in vegetables: A review. *J. Hort. Sci. Biotechnol.* 84:577–584.
- Reeve, J. and D. Drost. 2012. Yields and soil quality under transitional organic high tunnel tomatoes. *HortScience* 47:38–44.
- Selahle, K.M., D. Sivakumar, J. Jifon, and P. Soundy. 2015. Postharvest responses of red and yellow sweet peppers grown under photo-selective nets. *Food Chem.* 173:951–956.
- Simonne, A.H., E.H. Simonne, R.R. Eitenmiller, H.A. Mills, and N.R. Green. 1997. Ascorbic acid and provitamin A contents in unusually colored bell peppers (*Capsicum annuum* L.). *J. Food Compos. Anal.* 10:299–311.
- Stamps, R.H. 2009. Use of colored shade netting in horticulture. *HortScience* 44:239–241.
- Swiader, J.M. and G.W. Ware. 2002. *Producing vegetable crops*. Interstate Publishers, Danville, IL.
- Taylor, M.D. and S.J. Locascio. 2004. Blossom end rot: A calcium deficiency. *J. Plant Nutr.* 27:123–139.
- Vidigal, D.S., D.C.S. Fernandes, L.A.S. Dias, and F.L. Finger. 2011. Changes in seed quality during fruit maturation of sweet pepper. *Sci. Agr.* 68:535–539.
- Waterer, D. 2003. Yields and economics of high tunnels for production of warm-season vegetable crops. *HortTechnology* 13:339–343.
- Waterer, D. and J. Bantle. 2000. High tunnel temperature observations. 2 Aug. 2019. <http://www.usask.ca/agriculture/plantsci/vegetable/resources/veg/ht_temp.pdf>.
- Zheng, M.Z., B. Leib, D.M. Butler, W. Wright, P. Ayers, D. Hayes, A. Haghverdi, T. Grant, P. Vanchiasong, D. Muchoki, and L. Feng. 2019. Assessing heat management practices in high tunnels to improve organic production of bell peppers. *Scientia Hort.* 246:928–941.