High Tunnel and Open Field Production of Floricane- and Primocane-fruiting Raspberry Cultivars

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SUMMARY. Identical trials were conducted in a multibay high tunnel and an adjacent open field in southwestern Michigan to compare primocane-fruiting cultivars (Autumn Britten, Caroline, Chinook, Heritage) and floricanes-fruiting cultivars (Canby, Encore, Heritage, Nova) of red raspberry (*Rubus idaeus*). Floricane-fruiting plots of 'Heritage' were pruned to produce fruit on floricanes and primocanes (double cropping). The most productive cultivars in both environments were 'Nova' and 'Canby' (floricane) and 'Caroline' and 'Heritage' (primocane). These cultivars produced annual yields of 5.5 kg·m⁻¹ row in the tunnel and 2.5 kg·m⁻¹ row in the field. The order of primocane harvest (earliest to latest) was the same in the tunnel and field: 'Autumn Britten', 'Caroline', 'Chinook', and 'Heritage'. Cultivars with the greatest average berry weight in the tunnel and field were Encore and Nova (floricane) and Autumn Britten and Caroline (primocane). 'Chinook' and 'Autumn Britten' tended to have the highest incidence of gray mold (*Botrytis cinerea*) of primocane-fruiting cultivars, but incidence was similar in floricanes cultivars. Overall mold incidence was 1% in the tunnel and 13% in the field. Leaf spot (*Sphaerulina rubi*), cane anthracnose (*Elsinoe veneta*), spur blight (*Didymella applanata*), and botrytis cane blight (*B. cinerea*) were common in the field but absent in tunnel. Phytonutritional analyses of primocane fruit indicated that genotype differences were not consistent across the two environments. Relative cultivar characteristics (harvest season, yield, berry quality) were similar in the field and tunnels, but the tunnel environment tended to increase plant vigor, yield, and fruit quality and suppress several diseases.

Per capita consumption of fresh raspberries is increasing in the United States [U.S. Department of Agriculture (USDA), 2010], but nearly all of the new production to meet demand occurred in coastal areas of California (Gaskell, 2004; Pollack and Perez, 2006). Raspberries are grown in all midwestern and northeastern U.S. states, but in contrast to California producers, growers in these states tend to manage just a few acres and market directly to consumers rather than shipping longer distances. Producing consistent raspberry volumes and quality for wholesale marketing is difficult in midwestern and

eastern states because growing seasons are shorter and winters are colder than in coastal California locations. Frequent summer rains and high humidity also promote fruit rots and reduce raspberry shelf life.

High tunnels are plastic-covered, unheated greenhouses that may benefit raspberries in the midwestern and northeastern U.S. states. Tunnels vary in design from less expensive ranges of interconnected bays that may cover multiple acres to more sturdy and

expensive stand-alone structures (Giacomelli, 2009; Lamont, 2009). In snow prone regions, multiple-bay tunnels are referred to as three-season tunnels because they can be damaged by snow and need to be uncovered during the winter. Multiple-bay high tunnels have been widely adopted for fresh raspberry production in California because they improve fruit quality by moderating the environment and excluding rain and by extending the harvest seasons to periods when prices are higher (Gaskell, 2004). Tunnels provided similar benefits for primocane-fruiting blackberry (*Rubus* spp.) in Oregon (Thompson et al., 2009).

Primocane-fruiting raspberry in stand-alone tunnels in Pennsylvania produced higher yields with less gray mold and earlier maturation times than was typical for field-grown plants (Demchak, 2009). Stand-alone tunnels appear profitable for fresh raspberries (Heidenreich et al., 2007), but three-season, multibay structures may provide similar benefits at lower cost. The cost per unit surface area of four-season tunnels, such as those designed at The Pennsylvania State University (Lamont et al., 2002), is typically two to three times more than three-season, multibay structures. All tunnels are expensive investments, and potential growers in eastern U.S. states need more information on expected benefits and basic management options such as cultivar selection. The purpose of this study was to compare the production periods, yields, and fruit quality of raspberry cultivars in the open field and in three-season tunnels and describe the general effects of the tunnel environment on disease incidence.

Materials and methods

EXPERIMENTAL DESIGN, CULTIVARS, AND PLOT MAINTENANCE. Identical trials were planted in the open

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1.1209	lb/acre	kg·ha ⁻¹	0.8922
1.4882	lb/ft	kg·m ⁻¹	0.6720
28.3495	oz	g	0.0353
0.001	ppm	mg·g ⁻¹	1000
1	ppm	µg·g ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

field and in an adjacent high tunnel in Apr. 2005 at the Southwest Michigan Research and Extension Center in Benton Harbor, MI (lat. 42.1°N, long. 86.4°W). The site was on a hill with a gentle slope for air flow and was within the USDA Hardiness Zone 6a (Cathey, 1990). The soil was Spinks loamy fine sand (sandy, mixed, mesic Lamellic Hapludalfs). The tunnel and field plantings were not replicated because of lack of space. Rows in the field trial ran east to west and were 10 ft apart. The tunnel trial was under an interior bay of an eight interconnected bay high tunnel range (Haygrove Tunnels, Redbank, Ledbury, UK) just south of the field planting. The tunnel bay was 200 × 24 ft and 14 ft tall at the peak, with 5-ft-tall vertical sides. Tunnel rows were 8 ft apart. The tunnel was oriented from north to south and was covered with Luminance THB polyethylene (BPI Visqueen Horticultural Products, Stockton-on-Tees, UK). Plastic was installed in late June 2005, early May 2006, late Apr. 2007 and 2008 and removed each year in early November. The tunnel sides and ends were enclosed with plastic for the last 3 weeks of the fall season to retain heat. The rest of the year, the sides of the tunnels remained open.

Each trial contained primocane-fruited cultivars (Autumn Britten, Caroline, Chinook, Heritage) and floricanefruited cultivars (Canby, Encore, Heritage, Nova). Plots were single, 12-ft-long rows. Cultivars were replicated three times in a randomized complete block design, with each block consisting of a row. The experimental area of the field trial was surrounded by buffer rows and 6 ft of buffer plants ('Heritage') on the ends of all rows. Buffer plants were grown on the ends of the rows in the tunnel trial. Plots were managed as a hedgerow. Primocane-fruited plots were pruned to the ground in March and fruited only on primocanes. Floricanefruited plots were pruned in March by retaining the largest five to seven canes per linear foot of row and by removing floricanes after fruiting in August. The floricanefruited plots of Heritage produced berries on floricanes and primocanes (double cropping). Plants were supported by a 6-ft-tall trellis constructed of steel conduit positioned 1.5 ft apart and two to four strands of twine at varying heights to confine canes as they grew.

Weeds within the rows of the field planting were controlled by applications of oryzalin (Surflan A.S.; United Phosphorus, King of Prussia, PA) in April and by hand-weeding. Weeds in the tunnel were removed by hand or hoeing. The tunnel plots were sprayed with bifenazate (Acrامة 50WS; Chemtura, Middlebury, CT) in Aug. 2008 to control spider mites (*Tetranychus urticae*), but no other pesticides were applied. The field planting was sprayed in Aug. 2008 with carbaryl (Sevin XLR; Bayer CropScience, Research Triangle Park, NC) to control Japanese beetle (*Papillia japonica*). Plots were watered daily with a single trickle irrigation line per row at the equivalent of 0.25 inch water per day in 2005–06. A second irrigation line was added to the tunnel rows in 2007 so that these plots received 0.5 inch water per day in 2007–08. Irrigation generally began in May or June and concluded in early October. Irrigation of the field planting was altered based on rain events and general soil moisture observations. Total irrigation amounts in the tunnel and field were not recorded. Field-grown plants received 60 kg·ha⁻¹ nitrogen (N) (2005) or 80 kg·ha⁻¹ N (2006–08) applied as ammonium nitrate (32N–0P–0K) in two applications (May and June 2005, April and June 2006–08), plus 40 kg·ha⁻¹ potassium (K) each year as potassium sulfate (0N–0P–42K). Tunnel plants were fertilized with a soluble fertilizer (8N–0P–6.6K) injected through the irrigation system from the middle of May to August of each year. Rates varied from 5 to 8 kg·ha⁻¹ N per week or ≈100–140 kg·ha⁻¹ N per season, depending on irrigation requirements.

BERRY YIELD, SIZE, AND HARVEST TIMES. Berry yields and average weights were measured from 2005 to 2007 (primocane) and from 2006 to 2008 (floricane). Plots of 'Heritage' that were pruned for floricane fruit production were also harvested in the fall, as were plots of the floricane-fruited cultivar Nova, which produced modest primocane yields. Fruit were picked by hand every 3 to 6 d, and total weight and weight per 50 berries were recorded. To describe the relative harvest dates of cultivars, the day of the year (after 1 Jan.) was determined when 5% and 95% of the total yield was reached for each plot.

GRAY MOLD. Half-pint samples were retained on dates when sufficient fruit was available from at least one of the replicate plots of each cultivar. A replicate consisted of a set of samples collected from a plot of each cultivar in the tunnel and field. The number of sampling dates and total replicate samples varied each year. For floricane-fruited cultivars, 14 replicate samples were collected over five dates in 2007 and nine replicates were collected over three dates in 2008. For primocane-fruited cultivars, there were five dates and eight replicates in 2006 and six dates and 13 replicates in 2007. Samples were placed in half-pint clamshell containers enclosed in sealed black plastic bags and held for 1–2 d in a 2 °C cold room. Samples were then held at 18 °C until mold started to appear (usually after 12–36 h) and then sorted and counted to determine the percentage with visible mold.

BERRY PHYTONUTRIENT CONTENT. In 2007 and 2008, 200 g of ripe primocane fruit from 'Heritage', 'Autumn Britten', and 'Caroline' were collected and immediately frozen at –20 °C, and later freeze dried (Model 8 Freeze Drier; Labconco, Kansas City, MO) while still frozen. Samples were hand-pulverized, and seeds were removed from drupe tissue using an 80-mesh (0.18 mm) sieve. Duplicate 0.5-g aliquots of the finely powdered raspberry "flour" were extracted with 40 mL of extraction buffer containing acetone, water, and acetic acid (70:29.5:0.5 v/v/v, respectively) for 1 h (Singleton and Rossi, 1965) and then centrifuged for 20 min at 7798 g_n. Supernatants were suction-filtered through qualitative filter paper to remove fine particles, concentrated under partial vacuum via rotary evaporation at 40 °C to remove acetone and acetic acid, and brought to volume with distilled deionized water. The resulting extracts were analyzed in duplicate for total soluble phenolic contents (TP), total monomeric anthocyanin (TMA) levels, antioxidant capacities (AOXs) by the ferric-reducing ability of plasma (FRAP), and the 2,2-azino-bis 3 ethylbenzothiazoline-6-sulfonic acid (ABTS) procedures as specified by Singleton et al. (1999), Giusti and Wrolstad (2005), Benzie and Strain (1996), and Ozgen et al. (2006), respectively. Assay values were determined spectrophotometrically; sample absorbances for TP and AOXs were compared with those of standard

curves prepared for gallic acid or Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), respectively. Anthocyanin levels were calculated using the molar absorptivity (ϵ) and molecular weight (MW) of cyanidin 3-sophoroside ($\epsilon = 30,900$, MW = 611.2).

VEGETATIVE GROWTH, PLANT NUTRITION, AND DISEASE SEVERITY. Cane height and leaf node number were recorded on 10 randomly chosen primocanes in primocane-fruiting plots after they had begun flowering and ceased elongating in Aug. 2007. The same measurements were made on five randomly selected canes in floricanes-fruiting plots in Dec. 2008.

Plant nutrient levels were measured in July 2008 by collecting a composite sample of 20 fully expanded leaves from the middle of primocanes from each block (across all cultivars). Tissues were oven dried at 40 °C and ground with a Wiley mill to pass a 40-mesh (0.36 mm) screen and analyzed for total N colorimetrically following a Kjeldahl digestion (Bradstreet, 1965) using a QuikChem 8500 Autoanalyzer (Lachat Instruments, Milwaukee, WI). For other nutrient elements, tissues were ashed in a muffle furnace (Thermolyne model 30400; Thermo Fisher Scientific, Waltham, MA) at 500 °C for 6 h. The ash was dissolved in 1 N nitric acid and analyzed by direct current plasma emission spectrophotometry (Beckman Instruments, Fullerton, CA).

Disease severity was assessed in late Aug. 2007 and late Sept. 2008 on 20 canes per plot. The percentage of leaf area with raspberry leaf spot lesions and the percent of total cane area covered by anthracnose lesions were recorded. Incidence of spur blight and botrytis cane blight were assessed as percent of canes that had one or more lesions. Severity of powdery mildew was recorded as percent of the total leaf area covered by colonies. An automated weather station located on site recorded rainfall with a rainfall sensor (Rain Gauge Tipping Bucket TR-525; Texas Electronics, Dallas, TX).

STATISTICAL ANALYSES. Since tunnel and field plantings were not replicated, data were analyzed as separate studies that could not be compared statistically. Within each study, yield, average berry weight, phytonutrient data, cane height, and foliar disease data were analyzed by analysis of variance (ANOVA), and means were

separated by Fisher's protected least significant difference (LSD) test at $P \leq 0.05$ (SAS version 9.1; SAS Institute, Cary, NC). Data were transformed as needed before the ANOVA. Yield, average berry weight, and harvest time data were analyzed using years as repeated measures. Gray mold percentage data were also analyzed using harvest date as a repeated measurement factor, with data from each year analyzed separately because of unequal replication numbers, using the PROC MIXED procedure in SAS. Comparisons between cultivars were conducted using only data collected from common harvest dates. Disease incidence and severity data were analyzed by ANOVA followed by mean separation (Fisher's protected LSD at $P \leq 0.05$) using the StatGraphics program (StatPoint Technologies, Warrenton, VA). Data were also checked for equality of variance and, if needed, transformed before ANOVA.

Results and discussion

BERRY YIELD, SIZE, AND HARVEST TIMES. 'Caroline' and 'Heritage' produced the highest yields of primocane fruit in the field and tunnel (Fig. 1). 'Heritage' plots that were pruned to the ground so that they produced only primocane fruit yielded similar amounts of fall berries as 'Heritage' pruned for double cropping. 'Nova', which fruits primarily on floricanes, produced a small amount of primocane fruit in the fall. 'Nova' and 'Canby' produced the highest yields of floricanes fruit in the tunnel, and 'Nova' was the most productive in the field (Fig. 2). 'Heritage' pruned for double cropping produced the lowest floricanes yields in the tunnel and was among the least productive in the field (Fig. 2).

When 'Caroline' and 'Heritage' were in full production in 2006 and 2007, yields averaged 5.4 kg·m⁻¹ row in the tunnel and 2.8 kg·m⁻¹ row in the field. Since rows were spaced closer in the tunnel (8 ft) than in the field (10 ft), these yields were equivalent to 22,030 and 9016 kg·ha⁻¹ in the tunnel and field, respectively. 'Heritage' produced comparable yields in a four-season tunnel (Demchak, 2009), whereas the field yields were similar to those of productive cultivars in an earlier field trial in southwestern Michigan (Hanson et al., 2005). During 2007 and 2008, the two most productive floricanes-fruiting cultivars,

Fig. 1. Primocane fruit yields from raspberry cultivars grown in an open field and high tunnel in Benton Harbor, MI (2005–07). Lower case and upper case letters separate means of cultivars within the field and tunnel, respectively, via Fisher's protected least significant difference test at $P \leq 0.05$. Letters within bars separate means for individual years, whereas letters above bars separate means for 3-year total yields; 1 kg·m⁻¹ = 0.6720 lb/ft.

Fig. 2. Floricanes fruit yields from raspberry cultivars grown in an open field and high tunnel in Benton Harbor, MI (2006–08). Lower case and upper case letters separate means of cultivars within the field and tunnel, respectively, via Fisher's protected least significant difference test at $P \leq 0.05$. Letters within bars separate means for individual years, whereas letters above bars separate means for 3-year total yields; 1 kg·m⁻¹ = 0.6720 lb/ft.

Nova and Canby, produced an average of 5.7 kg·m⁻¹ row (23,140 kg·ha⁻¹) in the tunnel and 2.2 kg·m⁻¹ row (7260 kg·ha⁻¹) in the field. Thompson et al. (2009) reported that primocane-fruiting blackberry

yields were twice as high in a tunnel as in the field.

Yield differences between the tunnel and field plantings need to be considered observational since space limitations prevented us from replicating the tunnel and field environments. It is also important to note that key production practices (plant spacing, irrigation, fertilization) differed between the field and tunnel plantings, and these may also have affected plant performance. Although tunnel and field yields could not be statistically compared in this or previous similar studies (Demchak, 2009; Thompson et al., 2009), yields from tunnels have numerically been much higher than typical field production levels.

‘Encore’ and ‘Nova’ produced heavier fruit than ‘Canby’ or ‘Heritage’ in the tunnel and field (Table 1), whereas ‘Autumn Britten’ and ‘Caroline’ produced the heaviest primocane fruit in both environments (Table 1).

‘Autumn Britten’ produced the earliest primocane fruit, followed by ‘Caroline’, ‘Chinook’, and ‘Heritage’ (Table 2). The order of primocane fruit maturity was the same in the tunnel and field, but tunnel harvest began ≈1 week earlier than in the field. Based on the date of 95% harvest, ‘Autumn Britten’ and ‘Chinook’ concluded harvest earlier than ‘Caroline’ or ‘Heritage’ in the field, and ‘Autumn Britten’, ‘Caroline’, and ‘Chinook’ concluded harvest earliest in the tunnel. Primocane fruit harvest continued ≈1 week later in the tunnel than the field.

‘Canby’ and ‘Nova’ produced the earliest floricanes, and ‘Heritage’ fruit matured the latest. Harvest of floricanes-fruiting cultivars occurred in roughly the same order in the field and tunnel, but tunnel plants fruited several days longer than those in the field.

Tunnel plastic was installed each year between late April and late June. Earlier installation may hasten harvest, but also increase the risk of tunnel damage from snow accumulation and cold injury to canes. Raspberries in four-season tunnels in Pennsylvania began fruiting 3–4 weeks earlier than field plants and continued 3–4 weeks longer in the fall (Demchak, 2009). In the present study, 2–3 weeks separated the end of floricanes fruiting and the beginning of primocane fruiting.

Table 1. Mean berry weight of floricanes and primocane fruit from red raspberry cultivars grown in a high tunnel and open field for 3 years in Benton Harbor, MI.

Cultivar	Mean berry wt (g) ^z					
	Yr 1		Yr 2		Yr 3	
	Tunnel	Field	Tunnel	Field	Tunnel	Field
<i>Floricanes fruit</i>						
Canby	2.2 ab ^y	1.9 a	2.8 a	2.3 a	3.1 a	2.5 a
Encore	3.5 c	2.6 b	5.1 c	4.0 c	5.2 b	3.7 b
Heritage	1.8 a	1.5 a	2.4 a	1.8 a	2.7 a	2.1 a
Nova	3.0 bc	2.5 b	4.1 b	3.2 b	4.6 b	4.0 b
<i>Primocane fruit</i>						
Autumn Britten	2.8 b ^y	2.3 b	2.7 cd	2.6 b	2.9 ab	3.0 c
Caroline	2.5 b	1.9 b	2.5 bc	2.2 ab	3.0 ab	2.9 bc
Chinook	2.2 a	1.9 a	2.1 ab	1.5 ab	2.4 a	2.0 a
Heritage (fall cropped) ^x	2.1 a	1.6 a	2.2 a	1.9 a	2.5 a	2.3 ab
Heritage (double cropped) ^x	2.2 a	1.5 a	2.2 ab	1.8 a	2.4 a	2.3 a
Nova	—	—	3.1 d	2.3 b	3.2 c	3.9 d

^zDates are means of 2007–09 (floricanes fruit) and 2006–08 (primocane fruit); 1 g = 0.0353 oz.

^yMeans within columns and each fruit type (floricanes or primocane) followed by the same letter are not significantly different by Fisher’s protected least significant difference test at $P \leq 0.05$.

^xAll canes pruned to the ground each spring. In “double-cropped” plots, floricanes were retained for summer production in addition to fall production on primocanes.

Table 2. Dates for floricanes and primocane fruit harvest from red raspberry cultivars grown in a high tunnel and open field in Benton Harbor, MI.

Cultivar	Dates when total fruit harvest reached			
	5% of total		95% of total	
	Tunnel	Field	Tunnel	Field
<i>Floricanes fruit</i> ^z				
Canby	27 June a ^y	27 June ab	20 July a	15 July a
Encore	3 July b	1 July b	25 July b	18 July a
Heritage	7 July c	6 July c	21 July a	18 July a
Nova	28 June a	26 June a	22 July ab	15 July a
<i>Primocane fruit</i> ^z				
Autumn Britten	13 Aug. a	21 Aug. a	19 Oct. ab	6 Oct. a
Caroline	22 Aug. b	28 Aug. b	19 Oct. ab	18 Oct. b
Chinook	23 Aug. bc	2 Sept. bc	18 Oct. a	11 Oct. ab
Heritage (fall cropped) ^x	27 Aug. bc	5 Sept. c	23 Oct. b	12 Oct. b
Heritage (double cropped) ^x	25 Aug. c	5 Sept. c	23 Oct. b	13 Oct. b

^zDates are means of 2007 and 2008 (floricanes fruit) and 2006 and 2007 (primocane fruit).

^yMeans within columns and each fruit type (floricanes or primocane) followed by the same letter are not significantly different by Fisher’s protected least significant difference test at $P \leq 0.05$.

^xAll canes pruned to the ground each spring on fall cropped plants. In “double-cropped” plots, floricanes were retained for summer production in addition to fall production on primocanes.

Growers could potentially shorten or eliminate this period by staggering plastic installation dates (Meesters and Pitsisoudis, 1999). The vertical sides and ends of the tunnel were covered with plastic in mid-October to retain heat but this only extended primocane fruit harvest into early November, ≈1 week later than in the field. Fall production appeared to conclude because of cold night temperatures and shortening days.

GRAY MOLD. Floricanes-fruiting cultivars did not differ in mold

incidence, except in 2007 when the incidence was higher on ‘Nova’ than ‘Canby’ or ‘Heritage’ in the field trial (Table 3). ‘Chinook’ had a higher rot incidence on primocane fruit than other cultivars in the field trial in 2006 and higher than ‘Caroline’ and ‘Heritage’ in the tunnel (Table 3). In 2007, ‘Autumn Britten’ had a higher mold incidence than other cultivars in the field trial only (Table 3). Not all primocane-fruiting cultivars were evaluated for fruit rot each year. ‘Heritage’ that was pruned for floricanes and

primocane fruiting was not evaluated in 2006, and 'Chinook' was omitted in 2007 because fruit numbers were inadequate.

Although the field and tunnel trials could not be compared statistically, mold incidence on primocane fruit across all cultivars and years was 1.4% in the tunnel and 13.5% in the field. Similar trends were seen in floricanes-fruiting cultivars in this and an earlier study (Demchak, 2009). Low rot incidence likely resulted from the exclusion of rain since fruit infection by *B. cinerea* requires a water film (Jarvis, 1962). Tunnel fruit remained dry except perhaps some fruit near the sides and ends that may have been exposed to wind-blown rain. For comparative reasons, no fungicides were applied in either trial. Mold incidence in the field trial could likely have been lowered by fungicide use.

BERRY PHYTONUTRIENT CONTENT. Cultivars did not differ significantly in TP levels in either environment over 2 years. Overall means in 2007 and 2008 were 22.9 and 20.3 mg·g⁻¹ dry weight for field-grown raspberries, respectively, and 20.3 and 19.0 mg·g⁻¹ for tunnel-grown raspberries. Anthocyanin levels were unaffected by cultivar in 2007 (Table 4). In 2008, anthocyanin levels were higher in 'Caroline' fruit from the field than 'Heritage' or 'Autumn Britten', but cultivars in the tunnel did not differ. Cultivars differed in the two assays of AOX (FRAP, ABTS) in 2008 (Table 4), but not in 2007 (data not shown). In 2008, statistical patterns among means differed between trials and assay method (FRAP, ABTS). Because of unique structure-activity relationships between individual antioxidant compounds and assay reagents, assay methods often differ in their estimates of AOX (Ozgen et al., 2006). 'Caroline' and 'Heritage' tended to have higher AOXs than 'Autumn Britten', which was consistent with results of a study from Ohio production sites, where total anthocyanin values of 'Heritage' and 'Caroline' also exceeded those of 'Autumn Britten' (J.C. Scheerens, unpublished data). In contrast, Cheplick et al. (2007) reported that TP content and ABTS AOX were higher in 'Autumn Britten' than three other cultivars. Phytonutrient values in this study were similar to previous reports for red raspberries (e.g., Anttonen and Karjalainen,

Table 3. Botrytis mold incidence in floricanes (2007, 2008) and primocane (2006, 2007) fruit from raspberry cultivars grown in a high tunnel and open field in Benton Harbor, MI. Fruit were held for 2–4 d to simulate commercial storage.

Cultivar	Mold incidence (%)			
	Yr 1		Yr 2	
	Tunnel	Field	Tunnel	Field
<i>Floricanes fruit</i>				
Canby	0.0 a ^z	2.1 a	3.7 a	19.9 a
Encore	0.0 a	4.0 a	2.3 a	30.0 ab
Heritage	0.0 a	1.2 a	2.1 a	20.2 a
Nova	0.0 a	4.3 a	3.0 a	40.9 b
<i>Primocane fruit</i>				
Autumn Britten	0.5 ab	6.3 a	2.7 a	14.2 b
Caroline	0.3 a	6.7 a	1.4 a	4.3 a
Chinook	0.6 b	17.2 b	— ^y	— ^y
Heritage (fall cropped) ^y	0.3 a	4.4 a	3.2 a	8.5 a
Heritage (double cropped) ^y	— ^x	— ^x	3.3 a	7.0 a

^zMeans within columns and each fruit type (floricanes, primocane) followed by the same letter are not significantly different by Fisher's protected least significant difference test at $P \leq 0.05$.

^yAll canes pruned to the ground each spring. "Double-cropped" plots were pruned by retaining floricanes for summer production in addition to fall production on primocanes.

^x'Heritage' plots pruned for floricanes fruiting were not included in shelf life comparisons in Year 1 (2006). 'Chinook' fruit were not included in Year 2 (2007) because of limited berry numbers.

Table 4. Anthocyanin and ferric-reducing ability of plasma (FRAP) and the 2,2-azino-bis 3 ethylbenzothiazoline-6-sulfonic acid (ABTS) antioxidant capacity in primocane fruit of three raspberry cultivars grown in a high tunnel and open field in Benton Harbor, MI, 2008.

Cultivar	Anthocyanin		FRAP		ABTS	
	[Trolox equivalents (μmol·g ⁻¹ dry wt)] ^z		[Trolox equivalents (μmol·g ⁻¹ dry wt)] ^y		[Trolox equivalents (μmol·g ⁻¹ dry wt)] ^y	
	Tunnel	Field	Tunnel	Field	Tunnel	Field
Autumn Britten	4.1 a ^x	4.5 b	180 b	237 b	273 c	339 ab
Caroline	4.5 a	6.0 a	276 a	320 a	315 b	381 a
Heritage	5.0 a	4.7 b	259 a	246 b	339 a	292 b

^zValues are based on the molar absorptivity (ε) and molecular weight (MW) of cyanidin 3-sophoroside (ε = 30,900, MW = 611.2).

^yValues represent Trolox equivalents based on a standard trolox curve; 1 μg·g⁻¹ = 1 ppm.

^xMeans ($n = 6$) within columns followed by the same letter are not significantly different by Fisher's protected least significant difference test at $P \leq 0.05$.

2005; Liu et al., 2002; Wada and Ou, 2002; Wang and Lin, 2000; Wu et al., 2004).

Results suggest that phytonutrient values of red raspberries are affected by the interaction of genotype and environment, as was reported by others (Anttonen and Karjalainen, 2005; Connor et al., 2005a, 2005b). For example, total anthocyanins and AOXs (FRAP and ABTS) were always highest in field-grown 'Autumn Britten' and 'Caroline', whereas 'Heritage' berries were highest in the tunnel (Table 4). Total anthocyanins and AOXs in both tunnel and field samples were also numerically higher in 2008 than 2007. Environmental conditions around fruit and perhaps phytonutrient levels can be modified by tunnel covering

dates, venting practices, and selection of plastic film type. Films varying in ultraviolet light transparency did not affect the phenolic levels in raspberry fruit, but high ultraviolet transmittant films increased phenolics in red lettuce (*Lactuca sativa*) (Ordidge et al., 2010). Ozgen et al. (2008) also reported that black raspberries (*Rubus occidentalis*) from different locations varied in TMA and FRAP values, but Thompson et al. (2009) found that tunnel environments did not appear to affect phenolic and anthocyanin levels in blackberries.

VEGETATIVE GROWTH, PLANT NUTRITION, AND DISEASE INCIDENCE. In the field trial, 'Chinook' produced shorter canes (89 cm) than the other primocane fruiting cultivars (mean

123 cm), but canes of floricane-fruiting cultivars were of similar length (mean 147 cm). In the tunnel, primocane fruiting cultivars did not differ in cane height (mean 177 cm), but the double-cropped 'Heritage' plants produced shorter canes (217 cm) than 'Canby' (276 cm), 'Encore' (270 cm), or 'Nova' (263 cm). Cane lengths across floricane cultivars averaged 256 cm in the tunnel and 147 cm in the field. Mean cane length of primocane-fruiting cultivars averaged 177 and 115 cm in the tunnel and field, respectively. Tunnels promoted cane vigor in other studies (Demchak, 2009), which may be a response to partial shade, reduced wind, and modified temperature. More study is needed to determine how tunnel venting and plastic installation and removal dates affect cane heights since canes can grow too tall for efficient harvest and management.

Based on nutrient levels in leaf samples from 2008, nutrition was adequate with the possible exception of K and boron (B) levels in tunnel plants. Compared with raspberry standards (Bushway et al., 2008), tunnel plants were low in K (1.1%, sufficient range 1.5% to 2.5%) and B (18 $\mu\text{g}\cdot\text{g}^{-1}$, sufficient range 30 to 70 $\mu\text{g}\cdot\text{g}^{-1}$), whereas all nutrients were sufficient in field plants. This suggests that the shorter canes and lower yields in field plants were not caused by limited nutrition. A greater knowledge of nutrient needs and dynamics in high tunnels might help improve nutrient management.

Foliar and cane diseases were observed only on field plants. Raspberry leaf spot and cane anthracnose were present in 2007, but only in the field planting. The incidence of leaf spot was significantly higher on 'Canby' (6.3%) and 'Encore' (8.0%) than 'Heritage' (1.2%) or 'Nova' (0.7%). The incidence of anthracnose was higher on 'Canby' (3.8%) than other floricane-fruiting cultivars (mean 0.1%). 'Chinook' had a higher incidence of leaf spot (6.7%) than other primocane-fruiting cultivars (mean 1.0%). No anthracnose was observed in 2007 on primocane-fruiting canes in the field or tunnel.

Disease incidence was higher in 2008 (Table 5) than 2007. June and July rainfall was greater in 2008 (6.0 inches) than 2007 (3.5 inches), which likely promoted disease in 2008. 'Canby' and 'Encore' were again the most susceptible floricane-fruiting

Table 5. Leaf or cane area infected by raspberry leaf spot, anthracnose cane infections, spur blight, and botrytis cane blight in raspberry cultivars grown in an open field in Benton Harbor, MI (Sept. 2008).

Cultivar	Leaf or cane area infected (%)			
	Raspberry leaf spot	Anthracnose on canes	Spur blight	Botrytis cane blight
<i>Floricane-fruiting cultivars</i>				
Canby	16.3 c ^z	17.3 c	0.0 a	0.0
Encore	15.7 c	1.3 a	21.7 b	0.0
Heritage (double cropped) ^y	6.0 b	7.7 b	3.3 a	0.0
Nova	0.5 a	0.0 a	0.5 a	0.0
<i>Primocane-fruiting cultivars</i>				
Autumn Britten	4.8 a	1.8 a	3.3 a	0.0 a
Caroline	11.7 c	2.5 a	10.0 a	1.7 a
Chinook	12.3 c	0.0 a	5.0 a	40.0 c
Heritage	8.7 b	2.0 a	5.0 a	23.3 b

^zMeans within columns followed by the same letter are not significantly different by Fisher's protected least significant difference test at $P \leq 0.05$.

^y'Heritage' plots were pruned by retaining floricanes for summer production in addition to fall production on primocanes.

cultivars to raspberry leaf spot, and 'Chinook' was the most susceptible primocane-fruiting cultivar (Table 5). The incidence of anthracnose was high on 'Canby', moderate on 'Heritage', and low or absent on 'Encore' and 'Nova'. Primocane-fruiting cultivars did not differ in anthracnose incidence. Spur blight was also present in the field plants in 2008 and was most severe on the floricane-fruiting cultivar Encore (Table 5). The incidence of botrytis cane blight was highest on 'Chinook' and 'Heritage', with 'Caroline' being highly resistant and the other primocane fruiting cultivars immune. No botrytis cane blight was noticed in floricane-fruiting cultivars. The absence of cane and leaf diseases on tunnel plants reflects the lack of free moisture needed for infection by most fungal pathogens.

Conclusions

Relative cultivar differences in productivity, harvest times, and rot incidence were similar in the field and tunnel trials. 'Nova' and 'Encore' (floricane fruiting) and 'Caroline' and 'Heritage' (primocane fruiting) had the highest yields and berry quality in both settings. Although the tunnel and field environments were not replicated and plants were managed differently in each, tunnels generally tended to lengthen harvest periods and promoted plant vigor, yield, and fruit quality, and reduced the incidence of fruit, foliar and cane diseases, and

consistently affect berry phytonutritional contents.

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