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High Tunnel versus Open Field: Management of Primocane-fruiting Blackberry Using Pruning and Tipping to Increase Yield and Extend the Fruiting Season

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***Abstract*. Primocane-fruiting blackberries (*Rubus* subgenus *Rubus* Watson) may offer opportunities for season extension and off-season fruit production, particularly in mild climates with protected culture. In May 2005, plants of 'Prime-Jan'® were established at the Oregon State University–North Willamette Research and Extension Center, Aurora, OR. Half of the planting was established under a high tunnel and the remainder planted in an adjacent open field. In 2006 to 2007, primocanes were subjected to four treatments to promote branching and/or delay harvest: 1) all primocanes within the plot were cut to the ground when averaging 0.25 m tall, then later emerging canes soft-tipped when reaching 0.5 m tall (C0.25m/T0.5m); 2) all primocanes within the plot were cut to the ground when averaging 0.5 m tall, then later emerging canes soft-tipped when reaching 0.5 m (C0.5m/T0.5m); 3) primocanes double-tipped: all primocanes within the plot were soft-tipped when averaging 0.5 m tall with subsequent lateral branches then soft-tipped when reaching 0.5 m long (T0.5m/Tb0.5m); and 4) primocanes were soft-tipped when averaging 0.5 m tall (T0.5m; control). The tunnel was covered with plastic from 5 Sept. 2006 and 31 Aug. 2007, ≈1 to 2 weeks before harvest until the end of harvest to protect fruit from inclement weather. On average, fruit harvest began on 12 Sept. in the open field and tunnel, but lasted ≈3 weeks longer in the tunnel, ending on 16 Nov., on average. Primocanes that were double-tipped had nearly twice the flowers and fruit than canes that were soft-tipped only once (T0.5m; control). In the tunnel, cumulative yield of double-tipped primocanes averaged 10.7 $t \cdot ha^{-1}$ in 2006 and 19.3 $t \cdot ha^{-1}$ in 2007, a 267% and 159% increase compared with the control, respectively. On average, cumulative yield for all treatments was less in the open field than in the tunnel, although cultural systems could not be compared statistically. Harvest was not delayed in the C0.25m/T0.5m treatment in 2006 compared with the control and the double-tipped treatments; however, in 2007, harvest was delayed by 2 weeks in C0.25m/T0.5m. In contrast, harvest was delayed by ≈4 weeks when primocanes were cut to the ground at 0.5 m (C0.5m/T0.5m). Primocanes that were double-tipped produced heavier fruit than other treatments (33% heavier than the control, on average). Double-tipped primocanes did not have more ovules per flower, but had significantly more drupelets set compared with the control. In addition, plants growing under the tunnel tended to produce heavier fruit (32%, on average) than those grown in the open field. Harvest date affected fruit pH in 2006, but not in 2007. In 2006, fruit pH was highest in the early season. All other differences in fruit chemistry were not significant. The pruning and tipping systems used here increased yield and offered options for season extension.**

The ability to produce fruit in the off-season offers an economic advantage for fresh market growers. The target for off-season, late, fresh market blackberry harvest in North America is from mid-September through October, before imports from Mexico begin (Mark Hurst, Hurst's Berry Farm, Sheridan, OR, personal communication). Blackberry prices are typically highest during this annual lag period in fruit production.

Primocane-fruiting blackberries may offer the advantage of extending the harvest into the fall and winter months, particularly in milder climates (average annual minimum temperature –12 °C or greater; Strik and Thompson, 2009). Oliveira et al. (1996, 1998, 2004) and Jordan and Ince (1986) have shown that harvest of primocane-fruiting raspberry can easily be delayed in production systems that include summer pruning of primocanes, tipping, and tunnel protection. With the use of greenhouses, scheduling primocane-fruiting raspberry for year-round production is possible (Dale et al., 2001, 2005) and often includes the combination of floricane- and primocane-fruiting cultivars (Dijkstra and Scholtens, 1993; Faby, 1993; Hamminga, 1995; Oliveira et al., 2004). Scheduling floricane-fruiting blackberry for year-round production has been reported using artificial chilling and forcing in greenhouses (Bal and Meesters, 1995). Use of pruning techniques and application of chemicals to stimulate budbreak and flowering of floricane-fruiting blackberries to extend the fruiting season is common in Mexico (Strik et al., 2007).

Few studies on primocane-fruiting blackberry production have been done, because this crop is relatively new. Strik et al. (2008), studying 'Prime-Jan'® and 'Prime-Jim'® (Clark et al., 2005) in Oregon, noted that when harvest in unprotected fields was curtailed in October as a result of rain, there were still flower buds, flowers, and unripe fruit present on most treatments, particularly those tipped at 1 m (compared with an untipped control). A tunnel would have allowed for much later harvest.

Tunnel production has become very popular in recent years, providing the ability to protect fruit from inclement weather and to advance or extend the growing season, giving growers a significant advantage over production in the open field. However, it is unclear if the presence of plastic over a tunnel affects synthesis of primary or secondary plant metabolites. Phenolic compounds, for example, have numerous defense functions in plants and thus environmental factors such as light, temperature, and humidity as well as internal factors (i.e., genetics, hormones, nutrition) contribute to their synthesis (Strack, 1997). Flavonoids are polyphenolic compounds that constitute a large group of secondary plant metabolites, including anthocyanins, which are commonly found in berries and are positively associated with biological effects in vitro, including antioxidant, anti-inflammatory, antiallergic, antiulcer, antibiotic, and anticarcinogenic properties (Bravo, 1998; Cho et al., 2004). No work has been published to date on the impact of production systems on the fruit chemistry of primocane-fruiting blackberries.

The objectives of this study were to: 1) determine the effect of pruning primocanes to crown height and/or soft-tipping on yield and fruiting season of 'Prime Jan'; and 2) evaluate the effect of fruiting season on the chemistry of fruit ripened on plants grown in tunnel and in open field production systems.

Materials and Methods

Tissue cultured plugs (300 count; ≈6 weeks old) of 'Prime-Jan' were potted into 1-L pots using a soilless, peat-based bedding plant mix on 19 Nov. 2004. Plants were fertigated weekly using a Hozon brass siphon mixer (1:16 ratio; Phytotronics Inc., Earth City, MO) with 100 ppm of 20N–4P–14K Peter's® Professional water-soluble fertilizer (The Scotts Co., Marysville, OH). Plants were kept in a greenhouse under long-daylighting conditions (18-h day, 6-h night) with minimum and maximum daily temperatures of ≈11 and 29 °C, respectively, from 19 Nov. 2004 to 18 Apr. 2005. Plants were repotted in early 2005 into 7.5-L containers and acclimated in a Cravo® (Cravo Equipment Ltd., Brantford, Ontario, Canada) retractable roof structure until field planting.

On 6 May 2005, plants were transplanted to the field sites at the North Willamette Research and Extension Center, Aurora, Ore. (NWREC; lat. 45°17′ N, long. 122°45′ W; U.S. Dept. of Agriculture–Agricultural Res. Serv. hardiness zone 8; elevation 46 m; average last freeze date 17 Apr.; average first freeze date 25 Oct.; the weather records for this site can be viewed at Anonymous, 2008).

The site was a Willamette soil type (fine-silty, mixed Mesic Pachic Ultic Argixerolls) with a pH of 5.6. Five t·ha^{-1} of dolomite lime [$CaMg(CO_3)_2$], 48 kg·ha^{-1} of potassium, and 2.7 kg·ha^{-1} of boron were incorporated into the soil the fall before planting. Half of the plants were established in an uncovered high tunnel (61 × 8.5 m; Haygrove Tunnels, Herefordshire, U.K.). The remaining plants were established in an "open field" planting adjacent to the high tunnel with an unplanted buffer of ≈15 m between the two plantings. Plants were spaced 0.6 m in the row with 3 m between rows.

The tunnel and open field plantings were drip-irrigated (3.8 L·hr^{-1} emitters at 0.6-m spacing) as required, typically 30 min twice daily (3.8 L·d^{-1}), from June through September, and 15 min every other day (0.95 L·d^{-1}) in October and Nov. 2006 and 2007. Luminance THB (Visqueen Building Products BPI, London, U.K.) plastic film (6 mm) was placed over the tunnel on 5 Sept. 2006 and 31 Aug. 2007, ≈1 to 2 weeks before fruit harvest, and removed on 13 Nov. 2006 and 30 Nov. 2007, respectively. When present, plastic only covered the roof of the tunnel; the sides (1.5 m) and ends (8.5 m) were left open. No supplemental heat was provided in the tunnel. In late November of each year, plants from all treatments were pruned to the ground. Plots were fertilized with 55 kg·ha^{-1} of nitrogen, 15.4 kg·ha^{-1} of phosphorus, and 54.8 kg·ha^{-1} of potassium each spring as a split application in April and May. Weeds were controlled by use of pre-emergent herbicides and mechanical methods as required. The hedgerow width of each plot was maintained at 0.45 m using cultivation. In the planting year, 2005, plants grew untrained and unmanipulated and no data were collected.

There were four replicates of the following treatments arranged as a randomized complete block design in the tunnel and field in 2006 to 2007: 1) all primocanes within the plot were cut to the ground (just above the crown) when averaging 0.25 m tall, then later emerging primocanes were soft-tipped (2 to 5 cm of the tip removed) when reaching 0.5 m tall (C0.25m/T0.5m); 2) all primocanes within the plot were cut to the ground when averaging 0.5 m tall, then later emerging primocanes soft-tipped when reaching 0.5 m tall (C0.5m/T0.5m); 3) primocanes double-tipped: all primocanes within the plot were soft-tipped when averaging 0.5 m tall, then any subsequent lateral branches soft-tipped when reaching 0.5 m long (T0.5m/Tb0.5m); and 4) all primocanes soft-tipped at 0.5 m (T0.5m; control). Five-plant plots were 3 m long with 1.5 m separating plots.

Data collection per plot in 2006 and 2007 included: date of primocane emergence, pruning and soft-tipping, first open flower, and stage of full black king fruit; total primocane length at bloom; apical branch length (the first lateral branch to emerge below the site of tipping; data collected biweekly in 2006 only); number of fruiting and nonfruiting canes; mean fruiting and nonfruiting cane length; and primocane fresh weight per plot in late November of each year (plot fresh weight included primocanes and any unsenesced leaves). A subsample of three primocanes per plot was collected and data recorded on: number of branches, total branch length (2006 only), total number of nodes (main cane + branches), total number of reproductive nodes (nodes that bore a flower bud or fruiting lateral), and total number of fruiting sites per cane (remnant pedicels of floral axes were counted where fruit excision was evident). The percentage of reproductive nodes (proportion of nodes that developed a flower bud or fruiting lateral) was calculated. Fruit harvest date (berries were picked every 7 d), yield per plot, and average berry weight (n = 25) were recorded and subsamples of fruit (n = 10 in 2006; n = 5 in 2007) from double-tipped and control treatments were frozen for later counts of set drupelets and unset ovules. The total number of ovules per flower was estimated by adding the number of drupelets and unset ovules (Strik et al., 1996). Cumulative yield was determined.

In 2006, photosynthetically active radiation (*PAR*; µmol·m^{-2}·s^{-1}; averaged over 15 s) was measured on full sun days using a LI-250 photometer (LI-COR Biosciences, Lincoln, NE) in the tunnel and field during early, mid-, and late season fruit harvests. Photometer readings were collected 1 h before, during, and 1 h after solar noon at upper canopy height (≈1 m).

In both years, percent soluble solids (°Brix; TSS), pH, titratable acidity, total monomeric anthocyanins (TACY), and total phenolics were determined using pooled samples of berries from all treatments in both tunnel and open field during early (21 Sept.), mid- (12 Oct.), and late season (2 Nov.) harvests in 2006 and early (2 Oct.) and late season (6 Nov.) harvests in 2007. Percent soluble solids (n = 9 in 2006; n = 3 in 2007) was determined using a digital refractometer (Atago Palette PR-100, Tokyo, Japan). Berry pH (n = 3) was measured using a mixture of fruit (10 g subsample) and distilled water (1:9 w/v) that was homogenized using a kitchen blender before submersion of the electrode from a calibrated pH meter (IQ240; IQ Scientific Instruments, Inc., San Diego, CA). Titratable acidity was determined using a mixture of blended fruit (20-g subsample) and distilled water (1:2 w/v) titrated (Brinkman Digital Buret, Brand, W. Germany) with 0.1 N NaOH to an end point of pH 8.1 and expressed as equivalent weight of anhydrous citric acid in g/100 g fresh weight (FW).

The extraction procedure for TACY and total phenolics was modified from the method of Rodriguez-Saona and Wrolstad (2001) by using bulk samples of fresh fruit (100 g), which were squeezed through cheesecloth to yield a 15-g subsample of blackberry juice. Extractions were replicated twice for each sample and date and were stored at –70 °C until analyzed.

Total monomeric anthocyanins were determined using the pH differential method described by Giusti and Wrolstad (2001). All analyses were replicated twice with means calculated.

Total phenolics were determined as gallic acid equivalents (GAE) using the method of Singleton and Rossi (1965). The absorbance of samples and standards were measured at 765 nm using a Shimadzu 300 ultraviolet spectrophotometer (Shimadzu Scientific Instruments, Columbia, MD) and 1-cm path length disposable cells. Results were calculated as milligrams GAE/100 g FW. All analyses were replicated twice with means calculated.

Temperature at midcanopy (0.5 m) and of soil (at 5- and 10-cm depths) was collected using HOBO H8 data loggers with external sensors; ambient air temperature and relative humidity (RH) data were collected using HOBO Pro Series data loggers (Onset Computer Corp., Bourne, MA). Data points for temperature and RH were logged once per hour, offloaded biweekly, and averaged manually throughout the growing seasons.

Growth of apical branch length over time (2006 only) for each treatment was analyzed using analysis of variance (ANOVA) repeated

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measures (PROC GLM; Version 9.1; SAS Institute Inc., Cary, NC). Treatment effects on other data collected were analyzed using ANOVA in PROC GLM; means were separated using the PROC MEANS command, in which *t* tests generated a least significant difference value. The tunnel and open field cultural systems could not be compared statistically, because the plots were adjacent and not replicated. Thus, trends in the data are described.

Results and Discussion

Growth. In both years, primocanes began emerging in early February. Growth of 'Prime-Jan' was affected by primocane pruning. There was no apparent effect of the tunnel on primocane growth, because there was no plastic on the tunnel until harvest time in both years, when growth had slowed and fruit ripening began. Primocanes in the C0.5m/T0.5m treatment (cut 22 May and tipped 26 June, on average) were significantly delayed in development (Fig. 1). Apical branch length was shortest in the C0.5m/T0.5m treatment and averaged 0.45 m (data not shown); the average number of nodes per cane was 62 for the 2006 to 2007 seasons in both tunnel and open field (Table 1). In contrast, the apical branch length of primocanes that were tipped at 0.5 m (T0.5m; control; tipped 22 May, on average) averaged 1.1 m (data not shown); the long branches tended to arc toward the ground. The control treatment consistently had the longest apical branch length throughout the growing season (2006 only; data not shown) and averaged 104 nodes per cane over the 2006 to 2007 seasons (Table 1). Primocanes in the C0.25m/T0.5m treatment (cut 26 Apr. and tipped 7 June, on average; Fig. 1) or that were double-tipped (T0.5m/Tb0.5m; main cane tipped 22 May and 29 June for branches, on average) produced apical branches of similar length (data not shown), averaging 0.8 m at the end of the 2006 to 2007 seasons. Primocanes that grew after having been cut to the ground, however, consistently had fewer nodes than plants that were double-tipped (Table 1). The number of branches was not significantly affected by treatment (e.g., time of tipping) and averaged four branches per cane in 2006 and three branches per cane in 2007 (data not shown).

Flowering and reproductive morphology. Flower bud development occurred when the tunnel was not covered with plastic, because there was no apparent difference in flower number between plants grown in the tunnel and in the open field. On average, primocanes that were double-tipped developed twice the number of reproductive nodes and fruit and tended to have a higher percentage of reproductive nodes than any other treatment in both years (Table 1). Soft-tipped branches in double-tipped canes typically developed two to three inflorescences (0.10 to 0.15 m in length), whereas untipped branches in all other treatments ended in a single inflorescence. Other studies on 'Prime-Jan' have showed that soft-tipping at 1 m removed apical dominance and promoted branching (Strik et al., 2008; Thompson et al., 2007). The additional pruning of soft-tipped branches in the double-tipped treatment likely had a similar effect on promoting inflorescence development. However, it is important to tip main canes and branches before flower bud development; soft-tipping after flower buds have formed reduces yield (personal observation). Drake and Clark (2003) noted that tipping canes after plants had shifted to the reproductive mode (canes tipped 2 weeks after inflorescence appearance) was detrimental to yield. Primocanes that were tipped at 0.5 m (T0.5m; control) consistently averaged the lowest percentage of reproductive nodes, although differences among treatments were only significant in the tunnel in 2006 and 2007 (Table 1). In contrast, treatments that were cut to the ground to delay harvest averaged a higher percentage of reproductive nodes compared with the control, although again, differences were only significant in the tunnel in 2006 and 2007. It is possible that during regrowth, canes may have branched from the crown, subsequently averaging more canes per plant and thus producing a higher percentage of reproductive nodes overall.

Bloom was delayed by almost 1 month in primocanes managed as C0.5m/T0.5m

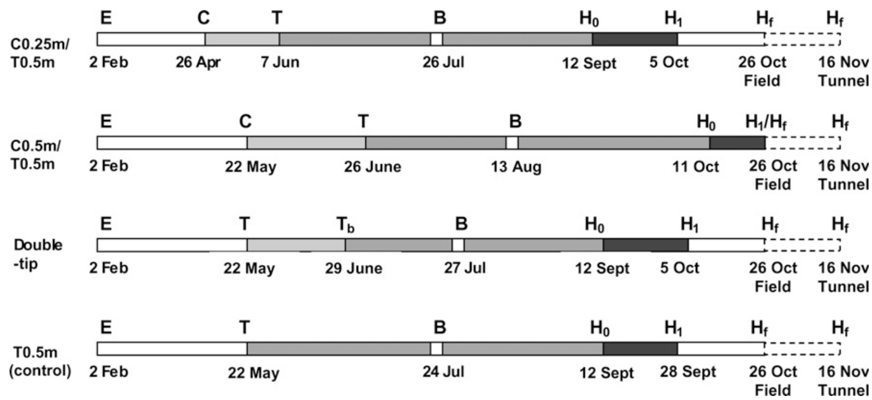

Fig. 1. Average date of primocane emergence (E), cutting (C), tipping main primocane at 0.5 m (T), tipping branches at 0.5 m (T_b), bloom (B), first fruit harvest (H_0), 50% harvest (H_1), and final harvest (H_f) of 'Prime Jan' blackberry grown in open field or a tunnel at the North Willamette Research and Extension Center, 2006 to 2007 (n = 8).

Table 1. The effect of pruning and tipping on the flowering and fruiting in primocanes of 'Prime-Jan' blackberry grown in a tunnel or the open field at North Willamette Research and Extension Center, 2006 to 2007 (n = 4; mean ± SE).

Year/culture	Treatment[z]	Total nodes/cane[y]	Fruiting sites/cane[x]	Reproductive nodes (%)	Fruiting canes/plot[w]
2006	C0.25m/T0.5m	64 ± 9.6	41 ± 2.6 b	52 b	54 ± 7.5 a
Tunnel	C0.5m/T0.5m	61 ± 6.2	48 ± 5.3 bc	68 ab	34 ± 15.4 b
	T0.5m/Tb0.5m	106 ± 8.7	111 ± 12.1 a	74 a	29 ± 3.9 b
	T0.5m	155 ± 28.1	27 ± 2.3 c	18 c	29 ± 2.7 b
	Significance[v]	NS	***	***	*
Field	C0.25m/T0.5m	58 ± 3.9	44 ± 4.5 ab	58	56 ± 5.4 a
	C0.5m/T0.5m	58 ± 9.2	26 ± 7.0 b	40	46 ± 4.0 b
	T0.5m/Tb0.5m	73 ± 8.2	56 ± 5.3 a	67	48 ± 6.5 ab
	T0.5m	81 ± 3.4	23 ± 7.5 b	36	41 ± 7.8 b
	Significance	NS	*	NS	*
2007	C0.25m/T0.5m	65 ± 2.3 b	43 ± 2.9 b	38 b	82 ± 3.3 a
Tunnel	C0.5 m/T0.5m	67 ± 3.0 b	50 ± 5.7 b	43 a	59 ± 1.2 b
	T0.5m/Tb0.5m	118 ± 4.5 a	99 ± 8.5 a	46 a	48 ± 5.1 b
	T0.5m	96 ± 3.5 a	53 ± 7.3 b	30 c	55 ± 3.2 b
	Significance	***	***	***	***
Field	C0.25m/T0.5m	69 ± 3.0 b	37 ± 2.1 b	36 c	87 ± 7.8
	C0.5m/T0.5m	60 ± 2.5 b	38 ± 3.2 b	44 b	80 ± 5.3
	T0.5m/Tb0.5m	99 ± 4.4 a	100 ± 9.2 a	55 a	69 ± 5.2
	T0.5m	82 ± 4.0 b	51 ± 4.5 b	35 c	73 ± 7.9
	Significance	*	***	***	NS

[z]C0.25m/T0.5m: all primocanes cut to the ground when 0.25 m tall, then later emerging primocanes soft-tipped at 0.5 m; C0.5m/T0.5m: all primocanes cut to the ground when 0.5 m tall, then later emerging primocanes soft-tipped at 0.5 m; T0.5m/Tb0.5m: all primocanes soft-tipped at 0.5 m tall, then subsequent lateral branches soft-tipped at 0.5 m long; and T0.5m; control: all primocanes soft-tipped at 0.5 m.

[y]Total number of nodes/cane (main cane + branches).

[x]Total flowers/cane.

[w]Number of canes per plot with evidence of fruiting.

[v]NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, within year and culture. Means followed by the same letter within year and culture are not significantly different ($P > 0.05$).

compared with other treatments (Fig. 1). In 2006, primocanes were significantly longer at bloom (1.4 m; $P \leq 0.001$) in control plants, T0.5m, than in the T0.5m/Tb0.5m and C0.25m/T0.5m treatments (1.2 m, on average). Primocanes that were managed as C0.5m/T0.5m were significantly shorter at bloom than any other treatment, averaging 0.98 m (data not shown). In 2007, there was no significant effect of treatment on primocane length at bloom, although trends were similar (data not shown).

Fruiting season and yield. The date of first fruit harvest was similar in the tunnel and field in 2006 and 2007; plastic was not placed on the tunnel until ≈1 to 2 weeks before the first harvest. The average date of the terminal fruit turning fully black, 14 Sept., and thus beginning harvest, was delayed ≈4 weeks in the C0.5m/T0.5m treatment ($P \leq 0.001$) compared with all other treatments (Fig. 1). In both years, yield was low for the first few harvests; treatment effects on yield became more apparent after this time (Fig. 2).

Tunnel protection extended fruit harvest by ≈3 weeks in both years. Thus, cumulative yield for all treatments, except the control in 2006 (T0.5m), was higher in the tunnel than in the open field (Table 2; Fig. 2). In the tunnel, cumulative yield was significantly higher in double-tipped primocanes (T0.5m/Tb0.5m) than all other treatments in both years. In 2006 and 2007, double-tipping primocanes in the tunnel increased yield by 267% and 159%, respectively, as compared with the control (Table 2). Although the cultural systems could not be compared statistically, cumulative yield for double-tipped primocanes was 47% less in the open field than in the tunnel, on average. Strik et al. (2008) reported that tipping primocanes at 1.0 m increased yield threefold and berry weight in 'Prime-Jan' and 'Prime-Jim' compared with untipped canes. They reported a yield of 5.7 $t \cdot ha^{-1}$ in 'Prime Jan' that was tipped at 1 m, but found that yield would have been much higher had harvest not been curtailed by rain in their open field study (Strik et al., 2008). In this study, tipping canes at 0.5 m (T0.5m; control) produced yields of 3 to 4 $t \cdot ha^{-1}$ in the open field. It is not known if tipping at 1 m would have produced a higher yield than tipping at 0.5 m.

In 2007, primocanes in the "cut" treatments (C0.25m/T0.5m and C0.5m/T0.5m) had the lowest yields in the tunnel and open field (Table 2). Plots that were managed as C0.5m/T0.5m produced primocanes that were significantly delayed in growth, flowering, and fruiting. Yields were also greatly reduced as a result of the shortened growing season, low light, and cool fall temperatures. Similar results have been reported in primocane-fruiting raspberry. In Portugal, Oliveira et al. (1996, 1998, 2004) found that cutting primocane-fruiting raspberries to the ground in July and August extended the harvest season to December and January, but low light and temperature limited yields. Biomass removal (cutting) of actively growing primocanes during the summer likely removed a large amount of soluble protein and carbohydrate photoassimilates in the whole plant system. Oliveira et al. (2007) found that primocanes of 'Autumn Bliss' that had been cut to the ground in late July (when ≈0.6 m tall) subsequently produced low yields yet high levels of reserves in the roots at the end of harvest in December. It is unclear whether these plants accumulated root reserves at the expense of fruiting. However, under growth-limiting conditions (low light, cool temperature), it is possible that the root system sink was stronger than the fruiting sink. Because cutting primocanes to the ground in the summer did not deplete carbohydrate reserves in 'Autumn Bliss', it remains a viable option for season extension in primocane-fruiting raspberry. The same may be true for primocane-fruiting blackberry. However, cutting canes to the ground at heights such as the C0.5m/T0.5m treatment used in our study would only be possible in warm climates or in a heated tunnel in cooler climates as a result of the long delay in growth and development.

Primocanes that were managed as C0.25m/T0.5m produced less yield in 2007 than in 2006 in the tunnel and field; all other treatments produced more fruit in 2007 than 2006,

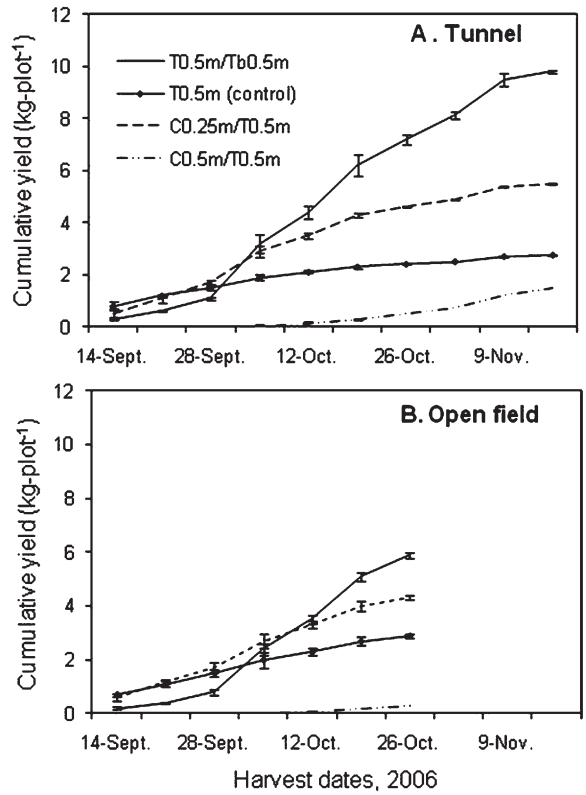

Fig. 2. Cumulative yield (kg/plot) of 'Prime-Jan' blackberry as affected by primocane pruning in the (**A**) tunnel and (**B**) open field, North Willamette Research and Extension Center, 2006 (n = 4).

Table 2. The effect of primocane pruning and tipping on yield and berry weight of 'Prime-Jan' blackberry grown in a tunnel or the open field at the North Willamette Research and Extension Center, 2006 to 2007 (n = 4; mean ± SE).

		Tunnel		Field	
Year	Treatment[z]	Yield (kg/plot)	Berry wt (g)	Yield (kg/plot)	Berry wt (g)
2006	C0.25m/T0.5m	5.4 ± 0.6 b	5.0 ± 0.1 b	4.3 ± 0.6 ab	3.4 ± 0.4 a
	C0.5m/T0.5m	1.5 ± 0.3 c	4.0 ± 0.5 c	0.3 ± 0.09 c	1.9 ± 0.5 b
	T0.5m/Tb0.5m	9.9 ± 1.2 a	6.8 ± 0.1 a	5.8 ± 1.0 a	4.1 ± 0.4 a
	T0.5m	2.7 ± 0.4 c	4.4 ± 0.2 bc	2.8 ± 0.5 b	3.1 ± 0.4 a
	Significance[y]	***	***	***	*
2007	C0.25m/T0.5m	4.4 ± 0.3 c	6.9 ± 0.1 c	2.0 ± 0.2 c	5.9 ± 0.3 b
	C0.5m/T0.5m	4.9 ± 0.5 c	7.5 ± 0.2 b	1.3 ± 0.1 c	5.7 ± 0.1 b
	T0.5m/Tb0.5m	17.9 ± 1.1 a	8.1 ± 0.9 a	8.4 ± 0.4 a	7.2 ± 0.1 a
	T0.5m	6.9 ± 0.5 b	6.5 ± 0.1 c	4.0 ± 0.5 b	5.9 ± 0.3 b
	Significance	***	***	***	**

[z]C0.25m/T0.5m: all primocanes cut to the ground when 0.25 m tall, then later emerging primocanes soft-tipped at 0.5 m; C0.5m/T0.5m: all primocanes cut to the ground when 0.5 m tall, then later emerging primocanes soft-tipped at 0.5 m; T0.5m/Tb0.5m: all primocanes soft-tipped at 0.5 m tall, then subsequent lateral branches soft-tipped at 0.5 m long; and T0.5m; control: all primocanes soft-tipped at 0.5 m.
[y]NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, within tunnel or field. Means followed by the same letter within year and culture are not significantly different ($P > 0.05$).

as expected with a more mature planting (Table 2). It is possible that perennial removal of biomass by cutting canes in mid-spring (26 Apr.; C.25m/T0.5m), soon after the first split application of fertilizer (average first application date 10 Apr.; average second application date 18 May for 2006 to 2007), may have negatively impacted regrowth, crown nutrient status, and subsequent fruit production in 2007. Plant nutrition, however, was not monitored. In contrast, plants that were cut to the ground in late spring (22 May; C0.5m/T0.5m) did not have lower yields in 2007. The second split -application of fertilizer, however, coincided well with primocane regrowth. Nonetheless, the trend for heavier berries in 2007 was consistent for all treatments (Table 2). In both years, plots that were managed as C0.25m/T0.5m produced the highest number of fruiting canes (Table 1). The number of nonfruiting canes was similar for all treatments, averaging three per plot for both years (data not shown). Cutting canes to the ground when they are relatively short is thus a method to increase cane number in primocane-fruiting blackberry but may not improve yield. Cutting canes to the ground, thus removing existing primocanes and forcing regrowth in the off-year, has been used successfully to increase cane number and subsequent yield in alternate year production systems of trailing blackberry (Bell et al., 1995).

Harvest in the open field ended on 28 Oct., on average, as a result of rain. In contrast, harvest in the covered tunnel continued until 16 Nov., on average (Figs. 1–3). However, even in the tunnel, fruit ripening began to slow (drupelets remained red) and overall quality began to decline with cool October and November temperatures and desiccating winds (drupelets on fruits became shriveled and sunken after wind events). The tunnel had no effect on canopy and soil temperature or RH (data not shown) because the ends and sides were open.

Fruit weight and chemistry. Primocanes that were double-tipped produced heavier fruit than other pruning treatments, 33% heavier than the control, on average (Table 2; Fig. 4). Berry weight in the tunnel averaged 6.8 g for 2006 and 2007; the average for the open field was 4.7 (Table 2). Although they cannot be compared statistically, the difference suggests that production in the tunnel may have led to increased berry weight. If this were the case, possible causes may include: plastic-induced light diffusion and an increase in subsequent photosynthetic activity within the plant canopy; a slightly higher RH in the fruiting zone; or slightly cooler fruit temperatures during the hottest part of the day (personal observation). We did not, however, detect a significant difference in RH, canopy temperature, or soil temperature (data not shown). It is possible that limiting the exposure of fruit to direct sunlight reduced berry temperature. We did not measure fruit temperature or evapotranspiration. It would be interesting to determine if photoselective shadecloth would produce similar results to those observed in our study.

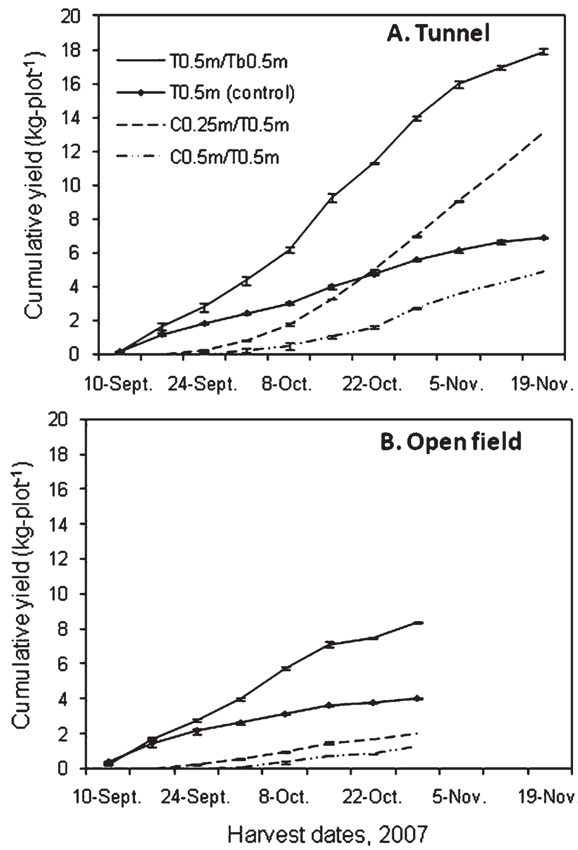

Fig. 3. Cumulative yield (kg/plot) of 'Prime-Jan' blackberry as affected by primocane pruning in the (**A**) tunnel and (**B**) open field, North Willamette Research and Extension Center, 2007 (n = 4).

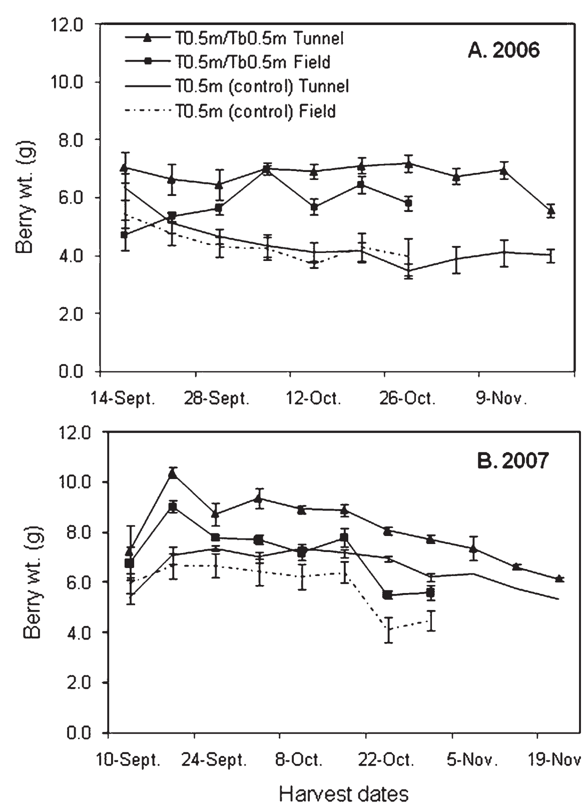

Fig. 4. The effect of double-tipping (T0.5m/Tb0.5m) or single-tipping primocanes at 0.5 m (T0.5m; control) on average berry weight of 'Prime-Jan' blackberry grown in the open field and tunnel in (**A**) 2006 and (**B**) 2007 at the North Willamette Research and Extension Center (mean ± SE).

In both years, counts of drupelets and unset ovules indicated that flowers on primocanes that were double-tipped did not have more ovules per flower but had significantly more drupelets set compared with those on tipped primocanes in the control (62 versus 48% set in 2006; 73 versus 63% set in 2007, respectively; Table 3). The higher drupelet set was likely the result of better pollination. Double-tipped plots had a greater concentration of flowers per plot with good uniformity among primocanes and thus attractive to pollinators (*Apis mellifera* L., *Bombus* spp. Latreille; personal observation). Of these species, the plastic covering the tunnel roof did not seem to inhibit pollinator flight or movement. In 2006, primocanes from both tipping treatments tended to have slightly more ovules in the early harvest season but a lower percentage of drupelets set in the late harvest season (Table 3). In contrast, early-season berries on double-tipped canes in 2007 had a higher percentage of drupelets set than late-season berries; percent drupelet set was fairly consistent throughout the 2007 harvest season in treatments that were tipped once at 0.5 m (control; Table 3). This occurrence of more ovules per flower early in the season is perhaps because the first, and often largest, flowers develop on the apices of the primary and secondary floral axes, as described in Thompson et al. (2007). This has also been reported by Strik et al. (1996) in other blackberry genotypes. Thus, berry weight is generally greater in the early harvest season and declines over time as fruits on tertiary and quaternary axes ripen. Berry weight declined in all treatments as the harvest season progressed in both years (Fig. 4). Furthermore, ovule viability and receptivity to pollen grains has been shown to decline with exposure to high temperatures (29 to 35 °C; Stanton et al., 2007). Drake and Clark (2003) reported that bloom time temperatures of 36 °C resulted in small, crumbly fruit from tipped treatments in 'Prime-Jan' and 'Prime-Jim'. Higher temperatures in the early harvest season (27 to 32 °C in 2006 and 2007) may have thus reduced ovule and/or pollen viability and ovule receptivity in flowers that were open when fruit collection began; all treatments had open flowers on tertiary and quaternary axes when harvest began.

Harvest date affected fruit pH in 2006, but not in 2007 (Table 4). In 2006, fruit pH was highest in the early season compared with mid- and late-season harvests. Presence of plastic on the tunnel did not appear to affect fruit chemistry other than possibly pH, which tended to be higher in the open field, although this could not be analyzed statistically (Table 4). In 2006, measurements of *PAR* were less under the tunnel than the open field on all sampling dates, by 31% on average, but this did not appear to affect berry chemistry.

Table 3. The average number of total drupelets, total ovules, and percent drupelet set of fruit from T0.5m/Tb0.5m (double-tipped) and T0.5m (control) treatments of 'Prime-Jan' blackberry from an early (21 Sept. 2006; 24 Sept. 2007) and late harvest (19 Oct. 2006; 22 Oct. 2007) in the tunnel and field combined (n = 10 in 2006; n = 5 in 2007).

Year/season	Treatment[z]	Total drupelets[y]	Total ovules[x]	Drupelet set (%)
2006	T0.5m/Tb0.5m	412 ± 10	799 ± 15	52 ± 1.1
Early	T0.5m	275 ± 13	661 ± 34	42 ± 2.8
Late	T0.5m/Tb0.5m	405 ± 12	557 ± 12	73 ± 1.7
	T0.5m	310 ± 14	583 ± 22	54 ± 2.7
Significance[w]		NS	***	NS
2007	T0.5m/Tb0.5m	474 ± 16	602 ± 16	79 ± 2.4
Early	T0.5m	390 ± 17	639 ± 17	61 ± 2.2
Late	T0.5m/Tb0.5m	403 ± 14	602 ± 15	67 ± 1.6
	T0.5m	367 ± 21	558 ± 18	65 ± 2.0
Significance		NS	NS	***

[z]C0.25m/T0.5m: all primocanes cut to the ground when 0.25 m tall, then later emerging primocanes soft-tipped at 0.5 m; C0.5m/T0.5m: all primocanes cut to the ground when 0.5 m tall, then later emerging primocanes soft-tipped at 0.5 m; T0.5m/Tb0.5m: all primocanes soft-tipped at 0.5 m tall, then subsequent lateral branches soft-tipped at 0.5 m long; and T0.5m; control: all primocanes soft-tipped at 0.5 m.
[y]Only fully sized drupelets were counted.
[x]Total counted as fertilized and unfertilized ovules.
[w]NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. The effect of harvest season on berry chemistry of 'Prime Jan' blackberry grown in a tunnel or open field at the North Willamette Research and Extension Center, 2006 to 2007 [n = 9 for pH and total soluble solids (TSS) in 2006; n = 3 for pH and TSS in 2007; n = 3 for titratable acidity in 2006 to 2007; n = 2 for total anthocyanins (TACY) and total phenolics in 2006 to 2007; mean ± SE].

Year	Culture[z]	Season[y]	pH	TACY[x] (mg/100 g)	Total phenolics (mg/100 g)[w]	TSS (%)	Titratable acidity (g/100 g)[v]
2006	Tunnel	Early	3.44 ± 0.07 a	256 ± 28.2	698 ± 112.8	11.7 ± 0.6	1.12 ± 0.02
		Mid	2.94 ± 0.05 b	225 ± 0.48	753 ± 18.1	11.3 ± 0.9	1.19 ± 0.05
		Late	3.07 ± 0.03 b	192 ± 21.7	690 ± 9.9	10.1 ± 0.4	1.38 ± 0.07
Significance			***	NS	NS	NS	NS
2006	Field	Early	3.44 ± 0.03 a	267 ± 6.03 a	677 ± 43.7	12.4 ± 0.5	1.24 ± 0.19
		Mid	3.05 ± 0.00 c	192 ± 18.4	733 ± 35.6	12.5 ± 0.6	1.28 ± 0.16
		Late	3.23 ± 0.03 b	179 ± 0.47	691 ± 1.7	10.4 ± 0.6	1.38 ± 0.04
Significance[u]			***	NS	NS	NS	NS
2007	Tunnel	Early	2.95 ± 0.08	242 ± 19.7	647 ± 63.0	9.4 ± 0.5	1.16 ± 0.13
		Late	2.91 ± 0.02	220 ± 19.5	658 ± 3.9	9.2 ± 0.2	1.41 ± 0.10
Significance			NS	NS	NS	NS	NS
2007	Field	Early	3.25 ± 0.07	183 ± 12.0	559 ± 46.4	8.8 ± 0.3	1.23 ± 0.06
		Late	3.09 ± 0.03	200 ± 9.5	619 ± 43.9	8.9 ± 0.1	1.30 ± 0.03
Significance			NS	NS	NS	NS	NS

[z]Plastic was placed on the top of the tunnel on 5 Sept. 2006 and 31 Aug. 2007, 1 to 2 weeks before first harvest.
[y]Fruit were collected for chemical evaluations on "early" (21 Sept.), "mid" (12 Oct.), and "late" season (2 Nov.) harvests in 2006 and "early" (2 Oct.) and "late" season (6 Nov.) harvests in 2007.
[x]Total anthocyanins expressed as milligrams of cyanidin-3-glucoside per 100 g fresh weight (FW).
[w]Total phenolics expressed as milligrams of gallic acid equivalents (GAE) per 100 g FW.
[v]Titratable acidity expressed as equivalent weight (EW) of anhydrous citric acid in g per 100 g FW.
[u]NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively, within tunnel or open field.

Summary

Using a tunnel to extend the fruiting season for 'Prime-Jan' is feasible in a mild climate like that of western Oregon. Primocanes that were double-tipped responded most favorably in terms of growth, time of harvest, and yield with an unheated tunnel in our climate. The pruning systems used here increased yield and offered options for season extension, particularly in warmer climates or in cooler climates with heated tunnels/greenhouses. Double-tipping 'Prime-Jan', in combination with protected culture, increased yield by 267% and 159% compared with soft-tipping once at 0.5 m (control) in 2006 and 2007, respectively. Double-tipped primocanes produced the highest yields during late September and early October, well within our objectives for target harvest dates. However, the labor costs of double-tipping would have to be weighed against the possible increased yields.

Levels of TACY, TSS, total phenolics, and pH tended to decline as the harvest season progressed in both the tunnel and open field systems. Differences between the cultural systems were not able to be analyzed, however.

The positive effect on yield, berry weight, and season extension found in our study may make tunnel production an economically viable option for growers in mild climates. However, economic analysis is necessary, because managing tunnel plastic placement, removal, and venting during wind events is labor-intensive.

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