Strawberry Cultivar Evaluation under High-tunnel and Organic Management in North Carolina

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ADDITIONAL INDEX WORDS. *Fragaria* × *ananassa*, day-neutral, June-bearing

SUMMARY. High-tunnel strawberry (*Fragaria* × *ananassa*) production for extended seasons has a great economic potential for small farmers. However, information on cultivars that are suitable for high tunnels is rather limited. In this study conducted in the 2014–15 season, strawberry plugs of eight June-bearing cultivars (Florida Radiance, Benicia, Camarosa, Camino Real, Chandler, Strawberry Festival, Sweet Charlie, and Winterstar) and two day-neutral cultivars (San Andreas and Albion) were evaluated for yield performance, fruit quality, and vegetative growth in organically managed high tunnels at two locations in North Carolina. Significant cultivar differences in whole-season yield were observed at Greensboro, NC; but not at Goldsboro, NC. The cultivar Florida Radiance had the highest marketable and total yields, followed by Winterstar and Chandler at Greensboro, whereas Benicia, Winterstar, and Chandler were the top producing cultivars at Goldsboro. Harvest of day-neutral cultivars San Andreas and Albion started in November. For June-bearing cultivars, Florida Radiance began to produce harvestable berries in late December, followed by Winterstar in early January. Peak harvest occurred in April for all cultivars. At the end of the season, ‘Albion’ had smaller canopy size than other cultivars. It also developed the fewest number of branch crowns and least above-ground biomass. Total soluble solid (TSS) content in April was lower than that observed early and late in the season for all cultivars, although Strawberry Festival exhibited a relatively stable TSS throughout the season. ‘Benicia’ produced the largest strawberries in the early season, but its fruit weight was remarkably reduced as the season progressed. Severe frost events occurred on 18 and 20 Feb. that caused an average of 61.5% and 32.2% open blossom damage at Greensboro and Goldsboro, respectively. The recommended cultivars based on this 1-year study are Florida Radiance, Benicia, and Camino Real for June-bearing cultivars, and Albion and San Andreas for day-neutral cultivars.

Strawberry is an important component of a healthy diet (Giampieri et al., 2012). Consumption of fresh strawberries increased from 2 lb/person in 1980 to 7.9 lb/person in 2013 [U.S. Department of Agriculture (USDA), 2014]. Corresponding with increasing demand, production of fresh strawberries reached 24.2 million cwt, with a market value of \$2.2 billion in 2012. North Carolina ranked fourth in strawberry production in the United States in 2013 (USDA, 2013). Distinguishing itself from other states, strawberry production in North Carolina is almost exclusively for local fresh markets, including pick-your-own operations, roadside stands, and farmers’ markets, with a market value of \$29.4

million in 2012 (McWhirt et al., 2015; USDA, 2013).

Commercial strawberry cultivars have undergone tremendous changes in the past few decades. Ninety-eight strawberry cultivars were introduced to the United States from 1980 to 2000 (Faedi et al., 2002), and more than 15 cultivars were released thereafter (Clark and Finn, 2010; Finn and Clark, 2012; Gasic and Preece, 2014). Changing production systems, reductions in

chemical control options, and increasing desires for off-season and high-quality strawberries drove strawberry breeding efforts in developing new cultivars to serve these diverse needs (Faedi et al., 2002; Hokanson and Finn, 2000).

According to photoperiodic flowering responses, strawberry cultivars are classified into three types: June-bearing, everbearing, and day-neutral. June-bearing or short-day cultivars require photoperiods less than 14 h to initiate flowering. They generally have one flush of harvest that peaks in the spring. Everbearing cultivars initiate flowering under long days, and often result in a fall harvest, or in some cases, two crops in 1 year. The third distinctive type, day-neutral cultivars are insensitive to daylength with regard to flower initiation and have multiple harvests throughout the season (Rowley et al., 2010a; Stewart and Folta, 2010).

Open-field annual hill production is the primary strawberry production system in North Carolina. With this system, strawberries are planted in the fall on raised beds covered with black plastic mulch. Harvests take place around May and last for 4 to 6 weeks (Fernandez et al., 2001; Poling, 1993). Two or three different strawberry cultivars are often grown to extend the harvest season. A typical mix includes June-bearing cultivars Chandler, Camarosa, and Sweet Charlie (Poling et al., 2005), which were released more than 20 years ago.

Apart from the short peak season, strawberries are shipped long distances to North Carolina. Driven by the growing interest of local and regional food, there is a strong demand for locally produced off-season strawberries. To extend the strawberry production season in North Carolina,

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
45.3592	cwt	kg	0.0220
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil	mm	39.3701
1	mmho/cm	mS·cm ⁻¹	1
28.3495	oz	g	0.0353
33.9057	oz/yd ²	g·m ⁻²	0.0295
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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doi: 10.21273/HORTTECH03559-16

approaches such as planting day-neutral strawberries, applying floating row-covers, and using overhead sprinkler irrigation have been explored (Ballington et al., 2008; Fernandez and Ballington, 2002; Poling, 2011). However, successful off-season production has been limited due to variable environmental conditions and pest damage.

While the majority of strawberries are produced conventionally, demand for organic strawberries is increasing. Consumers perceive organic fruit to be more environmental friendly, safer, tastier, and more nutritious than conventional ones (Zhao et al., 2006), and will pay premium prices for organic strawberries. In addition, organic strawberries are the most widely distributed organic produce item found year-round in mainstream retail stores (Carolina Farm Stewardship Association, 2013). According to Carolina Farm Stewardship Association (2013), a weekly gap of 11,410 lb existed between regional demand for organic strawberries and what North Carolina growers and California shippers are currently supplying.

High tunnels are one of the most important tools for small farmers to practice season extension. By increasing temperatures in winter and early spring, high tunnels advanced fruit production of June-bearing strawberries by 4 and 5 weeks in Utah and Kansas, respectively (Kadir et al., 2006; Rowley et al., 2010b). If managed properly, high tunnels also enhance organic production, as the structures limit access and interference of pests and weeds, and reduce the need for chemical control (Huff, 2015). Cultivar selection is one of the key factors to ensure success in high-tunnel production. Promising cultivars should be able to adapt to unique microclimatic conditions in high tunnels (i.e., high humidity, low light, and extreme differences between day and night temperatures). In addition, they should have the potential for fruiting in early and/or late seasons.

Considering the large number of newly released strawberry cultivars and the demand for off-season locally produced organic strawberries, objectives of this study were to evaluate performance of strawberry cultivars under organic and high-tunnel production systems, with the goal of

developing guidelines for organic high-tunnel strawberry production in North Carolina.

Materials and methods

PLANTING AND HIGH-TUNNEL MANAGEMENT. Experiments were conducted at two sites: University Farm of North Carolina Agricultural & Technical State University, Greensboro, NC (USDA Hardiness Zone 7b) and Small Farm Unit of the Center for Environmental Farming Systems, Goldsboro, NC (USDA Hardiness Zone 8a). Soil types were Enon fine sandy loam and Wickham loamy sand at Greensboro and Goldsboro sites, respectively. High tunnels [Greensboro (MCS Tuff high tunnel; Morgan County Seeds, Barnett, MO), Goldsboro (30 Budget Plus; Atlas Greenhouse Systems, Alapaha, GA)] at both sites were constructed in Aug. 2014 with north-south orientations. High tunnels were 30 ft wide and 96 ft long, with 8- and 6-ft side walls at Greensboro and Goldsboro sites, respectively. Both structures were covered with a single layer of 6-mil greenhouse-grade polyethylene film (FarmTek, Dyersville, IA). At Greensboro, the land was in the second year of organic transition, the previous crops were organically managed strawberries (up to June 2014, then no crops were planted before construction). In Goldsboro, the land had been managed organically for more than 10 years; the previous crops were organically managed sweet corn (*Zea mays*) before construction.

Ten strawberry cultivars were evaluated in the study: San Andreas and Albion are day-neutral cultivars; Florida Radiance, Benicia, Camarosa, Camino Real, Chandler, Strawberry Festival, Sweet Charlie, and Winterstar are June-bearing cultivars. Plugs of 'San Andreas', 'Florida Radiance', 'Benicia', 'Camino Real', and 'Winterstar' were conventionally raised (Norton Creek Farms, Cashiers, NC), while plugs of the other cultivars were organically raised (Cottle Strawberry Nursery, Faison, NC).

Strawberry plugs were transplanted on 30 Sept. 2014 on raised beds. Six beds, measured at 30 inches wide and 4 inches high with 4-ft center-to-center bed spacing, were made inside each high tunnel. The beds were covered with 48-inch, 1.25-mil embossed black plastic mulch (Berry

Hill Irrigation, Buffalo Junction, VA). One 8-mil drip tape with 8-inch emitter spacing was placed in the middle of each bed (T-Tape Systems; Rivulis Irrigation, San Diego, CA). A completely randomized experimental design with three replications of each cultivar was used at both sites. Each experimental plot contained 18 strawberry plants that were planted in two rows and staggered 14 inches apart.

High tunnels were closed when night temperatures were below 55 °F and opened during the day when temperatures reached 70–75 °F. Double layers of 1.5 oz/yard² rowcover (Gro-Guard; Atmore Industries, Atmore, AL) were laid directly on the plants at night for frost protection when outside temperatures were predicted to drop below 32 °F.

FERTILITY AND PEST MANAGEMENT. Both high tunnels were fertilized preplant with feathermeal (12N–0.5P–0K; Nutrimax, Greensboro, NC) at 60 lb/acre nitrogen (N), sulfate of potash (0N–0P–42K; Compass Minerals, Overland Park, KS) at 83 lb/acre potassium (K), soluble borate micronutrient (Beau-Ron®D; Drexel Chemical Co., Memphis, TN) at 0.98 lb/acre boron (B), and 10,000 lb/acre organic compost (Brooks Contractor, Goldston, NC). The organic compost had average properties of 6.9 pH, 2.91 mS·cm⁻¹ electric conductivity, and a carbon to nitrogen ratio of 10.9:1. Estimated available nutrients for the crop are 0.6% N, 0.03% phosphorus (P), 0.2% K, 10.3% calcium (Ca), 0.1% magnesium (Mg), and 0.1% sulfur (S). Plants were fertigated from March to May with fish emulsion (2N–0.9P–0K; SF Organics, Thomson, IL) at a weekly rate of 0.4 lb/acre N.

Organic Materials Review Institute listed pesticides potassium salts of fatty acids (M-Pede; Dow Agro-Sciences, Indianapolis, IN), *Isaria fumosorosa* Apopka Strain 97 (PFR-97; Certis US, Columbia, MD), and *Bacillus thuringiensis* sp. *kurstaki* (DiPel; Valent BioSciences Corp., Libertyville, IL) were applied in a rotational scheme at rates based on product labels to control two-spotted spider mites (*Tetranychus urticae*) and aphids [green peach aphid (*Myzus persicae*), melon aphid (*Aphis gossypii*), and strawberry aphid (*Chaetosiphon fragaefolii*)] at both sites. In addition, predatory mites [*Phytoseiulus persimilis*

(Spidex; Koppert Biological Systems, Howell, MI)] at a rate of 1.4 adults/ft² were introduced on 23 Jan. and 30 Jan. 2015 at Greensboro to control two-spotted spider mites. Landscape fabric was laid in row middles to control weeds at Greensboro, whereas hand weeding was conducted at Goldsboro.

DATA COLLECTION. Ripe strawberry fruit were harvested from 6 Nov. 2014 to 28 May 2015 and from 7 Nov. 2014 to 4 May 2015 at Greensboro and Goldsboro, respectively. Harvests were conducted once per week from November to February and twice per week in March, April, and May. Marketable and cull fruit (misshaped, damaged by diseases or insects, cold injured, or sunburned) were counted and weighed separately at each harvest. Following frost events from 18 to 20 Feb., percentages of damaged open blossoms were recorded on six randomly selected plants in each plot on 23 Feb. 2015. Plant canopy diameters were measured in early December, February, March, April, and May on six randomly selected plants in each plot. Border plants were avoided. Throughout the production season, runners were counted and removed on a weekly basis. At Greensboro, TSS contents of three typical marketable strawberry fruit per cultivar per replication were measured at six harvests (late February, early and late March and April, and early May) as described previously (Salamé-Donoso et al., 2010). A handheld refractometer (Spectrum Technologies, Aurora, IL) was used for the measurements. Fruit TSS was measured once at the Goldsboro site during peak harvest in the middle of April. About 18 of the youngest fully expanded strawberry leaves and petioles were sampled from each experiment plot on 30 Apr. 2015 at the Greensboro site. Plant samples were sent to the North Carolina Department of Agriculture & Consumer Services (Raleigh) for nutrient analysis. Data loggers (WatchDog 1650; Spectrum Technologies) were set at the height of plant canopies inside and outside of high tunnels to automatically record air temperatures at a 30-min interval throughout the season.

STATISTICAL ANALYSES. Analysis of variance was performed using the

Proc Mixed procedure of SAS (version 9.2C for Windows; SAS Institute, Cary, NC). Tukey's honest significant difference test ($\alpha = 0.05$) was conducted for multiple comparisons of different measurements among strawberry cultivars.

Results and discussion

YIELD. Cultivar effects on whole-season strawberry yields differed between the two locations. Significant differences among cultivars were observed at Greensboro, but not Goldsboro (Table 1). 'Florida Radiance' had the highest total yield (657 g/plant), followed by 'Winterstar' (total yield 585 g/plant) and 'Chandler' (total yield 569 g/plant) at Greensboro. 'Winterstar' and 'Chandler' also ranked second and third among the evaluated strawberry cultivars at Goldsboro in terms of the total yields, whereas Benicia was the top producer at this site with a total yield of 800 g/plant. Day-neutral cultivar Albion and June-bearing cultivar Sweet Charlie had the lowest yields at both locations; their total yields were 342 and 396 g/plant at Greensboro, and 440 and 332 g/plant at Goldsboro, respectively (Table 1). Comparing yield performances between the two day-neutral cultivars, Albion had lower total and marketable yields than San Andreas, although the difference was not significant. These results are similar to those reported by Ruan et al. (2011); however, higher yields of 'Albion' in contrast to 'San Andreas' were noticed in Washington State (Hoashi-Erhardt et al., 2012).

Although 'Winterstar' exhibited the second highest total yield, its marketable yield ranked fourth, after 'Benicia', 'Chandler', and 'Camino Real' at both locations. When averaging among cultivars, marketable yield accounted for 75% and 66% of total yields at Greensboro and Goldsboro sites, respectively (Table 1).

Harvest of day-neutral cultivars started earlier than that of June-bearing cultivars at both locations. The first harvest was from 'Albion' on 6 Nov. (Greensboro) and 7 Nov. (Goldsboro), and 14–17 d later for 'San Andreas'. Among the June-bearing cultivars, Florida Radiance matured the earliest, with the first harvest occurring 87 and 79 d after transplanting at Greensboro and Goldsboro, respectively. This was about 2 weeks earlier

than 'Winterstar' and a month earlier than other June-bearing cultivars (Table 2).

Peak harvest occurred in April for all strawberry cultivars evaluated in the study (Table 1). At Goldsboro, marketable yield in April accounted for more than 70% of entire season's harvest for June-bearing cultivars and 53% and 63% for day-neutral cultivars San Andreas and Albion, respectively. At Greensboro, the number ranged from 38% for 'Strawberry Festival' to 71% for 'Benicia' (Table 1). Results of the study confirmed previous observations that high tunnels advanced strawberry harvests by 4 to 5 weeks (Kadir et al., 2006; Rowley et al., 2010b) considering peak harvests normally occur in May for open-field strawberries in North Carolina (Poling et al., 2005). In March, 'Winterstar' had 73 and 65 g/plant total yield at Greensboro and Goldsboro, respectively, the highest among other cultivars in this month. However, marketable yields were only 34 and 36 g/plant at Greensboro and Goldsboro, respectively. Deformed fruit developed from frost damaged flowers was the primary reason for low market yield from Winterstar, as well as other cultivars in March.

Released in 2009 by the Institute of Food and Agricultural Sciences, University of Florida, 'Florida Radiance' has become one of the major strawberry cultivars in Florida and some other early spring production regions worldwide (Chandler et al., 2009; Ohlemeier, 2011; Whitaker et al., 2012). Although 'Florida Radiance' was categorized as a short-day cultivar, it develops more flowers under long-day conditions and requires less chilling for flower initiation than typical short-day cultivars (Whitaker et al., 2013). Because of this unique characteristic, 'Florida Radiance' is recommended for protected culture systems (Whitaker et al., 2013). Using 'Florida Radiance' as one parent, 'Winterstar' was also developed by University of Florida, and released in 2011 (Whitaker et al., 2012). 'Winterstar' shares many desirable characteristics with 'Florida Radiance'. In the present study, 'Florida Radiance' was superior in early yield compared with 'Winterstar'; however, 'Winterstar' had more consistent yield than 'Florida Radiance'. 'Benicia' is a newly released cultivar

Table 1. Monthly marketable and total yields (g/plant) of 10 organically managed strawberry cultivars grown under high tunnels in the 2014–15 season at Greensboro and Goldsboro, NC.

Cultivar	Marketable yield (g/plant) ^z					Total yield (g/plant)								
	November–December	January	February	March	April	May	Whole season	November–December	January	February	March	April	May	Whole season
							Greensboro, NC							
San Andreas	31 a ^y	42 a	38	12 c	188 abc	41 bc	353 bcd	35 a	52 ab	47 ab	17 d	221 b–c	83 ab	455 bcd
Albion	13 b	13 b	37	28 abc	121 c	43 bc	255 d	15 b	21 c	43 ab	32 cd	150 c	81 ab	342 d
Florida Radiance	3 b	43 a	59	59 a	274 a	74 abc	512 a	5 bc	70 a	68 a	70 ab	309 ab	135 ab	657 a
Benicia	0 b	8 b	42	31 abc	245 ab	17 c	344 bcd	0 c	8 c	49 ab	36 cd	363 a	60 b	517 a–d
Camarosa	0 b	3 b	42	32 abc	177 bc	84 abc	339 bcd	0 c	4 c	53 ab	45 a–d	206 b–c	132 ab	440 bcd
Camino Real	0 b	1 b	16	15 c	261 ab	107 ab	400 abc	0 c	2 c	18 b	23 d	313 ab	171 ab	529 abc
Chandler	0 b	5 b	40	20 bc	246 ab	132 a	444 ab	0 c	5 c	48 ab	27 cd	300 abc	189 a	569 abc
Strawberry Festival	0 b	18 ab	51	49 ab	137 c	99 ab	355 bcd	0 c	19 c	57 ab	58 abc	159 de	137 ab	431 bcd
Sweet Charlie	0 b	19 ab	46	27 abc	138 c	72 abc	302 cd	0 c	23 bc	54 ab	38 bcd	170 cde	112 ab	396 cd
Winterstar	0 b	12 b	28	34 abc	204 abc	78 abc	355 bcd	0 c	24 bc	60 ab	73 a	287 a–d	141 ab	585 ab
Significant	***	***	NS	**	***	**	***	***	***	*	***	***	*	**
							Goldsboro, NC							
San Andreas	42 a	31 a	34 a	23	193	44 ab	367	50 a	35 ab	42	43	291 ab	56 ab	517
Albion	19 b	26 ab	29 ab	16	187	19 b	295	34 ab	32 ab	32	27	290 ab	25 b	440
Florida Radiance	7 bc	18 abc	20 ab	26	279	24 ab	375	20 bc	43 a	37	43	402 ab	33 b	578
Benicia	0 c	3 bc	22 ab	3	441	85 ab	554	0 c	4 b	26	12	654 a	103 a	800
Camarosa	0 c	4 bc	21 ab	5	313	45 ab	388	0 c	5 b	31	26	425 ab	58 ab	545
Camino Real	0 c	0 c	5 b	2	316	101 a	425	0 c	1 b	7	28	409 ab	110 a	555
Chandler	0 c	5 bc	24 ab	5	356	46 ab	436	0 c	10 ab	31	21	491 ab	73 ab	626
Strawberry Festival	0 c	9 abc	15 ab	11	215	54 ab	304	0 c	10 ab	23	35	350 ab	73 ab	492
Sweet Charlie	0 c	7 bc	14 ab	20	133	12 b	186	1 c	10 ab	33	59	214 b	16 b	332
Winterstar	0 c	3 bc	7 ab	36	351	17 b	415	2 c	17 ab	34	65	600 ab	24 b	742
Significant ^y	***	**	*	NS	NS	*	NS	***	**	NS	NS	*	*	NS

¹1 g = 0.0353 oz.²Means within a column followed by the same letter were not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 2. First harvest dates and time after transplanting of 10 organically managed strawberry cultivars grown under high tunnels in the 2014–15 season at Greensboro and Goldsboro, NC.

Cultivar	Greensboro, NC		Goldsboro, NC	
	First harvest date	Time after transplanting (d)	First harvest date	Time after transplanting (d)
San Andreas	20 Nov.	51	24 Nov.	55
Albion	6 Nov.	37	7 Nov.	38
Florida Radiance	26 Dec.	87	18 Dec.	79
Benicia	22 Jan.	114	22 Jan.	114
Camarosa	22 Jan.	114	12 Jan.	114
Camino Real	29 Jan.	121	29 Jan.	121
Chandler	22 Jan.	114	8 Jan.	100
Strawberry Festival	22 Jan.	114	22 Jan.	114
Sweet Charlie	15 Jan.	107	19 Jan.	111
Winterstar	1 Jan.	93	5 Jan.	97

Table 3. Canopy diameters of 10 organically managed strawberry cultivars grown under high tunnels in the 2014–15 season at Greensboro NC.

Cultivar	Canopy diam (cm) ^z				
	December	February	March	April	May
San Andreas	22.7 abc ^y	19.1 bc	22.0 abc	27.4 bc	30.7 ab
Albion	19.3 bc	17.5 c	17.9 d	22.0 c	24.1 b
Florida Radiance	23.6 ab	22.9 ab	24.3 a	31.0 ab	37.5 a
Benicia	24.8 a	24.2 a	23.0 ab	25.2 bc	NA ^x
Camarosa	18.3 c	18.1 c	20.1 bcd	26.3 bc	30.0 ab
Camino Real	22.9 abc	23.2 ab	23.1 ab	28.7 b	31.2 ab
Chandler	24.2 ab	23.1 ab	23.4 ab	34.6 a	37.9 a
Strawberry Festival	20.7 abc	19.6 bc	20.7 a–d	28.0 b	33.6 a
Sweet Charlie	19.4 bc	19.1 bc	19.3 cd	27.3 bc	31.0 ab
Winterstar	21.5 abc	22.7 ab	21.9 abc	29.7 ab	36.3 a
Significant	**	***	***	***	**

^z1 cm = 0.3937 inch.^yMeans within a column followed by the same letter were not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.^xNA = not available.**, ***Significant at $P \leq 0.01$ and 0.001 , respectively.**Table 4. Number of branch crowns and fresh weights of leaves and stems of 10 organically managed strawberry cultivars grown under high tunnels in 2014–15 season at Greensboro and Goldsboro, NC.**

Cultivar	Greensboro, NC		Goldsboro, NC	
	Branch crowns (no.)	Fresh wt (g) ^z	Branch crowns (no.)	Fresh wt (g)
San Andreas	3.0 bcd ^y	115.9 c	3.1 ab	281.7
Albion	2.2 d	105.1 c	2.9 b	239.3
Florida Radiance	4.1 abc	209.1 ab	3.4 ab	284.4
Benicia	2.5 bcd	91.7 c	3.9 ab	411.7
Camarosa	2.3 cd	132.2 c	3.6 ab	440.5
Camino Real	3.3 bcd	132.8 bc	4.2 ab	419.7
Chandler	4.6 ab	160.6 bc	5.2 a	405.0
Strawberry Festival	3.2 bcd	157.6 bc	3.3 ab	361.7
Sweet Charlie	2.7 bcd	126.4 c	2.8 b	246.7
Winterstar	5.3 a	240.6 a	4.7 ab	374.4
Significant	***	***	*	NS

^z1 g = 0.0353 oz.^yMeans within a column followed by the same letter were not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.NS, *, ***Nonsignificant or significant at $P \leq 0.05$ or 0.001 , respectively.

by University of California, which is marketed for its high yield and large fruit (Gasic and Preece, 2014). Planting area of the cultivar has increased

from 62 to 1165 acres within 2 years in the Oxnard district of California (Burfield, 2013). Currently, there is very little information regarding

growing 'Benicia' under other production systems.

VEGETATIVE GROWTH. Canopy diameters of strawberry plants slightly declined from December to February and increased from March to May at Greensboro (Table 3). 'Albion' had the smallest canopy size in most months except in December at Greensboro. Throughout the season, 'Albion' and 'San Andreas' increased canopy sizes by 4.8 and 8 cm, respectively, while more than 10 cm growth was observed on most June-bearing cultivars. 'Chandler', 'Florida Radiance', and 'Winterstar' had canopy diameters of over 36 cm in May. They also developed the most branch crowns and had the highest values on fresh weights of leaves and stems at the end of the season (Table 4). Similar trends of the growth of plant canopies were observed at Goldsboro (data not shown), but 'Camarosa', 'Benicia', 'Camino Real', and 'Chandler' exhibited higher values on fresh weights of leaves and crowns at the end of the season (Table 4).

Small canopy sizes of day-neutral cultivars suggest plant density can be increased to maximize yield in limited spaces under high tunnels. By comparing yields of 'Albion' grown at four plant spacings, Portz et al. (2011) noticed that there was no significant difference in strawberry yields between 10- and 12-inch spacing (spacing was measured within rows, between plants, and between rows). With canopy diameter of 24.1 cm at Greensboro, plant spacing of 'Albion' could be reduced from the present 14-inch to 10- or 12-inch spacing without sacrificing yield.

Developing three to four branch crowns is important to achieving

adequate yield in the annual hill pasticulture system (Poling et al., 2005). A range of 2.2 to 5.3 branch crowns were formed at the end of the season in the present study. ‘Albion’ and ‘Sweet Charlie’ developed fewer than three branch crowns, and ‘Chandler’ and ‘Winterstar’ had more than four branch crowns at both locations (Table 4). Few runners were developed before April. This was particularly true for strawberries at Greensboro. At Goldsboro, ‘Camino Real’ had relatively more runners in fall, whereas ‘Strawberry Festival’ had more runners in spring (data not shown). Strawberry plants at Goldsboro generally developed more branch crowns and had higher fresh weight values of leaves and stems compared with plants at Greensboro. This is mainly because Goldsboro has warmer climate than Greensboro.

FROST DAMAGE. Severe frost events occurred from 18 to 20 Feb. at both locations (Fig. 1). The night temperatures under rowcovers in the high tunnels averaged 18.8 and 16.7 °F higher than temperatures outside the high tunnels at Greensboro and Goldsboro, respectively. The lowest temperature recorded outside during those 3 d was 6.5 °F at Greensboro, whereas the temperature inside the high tunnel was 29.6 °F during that same time. Strawberry plants may be permanently damaged when the temperature is lower than 22 °F (Poling et al., 2005). Therefore, severe cold damage was prevented for plants under rowcovers in high tunnels during these freeze events.

Under protected culture, periods with temperatures lower than 32 °F lasted for 4.5 and 5 h on 19 and 20 Feb. at Greensboro and lasted for 4 h on 20 Feb. at Goldsboro. The freezing temperatures resulted in an average of 61.5% and 32.2% open blossom damage at Greensboro and Goldsboro, respectively (Table 5). Many of the damaged flowers were primary or secondary flowers that develop large and early maturing fruit and have been reported to contribute the most to marketable yield (Pollard et al., 1989). Using plastic-covered low tunnels inside high tunnels or adding supplemental heating has achieved success in frost protection and early season strawberry production in Utah (Maughan et al., 2015). These

practices warrant future investigation to further early season production of strawberries in North Carolina.

FRUIT CHARACTERISTICS. Fruit quality of the same cultivar differed remarkably during the season. Of all the evaluated strawberry cultivars, TSS declined as the season progressed to the peak harvest, and reached the lowest value in early April (Table 6). However, TSS recovered toward the end of the season. When averaging among cultivars, TSS was 10.1% in February, 5.7% in early April, and 10.1% in early May. These data support previous observations that TSS of strawberries is correlated with crop load and not determined by temperature during the production season (Agüero et al., 2015).

In early April, TSS content of all evaluated strawberry cultivars, except Sweet Charlie, was lower than 7%, the minimum requirement for U.S. no. 1 grade strawberry fruit (Mitcham, 2014). In May, ‘Sweet Charlie’ had the highest TSS, although it was relatively low in late February. Similar to ‘Sweet Charlie’, ‘Albion’ also exhibited high TSS late in the season but relatively low TSS early in the season. Among all evaluated strawberry cultivars, TSS of Strawberry Festival was above cultivar average in all harvest periods (11.4% in February, 6.8% in early April, and 10.8% in early May).

Continuous decreasing fruit weight was observed for all the evaluated strawberry cultivars at both locations (Table 7), which supports the statement that fruit weight can be

a temperature-determined characteristic (Agüero et al., 2015). When temperatures rise, fruit become smaller (Chen, 2013). Fruit harvested late in the season are more likely developed from secondary or tertiary flowers in a flower cluster that may lead to smaller fruit size. With eight out of 10 cultivars, fruit weights in May were less than half of fruit weight in January. Of the evaluated strawberry cultivars, average fruit weight of Benicia was the greatest in January (46.2 g in Greensboro and 40.0 g in Goldsboro), significantly higher than day-neutral cultivars. However, fruit weight of ‘Benicia’

Fig. 1. Air temperatures inside and outside high tunnels from 18 to 20 Feb. 2015: (A) Greensboro, NC, (B) Goldsboro, NC; $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$.

Table 5. Percentages of frost damaged open blossoms of 10 organically managed strawberry cultivars grown under high tunnels in 2014–15 season at Greensboro and Goldsboro, NC.^z

Cultivar	Open blossom damage (%)	
	Greensboro, NC	Goldsboro, NC
San Andreas	65.8	47.1
Albion	67.6	30.0
Florida Radiance	59.2	22.0
Benicia	69.6	43.4
Camarosa	80.1	27.5
Camino Real	49.6	38.8
Chandler	70.6	34.8
Strawberry Festival	64.7	26.4
Sweet Charlie	53.2	35.0
Winterstar	34.7	17.2
Significant	NS	NS

^zFrost events occurred on 18 and 20 Feb. 2015; data were collected on 23 Feb. 2015.
NS = Nonsignificant at $P \leq 0.05$.

Table 6. Total soluble solids content of 10 organically managed strawberry cultivars grown under high tunnels in late February, March, April, and May in the 2014–15 season at Greensboro, NC.

Cultivar	Total soluble solid contents (%)					
	Late February	Early March	Late March	Early April	Late April	Early May
San Andreas	9.9 abc ^z	10.3	8.2 a	5.5 abc	7.0 ab	9.6 ab
Albion	8.9 bc	9.9	7.5 ab	6.4 ab	7.2 ab	11.3 a
Florida Radiance	11.5 ab	10.3	6.9 abc	6.1 abc	7.0 ab	9.0 ab
Benicia	9.8 abc	10.8	5.2 c	4.0 c	5.0 b	NA ^y
Camarosa	8.4 c	8.2	7.0 abc	6.2 ab	8.7 a	10.8 ab
Camino Real	10.1 abc	8.9	5.2 c	4.4 bc	5.1 b	8.0 b
Chandler	10.0 abc	9.7	5.6 bc	5.8 abc	5.8 ab	10.0 ab
Strawberry Festival	11.4 ab	10.6	7.8 ab	6.8 a	6.9 ab	10.8 ab
Sweet Charlie	8.7 bc	8.6	7.3 ab	7.0 a	7.9 ab	11.4 a
Winterstar	12.1 a	9.9	6.4 abc	4.9 abc	7.0 ab	9.8 ab
Significant	**	NS	**	**	**	*

^zMeans within a column followed by the same letter were not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.

^yNot available.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 7. Average fruit weight of 10 organically managed strawberry cultivars grown under high tunnels from November to May in the 2014–15 season at Greensboro and Goldsboro, NC.

Cultivar	Avg fruit wt (g) ^z					
	November–December	January	February	March	April	May
Greensboro, NC						
San Andreas	22.2 b ^y	20.8 bc	20.2 a	18.9 c	16.7 a	10.7 ab
Albion	13.5 c	16.8 c	20.5 a	19.3 bc	15.6 ab	12.2 a
Florida Radiance	42.3 a	27.1 bc	24.2 a	22.2 bc	14.2 abc	12.1 a
Benicia	NA ^x	46.2 a	30.0 a	31.4 a	16.5 ab	8.6 ab
Camarosa	NA	33.3 abc	26.3 a	17.4 cd	14.6 abc	10.8 ab
Camino Real	NA	35.0 ab	26.4 a	20.4 bc	17.2 a	13.0 a
Chandler	NA	22.0 bc	19.6 a	13.0 d	10.1 d	6.7 b
Strawberry Festival	NA	36.9 ab	20.6 a	17.1 cd	12.7 bcd	8.2 ab
Sweet Charlie	NA	29.1 abc	21.3 a	17.0 cd	11.3 cd	9.0 ab
Winterstar	NA	29.9 abc	27.6 a	25.0 b	15.7 ab	11.0 ab
Significant	***	**	NS	***	***	**
Goldsboro, NC						
San Andreas	24.5 b	19.6 bc	22.7	27.5 ab	18.6 abc	8.0
Albion	18.7 c	20.8 bc	21.8	27.8 ab	21.8 a	11.7
Florida Radiance	30.0 a	25.7 abc	19.9	27.1 ab	17.8 abc	11.9
Benicia	NA	40.0 a	31.8	21.9 ab	19.0 abc	9.9
Camarosa	NA	31.8 ab	25.7	21.3 ab	18.5 abc	7.5
Camino Real	NA	13.0 c	26.8	12.6 b	20.2 ab	12.7
Chandler	NA	23.8 abc	20.5	15.2 b	9.6 d	6.1
Strawberry Festival	NA	27.8 abc	26.6	19.3 ab	14.1 bcd	10.4
Sweet Charlie	NA	28.2 abc	25.3	26.7 ab	12.7 cd	7.7
Winterstar	NA	27.6 abc	27.9	35.9 a	13.3 cd	8.0
Significant	***	**	NS	**	***	NS

^z1 g = 0.0353 oz.

^yMeans within a column followed by the same letter were not significantly different by Tukey's honest significant difference test at $P \leq 0.05$.

^xNot available.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.01$ or 0.001, respectively.

decreased dramatically in later months. In May, the average fruit weights of 'Benicia' were 8.6 and 9.9 g at Greensboro and Goldsboro, respectively. Throughout

the season, 'Chandler' consistently had smaller fruit compared with other cultivars. In the peak season, the average fruit weights of 'Chandler' were 10.1 and 9.6 g at the

Greensboro and Goldsboro sites, respectively, which are significantly lower than other cultivars except Strawberry Festival and Sweet Charlie. Although 'Chandler' is one of the most commonly grown, open-field cultivars in North Carolina, it may not be the best performing cultivar in high tunnels.

PLANT HEALTH. At Greensboro, younger leaves of 'Benicia' showed crinkling and stunted growth, accompanied by reddish lesions on leaves, petioles, and calyx during peak production season. The crinkling leaves became necrotic and dead and the whole plant declined in 2 weeks. These symptoms were only present on 'Benicia' at Greensboro, and about 80% of the plants were infected. Plant samples were analyzed by the North Carolina State University Plant Disease and Insect Clinic (PDIC) in Raleigh and no pathogens were found. Analysis of nutrient concentrations in leaves and petioles of strawberry cultivars indicated that 'Benicia' had the lowest magnesium concentration (data not shown). A magnesium deficiency may be part of the cause for the plants decline.

Two-spotted spider mites and crown and root rot (caused by *Phytophthora cactorum*) were the primary pest problems that limited plant growth and yield at Goldsboro (data not shown). 'Florida Radiance' is highly susceptible to crown and root rot (Whitaker et al., 2013), which caused stunted plant growth and plant decline. This disease was first identified on 'Florida Radiance' in Goldsboro in late March by PDIC, and then severely affected two of the three 'Florida Radiance' plots, which might partially explain the lower yield of 'Florida Radiance' at the Goldsboro site than that of the Greensboro site. The crown rot symptom was not noticeable on other cultivars at Goldsboro until the end of April, when leaves and petioles of Benicia, Camarosa, and Chandler started to wilt and became necrotic. 'Camino Real' seemed to have the least disease incidence (data not shown). This agrees with the result that Camino Real was the most resistant, whereas 'Camarosa' was the most susceptible cultivar to crown and root rot pathogens (Fang et al., 2012).

Two-spotted spider mites were found on all evaluated strawberry cultivars at the end of the season at Goldsboro. By evaluating two-spotted spider mite resistance using 85 strawberry cultivars, Shanks and Barritt (1975) found that there was no difference in mite populations on the cultivars although some cultivars showed fewer leaf symptoms. By evaluating development of two-spotted spider mites on leaf disks, Monteiro et al. (2014) noticed mortality of the two-spotted spider mite was higher on ‘Camarosa’, ‘Diamante’, and ‘Seascape’ than on other strawberry cultivars. Due to the highly skewed distribution of the population of two-spotted spider mites in the high tunnels, no significant differences in two-spotted spider mite damage were detected among cultivars in the present study (data not shown).

Interest in off-season and organically produced strawberries is increasing among local producers in North Carolina. In the present study, ‘Florida Radiance’, ‘Benicia’, ‘Winterstar’, and ‘Chandler’ showed high yield potentials. However, ‘Chandler’ produced small fruit, which can be a potential problem for fresh markets since it requires extra labor for harvesting small-sized berries. Day-neutral cultivars Albion and San Andreas and June-bearing cultivars Florida Radiance, Winterstar, and Camino Real are promising cultivars to target the early market. ‘Benicia’ produced large berries in the early season, which could be a highly attractive characteristic for early markets such as Thanksgiving, Christmas, and Valentine’s Day.

For future studies, increasing plant density of day-neutral cultivars might be an approach to increase total yield per square foot in high tunnels. Given the frost damage to open blossoms that occurred in the winter season, additional frost protection practices such as low tunnels warrant further investigation in North Carolina. Taking into consideration the variable year-to-year environmental conditions and the properties of high-tunnel and organic production systems, further research spanning multiple years is necessary to provide a thorough evaluation of strawberry cultivars.

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