Effect of Reflective Fabric on Yield of Mature ‘d’Anjou’ Pear Trees

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Abstract. Reflective fabric was installed before bloom in 2009 and 2010 in alleyways of a mature, low-density ‘Anjou’ pear orchard (269 trees/ha). Four treatments were applied to study intracanopy light environments on fruit growth rate and size, cropload, yield, and fruit quality: 1) no fabric (NF); 2) partial-season fabric applied before full bloom (FB) and removed 75 days after full bloom (dafb) (PSF); 3) full-season fabric applied before FB and removed at harvest (FSF); and 4) shade cloth (60%) applied 60 dafb through harvest (SC). PSF and FSF improved yield by 12% and 18%, respectively, over the two-year period relative to NF. The high yields of fabric treatments were attributed to fruit number in the lower (less than 2.4 m) interior, mid-, and exterior zones of the canopy. Photosynthetic active radiation (PAR) was increased by fabric 28%, 95%, and 30% in the lower exterior, mid-, and interior canopy, respectively. Photosynthesis:light response curves indicated improved carbon assimilation of pear leaves developing in the elevated PAR environment of the lower canopy. Fruit growth rate and final size were unaffected by fabric treatments. FSF fruit size was similar to NF despite higher fruit density. Compared with NF, FSF had a small, non-significant effect on fruit maturity (increased softening) at harvest. Yield and fruit size of SC fruit were significantly reduced. The number of fruit in SC trees did not differ from NF in 2009, but the effect of shade reduced fruit number in 2010. Fabric did not affect fruit quality attributes after three and six months of regular atmosphere cold storage. Pears from SC trees did not attain ripening capacity after three months of cold storage and a 7-day ripening period and had lower sugar content compared with other treatments. The cumulative yield advantages associated with FSF support its use in mature pear orchards.

In the United States, ‘Anjou’ (*Pyrus communis* L. ‘Anjou’) winter pear production occurs solely in the Pacific northwestern states of Oregon and Washington. The annual North American production of ‘Anjou’ pear is 11.3 million boxes (20 kg/box) equating to 248,600 tons (Ing, 2002). ‘Anjou’ pear trees are inherently vigorous and non-precocious but have a long productive life; consequently, a large percentage of ‘Anjou’ acreage has not undergone renovation and exists at low tree densities (less than 300 trees/ha). Average ‘Anjou’ pear yields throughout Oregon’s Hood River Valley are 39 tons/ha (OAIN, 2010; U.S. Department of Agriculture, National Agricultural Statistics Service, 2006). Depending on prices, and given increased costs of production, economic models indicate that these

levels are insufficient to sustain grower profitability (Seavert et al., 2007).

Low-density pear orchards are characterized by multiple leader trees with a relatively large proportion of the canopy consisting of non-productive, structural wood. Large pear trees are associated with high production costs (Seavert et al., 2007), but commercially viable, size-controlling rootstocks are not currently available in the United States to renovate old orchards and improve production efficiencies (Elkins et al., 2012). The reliance on heading cuts during dormancy to control tree size encourages excessive early and midseason vegetative growth, which, in turn, limits intracanopy light distribution (Einhorn, personal observation). ‘Bartlett’ fruit set and fruit retention decreased under 80% shade cloth applied between 14 dafb and harvest (Garriz et al., 1998). Application of shade (0%, 30%, 50%, 65%, and 82.5%) 50 dafb was negatively, linearly related with ‘Bartlett’ fruit size, soluble solids content (SS), and leaf weight per area (Kappel, 1989). Kappel and Neilsen (1994) observed a positive relationship between light microclimate surrounding ‘Bartlett’ fruiting spurs, fruit size, SS (at harvest), and return bloom.

Until size-controlling rootstocks can be used, a short-term solution that improves yield or increases the proportion of target

fruit will be required for orchardists to remain competitive with existing plantings. Reflective mulches have been shown to improve the light environment, skin color, and profitability of apple, *Malus × domestica* Borkh. (Blanke, 2008; Iglesias and Alegre, 2009; Meinhold et al., 2011), and peach, *Prunus persica* L., (Layne et al., 2001). Higher tree yields and improved fruit size have also been documented for apple (Miller and Greene, 2003). There is limited information, however, regarding the effects of reflective fabric on pear productivity; specifically, its role on fruit size, yield, and quality of winter pear (Bertelsen, 2005). We hypothesized that application of reflective fabric would improve yield potential over time, increase intracanopy light, and strengthen fruit bud quality (measured indirectly as the number of fruit in different canopy zones) of large pear canopies. Secondary objectives were to determine if timing of fabric application affected fruit growth rate, final fruit size, and quality and to characterize the effect of shade on fruit growth and production.

Materials and Methods

Plant material and experimental design. Reflective fabric (Extenday™, Auckland, New Zealand) was installed Spring 2009 before bloom in a mature (greater than 70 years old), low-density ‘Anjou’ pear orchard (6.1 m × 6.1 m; 269 trees/ha) located in the lower Hood River Valley, OR (lat. 45.7° N, long. 121.5° W). Soil was a Van Horn series, fine sandy loam. A randomized complete block design was applied to four replications of four treatments: 1) [NF] No Fabric, 2) [PSF] Partial-Season Fabric applied prior to full bloom (FB) and removed 75 days after full bloom (dafb), 3) [FSF] Full-Season Fabric applied prior to FB and removed at harvest, and 4) [SC] 60% shade-cloth applied 60 dafb through harvest. The term Fabric is used to describe effects associated with both of the fabric treatments. Full bloom occurred on 24 Apr. 2009 and 13 Apr. 2010. Each replication of NF and fabric treatments consisted of 12-tree plots. Three equal lengths of fabric were installed in adjacent rows for each plot, and the four center trees were used for data collection (Fig. 1). Completion of the ‘Anjou’ June drop (≈70 dafb) and the cell division stage of fruit growth (≈60 dafb; Westwood, 1993) were the principal factors for selecting 75 dafb for removal of fabric from PSF trees. At 60 dafb, shade structures were erected to enclose two trees per replication in 60% shade cloth but ended 2 m from the ground to enable commercial applications of insecticides through an airblast sprayer. Otherwise, the experimental trees were managed commercially. The experiment was repeated on the same trees in 2010.

Light measurement. Photosynthetic active radiation (PAR) was measured with a ceptometer (AccuPAR LP-80; Decagon Devices, Inc., Pullman, WA) in each of the four experimental trees per replicate plot. PAR measurements were taken at midday (1200 to 1400 hr) on several dates in 2009 beginning 50 dafb. Light conditions were similar

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Fig. 1. Fabric and tree dimensions of a single replicate fabric plot. Xs represent trees. The center four trees per plot were used for data collection and are denoted by a circled x.

on all dates; clear sky readings exceeded $1500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The ceptometer was positioned horizontally at a height of ≈ 1.5 m at each of the four cardinal directions, and *PAR* was recorded at three canopy depths beginning at the perimeter of the canopy and working toward the center: 0 to 1 m, 1 to 2 m, and 2 to 3 m ($n = 16$ per replication). Tree spacing was 6.1 m within the tree row, so 3 m ended at the center of the canopy. Reflected *PAR* was measured by inverting the ceptometer at each of the canopy positions and depths described previously.

Fruit size and yield. In 2009 and 2010, 20 fruit per replication were randomly selected on limbs of similar cropload and canopy position and fruit diameter was measured weekly (Cranston Fruit Gauge; Cranston Machinery Co., Oak Grove, OR). Three of the four experimental trees per replication were harvested at commercial timing; 14 Sept. 2009 (143 dafb) and 20 Sept. 2010 (160 dafb). Individual tree yields were pooled for replicate means. One hundred fruit were randomly selected from each tree's yield (i.e., 300 fruit per replication) and weighed to derive average fruit weight. The fourth tree per replicate plot (one per treatment) was harvested before the commercial harvest. For these trees a polyvinyl chloride (PVC) scaffolding system was built to divide tree canopies into six distinct zones. Two 6.1-m PVC lengths were placed on the orchard floor in a perpendicular orientation and centered at the tree trunk. Each length was plumbed with PVC tees (spaced at 1-m intervals with one tee at each end; six tees for each of the two horizontal PVC lengths). Inserted into each tee was a 4.8-m PVC vertical pipe (roughly equivalent to the height of the trees). Verticals were marked with colored laboratory tape 2.4 m from the ground. Vertical lengths were tied to limbs within the canopy to maintain a 90° orientation in both directions. Tree flagging was used to connect the outer four upright PVC verticals at the 2.4-m marks. Canopy limbs and ladders were used to create a uniform circle around the exterior of the canopy. Because the circle was developed around a center point, tree canopies did not always fit perfectly within the perimeter of the circle; however, trees filled their space allotment and canopies did not vary greater than ± 30 cm from the outer circle. This pattern was repeated for the next two sets of PVC uprights

inward so that three concentric zones were established within canopies. Fruit were harvested in the 1-m zone between the outer circle of flagging and the next circle inward, termed the exterior canopy; between the second circle and third circle inward, termed the midcanopy; and within the remaining interior circle, termed the interior canopy. For each of these three canopy zones, fruit were separately harvested below and above 2.4 m, thereby creating six distinct zones. Given the time requirements for assembly and removal of scaffolding, and the detailed harvests, only one complete replication could be harvested per day (four total trees); thus, 4 d were required to complete these harvests. The remaining experimental trees per treatment replication were harvested on the fifth day (i.e., commercial harvest timing).

Fruit quality. At harvest, fruit firmness (FF) was measured on 20 fruit per tree (80 fruit per replication) with a Fruit Texture Analyzer (Güss Manufacturing, Strand, South Africa) using an 8-mm diameter probe. Sections of skin, ≈ 2 cm in diameter, were removed at the widest point of the fruit on opposite sides. An additional 40 fruit per tree were immediately placed in regular atmosphere cold storage (-1°C) after harvest and analyzed at three and six months from harvest. At each sampling period, fruit were ripened for 7 d in 20°C before determination of fruit quality attributes. FF was assessed on 20 fruit per tree (80 per replicate) as described previously. After FF measurements, a composite sample comprised of 10 fruit per replication was juiced (Juice Extractor 6001C; Waring Products, New Hartford, CT), and 0.5 mL of juice was pipetted onto a digital refractometer (Palette series, PR-101 α ; Atago USA, Inc., Kirkland, WA) to determine SS. Analysis of total acids (TA), as malic acid equivalents, was determined using 10 mL of juice + 10 mL of deionized water and titrated with 0.1 N sodium hydroxide to an end point pH of 8.1 using a titrator fitted with an automated sampler (DL15 and Rondolino; Mettler-Toledo Inc., Zurich, Switzerland). Juice from 100 mg of fresh fruit (≈ 10 -g slice taken from each of 10 fruits) was transferred to a graduated cylinder for determination of extractable juice (EJ). As pears ripen, the volume of EJ decreases (Chen et al., 1983); thus, EJ is a good ripening indicator.

Accumulated heat units. Accumulated heat units (AHUs) were calculated each year

from FB to 60 dafb using temperature data generated by an IFPNet meteorological station (Wy'East RC&D, 2009) located within 100 m from the experimental orchard. AHUs were derived by dividing the sum of the daily minimum and maximum temperatures by 2 and subtracting the low temperature threshold (7.2°C).

Light response curves. Photosynthesis (P_n):light response curves were generated in situ with a PP systems Ciras-2 gas analyzer (PP Systems, Amesbury, MA) using a cuvette fitted with a light-emitting diode light source (PP Systems). Measurements were taken on the first fully mature leaves of extension shoots, between 1200 and 1400 HR. Leaves were acclimated to the dark, then provided light in a stepwise manner (0, 50, 100, 200, 400, 600, 800, 1000, 1250, 1500, 1750, 2000 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). P_n was observed to stabilize before the next light level. Each curve took ≈ 25 min to complete. A total of six replicate leaves was used to estimate the response of shaded and exposed leaf populations; six curves were generated on each of 2 successive days (three for shade leaves and three for exposed leaves). Clear sky *PAR* exceeded $1500 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ on both dates.

Statistical analysis. Statistical analyses were performed using the SAS system software (SAS 9.2; SAS Institute, Cary, NC). Treatment means were compared using analysis of variance with PROC GLM and significance was tested at $P \leq 0.05$. Mean separation was determined by Fisher's protected least significant difference test. Regression analysis for fruit growth was performed by PROC REG.

Results and Discussion

Fruit size, maturity, and yield of whole trees. Cumulative fruit growth of exposed 'Anjou' was unaffected by fabric in either year (Fig. 2A–B) compared with NF. SC fruit growth was limited by 97 dafb and 128 dafb (46 d and 32 d before harvest) in 2009 and 2010, respectively (Fig. 2A–B). These results agree with earlier work showing a linear, negative relationship between 'Bartlett' fruit size and percent shade when applied between 50 dafb and harvest (Kappel, 1989). Reduced 'Bartlett' fruit growth was also observed when branches were covered with 80% shade from 76 dafb to harvest (Garriz et al., 1998). Fruit size of all treatments was markedly larger in 2009 than 2010 by 60 dafb (Fig. 2C). AHUs calculated between full bloom and 60 dafb were 480 and 317 for 2009 and 2010, respectively. As a result of the linear growth pattern of pear fruit between 60 dafb and harvest, the smaller fruit in 2010 required an additional 17 d to attain similar fruit size as in 2009 (Fig. 2C) based on the regression equation.

In 2009, total tree yields were 20% and 26% greater for PSF and FSF relative to NF, a projected yield increase of 20 to 25 tons/ha, respectively (Table 1). Compared with NF, the higher yields of fabric trees were attributed to greater fruit number but not fruit size (Table 1). In contrast, the number of fruit on

Fig. 2. Effect of groundcover treatment on cumulative fruit growth of 'Anjou' pears in 2009 (A), and 2010 (B), respectively. NF = no fabric; PSF = partial-season fabric applied before full bloom (FB) and removed 75 d after full bloom (dafb); FSF = full-season fabric applied before FB and removed at harvest; SC = 60% shade cloth applied 60 dafb through harvest. Fruit diameter of fabric treatments 60 dafb through harvest in 2009 and 2010 (C). Accumulated heat units from full bloom through 60 dafb were 480 and 317 for 2009 and 2010, respectively. Vertical hashed lines in A and B signify removal of fabric from PSF plots; bold lines at bottom of A and B represent application of shade. Asterisks at top of A and B signify significance at $P < 0.05$. Symbols in A and B are the means of four replicate trees ($n = 20$). Fruit size of all treatments was larger in 2010, but only fruit of fabric treatments were plotted in C to remove the effect of cropload on fruit size given the nearly identical yields of fabric treatments in 2009 and 2010 (see Table 1).

SC and NF trees did not statistically differ, but significantly lower yields of SC fruit were associated with smaller fruit size (Table 1; Fig. 2A–B). In a separate commercial 'Anjou' field trial, we have recently observed a 25% yield improvement for reflective fabric plots (four ≈ 1 -ha replications with or without fabric) in the first year (2010) relative to the untreated control (Dunley and Einhorn, unpublished data). In that study, fabric was removed 60 dafb. The increase in yield was a function of higher fruit set (similar to the Year 1 results of the present study); no differences in fruit size were detected.

Despite a $\approx 17\%$ yield increase for NF trees in 2010 (an additional 385 fruit per tree), FSF and PSF yields were numerically, but not significantly, higher. NF yields exceeded the average Oregon, Hood River County, yields by ≈ 2.5 - to 3-fold. The site has deep,

fertile soil and trees are productive. Interestingly, yields of individual fabric trees did not fluctuate between years (Table 1), indicating the potential for consistently high annual yields. Additional years of research will be required to confirm these observations and determine whether NF trees display some degree of biennial bearing. Aside from possessing a genetic disposition for biennial bearing, for which 'Anjou' has not been characterized, biennial, or alternate, bearing of fruit trees can be influenced by several environmental factors (Monselise and Goldschmidt, 1982). 'Anjou' pear trees are subject to carbohydrate limitations from year to year depending on environmental, pathological, or cropload conditions, all of which may affect consistent bearing (Monselise and Goldschmidt, 1982), especially the latter given that 'Anjou' trees are not thinned commercially. SC yield,

fruit size, and number were all significantly reduced in 2010 (Table 1). Over the two-year study, PSF and FSF increased yield by 12% and 18% relative to NF (24 and 38 additional tons/ha at the density of the experimental orchard), but only the cumulative yield of FSF was significantly higher than NF (Table 1). Although tree yields of FSF were numerically higher than PSF, a significant difference between the two fabric treatments was not detected (Table 1). Bertelsen (2005) reported yield improvement of pear from reflective fabric treatments, although results were inconsistent and varied depending on cultivar ('Clara Frijs' and 'Comice') and tree density (1250 or 2050 trees/ha); fruit size was slightly larger in fabric treatments, but not significantly. The authors are unaware of any additional published reports of reflective fabric use in pear orchards.

FSF and PSF fruit were not statistically, physiologically more advanced at harvest relative to NF; determined by FF (Table 1). Late-season application of reflective materials has been used to enhance skin color or advance maturity in peach (Layne et al., 2001) and apple (Andris et al., 1998; Doud and Ferree, 1980; Iglesias and Alegre, 2009; Miller and Greene, 2003). In 2010, the significantly smaller SC fruit were firmer than all other treatment fruit at harvest (Table 1), as similarly observed with shade-treated 'Bartlett' (Kappel, 1989).

Fruit quality. In 2009, SC fruit were significantly firmer than NF fruit after three months of cold storage and ripening [23.1 newtons (N) vs. 15.9 N, respectively] despite having similar FF as other treatments at harvest (Table 1). At six months, SC fruit were capable of softening to levels attained by other treatment fruit (data not shown). SC fruit attained ripening capacity after three months of cold storage in 2010, perhaps because fruit were harvested at a lower flesh pressure in 2010 compared with 2009 (Table 1). In both years, flesh pressures at harvest were well within the acceptable commercial range for 'Anjou' (58 to 67 N). 'Anjou' requires a minimum of 60 d cold storage when harvested at pressures greater than 60 N to develop ripening capacity and soften to acceptable FF (less than 17.5 N) for consumption (Chen and Mellenstien, 1981). Inability for 90 d cold storage to induce full ripening capacity would indicate insufficient maturity at harvest. EJ and TA did not differ among treatments after storage durations in either year. SS was significantly reduced for SC fruit in both years compared with NF (11.6% and 11.7% for SC compared with 12.8% and 12.2% for NF in 2009 and 2010, respectively), as similarly observed in 'Bartlett' (Kappel, 1989).

Fruit size, yield, and photosynthetically active radiation within canopy zones. Individual FSF tree canopies, divided into six zones, had significantly higher yields (total fruit weight and number of fruit) in the lower (0 to 2.4 m tree height) midcanopy compared with NF trees in both years and in the interior canopy in 2009 (Table 2). In 2009, PSF yield

Table 1. Fruit firmness, average fruit size, number of fruit per tree at harvest, tree yield, and projected per-hectare production of mature, low-density 'Anjou' trees treated with ground application of reflective fabric or overcanopy shade relative to a no-fabric control.

Treatment	Fruit firmness (N)		Avg. fruit size (g)		Fruit (no./tree)		Yield (kg/tree)			Projected production ² (tons/ha)		
	2009	2010	2009	2010	2009	2010	2009	2010	Cumulative	2009	2010	Cumulative
NF	68	61.1 b	231 a ^y	211 a	1386 b	1771 a	320 b	374 a	694 b	95	111	206
PSF	65.6	60.4 b	216 a	213 a	1805 a	1812 a	389 a	386 a	774 ab	115	115	230
FSF	64.8	60 b	225 a	214 a	1811 a	1954 a	405 a	419 a	823 a	120	124	244
SC	65.4	65.9 a	173 b	181 b	1381 b	962 b	238 c	173 b	411 c	71	51	122
<i>P</i> > <i>F</i>	0.32	<0.0001	<0.0001	0.0001	0.039	<0.0001	<0.0001	<0.0001	<0.0001			

²Projected production based on the measured tree yields at a planting density of 269 trees/ha.

^yMean separation within columns by Fisher's protected least significant difference test at *P* < 0.05.

NF = no fabric; PSF = partial-season fabric applied before full bloom (FB) and removed 75 d after full bloom (dafb); FSF = full-season fabric applied before FB and removed at harvest; SC = 60% shade cloth applied 60 dafb through harvest. Data are means of four replications; n = 400 (avg. fruit size); n = 80 (FF); n = 4 (yield and fruit no.).

Table 2. Yield, number of fruit, average fruit size, and fruit firmness at harvest in 2009 and 2010 for six different zones of mature, low-density 'Anjou' canopies treated with ground application of reflective fabric or overcanopy shade relative to a no-fabric control.

Treatment	Exterior ² canopy (< 2.4 m)		Exterior canopy (> 2.4 m)		Midcanopy (> 2.4 m)		Midcanopy (< 2.4 m)		Interior canopy (< 2.4 m)		Interior canopy (> 2.4 m)	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
<i>Yield (kg)</i>												
NF	70.9 ab ^y	89.5 a	189.8	202.7	10.5 c	19.9 b	83.8	77.2 a	2.3 c	5.7	12.9	8.5
PSF	80.5 ab	79.8 ab	148.6	163.2	24.8 b	21.6 b	92.8	90.6 a	8.2 ab	9.8	16	9.5
FSF	107.2 a	111.1 a	153.1	165.6	37.2 a	38.8 a	96.6	91.5 a	10.6 a	9.1	14.7	7.6
SC	52 b	49.5 b	126.7	92.9	14.9 bc	16.8 b	64.8	41.3 b	2.8 c	4.5	11.7	4.6
<i>P</i> > <i>F</i>	0.046	0.035	0.238	0.133	0.0004	<0.0001	0.294	0.014	0.019	0.199	0.789	0.511
<i>Yield (fruit no.)</i>												
NF	332 b	456 ab	843	922	55 c	112 b	382	350 ab	13 b	33	61	44
PSF	389 ab	438 ab	691	816	130 b	131 b	414	454 a	46 ab	64	75	52
FSF	550 a	607 a	724	816	196 a	214 a	450	447 a	58 a	54	75	42
SC	297 b	283 b	748	489	104 bc	112 b	380	227 b	28 ab	32	72	27
<i>P</i> > <i>F</i>	0.042	0.05	0.708	0.242	0.001	0.0005	0.831	0.027	0.05	0.318	0.931	0.583
<i>Avg. fruit weight (g)</i>												
NF	213 a	199	225 a	223	189 a	177	222 a	221 a	179 a	170 a	219 a	192
PSF	206 a	183	216 a	201	191 a	167	226 a	202 ab	178 a	159 a	218 a	187
FSF	194 ab	183	206 a	201	189 a	183	214 a	204 ab	182 a	178 a	196 b	182
SC	174 b	176	172 b	190	146 b	150	171 b	182 b	130 b	131 b	163 c	172
<i>P</i> > <i>F</i>	0.019	0.205	0.006	0.118	0.0005	0.081	0.002	0.023	0.005	0.0016	0.0002	0.648
<i>Fruit firmness (N)</i>												
NF	66.6	63.8 ab	67.2	63.8	68.4	65.5 b	67	66.3	68.9	69.3 ab	69.9	69.9
PSF	65.7	62 b	66	62.1	64.5	64 b	65.5	64.6	65.6	65.9 bc	66.6	63
FSF	63	60.9 b	64.7	61.4	64.3	61.9 b	65.5	63.9	65.2	61.8 c	66.2	64.3
SC	64.1	65.8 a	64.4	67	65.7	70.4 a	65.6	67.2	66.4	71.8 a	66.3	66.5
<i>P</i> > <i>F</i>	0.287	0.045	0.19	0.066	0.293	0.006	0.459	0.141	0.543	0.006	0.714	0.108

²Exterior canopy = outer edge of canopy to a depth of 1 m inward; midcanopy = 1 m to 2 m canopy depth; interior canopy = 2 m to 3 m into canopy ending at the center of the canopy. For each depth data were taken at two heights, < 2.4 m or > 2.4 m from the ground.

^yMean separation within columns by Fisher's protected least significant difference test at *P* < 0.05.

NF = no fabric; PSF = partial-season fabric applied before full bloom (FB) and removed 75 d after full bloom (dafb); FSF = full-season fabric applied before FB and removed at harvest; SC = 60% shade cloth applied 60 dafb through harvest. Data are means of four replications; n = 1 (yield and fruit no.); n = 100 (avg. fruit size); n = 20 (FF).

(weight and number of fruit) was intermediate between NF and FSF in the less than 2.4 m midcanopy zone only (Table 2). In 2010, PSF yield did not significantly differ from NF or FSF irrespective of the zone (Table 2). *PAR* was significantly increased in the exterior and midcanopy of fabric trees relative to NF trees by 28% and 95%, respectively (Table 3). In fact, relative to NF, reflected *PAR* was ~10-fold and 5-fold higher in these canopy zones for fabric treatments. *PAR* interception tended to be higher in the interior canopy of fabric trees, but not significantly (Table 3). Improved yield in lower FSF canopies was a direct consequence of higher *PAR* as similarly observed in apple (Miller and Greene, 2003). Other investigators have demonstrated fruit quality improvements in the lower

canopy above reflective films for apple (Glenn and Puterka, 2007; Iglesias and Alegre, 2009; Meinhold et al., 2011; Miller and Greene, 2003) and peach (Layne et al., 2001). Roughly 2% of full sunlight was reflected from NF sod alleyways compared with 14% from the fabric in the exterior canopy (Table 3). Comparable reflectance values from white fabrics have been previously documented (Atkinson et al., 2006; Blanke, 2008; Miller and Greene, 2003; Sandler et al., 2009).

The higher intercepted *PAR* in lower fabric canopies (614 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) relative to NF (481 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) would confer small but positive gains in pear leaf P_n (Fig. 3). Light-saturated gross P_n for exposed leaves (12 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was observed at ~50% of full *PAR* (Fig. 3). P_n :light response of pear

leaves was similar to that reported for apple (Lakso, 1994). These additional photoassimilates were likely necessary to size FSF fruit given their relatively high croploads (Table 2). Little is known, however, of the relative sink strength of fruit of European pear. As the season progressed, the sink strength of Japanese pear (*Pyrus pyrifolia* Nakai) fruit increased from ~40% (60 dafb) to greater than 80% beginning three months from harvest relative to the total amount of ¹³C recovered in leaves, current-season bourse shoots, two-year-old spur wood, and fruit (Zhang et al., 2005).

In 2009, the number of fruit in different zones of SC canopies was similar to NF, but yield was negatively and significantly affected by fruit size (Table 2). *PAR* was limited to the

Table 3. Light (*PAR*) interception and reflectance at three depths of mature ‘Anjou’ pear canopies as affected by reflective fabric applied to the orchard floor or overcanopy shade cloth (SC) relative to a no-fabric control (NF).^z

Treatment	Exterior ^y canopy		Midcanopy		Interior canopy	
	Interception ^x	Reflectance ^w	Interception	Reflectance	Interception	Reflectance
	<i>PAR</i> ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)					
NF	481 b ^v (31 ^u)	26 b (2)	136 b (8)	21 b (1)	78 ab (5)	18 b (1)
Fabric ^t	614 a (38)	229 a (14)	265 a (17)	137 a (9)	101 a (6)	85 a (5)
SC	93 c (6)	26 b (2)	79 bc (5)	13 b (1)	39 b (2)	11 b (1)

^zData are means of four replications; n = 16.

^yExterior canopy = outer edge of canopy to a depth of 1 m inward; midcanopy = 1 m to 2 m canopy depth; interior canopy = 2 m to 3 m into canopy ending at the center of the canopy.

^x*PAR* interception quantified with a ceptometer positioned in the canopy at 1.5 m height.

^w*PAR* reflectance quantified by inverting ceptometer at 1.5 m height.

^vMean separation within columns by Fisher’s protected least significant difference test at $P < 0.05$.

^tPercent of above canopy light incident on the orchard; average above canopy incident light was $1621 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

^uLight interception and reflectance were determined for both Fabric treatments (PSF and FSF), but data are not provided for each because PSF and FSF had equivalent *PAR* interception and reflectance values.

PAR = photosynthetically active radiation; PSF = partial-season fabric applied before full bloom and removed 75 d after full bloom; FSF = full-season fabric applied before full bloom and removed at harvest.

Fig. 3. Light response curves for exposed (solid symbols) and shaded (open symbols) ‘Anjou’ leaves within canopies. P_n = net photosynthesis; *PPF* = photosynthetic photon flux. Data are means of six leaves. Measurements were taken in the field at solar noon.

greatest extent in SC canopies at all depths, but significant differences were only observed in the exterior canopy compared with NF (Table 3). *PAR* levels in the exterior of SC canopies were similar to those measured in the interior of NF trees (Table 3), where a similar reduction in fruit size was also observed (Table 2). These results in combination with a shade-induced decrease in pear leaf weight per unit area (Kappel, 1989) are indicative of lower carbon assimilation of pear leaves and are further supported by shade leaf P_n curves (Fig. 3). Shade leaves had a characteristically low light compensation point, dark respiration rate, and P_n maxima (Fig. 3; Salisbury and Ross, 1992), the latter apparently deficient to meet the carbon demand of fruit.

Shade application in 2009 may have further contributed to a lower fruit set in SC trees in 2010 (Tables 1 and 3). Tustin et al. (1992) observed reductions in leaf area, bourse shoot development, and P_n of apple spurs shaded the preceding year. Alternatively, accumulated fruit abscission of ‘Bartlett’ was $\approx 75\%$ for shaded branches (80% shade cloth) compared with 25% for exposed branches (Garriz et al., 1998). Moreover, there is wide evidence for a positive role of light quantity

for flower initiation of fruit trees (Jackson and Sweet, 1972) and specifically ‘Anjou’ (Kappel and Neilsen, 1994; Khemira et al., 1993).

We did not determine whether light directly improved fruit bud quality in FSF through an increase in the number of reproductive buds or the dry matter content of those buds. Although we did not observe augmented fruit set in lower fabric canopy zones in the second year, relatively high and consistent fruit set of large fruit in these zones is indicative of improved fruiting strength. It is plausible that some combination of bud quality and improved P_n led to these differences. Khemira et al. (1993) proposed that greater than 30% of full sunlight is necessary for floral initiation in pear and other temperate-zone tree fruit species. This value greatly exceeds the average *PAR* interception in the midcanopy of fabric and NF trees (Table 3), yet roughly 32% and 25% of the total fruit per tree resided in these zones, respectively. ‘Clara Frijs’ pear trees treated with reflective fabric had nearly 2-fold the floral buds of control trees in the third year (Bertelsen, 2005); however, despite the high tree densities, trees were relatively small (12 years old, slender spindles), which starkly contrast the

large, multiple-leader ‘Anjou’ canopies of the present study. Intracanalopy *PAR* was also not measured in that study, thus limiting comparisons between their results and ours relative to the role of light on floral bud development.

Projected production (per ha) of FSF from cumulative average tree yields (Table 1) would have returned an additional \$13,818 per ha based on the average returns per unit for 2009 and 2010 (\$200 per 0.55 ton bin) compared with NF. Labor costs to harvest the additional fruit would have been \$1311 per ha based on a \$19 per bin harvest rate. Fabric installation and removal costs were not estimated in our study given the relatively small experimental plot sizes, but estimates from commercial tree-fruit use range from \$136 to \$618 per ha (V. Burgers, personal communication). After deducting all labor costs (assuming the highest installation costs) and the costs of the fabric (Meinhold et al., 2011), a net profit of \$3985 per ha would have been realized relative to NF. In this scenario, the seven-year projected life of the fabric would have been paid off after the first two years of use.

In conclusion, our data support the use of full-season reflective fabric in mature ‘Anjou’ pear orchards given its positive effect on light environment and yield and maintenance of fruit size. Although the interior, 2-m diameter column of our experimental trees only comprised 3.5% to 6% of the total tree yield, significant yield improvements in the lower, midcanopy had a marked impact on total tree yield of FSF (Table 2). Yield of PSF did not significantly differ from FSF or NF. A sustained evaluation of white reflective fabric applied full- or partial-season is ongoing to determine if the incremental yield improvements observed among NF, PSF, and FSF herein change in magnitude with time. In the short term, several methods are available to improve light use in low-density, mature pear plantings including summer pruning; application of reflective fabrics or particle films (Glenn and Puterka, 2007); and possibly through judicious use of water (Behboudian et al., 2011; Mitchell et al., 1984) and nitrogen. In the United States, bioregulators to control vegetative growth are not labeled for use with pear. Ultimately, genetic resources need to be developed that impart dwarfing and greater efficiency on pear canopies (Elkins et al., 2012).

Literature Cited

- Andris, H.L., C.H. Crisosto, and Y.L. Grossman. 1998. The use of reflective films to improve the apple fruit red color. *Plasticulture*. 116:33–43.
- Atkinson, C.J., P.A.A. Dodds, Y.Y. Ford, J. le Mièrre, J.M. Taylor, P.S. Blake, and N. Paul. 2006. Effects of cultivar, fruit number and reflected photosynthetically active radiation on *Fragaria* × *ananassa* productivity and fruit ellagic acid and ascorbic acid concentrations. *Ann. Bot. (Lond.)* 97:429–441.
- Behboudian, M.H., J. Marsal, J. Girona, and G. Lopez. 2011. Quality and yield responses of deciduous fruits to reduced irrigation, p. 149–189. In: Janick, J. (ed.). *Horticultural reviews*. Vol. 38. Wiley-Blackwell, Oxford, UK.

- Bertelsen, M. 2005. Reflective mulch improves fruit size and flower bud formation of pear cv 'Clara Frijos'. *Acta Hort.* 671:87–95.
- Blanke, M.M. 2008. Alternatives to reflective mulch cloth (Extenday™) for apple under hail net? *Sci. Hort.* 116:223–226.
- Chen, P.M., W.M. Mellenthin, and D.M. Borgic. 1983. Changes in ripening behavior of 'd'Anjou' pears (*Pyrus communis* L.) after cold storage. *Sci. Hort.* 21:137–146.
- Doud, D.S. and D.C. Ferree. 1980. Influence of altered light levels on growth and fruiting on mature 'Delicious' apple trees. *J. Amer. Soc. Hort. Sci.* 105:325–328.
- Elkins, R., R. Bell, and T. Einhorn. 2012. Needs assessment for future US pear rootstock research directions based on the current state of pear production and rootstock research. *J. Amer. Pomol. Soc.* 66:153–163.
- Garriz, P.I., G.M. Colavita, and H.L. Alvarez. 1998. Fruit and spur leaf growth and quality as influenced by low irradiance levels in pear. *Sci. Hort.* 77:195–205.
- Glenn, D.M. and G.J. Puterka. 2007. The use of plastic films and sprayable reflective particle films to increase light penetration in apple canopies and improve apple color and weight. *HortScience* 42:91–96.
- Iglesias, I. and S. Alegre. 2009. The effects of reflective film on fruit color, quality, canopy light distribution, and profitability of 'Mondial Gala' apples. *HortTechnology* 19:488–498.
- Ing, G. 2002. Pear production and utilization in North America. *Acta Hort.* 596:61–65.
- Jackson, D.I. and G.B. Sweet. 1972. Flower initiation in temperate woody plants: A review based largely on the literature of conifers and deciduous fruit trees. *Horticultural Abstracts* 42:9–24.
- Kappel, F. 1989. Artificial shade reduces 'Bartlett' pear fruit size and influences fruit quality. *HortScience* 24:595–596.
- Kappel, F. and G.H. Nielsen. 1994. Relationship between light microclimate, fruit growth, fruit quality, specific leaf weight and N and P content of spur leaves of 'Bartlett' and 'Anjou' pear. *Sci. Hort.* 59:187–196.
- Khemira, H., P.B. Lombard, D. Sugar, and A.N. Azarenko. 1993. Hedgerow orientation affects canopy exposure, flowering, and fruiting of 'Anjou' pear trees. *HortScience* 28:984–987.
- Lakso, A.N. 1994. Apple, p. 3–42. In: Schaffer, B. and P.C. Andersen (eds.). *Handbook of environmental physiology of fruit crops. Volume 1. Temperate crops.* CRC Press, Boca Raton, FL.
- Layne, D.R., Z. Jiang, and J.W. Rushing. 2001. Tree fruit reflective film improves red skin coloration and advances maturity in peach. *HortTechnology* 11:234–242.
- Meinhold, T., L. Damerow, and M. Blanke. 2011. Reflective materials under hailnet improve orchard light utilisation, fruit quality and particularly fruit colouration. *Sci. Hort.* 127: 447–451.
- Miller, S.S. and G.M. Greene. 2003. The use of reflective film and ethephon to improve red skin color of apples in the Mid-Atlantic region of the United States. *HortTechnology* 13:90–99.
- Mitchell, P.D., P.H. Jerie, and D.J. Chalmers. 1984. The effects of regulated water deficits on pear tree growth, flowering, fruit growth and yield. *J. Amer. Soc. Hort. Sci.* 109:604–606.
- Monselise, S.P. and E.E. Goldschmidt. 1982. Alternate bearing in fruit trees, p. 128–173. In: Janick, J. (ed.). *Horticultural reviews. Vol. 4.* AVI Publishing Co., Inc., Westport, CT.
- OAin (Oregon Agricultural Information Network). 2010. Commodity data sheet, pears. Oregon State University Extension Service, Corvallis, OR. 1 June 2012. <<http://oain.oregonstate.edu/EconInfo/CDSFiles/cds09/pears.pdf>>.
- Salisbury, F.B. and C.W. Ross. 1992. *Plant physiology.* Wadsworth, Belmont, CA.
- Sandler, H.A., P.E. Brock, II, and J.E. Vanden Heuvel. 2009. Effects of three reflective mulches on yield and fruit composition of coastal New England winegrapes. *Amer. J. Enol. Viticult.* 60:332–338.
- Seavert, C.F., J. Freeborn, and S. Castagnoli. 2007. *Orchard Economics: Establishing and producing medium-density pears in Hood River County.* Oregon State Univ., EM 8822-E.
- Tustin, S., L. Corelli-Grappadelli, and G. Ravaglia. 1992. Effect of previous-season and current light environments on early-season spur development and assimilate translocation in 'Golden Delicious' apple. *J. Hort. Sci.* 67: 351–360.
- U.S. Department of Agriculture, National Agricultural Statistics Service. 2006. 2006 Oregon fruit tree inventory survey. U.S. Dept. Agr., Oregon Field Office, Portland, OR.
- Westwood, M.N. 1993. *Temperate-zone pomology: Physiology and culture.* 3rd Ed. Timber Press, Portland, OR.
- Wy'East RC&D. 2009. Integrated fruit production. IFPNet. 16 Apr. 2011. <<http://www.integratedfruitproduction.com/IFPNET/tabid/92/Default.aspx>>.
- Zhang, C., K. Tanabe, F. Tamura, A. Itai, and S. Wang. 2005. Spur Characteristics, fruit growth, and carbon partitioning in two late-maturing Japanese pear (*Pyrus pyrifolia* Nakai) cultivars with contrasting fruit size. *J. Amer. Soc. Hort. Sci.* 130:252–260.