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Enhancing Red Fruit Coloration of Apples in the Southeastern US with Reflective Fabrics

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Abstract: For some apple cultivars, inadequate red fruit color development can reduce crop value. The use of reflective groundcovers has been demonstrated to improve red coloration in apples in other regions, but evaluation in the southeastern USA has been limited. To address this, we compared the performance of multiple reflective groundcovers in 2018 and 2020 on mature 'Fuji' trees in Edneyville, NC, USA. Woven reflective (Extenday® DayBright, Lumilys® WH100, Beltech PD2911, and Belton experimental), mylar, and sod groundcovers were deployed ~5 weeks before anticipated harvest. The effects of the treatment on light reflectance (photosynthetically active and UV radiation), fruit color, fruit quality, and crop value were determined. Across both years of evaluation, reflective groundcovers were consistent in increasing the reflectance of photosynthetically active radiation. However, only Extenday® DayBright consistently increased reflected UV radiation (250–400 nm), red fruit coloration at commercial harvest, and crop value. Fruit maturity and sunburn incidence were not influenced by any treatment in both years. Reflected UV light quality was not characterized, but it is clear that $UV_{250–400nm}$ reflectance intensity is critical to enhance 'Fuji' fruit color development. Growers in the southeastern US can use reflective groundcovers to enhance red fruit coloration to meet market demands.

Keywords: blush; fruit quality; light distribution; *Malus x domestica*; mylar; ripening

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1. Introduction

Consumer preference for fresh fruit largely relies on visual cues such as fruit coloration to evaluate external quality [1]. The impact of these preferences is evident in production standards with higher prices placed on large, well-colored fruit. Although trends for fresh fruit consumption have decreased, apples remain a preferred fruit in the USA. As of 2019, approximately 4.5 kg of fresh apples were consumed per person annually [2]. In the southeastern USA, apples are an important commodity economically. The latest statistics for North Carolina report approximately USD 19 million in sales for 2017 and USD 35 million for Virginia in 2020 [3,4]. For production in the southeastern US to meet the standards for fresh fruit, an emphasis must be placed on producing highly colored fruit.

Anthocyanin is the primary red pigment in apple fruit; however, environmental conditions influence anthocyanin production [5,6]. Specifically, low nighttime temperatures (15 °C) and ultraviolet-B (UV-B) light promote anthocyanin formation [6,7]. Apple growers in the southeastern US struggle to meet market standards for sufficient marketable red fruit color development due to environmental conditions. Per the Köppen climate classification, this region has a humid subtropical climate, which is characterized by hot summers and high air humidity [8]. Other major humid subtropical climate regions include southeast China, southeast South America, and eastern Australia [8]. Monthly mean minimum temperatures proximal to fruit maturation can exceed 15 °C in this region. In 2018, an increase in regional market standards for minimum acceptable red fruit color (from 25% to 50% marketable red fruit color) occurred across multiple commercially important varieties.

Cultural practices, such as reflective groundcovers, are available to improve light distribution in the canopy to increase red fruit color. Deploying reflective groundcovers 4 to 7 weeks before anticipated harvest has been demonstrated to improve red fruit color [9–11]. Mupambi et al. [12] found that even in lower light environments such as under protective netting, reflective groundcovers installed during the fruit maturation phase still increased red fruit color. Using mylar, a reflective film, red fruit color of 'Gala' was increased when deployed 4 weeks before harvest in South Carolina, USA [13].

To our knowledge, woven reflective groundcovers have not been evaluated in the southeastern USA on apple. Our objective was to compare the efficacy of commercially available and experimental reflective groundcovers in the southeastern USA.

2. Materials and Methods

Trials were conducted in 2018 and 2020 in a commercial orchard in Edneyville, NC. Trees were trained to vertical axis and received plant protectant sprays that adhered to local recommendations throughout the growing season.

2.1. Experiment 1: 2018

The experiment was conducted in a mature block of 'Fugachee Fuji'/'G.11' planted at 2.1 × 4.3 m spacing. Reflective groundcovers were installed ~5 weeks before harvest. Woven reflective groundcovers (Beltech PD-2911 and Extenday®; 3.5 m width) were placed adjacent to 7-tree plots (15.2 m. long section) on each side of the row. Woven reflective groundcovers were secured to the ground using landscape staples. Mylar reflective groundcover (1 m width) was placed adjacent to 7-tree plots on each side of the row and positioned proximally to the drip line. Untreated control plots (sod groundcover) were included for comparison. To minimize edge effects, data were collected from trees in the center of plot. Specifically, two trees per plot with uniform crop load and canopy volume were selected (12 trees per treatment; 48 trees total).

Incident light and reflectance were quantified in the middle of the drive row (mid-row) and within the tree canopy. Measurements occurred 1.5 m above the ground on the north and south sides of the tree. Measurements were conducted on two mid-row positions and two trees from each plot (48 trees total). Incoming photosynthetically active radiation (PAR; 400–700 nm) and reflectance by groundcovers was quantified using a ceptometer (AccuPAR PAR/LAI Ceptometer Model LP-80; Decagon Devices Inc., Pullman, WA, USA). PAR measurements occurred proximally to solar noon on a cloud-free day. The ceptometer was held in a horizontal position for all measurements. Incident light was determined with ceptometer sensors oriented toward the sky. Light reflectance was quantified by inverting the sensor (facing the ground) at each at each position and direction. In-canopy measurements were carried out with the distal end of the ceptometer next to the trunk. Similarly, incoming UV radiation and reflectance (250–400 nm) was quantified using a $UV_{250–400}$ meter and sensor (LightScout UV Meter and Sensor; Spectrum Technologies, Inc., Plainfield, IL, USA). Measurements occurred at the same mid-row and canopy positions described above. In-canopy measurements were performed with the $UV_{250–400}$ meter positioned 15 cm from the trunk.

At commercial maturity, 30 August 2018, apples were harvested for yield and fruit quality assessments. Fruit were harvested from two trees per plot that had a uniform crop load and canopy volume. Early strains of 'Fuji' require multiple harvests, since fruit do not ripen uniformly. A second harvest was completed one week after the first. Fruit was placed in labelled containers and transported to the Mountain Horticultural Crops Research and Extension Center in Mills River, NC, USA (lat. 35.428079° N, long. 82.563295° W, elevation 649 m) for analysis.

Whole-tree yield, average fruit weight, fruit size distribution, percent (%) red fruit color (i.e., blush), and internal fruit quality were determined with an electronic fruit sorter (Durand-Wayland, Inc., LaGrange, GA, USA) outfitted with a color and infrared camera system and full transmittance spectrometer (TrueSort Electronics; Ellips, Eindhoven, The Netherlands).

At the first harvest date, 30 fruits per plot (180 fruit for each treatment; 720 fruit total) were sampled for fruit quality analysis. A benchtop colorimeter (ColorFlex EZ; Hunter Associates Laboratory, Reston, VA, USA) was used to quantify lightness, chroma, and hue. Two colorimeter measurements per fruit occurred near the equatorial region of the apple. Measurements occurred on the sun-exposed and shaded portion of the fruit peel of each fruit. Fruit were visually evaluated and incidence of sunburn was recorded. Fruit firmness was measured with a fruit texture analyzer (Güss GS-20; QA Supplies, Norfolk, VA, USA). Juice samples were collected during firmness ratings and soluble solids concentration were measured with a digital refractometer (model PR-32 alpha; Atago, Bellevue, WA, USA). Fruit was then cut at the equator and dipped in an iodine solution. Iodine staining patterns were evaluated in accordance with the Generic Cornell Starch-Iodine Index Chart for apples [14].

Using information collected from the electronic fruit sorter (fruit color, fruit size, and yield) and FOB pricing data from a local apple packer-shipper, a partial economic analysis was conducted to determine crop value. Costs of groundcovers, mounting supplies, and labor were not included in this analysis.

2.2. Experiment 2: 2020

This experiment was conducted in a mature block of 'DT2' Aztec Fuji®/'M.9' planted at 1.5 × 4.3 m spacing. Reflective groundcovers were installed ~5 weeks before harvest. Woven reflective groundcovers (Extenday® DayBright, Lumilys™ WH100, and Belton experimental) were placed adjacent to 10 tree plots (15.2 m long section) on each side of the row. Woven reflective groundcovers were secured according to manufacturer recommendations. Untreated control plots (sod groundcover) were included for comparison. To minimize edge effects, data was collected from trees in the center of plot.

Incident light and reflectance of PAR and $UV_{250–400nm}$ radiation quantified on a single mid-row position on east and west sides of the tree from each plot as in the previous experiment. In-canopy light measurements were not performed in 2020. At commercial maturity, 1 October 2020, apples were harvested for yield and fruit quality assessments. Fruit was harvested from one tree per plot that had a uniform crop load and canopy volume (5 trees per treatment; 20 trees total), placed in labelled containers and transported to the Mountain Horticultural Crops Research and Extension Center in Mills River, NC, USA to be evaluated with an electronic fruit sorter as in the previous experiment. Fruit quality analysis was completed as previously reported with 20 fruit per plot (100 fruit for each treatment; 400 fruit total). Partial economic analysis was conducted as described in Experiment 1.

2.3. Statistical Analysis

The experiments consisted of four treatments with a minimum of five replications arranged in a randomized complete block design. The PC version of SAS (version 9.4; SAS Institute, Cary, NC, USA) was used to carry out all statistical analysis. Tukey's honest significance test in PROC MIXED was used to test mean separation among treatments at $p = 0.05$.

3. Results

3.1. Experiment 1: 2018

When compared to the control, woven groundcovers (Beltech PD-2911 and Extenday®) significantly increased PAR reflected mid-row and in-canopy (Table 1). $UV_{250–400nm}$ radiation reflected from Extenday® was 20 times greater than the control (Table 1). In-canopy reflectance of UV radiation was observed with Extenday™ at 12 times greater than the control. Beltech PD-2911 was designed to have UV absorbance capabilities. This was evident from measured UV radiation levels of Beltech PD-2911, which did not differ from the control in any canopy position.

Table 1. Comparison of reflective groundcovers on incoming and reflected PAR and UV radiation in the middle of the drive row and in-canopy of 'Fugachee Fuji' trees in Edneyville, NC in 2018.

	PAR (400–700 nm; μmol·m^{-2}·s^{-1})							
	Mid-Row				**In-Canopy** [z]			
	Incoming [y]		**Reflected** [x]		**Incoming**		**Reflected**	
Control	1401 ± 67.1 [y]	a	72 ± 4.8	c	432 ± 113.4	a	39 ± 5.7	b
Beltch PD-2911	1516 ± 69.1	a	517 ± 35.1	a	470 ± 29.5	a	158 ± 12.2	a
Extenday®	1465 ± 141.3	a	570 ± 39.5	a	370 ± 60.7	a	173 ± 37.7	a
Mylar (Sun-Up)	1361 ± 60.4	a	231 ± 30.6	b	459 ± 10.7	a	91 ± 4.6	ab
	UV (250–400 nm; μmol·m^{-2}·s^{-1})							
	Mid-row				**In-canopy** [w]			
	Incoming		**Reflected**		**Incoming**		**Reflected**	
Control	132 ± 12.0 [v]	a	2 ± 0.2	d	14 ± 5.1	a	1 ± 0.1	b
Beltch PD-2911	138 ± 8.3	a	7 ± 0.3	c	29 ± 11.0	a	2 ± 0.3	b
Extenday®	136 ± 12.6	a	40 ± 1.8	a	34 ± 10.4	a	12 ± 2.2	a
Mylar (Sun-Up)	126 ± 12.3	a	17 ± 1.9	b	11 ± 1.5	a	3 ± 0.8	b

[z] In-canopy PAR measurements were carried out with the distal end of the ceptometer next to the trunk; [y] Incident light was measured with ceptometer sensors oriented toward the sky approximately 1.5 m above the ground; [x] Light reflectance was quantified by inverting the sensor (facing the ground); [w] In-canopy UV measurements were performed with the meter positioned 15 cm from the trunk; [v] Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE; PAR = photosynthetically active radiation.

At harvest, Extenday® significantly increased the proportion of fruit with >50% blush when compared to the control (Table 2). Additionally, the proportion of fruit with <15% marketable blush was significantly lower than the control.

Table 2. Comparison of reflective groundcovers on the proportion of 'Fugachee Fuji' apples harvested in blush categories in Edneyville, NC in 2018.

	≥50% Blush [z]		**≥15%, <50% Blush**		**<15% Blush**	
Control	21 ± 4.4 [y]	b	49 ± 2.0	a	30 ± 4.6	a
Beltch PD-2911	31 ± 6.5	ab	47 ± 3.6	a	22 ± 4.0	ab
Extenday®	50 ± 8.0	a	39 ± 3.8	a	11 ± 4.3	b
Mylar (Sun-Up)	29 ± 7.1	ab	50 ± 3.3	a	21 ± 4.1	ab

[z] Percent red fruit color of the surface area of fruit recorded with electronic fruit sorter; [y] Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE.

Red fruit color was further characterized using a colorimeter to determine lightness, chroma, and hue using the CIE L*a*b* color space. Lightness is used to describe color on a rectangular grid and a lower value would indicate a deeper red color. Chroma is an estimate of the saturation of the color with a higher number indicating a stronger, vivid color and a lower number indicating a weaker color. Hue, ranges from 0–90°, and a lower value refers to a darker red. Extenday® reduced lightness when compared to the control, and had a deeper red color. Fruit from Beltech PD-2911 plots had the lowest chroma, indicating a weaker color with less saturation. Fruit from the Extenday® plots had the lowest hue angle/darker red compared to all other treatments (Table 3).

Table 3. Comparison of reflective groundcovers on lightness (L*), chroma (C*), and hue (h°) of 'Fugachee Fuji' apples in Edneyville, NC in 2018 [z].

	L*		C*		h°	
Control	64.2 [y] ± 1.5	a	38.7 ± 0.4	a	63.4 ± 2.9	a
Beltech PD-2911	62.3 ± 1.3	ab	37.2 ± 0.5	b	59.2 ± 2.7	a
Extenday®	60.8 ± 1.3	b	38.1 ± 0.4	a	54.5 ± 2.6	b
Mylar (Sun-Up)	62.8 ± 1.5	ab	38.2 ± 0.5	a	60.7 ± 2.9	a

[z] Two colorimeter measurements per fruit occurred near the equatorial region of the apple on the sun exposed and shaded portion of the fruit peel of each fruit; [y] Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE.

Reflective groundcovers did not influence fruit maturity indices or sunburn incidence (Table 4). Crop density (no. of fruits/cm^2) was consistent and did not differ across treatments (Table 5).

Table 4. Comparison of reflective groundcovers on incidence of sunburn and fruit quality measurements of 'Fugachee Fuji' apples in Edneyville, NC in 2018.

	Sunburn		Firmness		Soluble Colids Conc.		Starch Rating	
	(% of Total)		(N)		(%)		(1–8)	
Control	23 ± 4.4 [z]	a	61.8 ± 0.7	a	13.4 ± 0.2	a	7.7 ± 0.1	a
Beltech PD-2911	29 ± 4.0	a	60.9 ± 0.5	a	13.0 ± 0.1	a	7.5 ± 0.1	a
Extenday®	29 ± 4.9	a	60.5 ± 0.4	a	13.1 ± 0.2	a	7.4 ± 0.2	a
Mylar (Sun-Up)	25 ± 2.4	a	61.8 ± 0.8	a	13.4 ± 0.2	a	7.6 ± 0.1	a

[z] Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE.

Table 5. Comparison of reflective groundcovers on crop density, yield, average fruit weight, and estimated crop value of 'Fugachee Fuji' apples in 2018.

	Crop Density		Yield		Average Fruit wt.		Crop Value
	(no. fruit/cm^2 TCSA) [z]		(kg)		(g)		USD/tree [x]
Control	5 [y] ± 0.5	a	24 ± 2.3	a	216 ± 5.1	a	20 ± 2.7
Beltech PD-2911	4 ± 0.5	a	23 ± 4.7	a	220 ± 4.8	a	23 ± 3.7
Extenday®	5 ± 0.6	a	22 ± 4.7	a	207 ± 8.5	a	28 ± 3.1
Mylar (Sun-Up)	4 ± 0.4	a	22 ± 3.8	a	214 ± 6.6	a	22 ± 4.2

[z] TCSA = trunk cross-sectional area; [y] means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE; [x] Costs of groundcovers, mounting supplies, and labor were not included in this analysis. FOB pricing data from a local apple packer-shipper were used to estimate crop value.

Using prices provided by a regional grower/packer, an estimated crop value was completed (Table 5). With more fruit exceeding 50% red fruit color, Extenday™ has a higher estimated value compared to all other treatments. However, it must be noted, that this estimated crop value does not consider the cost of materials, installation, or harvest; rather, the only input is the price per weight assigned to different grades that are determined by fruit size and color.

3.2. Experiment 2: 2020

On a cloud-free day, incident light was consistent throughout the plots. PAR measured proximally to solar noon found all reflective groundcovers reflected significantly more light compared to the control (Table 6). However, there were no significant differences between reflective groundcovers. This trend was consistent with light measured on a uniformly cloudy day. Again, all reflective groundcovers reflected significantly more light compared to the control but were not significantly different from each other.

Table 6. Comparison of reflective groundcovers on mid-row incoming and reflected PAR and UV radiation measured on cloud-free (21-Sep-20) and uniformly cloudy (25-Sep-20) dates in Edneyville, NC.

	PAR (400–700 nm; μmol·m^{-2}·s^{-1})							
	21-Sep-20				**25-Sep-20**			
	Incoming [z]		**Reflected [y]**		**Incoming**		**Reflected**	
Control	1770 ± 14.9 [x]	a	88 ± 2.1	b	407 ± 42.0	a	18 ± 2.2	b
Extenday®	1766 ± 21.1	a	939 ± 47.9	a	361 ± 22.5	a	170 ± 14.7	a
Lumilys®	1772 ± 17.0	a	879 ± 40.9	a	331 ± 38.3	a	132 ± 15.9	a
Belton	1777 ± 10.8	a	969 ± 36.3	a	389 ± 49.8	a	174 ± 21.2	a
	UV (400–700 nm; μmol·m^{-2}·s^{-1})							
	21-Sep-20				**25-Sep-20**			
	Incoming		**Reflected**		**Incoming**		**Reflected**	
Control	154 ± 2.6	a	3 ± 0.1	d	42 ± 4.0	a	1 ± 0.1	c
Extenday®	153 ± 4.0	a	61 ± 3.7	a	40 ± 2.4	a	14 ± 1.1	a
Lumilys®	153 ± 4.3	a	13 ± 0.8	c	38 ± 4.8	a	2 ± 0.3	c
Belton	155 ± 2.5	a	40 ± 1.4	b	41 ± 5.1	a	9 ± 1.1	b

[z] Incident PAR was determined with sensors oriented toward the sun approximately 1.5 m above the ground; [y] Light reflectance was quantified by inverting the sensor (facing the ground); [x] Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE; PAR = photsynthetically active radiation.

UV$_{250\text{–}400\mathrm{nm}}$ reflectance, measured on the same dates as PAR, varied between reflective groundcovers and the control (Table 6). Specifically, on a cloud-free day, Extenday® DayBright reflected the most UV$_{250\text{–}400\mathrm{nm}}$ radiation with a 20-fold increase in reflectance when compared to the control. Belton experimental groundcover, although significantly lower than Extenday® DayBright, reflected the second highest amount of UV$_{250\text{–}400\mathrm{nm}}$ radiation with 13 times greater reflectance relative to the control. Of the woven groundcovers evaluated, Lumilys® WH100 reflected the least UV$_{250\text{–}400\mathrm{nm}}$ radiation, but still had greater UV$_{250\text{–}400\mathrm{nm}}$ reflectance when compared to the control. On a uniformly cloudy day, Extenday® DayBright and Belton experimental reflected significantly more UV$_{250\text{–}400\mathrm{nm}}$ light compared to the control and Lumilys® WH100. However, Extenday® DayBright reflected significantly more ambient light compared to Belton experimental with 14 μmol·m^{-2}·s^{-1} UV$_{250\text{–}400\mathrm{nm}}$ light reflected compared to 9 μmol·m^{-2}·s^{-1}, respectively.

There were significant differences between treatments with respect to the percentage of fruit coverage with marketable blush. Extenday® DayBright was the only treatment significantly higher than the control for average percent blush at 58% (data not presented). This trend continued when looking at the proportion of harvested fruit with >50% blush and <15% blush (Table 7). For these two categories, Extenday® DayBright was the only treatment that had a significantly higher proportion of fruit >50% blush and significantly less fruit <15% blush compared to the control at harvest.

Table 7. Comparison of reflective groundcovers on the proportion of 'DT2' Aztec Fuji® apples harvested in blush categories in Edneyville, NC in 2020.

	≥50% Blush [z]		**≥15%, <50% Blush**		**<15% Blush**	
Control	34 ± 7.7 [y]	b	53 ± 5.6	a	13 ± 2.9	a
Extenday®	70 ± 4.1	a	28 ± 3.7	a	2 ± 0.9	b
Lumilys®	62 ± 6.6	ab	33 ± 4.9	a	4 ± 2.2	ab
Belton	50 ± 12.9	ab	42 ± 9.9	a	8 ± 3.1	ab

[z] Percent red fruit color of the surface area of fruit recorded with electronic fruit sorter; [y] means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE.

Red fruit color was characterized using a colorimeter as in the previous study. Evaluating the treatments, only Extenday® DayBright was significantly lower than the control for lightness indicating a deeper red color of the fruit (Table 8). Lumilys® WH100 was the only treatment significantly different from the control for chroma indicating a strong red color. For hue, Extenday® DayBright again was the only treatment significantly lower than the control and numerically the lowest value, indicative of a darker red.

Table 8. Comparison of reflective groundcovers on lightness, chroma, and hue of 'DT2' Aztec Fuji® apples in Edneyville, NC in 2020 ^{z}.

	L*		**C***		**h°**	
Control	49.2 ± 3.8 ^{y}	a	30.0 ± 1.2	b	48.8 ± 8.4	a
Extenday®	47.1 ± 2.9	b	30.4 ± 0.9	ab	41.4 ± 7.2	b
Lumilys®	48.5 ± 3.3	ab	30.8 ± 1.0	a	44.5 ± 7.6	ab
Belton	47.7 ± 3.2	ab	29.9 ± 1.1	b	45.7 ± 7.6	ab

^{z} Two colorimeter measurements per fruit occurred near the equatorial region of the apple on the sun exposed and shaded portion of the fruit peel of each fruit; ^{y} means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE.

We did not observe any treatment effects on fruit maturity (Table 9). At harvest, whole-tree yield, crop load, and fruit weight did not differ across treatments, indicating that uniform trees were selected as experimental units in the study (Table 10).

Table 9. Comparison of reflective groundcovers on fruit quality of 'DT2' Aztec Fuji® apples in Edneyville, NC in 2020.

	Firmness		**Soluble Solid Concentration**		**Starch Rating**	
	(N)		**(%)**		**(1–8)**	
Control	63.2 ^{z} ± 0.2	a	13.1 ± 0.3	a	7.4 ± 0.1	a
Extenday®	62.7 ± 0.1	a	13.1 ± 0.1	a	7.0 ± 0.1	a
Lumilys®	61.4 ± 0.2	a	13.1 ± 0.2	a	7.3 ± 0.2	a
Belton	63.6 ± 0.2	a	12.9 ± 0.4	a	7.5 ± 0.1	a

^{z} Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; means are presented ± SE.

Table 10. Comparison of reflective groundcovers on crop density, yield, average fruit weight, and estimated crop value of 'DT2' Aztec Fuji® apples in Edneyville, NC in 2020.

	Crop Density		**Yield**		**Average Fruit wt.**		**Crop Value**
	(no. fruit/cm^2 TCSA) ^{z}		**(kg)**		**(g)**		**USD/tree ^{x}**
Control	6 ^{y} ± 0.5	a	46 ± 5.7	a	215 ± 2.5	a	48 ± 4.6
Extenday®	6 ± 0.7	a	44 ± 3.8	a	223 ± 9.9	a	61 ± 4.9
Lumilys®	6 ± 0.6	a	38 ± 2.4	a	218 ± 9.5	a	53 ± 7.1
Belton	7 ± 1.0	a	45 ± 3.2	a	204 ± 11.6	a	49 ± 1.4

^{z} TCSA = trunk cross-sectional area; ^{y} Means within columns not followed by a common letter are significantly different based on Tukey's honest significance test at $p = 0.05$; ^{x} Costs of groundcovers, mounting supplies, and labor were not included in this analysis. FOB pricing data from a local apple packer-shipper were used to estimate crop value; means are presented ± SE.

With the input of prices provided by a regional grower/packer, as in 2018, an estimated crop value (FOB pricing) was assigned to treatments (Table 10). Moreover, only considering returns on harvested fruit and not the cost of inputs, Extenday® DayBright remained the highest value treatment with an estimated return of USD 61/tree. Across both years of the study, Extenday® DayBright increased the proportion of fruit harvested in premium grades. That is, fruit exceeding a minimum threshold of 50% blush. The use of regional prices shows that even in instances with limitations on fruit size, crop value is increased with improved fruit coverage of marketable blush, further highlighting the importance of improving fruit color to remain competitive and meet the demand of consumers in fresh markets.

4. Discussion

Multiple factors can influence red fruit color development in apples [1]. Our research focused on the effects of reflective groundcovers on 'Fuji' red color development across a two-year period. However, we acknowledge that scion strain, rootstock, and environmental conditions varied across years. In the southeastern US, 'Fugachee Fuji' ripens ~3 weeks earlier that of the original strain of 'Fuji'. 'DT2' fruit maturation aligns with that of the original strain; however, this strain was selected due to observed increased red fruit color development. Rootstock selection can have dramatic and direct impacts on vegetative growth and canopy light environment, and can have indirect effects on fruit quality [1]. Despite these potential sources of variability, we observed a significant positive influence on marketable blush of the fruit, the proportion of fruit with >50% blush, and estimated crop value with Extenday® DayBright across a two-year period.

All woven reflective groundcovers evaluated in these experiments had equivalent levels of PAR reflectance; however, $UV_{250\text{–}400nm}$ light reflectance varied widely across groundcovers evaluated. Extenday® DayBright had the highest $UV_{250\text{–}400nm}$ light reflectance, marketable blush, and crop value relative to all other products evaluated in this study, which aligns with previous reports [15–18]. While we observed comparable PAR reflectance between the woven groundcovers evaluated, Schuhknecht et al. [18] observed greater PAR reflectance at three different canopy heights (45, 135, and 200 cm) with Extenday® compared to Lumilys®.

The mylar used in our research was 1.0 m wide, while all woven groundcovers were 3.5 m wide. Layne et al. [13] observed significant increase in fruit coverage of marketable red fruit color with mylar (1.5 m width; positioned in the row-middle) in the southeastern US. Due to environmental conditions (warm temperatures, frequent rainfall, and high humidity), disease management programs in the southeastern US are intensive and require fungicide applications on 7 to 10 d intervals. Mylar used in most agricultural applications is a fragile material and cannot withstand orchard traffic with heavy equipment. To minimize damage to mylar, we deployed relatively narrow sections of mylar that were positioned proximally to the canopy dripline. The limited responses with this material in our research are likely related to the deployment strategy and proportion of the orchard floor with reflective material. Green et al. 1995 [19] observed increased absorption of PAR by trees as coverage of the orchard floor with foil was increased. However, multiple reports have demonstrated that Extenday® was more effective in increasing marketable blush when compared to mylar [16,17].

Woven reflective groundcovers have the advantage of greater durability relative to mylar and can be used across multiple seasons, and minor–moderate contamination with soil and debris surprisingly increased light reflection of PAR and UV-B light [15]. Extenday® and Lumilys® reflect light diffusely and uniformly, while mylar is a regular reflector [20]. Optical properties of the Beltech/Belton woven groundcovers is unclear and proprietary. With any reflective groundcover, increased waste generated is a notable environmental concern. Alternative deployment strategies of reflective groundcovers and use of recyclable materials have been identified [21]. Alternative technologies, such as pneumatic defoliators or agrichemicals, may also be environmentally and economically sustainable strategies to improve red fruit color development of apple [22].

While UV light is important for red pigment development in apples, it is important to note that reflective groundcovers that increase PAR reflectance and absorb more UV light may have practical applications in other apple-producing regions and/or cropping systems. Excessive UV radiation and heat can have negative impacts on vegetative and reproductive development in some cropping systems. In a separate study, mylar increased sunburn incidence when compared to Extenday® and sod groundcover [12]. The reflective properties of mylar (higher reflected and diffuse light intensity relative to Extenday®) were attributed to increased sunburn [12]. Extenday® did not increase canopy air temperature or leaf temperature when compared to sod groundcover [23]. In the current study, we did not observe any increase in fruit sunburn incidence with reflective groundcovers. Additionally, fruit maturity parameters were unaffected by groundcover treatments in accordance with previous studies [12,13,17,24].

5. Conclusions

All reflective groundcovers were successful in increasing PAR reflectance compared to the control. With increased UV reflectance relative to other treatments, Extenday® DayBright positively increased the marketable blush of the fruit, the proportion of fruit with >50% blush, and crop value. Fruit maturity was unaffected by groundcovers. Across multiple years, our results reinforce the importance of UV reflectance intensity on apple fruit color development. It is clear that UV reflectance intensity is critical with an apparent threshold to enhance 'Fuji' fruit color development in the southeastern USA.

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