The Use of Reflective Film and Ethephon to Improve Red Skin Color of Apples in the Mid-Atlantic Region of the United States

Stephen S. Miller[1] and George M. Greene, II[2]

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SUMMARY. **Replicated studies were conducted from 1996 to 1999 to evaluate the effect of a metalized reflective film (RF) on red color development in several apple (*Malus ×domestica*) cultivars that often develop poor to marginal color in the mid-Atlantic growing region. Film was applied to the orchard floor in the middle between tree rows or under the tree beginning 5 to 7 weeks before the predicted maturity date. Light reflected into the canopy from the RF was measured and compared with a standard orchard sod, a killed sod or various polyethylene films. Fruit color was estimated visually and with a hand-held spectrophotometer. Fruit quality (firmness, soluble solids, starch index) was determined from a representative sample of fruit. RF increased the level of photosynthetic photon flux (*PPF*) reflected into the canopy resulting in darker, redder colored 'Delicious', 'Empire', and 'Fuji' apples with a greater proportion of surface showing red color. RF increased canopy temperature and fruit surface temperature. A white polyethylene film increased reflected *PPF* and fruit color, but generally not to the extent of the metalized RF. Large [>13 ft (4.0 m) height] well-pruned 'Delicious' trees showed increased fruit color, especially when the RF was placed under the canopy, but 'Empire' trees of similar size and a more dense canopy showed no effect. The effect of the RF was most pronounced in the lower portion [up to 8 ft (2.4 m) height] of the canopy. A high-density RF was as effective as a low-density RF and the high-density film was about 60% less expensive. A high-density RF may be a cost effective method to enhance red color on selected apple cultivars in the mid-Atlantic region. Comparisons between ethephon and the RF were variable: ethephon appeared to have more effect on color in 'Empire' than the RF, but less effect than the RF on 'Hardibrite Delicious'. Ethephon consistently advanced fruit maturity. Chemical name used: (2-chloroethyl)phosphonic acid (ethephon).**

Red color is an important criterion for U.S. grade standards for apple. Consumer taste panels and pomologists indicate that red color is an important sensory attribute when evaluating apple-eating quality (Cliff et al., 1998; Greene, 1998). Some popular apple cultivars such as 'Delicious', 'Empire', 'Jonagold', or 'Fuji', often produce poor or marginal red color when grown under the warm, humid environmental conditions found in the mid-Atlantic region of the U.S. Many factors, directly or indirectly, influence color development in apples including temperature (Creasy, 1968; Curry, 1997), nutrition (Fallahi and Mohan, 2000; Reay et al., 1998; Williams and Billingsley, 1974), canopy architecture (Elfving et al., 1990), pruning (Autio and Greene, 1990), and plant growth regulators (Miller, 1988).

Light is required for production of the red color pigment, anthocyanin, in apples (Faragher, 1983; Proctor, 1974; Walter, 1967). Studies have clearly shown that increasing fruit exposure to light will increase red color development (Elfving et al., 1990; Heinicke, 1966). This has encouraged researchers to investigate practical means of providing supplemental light to enhance red color in apple and peach (*Prunus persica*). Several studies have shown that placing a reflective material on the ground between the tree rows (Andris and Crisosto, 1996; Layne et al., 1999; Moreshet et al., 1975) or under the tree's canopy (Doud and Ferree, 1980a) can improve the surface red color on selected apple and peach (Layne et al., 2001) cultivars. On apple, one study reported an increase in fruit size and sugar levels (Moreshet et al., 1975) from a RF, but most studies have found no effect on fruit quality (Andris and Crisosto, 1996; Doud and Ferree, 1980a; Layne et al., 1999). The most pronounced effect of the RF has been noted in the lower half of the tree canopy (Doud and Ferree, 1980a; Moreshet et al., 1975). RF has been reported to advance fruit maturity in apple (Andris and Crisosto, 1996) and peach (Layne et al., 2001).

Commercial apple orchard trials (Toye, 1995) with reflective mulches have reported improved fruit color with fewer pickings required, but not all experiences have been positive and some problems have been identified with the use of RFs. Materials must be positioned so light can strike them, which can be difficult in some high-density plantings, and the materials are subject to tearing from vehicular and worker trafficking (Warner, 1997).

The objective in this study was to determine the effect of a metalized reflective polyethylene film on red skin color and quality of several apple cultivars grown in the mid-Atlantic region. The study extended over 4 years and included trees of various ages and sizes, and trained to several canopy forms. Ethephon [(2-chloroethyl) phosphonic acid] (Aventis CropScience, Research Triangle Park, N.C.), a commercially available plant growth regulator with demonstrated fruit color enhancing properties (Miller, 1988), was included in some experiments for comparison.

Materials and methods

All trees used in these experiments were bearing trees planted in north–south (N–S) oriented rows. All test plots had a herbicide strip about 6 to 10 ft (1.8 to 3.0 m) wide under the tree canopy with sod drive middles. The primary reflective film (RF) used was a 5 ft (1.5 m) wide 1.25-mil [0.00125-inch (0.03-mm)] metalized silver low-density polyethylene film supplied in a continuous 2000-ft (610-m) roll from Clarke Ag Plastics (Greenwood, Va.). One or more guard trees were used on either side of RF treated

Research conducted at USDA, AFRS, Kearneysville, W.Va. Use of trade names does not imply endorsement of the products named, or criticism of similar ones not named.

[1]Research horticulturist, USDA, Appalachian Fruit Research Station, 45 Wiltshire Road, Kearneysville, WV 25430.

[2]Associate professor, The Pennsylvania State University, Fruit Research and Extension Center, Biglerville, PA 17307.

trees. In all tests the RF was placed on the east (E) and west (W) side of test trees 5 to 7 weeks before the predicted maturity date (PMD). The PMD was based on bloom date and historical records. The RF was placed in one of two locations, the drive middle or under the canopy, and secured to the orchard floor with landscape pins, 6-inch (15.2 cm) nails, soil, or pressed into a narrow kerf formed by a disc and a specially designed plastic-laying machine (Clarke Ag Plastics). When placed in the drive middle, the RF was positioned so one edge was parallel and directly beneath the drip line of the treatment tree(s). When placed under the canopy, one edge of the RF was touching the tree trunk for trees less than 5 years old; for older trees the RF was placed with one edge directly beneath the drip line and the film extended toward the trunk. Drip irrigation lines, when present, were placed under the RF.

LIGHT QUANTITY DETERMINATION. The level of *PPF* reflected into tree canopies, was determined with a ceptometer light bar (Sunfleck SF80; Decagon Devices, Inc., Pullman, Wash.) or with a quantum light data logger (No. 3600; Spectrum Technologies, Inc., Plainfield, Ill.). Incident *PPF* was measured on a horizontal plane 5 ft above the orchard floor with the sensor pointing skyward with an unobstructed view. Measurements of *PPF* were taken between 1100 and 1330 HR and percent *PPF* for the tree canopy was calculated. Additional details of sensor placement in the canopy are described below.

FRUIT QUALITY AND COLOR EVALUATION. At harvest all samples were a composite of 10 fruit collected at random. No minimum criteria such as color or size was imposed in selecting the random sample. A stepladder was used to select fruit in the upper canopy of tall trees that could not be reached from the ground. Two to four samples were collected from individual treatment trees or in some cases, multiple-tree plots. In each case, at least one sample was collected from the E side of the canopy and one from the W side. Sample collection began 7 d to 3 weeks before the PMD. Fruit samples were stored in a standard dark refrigerated cold storage [32.0 ± 1.8 °F (0.0 ± 1 °C)] for 7 to 10 d before analysis. Fruit were removed from cold storage and allowed to equilibrate to room temperature [70 °F (21 °C)] overnight before color and quality evaluations were recorded. Fruit surfaces were gently cleaned of spray residue and dust with a soft paper towel prior to taking color space readings. Mean fruit weight was determined by weighing the 10-fruit samples. Soluble solids concentration (SSC) was determined with an digital refractometer (Atago PR100; NSG Precision Cells, Inc., Farmingdale, N.Y.) from a composite juice sample from the 10-apple sample. All remaining fruit quality factors were measured on individual fruits with 10 fruit per sample. Flesh firmness was recorded on opposite sides of each fruit with a penetrometer (model FT-327; McCormick Fruit Tech, Yakima, Wash.) fitted with a 0.44-inch (11.1-mm) tip and mounted in a drill press stand. Starch-iodine index (SI) was visually rated using the technique and the 1 to 8 scale as described by Blanpied and Silsby (1992) [except in 1996 a 1 to 9 scale was used (Smith et al., 1979)].

Color was determined from a visual rating and/or with the aid of a hand-held spectrophotometer. The visual rating was performed by a single individual and was a percent estimate of the total fruit surface showing dark red color. Color space readings, as L*a*b* values, were recorded with a hand-held spectrophotometer (MiniScan XE Model D/8-S; Hunter Associate Labs, Inc., Reston, Va.) using CIE illuminant D65 and an 8 mm diameter aperture. Measurements were recorded from the four quadrants at the equator of individual fruits (except in the 1996 experiments when only a single reading was taken in an area visually perceived as the darkest red color). Hue angle (h°) was calculated from a* and b* readings according to McGuire (1992). In the 1998 experiment, the color of fruit from the commercial orchard were also characterized with an color sorter (USM MegaSort II PWS/Merlin; Agri-Tech, Inc. Woodstock, Va.).

1996 EXPERIMENTS. Independent trials were conducted at the USDA Appalachian Fruit Research Station (AFRS), Kearneysville, W.Va., on three apple cultivars with trees of various ages and training systems and the RF placed in the row middle for all trials as follows: 1) 8-year-old 'Hardibrite Spur Delicious'/'Malling Merton 111' (MM.111) apple trees trained to a 45° Y-form trellis system [mean height = 7 ft (2.1 m)]. A killed-sod treatment was also included in which the grass sod in the drive middle was killed with a contact herbicide (paraquat) prior to applying treatments; 2) 'Empire' including 7-year-old trees on 'Malling 9' (M.9) rootstock trained to a Y trellis (mean height = 7 ft), 10-year-old trees on semi-dwarf 'Malling 9/Malling Merton 106' (M.9/MM.106) rootstock trained as freestanding central leader trees [mean height = 11 ft (3.4 m)], and 9-year-old standard trees on seedling rootstock trained as central leader trees [mean height = 15 ft (4.6 m)]; and 3) 7-year-old 'Fuji'/'East Malling-Long Ashton 7' (M.7 EMLA) trained to the central leader form [mean height = 12 ft (3.7 m)]. Grass sod drive middles served as the nontreated control. Treatments were arranged in a randomized complete block of four single-tree replications. Multiple, low rate [100 or 125 $mg \cdot L^{-1}$ (ppm)] sprays of ethephon applied with a handgun sprayer were included as individual treatments on the 'Empire'/M.9 trees. The 100 $mg \cdot L^{-1}$ rate was applied as a weekly spray beginning 5 weeks before the PMD. The 125 $mg \cdot L^{-1}$ rate was applied in four biweekly sprays beginning 7 weeks before the PMD. A spray adjuvant, Regulaid (Kalo, Inc., Overland Park, Kan.), was included at 0.1% (v/v) in all ethephon sprays.

1997 EXPERIMENTS. Two trials were conducted on Y-form trellised trees at AFRS, Kearneysville. In the first trial, three treatments were applied to 9-year-old 'Hardibrite Spur Delicious'/MM.111 trees about 7.9 ft (2.4 m) high: 1) RF placed under the tree canopy, 2) the RF placed in the center of the drive middle (Fig. 1), and 3) a control with herbicide strip under the canopy and sod drive middle. Treatments were applied to three-tree plots and replicated four times beginning 5 weeks before the PMD (29 Sept.).

Three-year-old 'Fuji'/M.9 trees trained to a Y-trellis about 6.5 ft (2.0 m) high were used in a second trial. Four treatments were arranged in a randomized complete block with four-tree plots per replication: 1) the standard metalized RF, 2) a 4.2-ft (1.3-m) wide white high-density polyethylene (manufacturer unknown), 3) a 3.9-ft (1.2-m) wide 6-mil [0.006-inch (0.15-mm)] black polyethylene film (Warp Bros., Chicago), and 4) a control with herbicide strip under the canopy and a sod drive middle. Treatments were established 7 weeks before the PMD (15 Oct.).

Fig. 1. Reflective film applied to the row (drive) middle or under the canopy of 9-year-old 'Hardibrite Spur Delicious'/'Malling Merton 111' (MM.111) apple trees trained to a Y-trellis. Note the bright canopy from the film's reflected light and the canopy temperature data logger in the wooden shelter (arrow).

The following parameters were monitored during both trials on selected days between 15 Aug. and 17 Oct. 1997: canopy air temperature, fruit surface temperatures, *PPF*, and the ratio of red to far-red [660 R : 730 FR (nm)] light. Canopy air temperature was recorded with dataloggers (Optic StowAway; Spectrum Technologies, Inc., Plainfield, Ill.) placed in small weather shelters located about half way up the E side on the outer edge of the canopy and shielded from direct sunlight during the day, but exposed to any reflected light. Mean whole-canopy temperature was calculated from mean hourly temperatures (recorded at 1-min intervals) recorded on a 24-h cycle on 16 selected days between 19 Sept. and 17 Oct. for the 'Hardibrite Delicious' with the RF placed in the center of the drive middle. Fruit surface temperature was recorded with a Raynger ST6LSU infrared temperature sensor (Raytek Corp., Santa Cruz, Calif.) with an emissivity value of 0.95. A single reading was recorded on 50 individual fruit per treatment exposed to reflected light, indirect light (shaded fruit), and direct sunlight. Six *PPF* readings were taken per replication. To take readings, the light bar was placed horizontally in a north–south direction with the sensor bar angled to the plane of the canopy and pointing away from the canopy toward the RF material (resulted in light sensor surface positioned at a 45° angle from vertical). The R/FR light was recorded in the same position as PPF readings using a R/FR light sensor with fiber optic probe (SKR100/116; Skye-Probetech, Perkasie, Pa.). All light readings were taken on the E side of the canopy, which was fully developed at the time the measurements were taken. Days were used as replications.

Fruit was harvested 1 week before the PMD and on the PMD (except 'Fuji' which was initially harvested 9 d before the PMD). Each side of the canopy was divided at the midpoint between top and bottom and a 10-apple sample was harvested at random from each of the four resulting locations (designated lower east, upper east, upper west, and lower west). Fruit color and quality were determined as described above.

1998 EXPERIMENT. An orchard of standard size 32-year-old 'Miller Spur Delicious'/seedling rootstock located near Fairfield, Pa. (El Vista Orchards, Inc.) was selected to evaluate the RF material. Trees were spaced 13 × 22 ft (4.0 × 6.7 m), trained as modified leaders, and had good light penetration throughout the canopies. Canopy height averaged about 16.5 ft (5.0 m) and canopy width about 15 ft (perpendicular to the row). Based on fruit development and climatic conditions, harvest was predicted for 24 Sept.

Three treatments were established on 20 Aug., 5 weeks before the PMD: 1) a grass sod drive middle control; 2) a single strip of RF positioned in the center of the drive middle on each side of the tree row (row middle); and

Fig. 2. Quantum light data loggers (model 3600; Spectrum Technologies, Inc., Plainfield, Ill.) positioned at two heights in the canopy of a 32-year-old 'Miller Spur Delicious'/seedling apple tree. Loggers positioned to capture light reflected from the metalized reflective film. Pole marked in 1-ft (30.5 cm) increments.

3) a single strip of RF positioned under the tree canopy as previously described (under canopy). Treatments were applied to four-tree plots in a completely randomized design with three replicated plots per treatment. Plots were selected based on a visual examination by the authors considering uniformity of tree size, canopy density, and crop load. The RF was positioned down the row so all four trees received similar exposure to the reflected light.

Ambient air temperature was recorded with an Optic StowAway Temp datalogger placed in a white wooden weather shelter located in the middle of the block at a vacant tree spot. It was positioned 4.9 ft (1.5 m) above the orchard floor. *PPF* was recorded at 15-min intervals with quantum light dataloggers (No. 3600; Spectrum Technologies) Incident *PPF* was recorded with a quantum data logger positioned near the temperature logger with an unobstructed view of the sky. Two quantum loggers were placed in specially constructed aluminum shelters coated with flat white latex paint and positioned at two heights [about 5.9 ft and 11.8 ft (1.8 m and 3.6 m) above the orchard floor] within the canopy of a single tree selected from each of the three treatments. The loggers were positioned so the sensor's detector would capture the light reflected from the RF material (Fig. 2).

Four 10-apple samples were collected at random for color analysis from specified locations in each of the two middle trees in a four-tree plot. Fruit samples were collected 3, 2, and 1 week before the PMD. The canopy sample locations were defined as east = representing the east half of the canopy; west = the west half of a tree's canopy; lower = from the ground to a height of 6.5 ft; and upper = the canopy at a height of 10 to 16.5 ft.

On 1 Oct. the grower-cooperator harvested all the fruit from the two middle trees in each plot into 18-bushel [756-lb (343-kg)] standard orchard field bins. Bins were transported to a packing house and fruit sorted with a color sorter (USM MegaSort II PWS/Merlin; Agri-Tech, Inc.). Fruit were segregated into three color classes: 85 to 100% red color; 65% to 84% red color, and less than 65% red color. Percentage fruit in each color class was calculated from the total number of apples harvested per two-tree plot.

1999 Experiment. A less expensive high-density RF material {0.5-mil [0.0005-inch (0.0127-mm)]} (Clarke Ag Plastics) was compared with the more expensive low-density RF used in previous trials at AFRS, Kearneysville. The commercial recommendation of a single ethephon spray at 300 $mg \cdot L^{-1}$ applied 9 d before the PMD (27 Sept.) was included for comparison. The RF materials were installed 7 weeks before the PMD in a block of 10-year-old 'Hardibrite Spur Delicious'/MM.111 apple trees trained to a Y-trellis. Each treatment was replicated six times with five-tree plots in a RCB design. Fruit color and quality were measured as previously described.

Data analysis. All data was subjected to ANOVA and means separated by Duncan's new multiple range test or Tukey's *t* test. Percentage data was transformed to the arcsin for analysis with actual measured values reported.

Results and discussion

1996 Experiment. Placement of RF in the orchard drive middle of 'Hardibrite Delicious' apple trees trained to a Y-trellis, 5 weeks before the PMD, increased the percent surface red color from 32% to 75% and resulted in darker (lower L*), redder (lower h°) colored apples at harvest (Table 1). The RF did not affect the fruit size, firmness, or SSC (data not shown). The RF treated fruit had a lower SI rating (indicates less mature), but the difference was small and probably of little practical significance. These results were similar to those reported earlier by Moreshet et al. (1975) in Israel and more recently for 'Fuji' grown in California by Andris and Crisosto (1996). Fruit from the E side of the canopy was darker and redder than from the W side of the canopy (Table 1), but there was no difference in the amount of red color between the E and W sides of the canopy. The reason for this difference is not clear since both sides of the canopy appeared to have equal sun exposure. However, there are often more clouds after midday in this region, and that may have had an effect. Doud and Ferree (1980b) reported that the daily quantity of light reflected from under tree reflectors was dependent on climatic conditions and time of day. No light measurements were taken in this experiment. There was no canopy side × treatment interaction.

The RF had no effect on the color or quality of 'Empire' apples grown on semi-dwarf or standard size trees (data not shown) except that the SI rating was lower in fruit from the RF treated trees (6.7) compared to control fruit (7.4) on the PMD indicating that the RF had delayed fruit maturity. The semi-dwarf trees had a reasonably open canopy exposed to light, but the standard trees had a moderately dense canopy and light penetration was likely limited into the canopy of these trees. Several studies (Andris and Crisosto, 1996; Doud and Ferree, 1980a; Layne et al., 1999; Moreshet et al., 1975) have reported positive color response from a RF on trees about 10 ft in height, but there have been no reports where RF was used on trees 13 ft in height or taller, as were the standard 'Empire' in this study.

The RF increased percent surface

Table 1. Effect of a reflective film (RF), sod, or a killed sod in the orchard row (drive) middle on color and starch index rating of apples harvested from 8-year-old 'Hardibrite Spur Delicious'/'Malling Merton 111' (MM.111) trees trained to a Y-trellis canopy. Fruit harvested 24 Sept. 1996.

Main treatment	L*[z]	Hue angle[y]	Surface dark red color[x] (%)	Starch index[w] (1–9)
Canopy side				
East	38.5 b[v]	25.6 b	32 a	5.4 a
West	40.7 a	29.1 a	28 a	5.4 a
Treatment				
Sod	40.2 a	28.6 a	28 b	5.7 a
Killed sod[u]	41.1 a	30.6 a	21 c	5.5 a
RF	38.3 b	24.3 b	37 a	4.9 b

[z]L*= lightness (0 = black, 100 = white).
[y]Hue angle = arctangent b*/a* (0 = red-purple, 90 = yellow).
[x]Visual rating.
[w]Starch index rating: 1 to 3 = immature, 4 to 6 = mature, 7 to 9 = overmature.
[v]Mean separation within columns by Duncan's new multiple range test, $P \leq 0.05$.
[u]Original sod cover killed with a contact herbicide.

Table 2. Effect of a reflective film (RF) or low-dose ethephon sprays on the color and quality of 'Empire'/'Malling 9' (M.9) apples grown on a Y-trellis and harvested on or before the predicted maturity date (PMD).

Main treatment	Ethephon dose/spray [mg·L^{-1} (ppm)]	L*[z]	Hue angle[z]	Surface red color (%)	SSC[y] (%)	Starch index rating[x] (1–9)
			2 weeks before the PMD, 10 Sept.			
Canopy side						
East	---	39.3 b[w]	27.6 b	34 a	11.9 a	6.4 a
West	---	41.4 a	31.9 a	31 a	11.7 a	5.7 b
Treatment						
RF	0	42.1 a	31.2 ab	34 b	11.0 c	5.0 c
Ethephon, weekly[v]	100[u]	38.8 b	27.4 bc	31 bc	12.2 ab	6.8 a
Ethephon, bi-weekly	125	37.5 b	26.3 c	42 a	12.4 a	6.7 a
Control	0	43.0 a	34.3 a	25 c	11.6 b	5.7 b
			1 week before the PMD, 17 Sept.			
Canopy side						
East	---	35.6 b	25.1 a	38 a	12.4 a	7.6 a
West	---	36.9 a	24.8 a	40 a	11.9 b	7.4 a
Treatment						
RF	0	36.9 a	24.1 a	37 bc	11.2 c	6.8 c
Ethephon, weekly	100	34.8 b	24.8 a	43 ab	12.7 a	8.1 a
Ethephon, bi-weekly	125	34.6 b	24.2 a	46 a	12.9 a	7.7 ab
Control	0	38.6 a	26.8 a	30 c	11.9 b	7.3 bc
				PMD, 25 Sept.		
Canopy side						
East	---	---[t]	---	54 a	13.0 a	8.2 a
West	---	---	---	45 b	12.6 a	8.1 a
Treatment						
RF	0	---	---	43 b	12.1 c	7.8 b
Ethephon, weekly	100	---	---	54 a	13.5 a	8.4 a
Ethephon, biweekly	125	---	---	59 a	13.2 ab	8.3 a
Control	0	---	---	42 b	12.7 bc	8.2 ab

[z]L* = lightness (0 = black, 100 = white); Hue angle = arctangent b*/a* (0 = red-purple. 90° = yellow).
[y]SSC = soluble solids concentration.
[x]Starch index rating: 1 to 3 = immature, 4 to 6 = mature, 7 to 9 = overmature.
[w]Mean separation within columns for main effects and harvest date by Duncan's new multiple range test, $P \leq 0.05$.
[v]Weekly spray initiated 5 weeks before PMD, five sprays applied; biweekly spray initiated 7 weeks before PMD, four sprays applied.
[u]100 mg·L^{-1} = 100 parts per million (ppm).
[t]Significant canopy side × treatment interaction, $P = 0.02$. See text for explanation.

red color of 'Empire'/M.9 apples growing on a Y-trellis 2 weeks before the PMD (10 Sept.), but it had no effect on L* or h° at this time (Table 2). Fruit from the E side of the canopy had a darker, redder color than fruit from the W side of the canopy 2 weeks before the PMD. However, when harvested on the PMD (25 Sept.) there was no difference in percent surface red color between control and RF treated fruit. There was a significant location x treatment interaction for L* and h° at the PMD ($P = 0.02$). The RF increased red color on fruit from the west canopy (RF h° = 22.2 versus 29.2 for control) but not from the east canopy (RF h° = 20.9 versus control h° = 20.5) on the PMD. The RF affected L* on the W side of the canopy (RF L* = 35.3 versus 38.6 for control) but not on the E side. There was a trend toward higher starch levels (lower SI rating) for RF treated fruit, but differences were not significant except at the initial harvest date (10 Sept.) (Table 2). Fruit from RF treated 'Empire'/M.9 were smaller [an average of 0.7 to 1.1 oz (20 to 30 g)] than untreated fruit at each of the three harvest dates (data not presented).

Weekly and biweekly low rate ethephon sprays produced darker, redder colored fruit with more red color at the earliest harvest date compared with fruit from control or RF trees (10 Sept.) (Table 2). Fruit treated with ethephon and harvested from the W side of the

Table 3. The effect of a reflective film (RF) applied to the orchard floor row (drive) middle on the color of 'Fuji' apples on 7-year-old central leader trained trees harvested on or 1 week before the predicted maturity date (PMD).

Treatment	L*[z]	Hue angle[y]	Surface red color (%)
		1 week before PMD, 2 Oct.	
RF	57.0 a	71.5 a	8.2 a
None(Control)	59.0 a	81.1 a	4.0 b
		PMD, 10 Oct.	
RF	52.8 a	47.6 b	24.2 a
None	55.5 a	59.3 a	13.3 b

[z]L*= lightness (0 = black, 100 = white).
[y]Hue angle = arctangent b*/a* (0 = red-purple, 90 = yellow).
[x]Mean separation within columns for harvest dates by Duncan's new multiple range test, $P \leq 0.05$.

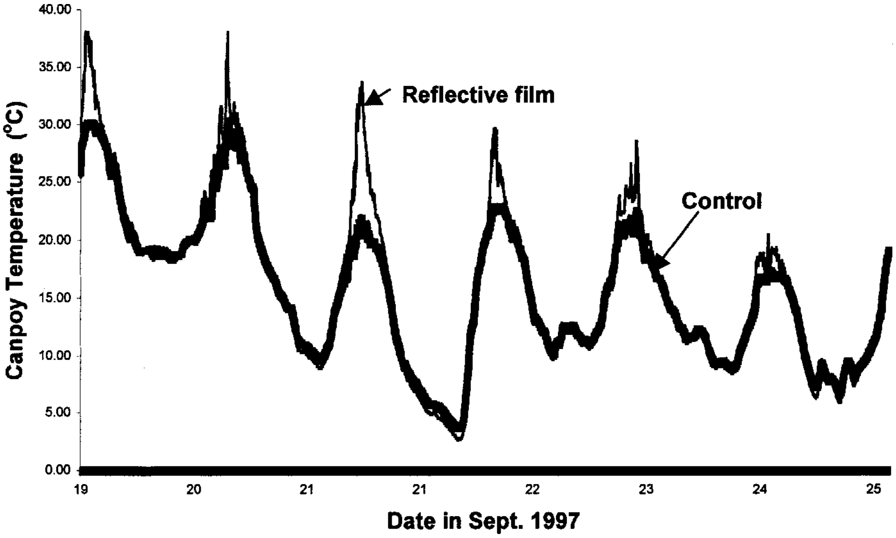

Fig. 3. Effect of a metalized reflective film on canopy temperature in 9-year-old 'Hardibrite Spur Delicious'/'Malling Merton 111' (MM.111) apple trees trained to a Y-trellis. Temperature recorded on data loggers in weather shelters placed 5.7 ft (1.75 m) above the orchard floor on the east side of the tree canopy; °F = 1.8 (°C) + 32.

Table 4. Fruit surface temperature of 'Hardibrite Spur Delicious' apples grown on a Y-trellis as affected by light from several sources.

Fruit illuminated by	Fruit surface temp [°F (°C)][z]
Indirect light (shade)	75.6 c [y] (24.2)
Reflected light	82.0 b (27.8)
Direct light (full sun)	90.7 a (32.6)

[z]Ambient air temperature ≈73.4 °F (23 °C)
[y]Mean separation by Duncan's new multiple range test, $P \leq 0.05$.

canopy on the PMD were darker colored and redder, but only the biweekly ethephon sprays produced this result on the E side of the canopy (data not shown). Ethephon treated fruit had a higher percent surface red color than control or RF treated fruit when harvested on the PMD (Table 2). Fruit treated at the weekly ethephon rate were less firm [15.5 lb force (68.9 N)] than RF treated fruit [16.7 lb force (74.3 N)], but did not differ from control fruit when harvested on the PMD. Weekly ethephon sprays increased SSC levels above that for RF or control treated fruit when harvested on the PMD. Response reported here for ethephon sprays is consistent with numerous studies of ethephon use on apple (Miller, 1988).

Applying RF in the drive middles of semi-dwarf 'Fuji'trees doubled the amount of red color 1 week before the PMD (2 Oct.) and on the PMD (10 Oct.) (Table 3). The RF had no effect on the lightness of fruit color, flesh firmness, SSC, SI rating, or fruit size (data not shown). The results here are similar to those reported by Andris and Crisosto (1996) for 'Fuji' grown in California's San Joaquin Valley.

The color response observed in these experiments was similar to that reported by others (Andris and Crisosto, 1996; Doud and Ferree, 1980a; Moreshet et al., 1975) and suggested that the most efficient use of RF may be obtained with small stature trees, especially those trained to a Y-trellis system.

1997 Experiments. RF placed in the center of the drive middles altered the canopy microclimate. The mean midday (1100 to 1500 HR) canopy temperature was higher for the RF canopy [82.6 °F (28.1 °C)] compared to the control canopy [75.7 °F (24.3 °C)] ($P < 0.0001$). Peak differences consistently occurred between 1100 and 1300 HR (Fig. 3) when the RF was directly exposed to incident light. The time and magnitude of the temperature increases found in this study are consistent with those reported by Layne et al. (2001) for a peach orchard in SC. The largest temperature difference recorded in our study was 19.8 °F (11.0 °C) between 1200 and 1300 HR on 21 Sept. (Fig. 3). On cloudy or heavily overcast days, temperature difference between the RF treated canopy and the control canopy was generally 1.8 °F (1 °C) or less, although the RF treated canopy temperature was consistently higher than the control canopy's temperature. Reflective film increased the surface temperature of the 'Hardibrite Spur Delicious' fruit exposed to reflected light [mean of + 6.5 °F (3.6 °C)] compared with fruit exposed to indirect light (shaded fruit) (Table 4). Fruit exposed to direct light had a higher surface temperature than either fruit exposed to reflected or indirect light (Table 4). Curry (1997) reported an optimum temperature of 77 °F (25 °C) for maximum anthocyanin accumulation in preclimacteric 'Redchief Delicious' and 'Fuji' apple skin tissue under high intensity light for 48 h. Preclimateric apple tissue at temperatures of 95 °F (35 °C) and above developed very little red color. In our study, subsurface temperature was not measured, but surface temperatures for fruit exposed to reflected light were near the optimal temperature for anthocyanin accumulation reported by Curry (1997). *PPF* measurements were not recorded at the fruit surface where temperature measurements were taken in this study.

The metalized RF or a white polyethylene film increased the percent reflected PPF compared with the control in the 3-year-old 'Fuji' on a Y-trellis (Table 5). There was an average

Table 5. Effect of various reflective film materials on percent incident photosynthetic photon flux (*PPF*) and red:far red (R/FR) light reflected into the canopy of 3-year-old 'Fuji'/'Malling 9'(M.9) apple trees trained to a Y-trellis.

Groundcover material	Mean incident *PPF* reflected[z]	Mean R/FR_{10nm} [y]
Black polyethylene	8.5 c[x]	0.36 c
White polyethylene	24.3 b	0.80 b
Metalized film	37.8 a	1.09 a
Bare soil (control)	9.3 c	0.35 c

[z]Light measured as photosynthetically active radiation with a Sunfleck SF80 ceptometer light bar (Decagon Devices, Inc., Pullman, Wash.).
[y]R/FR_{10nm} corresponds to the ratio of red (660 nm) to far red (730 nm) light determined with an SKR100/116 Red/Far Red Light Sensor with fiber optic probe (Skye-Probetech, Perkasie, Pa.).
[x]Mean separation within columns by Duncan's new multiple range test, $P \leq 0.05$.

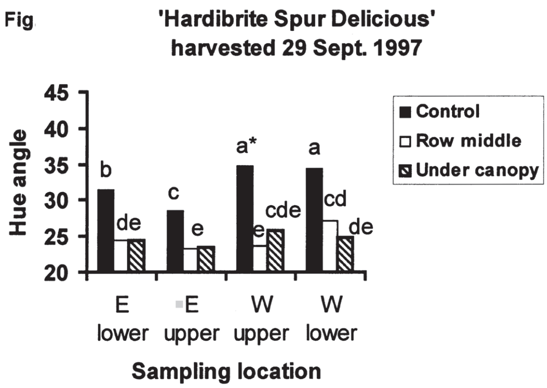

Fig. 4. The effect of a metalized reflective film placed in the orchard row (drive) middle or under the canopy on the hue angle of 'Hardibrite Spur Delicious' apples grown on a Y-trellis and harvested on the predicted maturity date (29 Sept. 1977). Fruit harvested from the east (E) and west (W) side of the canopy in the lower [ground to 3.9 ft (1.2 m) height] and upper [3.9 to 7.8 ft (2.4 m) height] portion of the canopy. Letters (*) represent mean separation among all treatments and locations according to Duncan's new multiple range test, $P \leq 0.05$; hue angle = arctangent b*/a* (0 = red-purple, 90 = yellow).

increase in reflected PPF into the canopy of 28.5% with the metalized RF and a 15% increase with the white polyethylene film compared to the control treatment. The metalized film reflected more light than the white polyethylene film, which supports the findings of Andris (1997). The percent of incident *PPF* reflected from black polyethylene did not differ from the control and compares with that reported by Decoteau et al. (1989) in studies with tomatoes (*Lycopersicon esculentum*). Levels of both direct PPF or that reflected from the metalized film or the sod orchard floor, were near identical to those reported by Layne et al. (2001) for peach orchards in SC. The metalized RF and the white polyethylene increased the ratio of R/FR light reflected onto the canopy compared with the control or black polyethylene film (Table 5). The ratio of R/FR light was greater for the metalized RF than the white polyethylene. While RF increased both the level of red and far red light, the greatest increases were associated with red light.

RF resulted in darker colored, redder 'Hardibrite Spur Delicious' and 'Fuji' apples with more surface showing dark red color. However, the two-way interaction of treatment x canopy sample location was significant ($P \leq 0.009$) for L*, h°, and the percent surface showing dark red color for each cultivar at all harvest dates. Since these factors behaved similarly, only the results for the h° will be presented.

There was an average 24.7% reduction in h° compared with the control (indicates redder color) for 'Hardibrite Delicious' apples harvested from the two RF placement treatments over the four sampling locations and for the two harvest dates. Placement of the film produced no difference in h° except for fruit harvested from the lower W side of the canopy 1 week before the PMD (22 Sept.). Fruit harvested from the lower W side were significantly redder if the RF was placed under the canopy (h° = 28.2) compared to positioning it in the drive middle (h° = 33.4). Fruit harvested on the PMD showed no difference in h° when the RF was placed under the canopy or in the row drive middle (Fig. 4). While RF enhanced red color at all locations in the canopy, the greatest effect appeared to be associated with the fruit on the W side of the canopy. RF resulted in an average 26.4% reduction in h° for fruit harvested from the W canopy and a 20.2% reduction in h° for fruit harvested from the E canopy compared with control fruit. These results suggest that for small stature trees planted in north–south rows RF is equally effective when positioned in the row middle or under the canopy. Placing the film under the canopy could prolong its life and make other orchard operations easier especially in orchards experiencing excess traffic, however, placing the film under the canopy may be more labor intensive. The results further suggest that in a N–S-oriented Y-trellis planting, if RF material is limiting, placing RF only on the W side of the canopy may produce the greatest economic benefit through improved red color development.

The effect of a metalized RF or white polyethylene film placed under the canopy on h° of 'Fuji' apples harvested from a N-S oriented Y-trellis on the PMD (15 Oct.) is illustrated in Fig. 5. Because the response to black polyethylene did not differ from the control treatment, data for black polyethylene is not shown. In general, response was similar to the effect of RF on 'Hardibrite Delicious', but with some exceptions. Both the metalized and white polyethylene films lowered h° resulting in redder apples at each harvest date (6 and 15 Oct.) for all sampling locations (Fig. 5) except for fruit from the upper half of the E side canopy, which consistently produced the reddest fruit among all sampling locations on control trees, probably due to good exposure to the sun. This is in contrast to results with metalized RF on 'Hardibrite Delicious' (Fig. 4). 'Fuji' (Fig. 5) and 'Hardibrite' (Fig. 4) apples also differed in the magnitude of the h° response to metalized RF between the E and W canopies at the PMD. For 'Hardibrite', the metalized RF reduced h° an average of 20.2% below control apples in the E canopy compared to 26.4% for apples harvested from the W canopy. With 'Fuji', the metalized RF

Fig. 5. Effect of a metalized reflective film (RF) or a white polyethylene (poly) film placed under the tree canopy on the hue angle of 'Fuji' apples grown on a Y-trellis and harvested on the predicted maturity date (15 Oct. 1997). Fruit were harvested from the east (E) and west (W) side of the canopy in the lower [ground to 3.3 ft (1.0 m) height] and upper [3.3 to 6.6 ft (2.0 m) height] portion of the canopy. Letters (*) represent mean separation among all treatments and locations according to Duncan's new multiple range test, $P \leq 0.05$; hue angle = arctangent b*/a* (0 = red-purple, 90 = yellow).

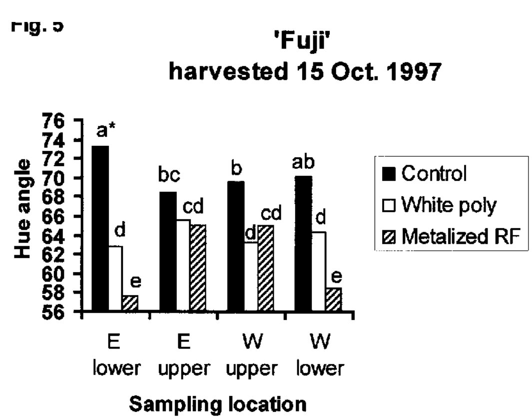

Table 6. Mean percent incident photosynthetic photon flux (*PPF*) reflected into the canopy of standard size 32-year-old 'Miller Spur Delicious'/seedling apple trees at two levels in the canopy from a reflective film (RF) placed at two locations on the orchard floor.

	PPF (%) reflected into canopy		
Canopy	Reflective film (RF) location		
position[z]	Control (no RF)	Row middle	Under canopy
Lower	2.2 c[y]	9.1 b	17.6 a
Upper	2.0 c	9.4 b	8.8 b

[z]Sampling height in the canopy: lower = ground to height of 6. 5 ft (2.0 m); upper = height 10 to 16.5 ft (3.1 to 5.0 m) in the canopy.
[y]Mean separation across treatments and canopy positions, Duncan's new multiple range test, $P \leq 0.05$.

reduced h° by 13.1% on apples harvested from the E canopy compared to an 11.5% reduction on apples from the W canopy. The reason for a difference between the two cultivars is not easily explained, but may be due to inherent cultivar response mechanisms.

For 'Fuji', the greatest effect on h° occurred on apples from the lower canopy exposed to the metalized RF. The metalized RF reduced h°, on average, 17.8% below that of control fruit in the lower canopy over the two harvest dates. In comparison, white polyethylene reduced h° an average of 10.1% below control fruit. The effect of the metalized RF was consistent with the earlier findings with 'Hardibrite Delicious' trees and supports work by others who have shown the greatest effect from RF is in the lower part of the canopy (Doud and Ferree, 1980a; Moreshet et al., 1975).

RF had little or no effect on fruit weight, flesh firmness, SSC, or starch levels (data not shown). The decrease in fruit maturity associated with RF in 1996 was not observed in 1997 and, in fact, fruit from the 'Hardibrite Delicious' trees had a slightly lower starch level (but not significantly lower) where the RF was placed in the drive middle (data not shown).

1998 Experiments. Reflected *PPF* was increased within the canopy from 4- to 8-fold (on average) when RF was placed in the row middle or under the canopy as measured over an 11-d period from 12 to 22 Sept. (Table 6). The greatest increase in reflected *PPF* occurred in the lower portion of the canopy when RF was positioned under the canopy. Color response to RF was not affected by directional position (E or W side of the tree) (data not shown). There was a significant canopy location × treatment interaction for L* (P = 0.048). Control trees responded differently than RF treated trees in terms of color lightness at all three harvest dates (Table 7). Upper canopy fruit from control trees had a darker color (lower L*) and a greater percent of surface showing a dark red color than lower canopy fruit from the same trees. This is not unexpected, as numerous studies with both apple and peach have demonstrated that fruit in the lower, more shaded portions of the canopy have less red color and are generally lighter color (Bible and Singha, 1993; Heinicke, 1966; Moreshet et al., 1975) than fruit from the upper part of a tree's canopy that is better exposed to sunlight. Color lightness of fruit did not differ between the upper and lower canopy locations with RF (Table 7), but the trend was toward darker colored fruit in the lower canopy. This suggests that RF had a greater effect on the color development of fruit in the lower canopy than the upper canopy.

Hue angle was not affected by canopy location at any of the three harvest dates (data not shown), however, there was a trend for redder fruit (lower h°) from the upper canopy of check trees. Hue angle was affected by RF positioned in the row middle or under the canopy at all three harvest dates (Table 8). Placing the RF under the canopy resulted in redder fruit at all three harvest dates. The percent of surface showing dark red color was also greater for RF treated fruit for both film positions when fruit was harvested on 4 and 18 Sept.

Fruit size (length, diameter, and weight), flesh firmness, and starch levels were not affected by RF treatments (data not shown). The fruit SSC was increased by the RF treatments over controls at all harvest dates except when the RF was placed in the row middle and fruit were harvested on 4 Sept. Bulk fruit samples harvested on 1 Oct. and graded by the grower with a

Table 7. Location of a reflective film (RF) on the orchard floor affects fruit color at two canopy levels in 32-year-old 'Miller Spur Delicious'/seedling apple trees.

Treatment[z]			Surface dark
RF	Canopy level	L*[y]	red color (%)
	Harvested 4 Sept. 1998		
Control (none)	Lower (L)	47.2 a [x]	4.7 b
	Upper (U)	45.1 b	8.4 a
Row middle	L	46.3 a	11.2 a
	U	46.3 a	8.5 a
Under canopy	L	44.2 a	13.0 a
	U	44.4 a	12.1 a
	Harvested 11 Sept. 1998		
Control	L	44.1 a	9.1 b
	U	41.8 b	18.1 a
Row middle	L	42.5 a	14.0 a
	U	42.0 a	19.0 a
Under canopy	L	41.5 a	11.6 b
	U	41.6 a	16.3 a
	Harvested 18 Sept. 1998		
Control	L	44.7 a	11.4 b
	U	42.3 b	17.1 a
Row middle	L	43.6 a	15.8 b
	U	43.0 a	24.0 a
Under canopy	L	40.7 a	24.2 a
	U	40.8 a	28.9 a

[z]RF = location of the film; control is the no RF treatment. Sampling height in the canopy: lower = ground to height of 6. 5 ft (2.0 m); upper = height 10 to 16.5ft (3.1 to 5.0 m) in the canopy.
[z]L*= lightness (0 = black, 100 = white).
[x]Mean separation within columns for harvest date within RF treatments and between canopy levels, Duncan's new multiple range test, $P \leq 0.05$.

Table 8. Effect of the location of a reflective film (RF) on red color and soluble solids concentration (SSC) of apples harvested from 32-year-old 'Miller Spur Delicious'/ seedling trees.

RF treatment[z]	Hue angle	Surface dark red color (%)	SSC (%)
		Harvested 4 Sept. 1998	
None (control)	37.3 a[x]	7 c	11.1 b
Row middle	37.6 a	10 b	11.5 ab
Under canopy	31.9 b	13 a	11.7 a
		Harvested 11 Sept. 1998	
Control	32.0 a	14 a	11.5 b
Row middle	29.9 b	17 a	12.2 a
Under canopy	28.2 b	14 a	12.2 a
		Harvested 18 Sept. 1998	
Control	32.4 a	14 c	12.6 b
Row middle	30.9 a	19 b	13.4 a
Under canopy	27.1 b	26 a	13.5 a

[z]Location of the film on the orchard floor.
[y]Hue angle = arctangent b*/a* (0 = red-purple, 90 = yellow).
[x]Mean separation within columns for harvest date, Duncan's new multiple range test, $P \leq 0.05$.

Table 9. Effect of a reflective film (RF) on red color of 'Miller Spur Delicious' apples from 32-year-old trees as determined by an Agri-Tech USM MegaSort II PWS/Merlin Color Sorter (Agri-Tech, Inc. Woodstock, Va.).

RF	Mean % fruit in color class[y]		
treatment[z]	≥85%	65%–84%	≤64%
None (control)	24.7	54.1	20.9
Row middle	40.5	46.4	17.3
Under canopy	41.9	48.9	8.9

[z]Location of the film on the orchard floor.
[y]Fruit harvested 1 Oct. 1998; mean of three plots with an average of 3180 fruit/plot; percent is surface red color.

Table 10. Effect of two reflective films (RF) or ethephon on color, firmness and starch index rating of 'Hardibrite Spur Delicious' apples harvested from 10-year-old Y-trellis trained trees.

Treatment[z]	L*[y]	Hue angle[y]	Flesh firmness (lb force)[x]	Starch index (1–8)[x]
		Harvested 20 Sept. 1999		
High-density RF (0.5 mil)	41.2 c[w]	28.6 c	16.6 a	3.7 b
Low-density RF (1.25 mil)	41.8 c	29.7 c	16.4 ab	3.7 b
Ethephon [300 mg·L^{-1} (ppm)]	44.9 b	34.3 b	16.3 b	4.3 a
Control	46.3 a	36.8 a	16.5 ab	3.6 b
		Harvested 27 Sept. 1999		
High-density RF (0.5 mil)	39.3 d	26.5 d	16.5 a	4.0 c
Low-density RF (1.25 mil)	40.6 c	28.0 c	16.6 a	4.1 c
Ethephon (300 mg·L^{-1})	42.0 b	30.4 b	16.1 b	5.8 a
Control	44.1 a	32.9 a	16.1 b	4.8 b

[z]RF installed 9 Aug. 1999; ethephon applied dilute handgun on 18 Sept. 1999; 1 mil = 0.001 inch (0.025 mm).
[y]L*= lightness (0 = black, 100 = white); hue angle = arctangent b*/a* (0 = red-purple, 90 = yellow).
[x]1.0 lb force = 4.45 N; starch index rating: 1 to 3 = immature, 4 to 6 = mature, 7 to 8 = overmature.
[w]Mean separation within columns for harvest date by Duncan's new multiple range test, $P \leq 0.05$.

commercial fruit grader showed no statistical differences in fruit color, however, there was a strong trend toward increased red color where the RF material was applied (Table 9). Fruit from RF plots had the highest percent (40% and 42%) of highly colored fruit in the 85% red color or greater classes while check trees had the lowest percent (25%) fruit in this class.

The results from this experiment demonstrated the potential for RF to increase red color on 'Delicious' apples growing on tall trees when the canopy is judged to be open to light penetration. Positioning the film under the canopy provided a more favorable fruit coloration response than placing the film in the row middle.

1999 EXPERIMENT. A less expensive high-density RF was as effective as the more costly low-density film for increasing red color and the darkness of color on 'Hardibrite Delicious' apples harvested 1 week before and on the PMD (27 Sept.) (Table 10). The effect of the low- or high-density RF on color was better than that obtained with the commercially recommended ethephon application. When harvested on the PMD, RF treated fruit were firmer and had a higher starch level than control or ethephon treated fruit suggesting the films had delayed fruit maturity. This is in contrast to the findings of Layne et al. (2001) with peach where the RF advanced maturity. Treatments had no effect on fruit weight (data not shown).

The cost of various RF materials (supplied by Clarke Ag Plastics) per acre in 1999 at selected tree-row spacings is presented in Table 11. Material costs ranged from $183/acre ($452/ha) for the 1.25-mil low-density material in a wider spaced [22-ft (6.7-m) row spacing], low-density planting to $288/acre ($712/ha) in a more narrow [14-ft (4.3-m) row spacing] higher density planting, when material was purchased in quantity discount lots. Cost per acre for high-density, 0.5-mil RF was about $76/acre ($188/ha) (or 60% less than low-density film). Low-density plastic is not as strong as the high-density material, but has more elasticity. Making an assumption that an average yield might be 500 bushels/acre (23.5 t·ha^{-1}) with a 5% cullage and given the 16.5% increase in highly colored fruit in the El Vista orchard (1998), we can estimate the return from the use of RF. If we make an additional assumption that 10% of the crop would be bag size fruit and improved color on these fruit would result in no increase in returns, the result is 70.5 bushels (427.5 bushels × 16.5%) (1.34 t) subject to improved returns due to enhanced color. Based on an increase of $3.00/bushel ($0.16/kg) for the higher colored fruit, the grower in this example would realize an additional gross return of $212/acre ($524/ha) from the use of the metalized RF. Based on these costs, a grower could realize a benefit from the use of

Table 11. Material cost per acre for 5-ft-wide (1.5-m) reflective film of various thicknesses and densities, 1999.[z]

Orchard tree row spacing	Reflective film cost per acre ($/acre) 1.25-mil Low-density[y]	0.9-mil Low-density	0.5-mil High-density[x]
22 ft (6.7 m)	183–237[w]	132–170	76
18 ft (5.5 m)	224–290	162–208	93
14 ft (4.3 m)	288–373	208–267	120

[z]1 mil = 0.001 inch (0.025 mm); $1/acre = $2.47/ha. Material costs provided by Clarke Ag Plastics, Greenwood, Va.
[y]Material will stretch but is not as strong as high-density plastic.
[x]Material is stronger than low-density plastic but will not stretch.
[w]Cost range based on quantity purchase.

a high density film in plantings from 14 to 22 ft row spacing.

Conclusions

Based on this series of experiments with apple during a 4-year period the following conclusions were reached: 1) a metalized RF, when placed on the orchard floor between tree rows or under the edge of the canopy, will increase significantly the level of light reflected into the canopy; 2) RF placed in the orchard 5 to 7 weeks before harvest, will generally increase the red color on apple cultivars such as 'Delicious', 'Empire', and 'Fuji' growing in the mid-Atlantic region; 3) small stature trees [less than 10 ft (3 m) height] in a high density planting, and especially those trained to a Y-trellis, are more likely to show a positive fruit color response to RF than trees of a larger stature; however, larger standard size trees [13 to 18 ft (4.0 to 5.5 m) height] may show increased red color if trees are well pruned and open to light penetration; 4) the color response to RF is greatest in the lower portion of the canopy, generally up to a height of about 6.5 ft (2 m); 5) RF may delay apple maturity based on the starch index rating system; 6) a high-density RF is equal to or better than a low-density RF for improving color and the high-density film is more cost-effective; and 7) RF may be more effective than ethephon for color enhancement of 'Delicious', but not as effective as ethephon on 'Empire'. RF will not advance fruit maturity as commonly occurs with the use of ethephon.

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