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Metalized-striped Plastic Mulch Reduces Root-zone Temperatures during Establishment and Increases Early-season Yields of Annual Winter Strawberry

Stephen S. Deschamps and Shinsuke Agehara[1]
Department of Horticulture, University of Florida, Gulf Coast Research and Education Center, 14625 County Road 672, Wimauma, FL 33598

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***Abstract*. Black plastic mulch is used predominantly for winter strawberry (*Fragaria ×ananassa* Duch.) production in Florida because of its warming effects. However, black plastic mulch can increase heat stress during establishment, especially when growers advance planting dates (e.g., late September) to improve earliness. Consequently, we designed a new plastic mulch film that has a metalized center stripe with black shoulders. We hypothesized that metalized-striped mulch can minimize heat stress during establishment, while maintaining the warming effects of black mulch during winter. We conducted field trials over two seasons to evaluate black mulch, fully metalized mulch, and metalized-striped mulch using two cultivars differing in heat stress tolerance and fruit production patterns: 'Florida Radiance' and 'Florida Beauty'. The effect of plastic mulch type on plant growth and yield was generally consistent across both seasons. Compared with black mulch, metalized-striped mulch reduced afternoon root-zone temperature (RZT) by up to 3.1 °C and reduced the duration of heat stress conditions (RZT > 30 °C) by 119 hours across October and November, but exhibited equivalent soil warming during winter. Yield increases by metalized-striped mulch compared with black mulch ranged from 19% to 34% in the early season (November–January), 6% to 20% in the late season (February–March), and 12% to 26% over the entire season. Statistical significance was detected for the 2016–17 early-season yield and when yield data were expressed on a weekly basis. Compared with black mulch, metalized-striped mulch improved fruit number significantly without affecting fruit weight or canopy area, suggesting that heat stress on black mulch negatively affects flower and fruit development more than plant growth. Weekly fruit yield data indicate that metalized-striped mulch can produce greater yields than fully metalized mulch. Metalized-striped mulch is an easily implementable strategy for reducing establishment heat stress and improving fruit earliness in subtropical winter strawberry production regions.**

Florida is the primary producer of winter strawberries in the United States because of its mild subtropical climate. The price received by Florida strawberry growers is highly variable throughout the season, with the greatest prices typically seen during the early-season months of November, December, and January. According to U.S. strawberry market data from 2012–17, the average grower price in November was $22.80 per 3.6-kg flat, followed by $18.94, $14.38, $11.40, and $8.88 for the months of December through March, respectively (U.S. Department of Agriculture, 2018). Because the Florida strawberry industry is threatened by new challenges such as international competition, rising production costs, and growing labor shortages, Florida strawberry growers require further improvements in early yield to remain profitable (Wu et al., 2015).

Historically, Florida strawberry growers have planted in early to mid October. Bare-root transplants are typically established in raised beds covered with black plastic mulch, which has long been considered important to achieve adequate wintertime soil warming (Brooks, 1959). After planting, the fragile transplants can be exposed to high daily air temperatures exceeding 30 °C for up to 6 weeks. During this time, flower buds initiate and develop in the crowns while the plants establish a leaf canopy capable of supporting fruit production, which usually begins in mid November. Yields increase slowly throughout the winter, with peak production occurring in March.

To speed up establishment and increase early yields, Florida strawberry growers have recently begun to advance transplanting dates from mid October to late September. As a result, plants are exposed to even greater heat stress conditions than they normally would when planted in October. For example, maximum daily air temperatures were ≈34 °C in the third week of Sept. 2016, but only 28 °C in the second week of Oct. 2016. Combining advanced planting dates with black plastic mulch can likely cause excessive heat stress conditions, especially because establishment period soil temperatures often exceed 35 °C under black plastic mulch. A number of studies indicate that temperatures above 30 °C can induce physiological complications in strawberry, including slowed, abnormal growth (Geater et al., 1997; Hellman and Travis, 1988; Zhang et al., 1997); reduced protein content (Gulen and Eris, 2015); and low root-oxygen consumption (Sakamoto et al., 2016). Plants could experience excess heat stress, which leads to inhibited growth and fruit development when planted on black plastic mulch in late September. To avoid this, growers need an alternative to black plastic mulch.

Metalized mulch films have the potential to improve early-season fruit development by alleviating, at least in part, heat stress conditions during the establishment period (Andino and Motsenbocker, 2004; Vos et al., 1995). In general, reflective metalized mulch films can reduce soil temperatures compared with black mulch by reflecting a greater proportion of incoming solar radiation (Ham et al., 1993). Reflective metalized mulch films have proved widely effective at increasing marketable fruit yields compared with black mulch for a number of horticultural crops, including tomato (*Solanum lycopersicum*) and bell pepper (*Capsicum annuum*), which are both major crops in Florida (Andersen et al., 2012; Díaz-Pérez, 2010; Greer and Dole, 2003; Hutton and Handley, 2007). Relatively few studies have compared reflective mulch films to the standard black plastic mulch for subtropical strawberry production. Perhaps most notably, Albregts and Chandler (1993) found entirely white- and yellow-painted mulch films to improve early-season yields compared with black plastic mulch for Florida strawberry production. However, black plastic mulch outperformed yellow mulch and white mulch in the late season, possibly resulting from insufficient wintertime soil warming by these two more reflective mulch films. Consequently, we believe that subtropical winter strawberry growers would benefit from a multicolored mulch design that is reflective in the center and black on the shoulders. We hypothesized that by having the dual benefits

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[1]Corresponding author. E-mail: sagehara@ufl.edu.
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of reflective mulch and black mulch, metalized-striped mulch should maintain sufficiently cool RZTs during establishment, and sufficiently warm RZTs during the cool winter months.

Several previous studies have examined the effect of combining two different colors in one plastic mulch type, mostly by adding a black center stripe to reflective silver mulch. The positive effects of this multicolored mulch type compared with entirely black or silver mulch include increased canopy-level light capture, soil warming during spring establishment, improved yield of bell pepper, and reduced incidence of virus symptoms in tomato (Csizinszky et al., 1999; Díaz-Pérez, 2010; Hutton and Handley, 2007). Metalized mulch with a black center stripe is meant to warm transplants during spring establishment and reduce soil temperatures during hot summer months, which is the opposite soil warming pattern that we expected to observe using black mulch with a metalized center stripe. To our knowledge, the strategy of using black plastic mulch with a metalized center stripe has never been evaluated for strawberry production, or any other crop production system.

The objective of our study was to examine the effects of metalized-striped plastic mulch on soil temperature, plant growth, fruit yield, and earliness using two of Florida's most current early-yielding strawberry cultivars. 'Florida Radiance', which currently accounts for about 60% of Florida's strawberry market, is a short-day cultivar not recommended for September planting because it has a relatively weak plant habit and fruit can become elongated and unmarketable under high temperatures (Whitaker et al., 2008). 'Florida Beauty' is an early-yielding, weak day-neutral that possesses a compact canopy, making it well-suited for advanced planting dates (Whitaker et al., 2017). 'Florida Radiance' is a seasonal flowering genotype, so its flowering and fruiting are tightly controlled by photoperiod and temperature, whereas 'Florida Beauty' is an everbearing genotype that can basically produce flowers and fruit throughout the entire growing season (Heide et al., 2013). To understand the potential importance of using a multicolored mulch film, we compared metalized-striped mulch against fully metalized mulch as well as the industry standard black plastic mulch. To follow recent Florida strawberry-growing trends of advancing planting from mid October to late September, we examined the effect of metalized-striped mulch when planting was advanced to late September in two seasons.

Materials and Methods

Bed preparation and plant establishment. Strawberry field trials were conducted at the University of Florida's Institute of Food and Agricultural Science Gulf Coast Research and Education Center (GCREC) in Balm, FL, during the 2016–17 and 2017–18 winter and spring growing seasons. The field site's soil (Myakka fine sand siliceous hypothermic Oxyaquic Alorthod) had a pH and organic matter content of 6.8 and 1.5%, respectively. On 10 Sept. 2016 and 14 Aug. 2017, commercial equipment was used to prepare the GCREC's strawberry fields such that all beds were covered initially with entirely black plastic mulch. The beds used in our experiment measured 91 m long, 81 cm wide at the base, 71 cm wide at the shoulders, and 25 cm high at the bed top. During the initial preparation, beds were fumigated with PicClor 60 (1,3-dichloropropene + chloropicrin; 303 kg/ha) (TriEst Ag Group, Inc., Greenville, NC) to reduce incidence of soil pathogens and weeds. One line of drip irrigation tubing (0.95 L/h/emitter) with a 30.5-cm emitter spacing was laid 2.5 cm deep at each bed's center. To reduce the effect of experimental mulch types on fumigation efficacy, 0.02-mm-thick black plastic mulch was stretched over all beds. The experimental mulch types were not applied during the initial bed preparation days of 10 Sept. 2016 and 14 Aug. 2017. A map showing the experimental layout and bed dimensions is provided in Fig. 1.

On 27 Sept. 2016 and 14 Sept. 2017, four full-length beds underwent final preparation, which consisted of replacing the previously laid black plastic mulch with the experimental mulch films used in our trials. Each of the four beds were divided randomly into equal-length sections of black mulch, fully metalized mulch, and metalized-striped mulch (Can-Block XSB v-TIF silver/black; Imaflex, Inc., Thomasville, NC). Metalized coatings on the fully metalized mulch and metalized-striped mulch are a 25-nm-thick layer of aluminum. The center stripe on the metalized-striped mulch is 51 cm wide. Overhead photos of each plastic mulch film are provided in Fig. 1C. The experiment used a split-plot design, with mulch type as the whole-plot factor and cultivar as the subplot factor. During each season, 24 plots were used to test two cultivars on three mulch types across four beds, with each bed serving as a replicate. On 28 Sept. 2016 and 25 Sept. 2017, bare-root transplants with three to four leaves were received from Crown Nursery (Red Bluff, CA). On 29 Sept. 2016, transplants of 'Florida Radiance' were planted in their respective plots at a density of 32 plants per plot; transplants of 'Florida Beauty' were planted at a density of 16 plants per plot as a result of plant material constraints from the nursery. On 26 Sept. 2017, transplants of 'Florida Radiance' and 'Florida Beauty' were both planted in their respective plots at a density of 20 plants per plot. Plants were spaced in double rows with 38 cm between planting holes and 30 cm between rows. Following commercial practices, the plants received 9 h of overhead irrigation during daylight hours for 10 d after transplanting. A commercial standard strawberry fertilizer (6N–0.9P–3.3K) was administered through the drip tape three times per week at a rate of 1.12 kg N/ha/d. Plants were watered daily via

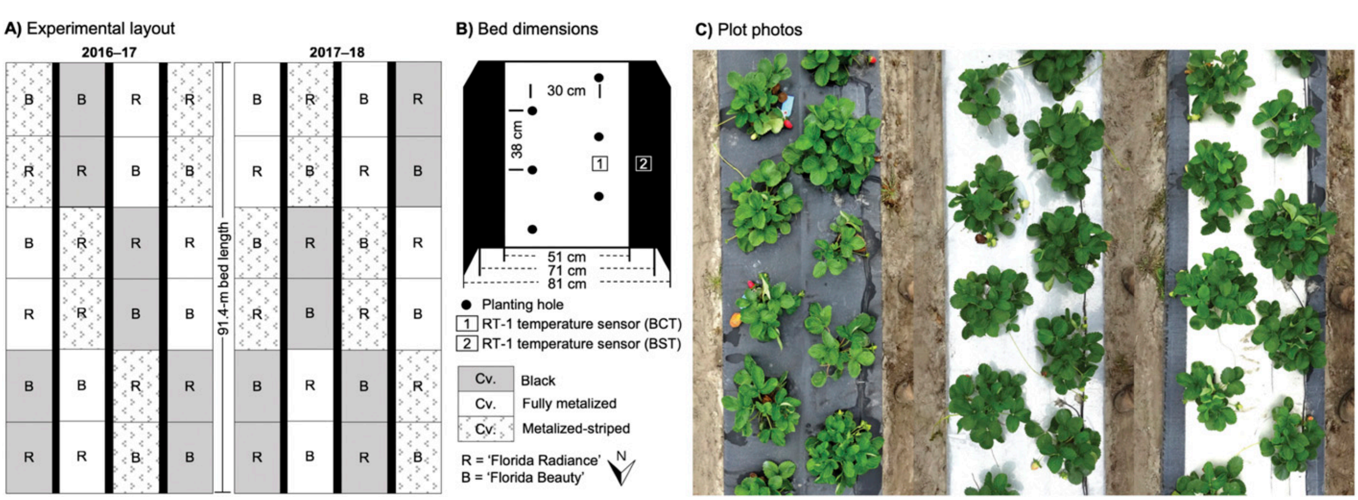


Fig. 1. (**A**) Experimental layout in the 2016–17 and 2017–18 seasons. (**B**) Overall bed width, bed shoulder width, and metalized stripe width are provided along with the location of planting holes and sensors for bed center temperature (BCT) and bed shoulder temperature (BST). (**C**) Overhead photos showing 'Florida Radiance' on black (left), fully metalized (middle), and metalized-striped (right) plastic mulches at 70 d after planting in the 2017–18 season.

drip irrigation. Pest and disease control were performed following current recommendations from the University of Florida (Peres, 2015).

Soil temperature. Soil temperature was monitored from November through February of the 2016–17 season and October through February of the 2017–18 season. Soil temperature was monitored using two Decagon RT-1 temperature sensors in two plots of each of the three mulch types; thus, 12 RT-1 sensors were used in total. Soil temperature was logged every 30 min by EM50G data loggers (Decagon Devices, Pullman, WA). Soil temperatures were monitored at both the bed center and the bed shoulder. Bed center temperature (BCT) was recorded at a 10-cm depth and 20 cm from the bed shoulder toward the bed center. Bed shoulder temperature (BST) was recorded at a 10-cm depth and 5 cm from the bed shoulder toward the bed center.

Plant growth. Canopy area measurements were taken three times during the 2016–17 season and six times during the 2017–18 season. Overhead photos of each experimental plot were captured using a camera elevated on a monopod to a height of 2.1 m over the bed surface. Canopy area was determined by analyzing the photos using the image processing software Image J (National Institute of Health, Bethesda, MD). The image scale was set according to the known bed width in each photo. Image color threshold was determined by adjusting hue, saturation, and brightness values to distinguish green canopy pixels from all background pixels. Threshold values were determined manually for each day on which photos were taken to account for differences in ambient light, cloud cover, and shadow distribution. After thresholding, the images were converted to a binary format in which canopy pixels became black and background pixels became white. The total area of the black canopy pixels was measured and recorded. Individual plant canopy areas were determined by dividing the whole-plot canopy area by the number of living plants per plot.

During the 2016–17 season, runners were removed, counted, and weighed at 10 and 12 weeks after planting. During the 2017–18 season, runners were sampled from all plots at 9 weeks after planting. At the end of the 2016–17 season, three plants from each plot were sampled randomly; separated into roots, leaves, and stems; and then dried at 65 °C for 48 h to determine tissue dry weight. At the end of the 2017–18 season, two plants from each plot were sampled randomly to determine fresh weight, crown number, petiole number, and leaf area.

Fruit yield and quality. Strawberries were harvested twice weekly from mid November to early March of both seasons. The harvested fruits were graded according to U.S. Department of Agriculture (2006) grading standards. Fruits weighing more than 10 g and free from disease, pest, or mechanical damage were considered marketable. The number and weight of fruit from each plot were recorded. To determine soluble solids content (SSC) for the 2016–17 season, four fruit from each 'Florida Radiance' plot were sampled on 25 Jan. and 15 Feb. To determine SSC for the 2017–18 season, four fruit from each 'Florida Radiance' plot were sampled on 25 Jan. Strawberry juice from the aggregate samples was analyzed with a digital refractometer to measure SSC for each plot.

Statistical analysis. During both seasons, there were six treatments, which were factorial combinations of three mulch types and two cultivars. There were four replications per treatment in both seasons, for a total of 24 plots (Fig. 1A). The experiments used a split-plot design, with mulch type as the whole-plot factor and cultivar as the subplot factor. All statistical analyses were performed using SAS Enterprise Guide 7.1 (SAS Institute, Cary, NC). Soil temperatures were compared between mulch types for each hourly average within a month using standard one-way analysis of variance (ANOVA). Yield, quality, and growth data were analyzed separately for each planting date by two-way ANOVA. The GLIMMIX procedure was used to analyze elongated fruit proportion data for both seasons. Mean separation was performed using the Tukey-Kramer method, and significance was established at $P < 0.05$ unless otherwise noted.

Results and Discussion

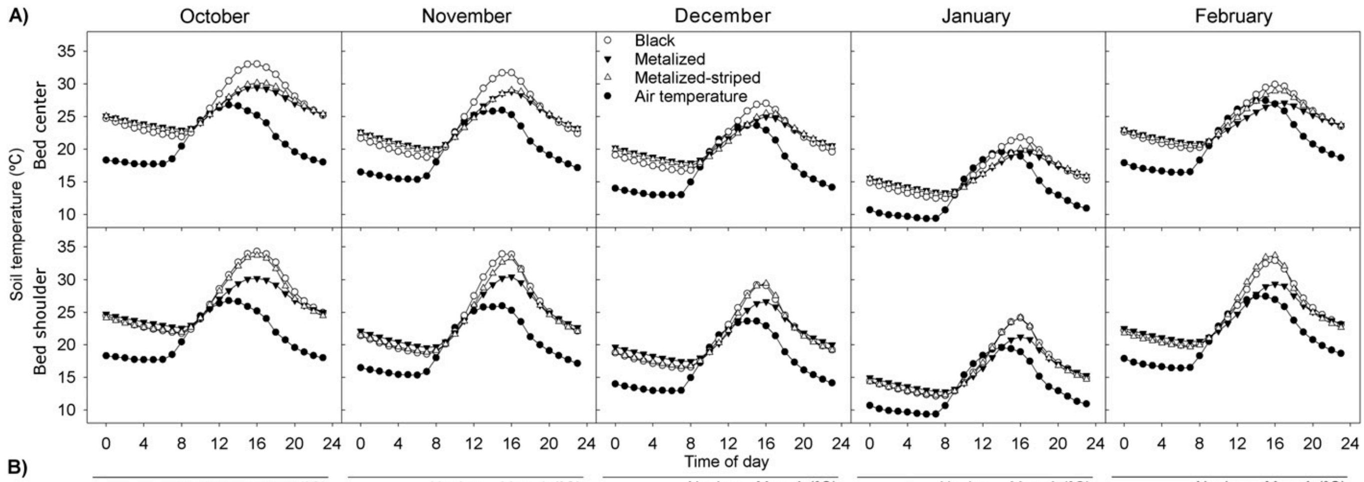
Because early-season strawberries garner higher market prices, improving early-season fruit yield is important to Florida growers. Metalized mulch films have the potential to improve early-season fruit development, at least in part, by alleviating heat stress conditions during the establishment period (Andino and Motsenbocker, 2004; Vos et al., 1995). In combination with the continued development of early-yielding cultivars, which can produce fruit at higher temperatures and longer photoperiods than the current major cultivars, metalized mulch films could prove critical to the long-term viability of Florida's strawberry industry by reducing heat stress and further improving early-season yields.

Root-zone cooling by metalized mulch types. High temperatures capable of inducing plant heat stress are a major concern for strawberry growers, especially during establishment, when plants are developing roots, crowns, and canopies capable of supporting fruit production. Black plastic mulch has high shortwave radiation absorption, causing it to increase RZTs drastically by conducting thermal radiation toward the bed center (Ham et al., 1993). Conversely, metalized mulch films have low shortwave radiation absorption, so they conduct less radiation into the soil and maintain lower RZTs than black mulch. To evaluate the RZT cooling effects of fully metalized mulch and metalized-striped mulch, we monitored BCT and BST at a 10-cm depth throughout the growing season.

Because soil temperature data showed the same trend in both seasons, only the more comprehensive data from the 2017–18 season, which included October soil temperature monitoring, are presented in Fig. 2A. Plants on black mulch experienced significantly higher BCTs than plants on fully metalized mulch or metalized-striped mulch, especially throughout the establishment period (October and November). In October, the average afternoon BCT was reduced significantly by 3.7 °C under fully metalized mulch and 3.1 °C under metalized-striped mulch compared with black mulch (Fig. 2B). In November, both fully metalized mulch and metalized-striped mulch reduced the average afternoon BCT significantly by 3.2 °C compared with black mulch. In addition to reducing the magnitude of establishment period heat stress conditions, the metalized mulch films also reduced significantly the duration of heat stress conditions. Because many reports suggest RZTs above 30 °C can result in poor growth and development of *Fragaria* species (Geater et al., 1997; Sakamoto et al., 2016; Zhang et al., 1997), we used 30 °C as a heat stress temperature threshold in our study. Throughout October, BCTs exceeded 30 °C for an average of 164 h under black mulch (Table 1). This duration was reduced significantly to 136 h under fully metalized mulch and reduced nonsignificantly to 153 h under metalized-striped mulch. Throughout November, BCTs exceeded 30 °C for an average of 108 h, but the duration was reduced significantly to only 40 and 46 h under fully metalized and metalized-striped mulch, respectively. Many previous studies have found metalized mulch films to maintain lower daytime RZTs than black mulch by reflecting more incoming shortwave radiation (Díaz-Pérez, 2010; Díaz-Pérez and Batal, 2002; Díaz-Pérez et al., 2005; Lamont, 2005; Tarara, 2000). Our results of reduced RZTs under more reflective mulch types are consistent with these previous observations.

Because they have different shoulder colors, fully metalized mulch and metalized-striped mulch had contrasting effects on BSTs throughout the growing season. Compared with black mulch, the average hourly BST in October was reduced significantly by as much as 4.1 °C under fully metalized mulch compared with only 1.1 °C under metalized-striped mulch (Fig. 2B). The same trend can be seen throughout November and December. By January, however, there were no significant differences in daytime BSTs between black mulch and metalized-striped mulch. In contrast, fully metalized mulch reduced the average afternoon BSTs in January by as much as 2.9 °C compared with black mulch. The reason that black mulch and metalized-striped mulch caused similar wintertime soil warming is their black shoulders. Plant canopies mostly covered the bed center by January (Fig. 2C). As a result, only the bed shoulders remained exposed to interact with incoming solar radiation. This caused greater daytime soil warming under black mulch and metalized-striped mulch, which both have black shoulders that absorb solar radiation effectively and conduct it as

A)



B)

October

	No. hrs ↑	No. hrs ↓	Max. Δ (°C) ↑	Max. Δ (°C) ↓
Bed center				
B vs M	9	9	1.15	3.66
B vs MS	8	8	0.82	3.12
M vs MS	4	1	0.83	0.21
Bed shoulder				
B vs M	10	12	0.88	4.12
B vs MS	5	9	0.28	1.21
M vs MS	9	12	3.53	0.83

November

	No. hrs ↑	No. hrs ↓	Max. Δ (°C) ↑	Max. Δ (°C) ↓
Bed center				
B vs M	12	7	1.40	3.17
B vs MS	12	8	1.08	3.23
M vs MS	0	1	--	0.19
Bed shoulder				
B vs M	11	8	1.07	3.70
B vs MS	4	7	0.29	1.68
M vs MS	6	14	2.84	0.80

December

	No. hrs ↑	No. hrs ↓	Max. Δ (°C) ↑	Max. Δ (°C) ↓
Bed center				
B vs M	14	4	1.40	2.28
B vs MS	13	6	1.03	2.09
M vs MS	0	2	--	0.50
Bed shoulder				
B vs M	11	6	1.13	2.82
B vs MS	4	4	0.25	0.87
M vs MS	6	13	2.80	0.93

January

	No. hrs ↑	No. hrs ↓	Max. Δ (°C) ↑	Max. Δ (°C) ↓
Bed center				
B vs M	13	6	1.01	2.39
B vs MS	11	1	0.75	0.87
M vs MS	1	0	0.23	--
Bed shoulder				
B vs M	9	6	0.73	2.87
B vs MS	0	0	--	--
M vs MS	5	10	2.94	0.71

February

	No. hrs ↑	No. hrs ↓	Max. Δ (°C) ↑	Max. Δ (°C) ↓
Bed center				
B vs M	9	6	0.84	2.95
B vs MS	8	0	0.49	--
M vs MS	0	6	--	0.35
Bed shoulder				
B vs M	6	3	0.70	3.59
B vs MS	0	1	--	0.35
M vs MS	4	9	4.52	0.88

C)

Fig. 2. (**A**) Average hourly root-zone temperatures at a 10-cm depth for the bed center and bed shoulder. (**B**) Tables showing the number of hours of statistically significant differences as well as the maximum change in temperature (↑ = increased temperature; ↓ = decreased temperature) for each comparison shown on the left (B = black mulch; M = fully metalized mulch; MS = metalized-striped mulch). Comparisons are given as the second mulch type relative to the first mulch type. (**C**) Representative photos of the growth stage of 'Florida Radiance' are given for each month.

thermal radiation along a temperature gradient toward the bed center. Consequently, metalized-striped mulch did not reduce BCTs compared with black mulch in January and February. Our data indicate that metalized-striped mulch is capable of warming winter soils just as well as black mulch, which has soil-warming properties that have long been considered necessary to attain profitable winter strawberry yields in Florida (Albregts and Chandler, 1993; Brooks, 1959).

Beyond reducing daytime soil temperatures compared with black mulch, we also found that fully metalized mulch and metalized-striped mulch resulted in higher nighttime and predawn RZTs than black mulch. In October, fully metalized mulch and metalized-striped mulch increased significantly the average BCT compared with black mulch for 9 h out of the night (data not shown), with a maximum increase of 1.15 °C occurring just before dawn (Fig. 2B). The ability of fully metalized mulch and metalized-striped mulch to act as insulators and trap heat in the root zone at night is a result of the optical properties of their aluminum coating—specifically, aluminum's low emissivity. Emissivity (ε) is a measure of the relative amount of longwave radiation emitted from a material's surface compared with the longwave radiation emitted by a perfectly emitting blackbody (ε = 1.0) at the same temperature and wavelength (Tarara, 2000). Ham et al. (1993) studied the optical properties of different plastic mulch surfaces and reported that mulch surfaces with high longwave transmittance also had high longwave emissivity. In their study, black mulch (ε = 0.87) resulted in the highest daytime temperatures and coolest nighttime temperatures, whereas aluminum-painted mulch (ε = 0.28) resulted in the coolest daytime temperatures but highest nighttime temperatures of all eight mulches examined.

Metalized (aluminum) mulch surfaces are characterized by low shortwave absorption, high shortwave reflection, and low longwave transmittance (Ham et al., 1993). Because of their low shortwave absorption, metalized mulch films are slow to gather energy throughout the day. However, the low emissivity and longwave transmittance of metalized mulch films produce an insulating effect whereby thermal radiation is not emitted rapidly from the bed surface at night. By comparison, black mulch gathers heat rapidly throughout the daytime and also emits heat rapidly to the cooler surrounding nighttime air. In this way, plants on black mulch experience greater diurnal RZT fluctuation than plants on fully metalized mulch or metalized-striped mulch. Despite this, there are several studies that suggest that diurnal RZT fluctuations have little overall effect on strawberry growth and yield when temperature extremes are avoided (Gonzalez-Fuentes et al., 2016; Kumakura and Shishido, 1994). We suspect that small changes in diurnal RZT fluctuation by the metalized mulch films were unimportant to affecting early yield in our study. Instead, we believe earliness improvement resulted from a reduction in the magnitude and duration of heat stress conditions throughout the hot early-season afternoons.

Metalized mulch types improve early yield. There was a trend of improved early-season fruit yield by fully metalized mulch and metalized-striped mulch in both seasons, although the effect was significant only during the 2016–17 season (Table 2). Conversely, the plastic mulch × cultivar interaction did not affect fruit yield significantly in either season. As a result, data presented in this section are pooled by the main effect of plastic mulch type.

During the 2016–17 season, fully metalized mulch and metalized-striped mulch increased early yields significantly by 11% and 19%, respectively, compared with black mulch. During the 2017–18 season, fully metalized mulch and metalized-striped mulch led to nonsignificant early-yield increases of 22% and 34%, respectively. By contrast, neither late-season nor total-season yields were affected significantly by plastic mulch type during the 2016–17 or 2017–18 season. Regardless, there was still a prominent trend of total-season yield improvement by fully metalized mulch and metalized-striped mulch. For example, metalized-striped mulch led to a nonsignificant total-season yield increase of 26% compared with black mulch during the 2017–18 season. Metalized-striped mulch resulted in numerically higher early and total yields than fully metalized mulch during both seasons.

As expected, early-season yields were more affected by plastic mulch type than late-season yields. Plastic mulches influence the daytime energy balance around the crop both above and below the soil, mostly by either reflecting or absorbing incoming solar radiation per their specific optical properties (Ham et al., 1993; Tarara, 2000). Because exposure of the mulch surface to incoming solar radiation is highest during the early season, when plant canopies are small, the mulches should impart their greatest impact on the plant energy balance during establishment.

Table 1. Effect of mulch type on the average number of hours in which bed center temperature (BCT) exceeded 30 °C.

	BCT > 30 °C (h)				
Mulch	Oct.	Nov.	Dec.	Jan.	Feb
Black	164 a[z]	108 a	21 a	1 a	57 a
Fully metalized	96 b	40 b	0 b	0 b	2 b
Metalized striped	107 ab	46 b	4 b	0 b	42 a

[z]Means within a column not followed by the same lowercase letter are significantly different at $P < 0.05$.

Two previous studies have examined the effect of reflective mulch for annual raised-bed strawberry production under subtropical conditions. In Brazil, Yuri et al. (2012) found no difference in winter strawberry yields between black and silver reflective mulch treatments. In Florida, Albregts and Chandler (1993) evaluated eight colors of plastic mulch for winter strawberry production. For two consecutive seasons, yellow mulch and white mulch increased early-season yields (then considered November through February) by 26% to 33% compared with black mulch, but they had no significant effect on total-season yields because of their negative impact on late-season yields. Compared with our study, Albregts and Chandler (1993) used cultivars and planting dates that were less likely to promote high early yields. Because of different market conditions, they planted roughly 3 weeks later and continued to harvest for almost 2 months longer than us. Their longer harvest period may account for differences in the effect of reflective mulch on late-season yields between our study and theirs. Using modern early-yielding cultivars and late-September planting dates, we observed significant increases in early yield and nonsignificant increases in late yield by fully metalized mulch and metalized-striped mulch. To our knowledge, our study is the first to report the successful use of reflective metalized mulch for improving early-season yields and producing numerically greater total-season yields than black plastic mulch under subtropical winter strawberry production conditions. The effects of root-zone cooling by the fully metalized mulch and metalized-striped plastic mulch on improved strawberry yields are discussed further in the following sections.

Metalized mulch types improve fruit development without affecting plant growth. In our study, yield gains by fully metalized mulch and metalized-striped mulch resulted from an increase in the number of fruit produced by each plant rather than an improvement in fruit size. In fact, the average fruit size during the 2016–17 early season was the same across all three mulch treatments (Table 3). During this same period, plants on fully metalized mulch and metalized-striped mulch produced 13% and 20% more fruit than plants on black mulch, respectively. This implies that significant early marketable yield increases during the 2016–17 season were almost entirely a result of improved fruit development and fruit set.

Interestingly, canopy image analysis did not reveal any changes in canopy area by plastic mulch type for any sampling date in either season (data not shown). This observation suggests that fruit development is more sensitive than vegetative growth to heat stress caused by black plastic mulch. It is well documented that temperatures above 30 °C can suppress floral development, pollen tube growth, pollen viability, and overall fruit set in strawberries (Kumakura and Shishido, 1994; Ledesma and Sugiyama, 2005; Wang and Camp, 2000). In a growth chamber experiment, Ledesma et al. (2008) found that, across two different short-day strawberry cultivars, increasing day/night temperatures from 23/18 to 30/25 °C reduced the number of inflorescences produced significantly. The 30/25 °C day/night treatment subsequently had a lower percentage of successful fruit set and number of fruits produced compared with the 23/18 °C treatment. Furthermore, Kadir et al. (2006) found that increasing day/night temperatures from 20/15 to 30/25 °C reduced fruit yields significantly without inhibiting shoot dry matter accumulation. They also found that exposure to 30 °C for more than 2 weeks inhibits strawberry flower development regardless of cultivar heat sensitivity. In our study, as discussed earlier, fully metalized mulch and metalized-striped mulch both reduced the magnitude and duration of heat stress conditions significantly compared with black mulch. Based on the

Table 2. Effect of cultivar, mulch type, and their interaction on early, late, and total yield of strawberries in the 2016–17 and 2017–18 seasons.

		2016–17			2017–18		
Cultivar	Plastic mulch	Early	Late	Total	Early	Late	Total
Florida Radiance	Black	12.1 bc[z]	15.0	27.1	8.8	15.3 ab	24.2
	Fully metalized	13.2 ab	16.4	29.6	11.8	15.9 ab	27.7
	Metalized striped	14.2 a	15.9	30.1	13.4	19.0 a	32.4
Florida Beauty	Black	11.2 c	13.9	25.1	10.5	12.1 b	22.6
	Fully metalized	12.9 ab	14.9	27.8	11.7	11.9 b	23.7
	Metalized-striped	13.7 a	14.8	28.4	12.6	13.9 b	26.5
Averaged data							
Florida Radiance		13.2	15.8	28.9	11.3	16.7 a	28.1 a
Florida Beauty		12.6	14.5	27.1	11.6	12.7 b	24.2 b
	Black	11.7 b	14.4	26.1	9.7	13.7	23.4
	Fully metalized	13.0 a	15.7	28.7	11.8	13.9	25.7
	Metalized striped	13.9 a	15.3	29.3	13.0	16.5	29.4
Source of variation (P value)							
Cultivar		0.1633	0.2311	0.1450	0.7297	0.0002	0.0062
Plastic mulch		0.0182	0.7326	0.1525	0.1796	0.0914	0.1272
Cultivar × plastic mulch		0.8187	0.9825	0.9943	0.3790	0.5364	0.3063

[z]Means within a column not followed by the same lowercase letter are significantly different at $P < 0.05$ according to Tukey's test.

Table 3. Effect of cultivar, mulch type, and their interaction on the number of marketable fruit per plant during the early, late, and total periods of the 2016–17 and 2017–18 seasons.

		2016–17					
		No. fruit/plant			Fruit size (g)		
Cultivar	Plastic mulch	Early	Late	Total	Early	Late	Total
Florida Radiance	Black	14.4B[z]	19.0	33.4	19.4ab	18.4 ab	19.0 ab
	Fully metalized	15.0B	20.3	35.3	20.0a	18.7 a	19.5 a
	Metalized striped	16.4A	20.4	36.8	19.8a	18.2 ab	19.2 a
Florida Beauty	Black	14.0B	17.8	31.8	17.7bc	18.1 ab	17.9 bc
	Fully metalized	17.0A	19.8	36.8	17.2c	17.8 ab	17.4 c
	Metalized striped	17.7A	20.8	38.4	17.4c	16.5 b	17.0 c
Averaged data							
Florida Radiance		15.3b	19.9	35.2	19.7 a	18.5 a	19.2 a
Florida Beauty		16.2a	19.4	35.7	17.4 b	17.5 b	17.4 b
	Black	14.2b	18.4	32.6	18.6	18.2	18.4
	Fully metalized	16.0ab	20.1	36.0	18.6	18.3	18.5
	Metalized striped	17.0a	20.6	37.6	18.6	17.4	18.1
Source of variation (*P* value)							
Cultivar		0.0409	0.7245	0.7207	0.0000	0.0100	0.0000
Plastic mulch		0.0079	0.5446	0.1038	0.9870	0.0964	0.2952
Cultivar × plastic mulch		0.0997	0.8626	0.5869	0.2607	0.2881	0.1263

[z]Means within a column not followed by the same lowercase letter are significantly different at $P < 0.05$, whereas means within a column not followed by the same uppercase letter are significantly different at $P < 0.10$, according to Tukey's test.

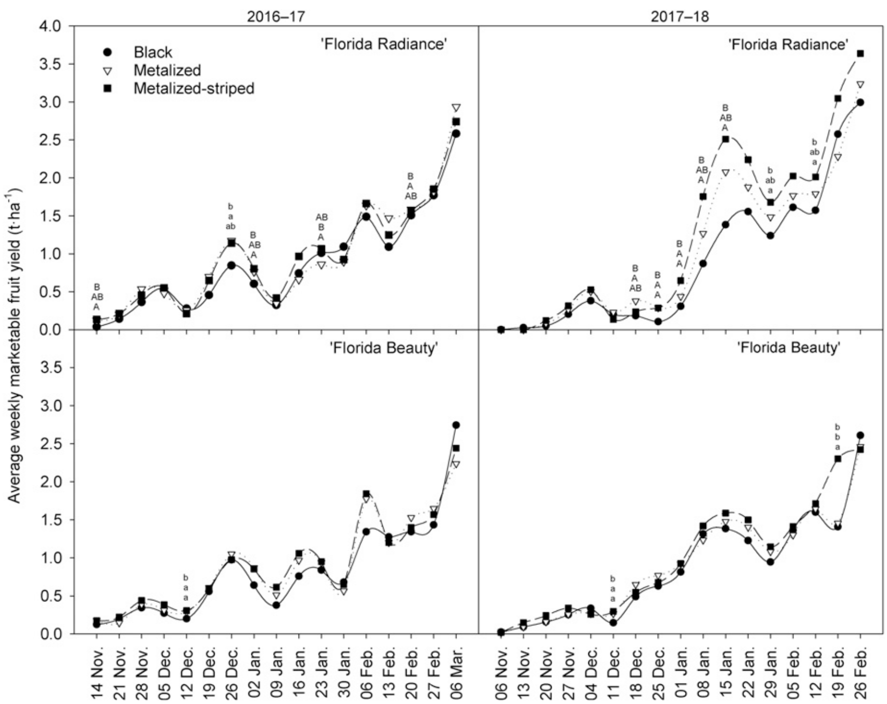


Fig. 3. Average weekly marketable fruit yield for 'Florida Radiance' (top) and 'Florida Beauty' (bottom) during the 2016–17 (left) and 2017–18 (right) seasons. Mean separation letters indicate significant difference at $P < 0.05$ if lowercase and $P < 0.10$ if uppercase, with the top, middle, and bottom letters corresponding to the means of black, metalized, and metalized-striped mulch, respectively.

evidence from previous studies that high root-zone and air temperatures can inhibit flower and fruit development, we believe heat stress mitigation by metalized mulch films in our study is responsible for alleviating, at least in part, floral inhibition in the crown, and improving early fruit set and marketable yields.

Fully metalized vs. metalized-striped mulch. The main objective of our new plastic mulch design is to create optimal growing conditions for winter strawberry production under subtropical conditions by using the metalized center stripe to cool the root zone during establishment, and by using the black shoulders to warm soils during winter. We hypothesized that metalized-striped mulch, by having the dual benefits of metalized and black-mulch films, can outperform fully metalized mulch. Several observations indicate that metalized-striped mulch is more beneficial than fully metalized mulch, although the direct comparisons between the two plastic mulches showed no significant difference. For example, metalized-striped mulch resulted in 7% more marketable fruit than fully metalized mulch during the 2016–17 early season (Table 2). During this same period, yields of 'Florida Radiance' were improved significantly by metalized-striped mulch, but not fully metalized mulch, compared with black mulch.

However, the benefits of adding a metalized center stripe to black plastic mulch were best illustrated during the 2017–18 season. Despite an above-average number of hot days during establishment (Fig. 3), metalized-striped mulch produced 10% greater early marketable yields than fully metalized mulch for both cultivars. Beginning in January, which experienced below-average daily temperatures, metalized-striped mulch began to outperform fully metalized mulch noticeably (Fig. 4). Weekly yields of 'Florida Radiance' were improved significantly compared with black plastic mulch for 5 weeks using metalized-striped mulch, but for just 3 weeks using fully metalized mulch. In addition, marketable late-season yields of 'Florida Beauty' were reduced by fully metalized mulch but improved by metalized-striped mulch compared with black mulch (Table 2). Our findings indicate that metalized-striped mulch is well suited to optimize soil microenvironment conditions throughout the dynamic environmental conditions of Florida's winter strawberry production season.

Practical applications of metalized-striped mulch. To stay cost-effective in an increasingly competitive winter strawberry market, Florida strawberry growers need a practical, easily implementable solution for reducing establishment heat stress and improving early fruit yields (Guan et al., 2016). Two strawberry cultivars that differ in heat stress tolerance and early-season yield patterns were used in this study. 'Florida Beauty', the earliest cultivar available in Florida, is day neutral, so it has the ability to initiate flowers at longer photoperiods and higher temperatures than short-day cultivars (Whitaker et al., 2017). As a result, 'Florida Beauty' is recommended for planting between 20 Sept. and 1 Oct. in Florida to allow for adequate vegetative growth before flowering begins. By contrast, 'Florida Radiance' is a short-day cultivar with a relatively weak plant habit and low heat tolerance, so it is

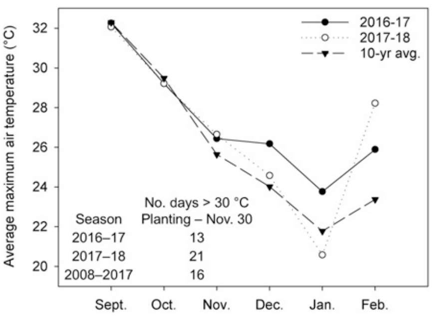


Fig. 4. Average maximum monthly air temperatures at a 60-cm height during the 2016–17 and 2017–18 seasons as well as the 10-year average (2008–17) are given. The table indicates the number of days in which the maximum daily temperature exceeded 30 °C from the planting to 30 Nov. Data were collected at the Gulf Coast Research and Education Center in Balm, FL, and were provided by the Florida Agricultural Weather Network.

recommended for planting between 5 and 15 Oct. (Whitaker et al., 2008). Despite such contrasting characteristics, no significant cultivar × plastic mulch interaction was found in our study. This observation suggests that metalized-striped mulch is a promising management option that can improve early yields consistently of a wide range of strawberry cultivars by mitigating heat stress associated with extremely early planting (e.g., late September in Florida).

In our trials, neither flavor (data not shown) nor fruit size were affected by plastic mulch type (Table 3). It is important that growers do not sacrifice fruit quality for the sake of increased early-season yields, because flavor and fruit size are two essential quality parameters considered by intermediary strawberry buyers and the end consumer (Gallardo et al., 2015). But perhaps most important to growers, information provided by the manufacturer (Imaflex, Inc., Thomasville, NC) suggests that for equal thickness and impermeability of fumigant gases, metalized-striped mulch costs only 2.7% more than entirely black plastic mulch. Overall, our findings indicate that black plastic mulch with a metalized-center stripe can improve early-season strawberry yields by up to 34% compared with black mulch without affecting fruit quality, late-season yields, or production costs negatively.

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