Southern Highbush Blueberry Production in High Tunnels: Temperatures, Development, Yield, and Fruit Quality During the Establishment Years

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Abstract. Growers interested in producing early, high-quality, southern highbush blueberries (*Vaccinium corymbosum* L.) in high tunnels face a lack of information regarding appropriate cultural methods. We sought to elucidate the optimal date to close high tunnels to hasten vegetative and reproductive growth of organic southern highbush blueberry cultivars Emerald and Jewel grown in Georgia. The three dates selected to close the high tunnels were 15 Dec., 2 Jan., and 16 Jan. High tunnels raised soil and daytime air temperatures during winter months, but the tunnels did not retain heat at night and did not provide freeze protection without the use of propane heaters. The high tunnel microclimate advanced both vegetative and reproductive growth compared with outdoor plants. Averaged over the 2-year study, the 15 Dec. tunnel closure advanced flower initiation by 38 days for ‘Emerald’ and 39 days for ‘Jewel’ compared with outdoor control plants. Synchronization of flowering of the two cultivars was poor in 2007 when ‘Emerald’ flowered much earlier than ‘Jewel’ and much better in 2008. In 2007, flower and fruit development of ‘Jewel’ were faster than that of ‘Emerald’ with Jewel going from the appearance of individual flowers to ripe fruit in 80 days as compared with 105 days for ‘Emerald’. Total yield was strongly correlated with fruit set ($r = 0.94$). ‘Emerald’ fruit contained higher concentrations of soluble solids and anthocyanins than ‘Jewel’ fruit, and anthocyanin concentrations increased throughout the harvest period. No fruit matured in 2008 as a result of freeze damage. The biggest obstacle for high tunnel production of southern highbush blueberries appears to be preventing freeze damage and assuring pollination. Cost-effective freeze protection and ways to promote good fruit set will be critical to successful production of early southern highbush blueberries in high tunnels.

Growers and researchers seek cultural methods that modify microclimatic conditions and enable season extension. High tunnels represent one such technology currently being explored for a wide variety of horticultural crops. A high tunnel is a passively ventilated plastic greenhouse covered with a single layer of polyethylene (Lamont, 2009; Waterer, 2003).

Research has documented many advantages of high tunnel cultivation. Early crop production (7 d to 21 d earlier than field), high yields per unit area (two to three times higher than field), and production of cleaner and higher-quality products are a few obvious advantages (Lamont, 2005). Less obvious are advantages such as reduced soil erosion, efficient water and fertilizer use,

reduced weed pressure resulting from exclusion of weed seeds, and reduced pest pressure (Lamont, 2005). High tunnels raise both air [by 10 to 20 °C (Kadir et al., 2006)] and soil temperatures [by 4 to 8 °C (Reiss et al., 2004)] above ambient conditions. This warming of air and soil enables out-of-season production of many horticultural crops. Success with crops like tomato, melons, peppers, and eggplant sparked interest in high tunnel production of small fruits (Waterer, 2003).

Positive findings have been reported for high tunnel cultivation of small fruits such as strawberries, raspberries, and blackberries (Demchak, 2009; Gaskell, 2004; Kadir et al., 2006; Kempler, 2002; Xiao et al., 2001). California has seen a recent increase in acreage dedicated to high tunnel-grown raspberries that reach the markets during periods of low supply (Gaskell, 2004). Kadir et al. (2006) reported superior yields and quality of high tunnel-grown as compared with field-grown strawberries. European raspberry growers also use high tunnels to produce high-quality fruit for the fresh market (Gaskell, 2004).

Blueberry (*Vaccinium* spp.) is a high-value crop, particularly when grown organically and during periods of low production (Williamson and Lyrene, 2004a). Previous findings suggest that high tunnels can advance the yield of blueberries by 1 week to 1 month (Bal, 1996; Baptista et al., 2006; Ciordia et al., 2002; Hicklenton et al., 2004; Ozeki and Tamada, 2006). The effects of high tunnels on fruit growth and development are cultivar-specific (Baptista et al., 2006; Renquist, 2005).

Season extension research has focused on both early and late blueberry production. Through careful cultivar selection and microclimate modification, the harvest period for highbush blueberries in The Netherlands was extended from 8 to 10 weeks to ≈5 months (Bal, 1996). The earliest berries were grown inside of heated greenhouses and harvested 2 months before field plants. Ripening was advanced 5 to 6 weeks in unheated high tunnels. A 2- to 3-week delay in harvest was achieved by spreading plastic rain covers over the plants just before the berries start to change color. Despite the previous research into season extension of blueberries, questions remain regarding the effects of different tunnel closure dates.

High tunnel production alters the microenvironment, and plant growth and development, but there is no information regarding the effects of high tunnels on fruit quality of blueberries. The health benefits of blueberries have received much attention (Mainland and Tucker, 2002). Anthocyanins, a class of flavonoids responsible for the blueberry’s distinctive color, contribute significantly to blueberry’s antioxidant properties (Beccaro et al., 2006; Moyer et al., 2002). Beccaro et al. (2006) reported a positive correlation between total monomeric anthocyanin content and ferric-reducing antioxidant power, a commonly used measurement of antioxidant strength. Prior et al. (1998) noted a similar trend between anthocyanin content and oxygen radical absorbance capacity (ORAC). They also reported that blueberries have high ORAC levels compared with many other fruits and vegetables.

We explored the feasibility of production of southern highbush blueberry in high tunnels in northern Georgia. The aim of the study was to determine the optimum tunnel closure date for generating large, early yields. We also quantified the effects of high tunnels on the microclimate, development, and fruit quality of southern highbush blueberry.

Materials and Methods

Plant materials and site preparation. A site was selected on the University of Georgia’s certified organic farm located on the Horticulture farm in Watkinsville, GA. Eight plots (6 m × 12 m) spaced at intervals of 7 m were leveled. Clear plastic (5 mil) was then stretched over each plot for 15 d for solarization purposes to kill weeds and weed seeds. Six plots were selected to contain the high tunnels and two were designated as outdoor

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controls. The metal frames of the high tunnels, 4.9 m × 11 m (Atlas Greenhouses, Alapaha, GA), were installed in the fall of 2006. Tunnels were designed with sidewalls that open to 1.5 m high to facilitate heat removal and ventilation.

The plots were then cultivated with a mechanical tiller to suppress weed growth. Two raised beds of ground, aged pine bark (1.8 m × 9.5 m × 20 cm) were established within each plot. Two-year-old 'Emerald' (Island Grove Ag Products, Hawthorne, FL) and 1-year old 'Jewel' plants (Warren Daniel, Lake Park, GA) were planted in Nov. 2006. Each bed contained 20 plants (one row of 10 'Emerald' and one row of 10 'Jewel' plants) for a total of 40 plants per tunnel. Plants were configured in a high-density arrangement with 1 m between plants and 75 cm between staggered rows. We selected 'Emerald' and 'Jewel' because of their low chilling requirement.

Fertilization was provided with a 5N–1.31P–3.32K organic granular fertilizer (5–3–4 McGeary Organics, Lancaster, PA) based on an application rate of 467 kg N/ha/year divided among five application dates. This high rate was used because of uncertainty regarding the release of mineral nitrogen (N) from the organic fertilizer and the possibility of significant N immobilization within the pine bark beds. Irrigation was provided with microjet sprinklers (54 L/h) placed every 2 m in each bed. One hour of irrigation, 3 d per week (76 L/m²/week) provided adequate moisture levels throughout fall, winter, and spring. During summer months, irrigation was increased to 2 h per week (152 L/m²/week). Frost protection on nights expected to be below 0 °C was provided with portable propane heaters (Dayton 3VE42, 2344 W; Dayton, Detroit, MI) placed inside each tunnel. Pollination was facilitated by the introduction of colonies of bumblebees (Minipol, Class C hive; Koppert Biological Systems, Romulus, MI) into each tunnel on the appearance of open blueberry flowers.

The four treatments consisted of three different times at which the tunnels were covered and closed (15 Dec., 2 Jan., and 16 Jan.) with a single layer of 6-mil polyethylene greenhouse plastic (K50 clear; Klerks Hyplast Inc., Chester, SC) and a control plot without a tunnel. Each treatment was replicated twice. Tunnel sidewalls were manually opened when outdoor temperatures exceeded ≈16 °C to facilitate heat removal. On 15 May of both years, high-tunnel sidewalls were opened and remained open for the duration of the growing season, but the plastic cover was not removed from the high tunnels.

Data Collection

Environmental conditions. Data loggers (Hobo U-12; Onset Computer Corp., Bourne, MA) in radiation shields at 24 cm above the pine bark beds recorded air temperature at the bottom of the canopy at hourly intervals in each plot. Attached soil temperature probes (TMC-1HD soil temperature sensor; Onset Computer Corp.) recorded pine bark bed

temperature at 10-cm depth. Daily maximum and minimum values for each variable were determined.

Flower and fruit development. In each plot, five plants of each cultivar were randomly selected. A branch section consisting of three inflorescences was then delimited. Inflorescences were observed once or twice per week and each flower was assigned a number based on its stage of development. The numbering system for the flower and fruit development is based on the system of stage development identification developed by Michigan State University. Stage 1 occurs when individual flowers can be differentiated. Stage 5 occurs when the petals abscise from the ovary [normally 4 to 7 d after anthesis and Stage 8 is a ripe fruit (Longstroth,

2002)]. The date of Stages 1, 5, and 8 and the number of days between these stages were determined.

Vegetative growth. Light interception was used as an indicator of vegetative growth because of its strong dependence on leaf area index (Wang et al., 2004). Six random sites were chosen in each plot. Areas near end walls were excluded to avoid interference caused by the high tunnel's frame. At solar noon on clear days [minimum photosynthetic photon flux (PPF) of 900 μmol·m⁻²·s⁻¹], a 1-m long line quantum sensor (LI-191; LI-COR, Lincoln, NE) was used to measure the PPF level above and below the plant canopy and the percentage of light intercepted by the canopy was calculated. Data were collected on six dates in 2007 and on five dates in 2008.

Fig. 1. Effects of high tunnels on minimum and maximum air temperatures during the 2006–2007 growing season. Only two treatments are shown but similar trends were observed in all high tunnels after closing them. Error bars indicate SD. Bars not shown are within the limits of the symbol. Note the increase in maximum temperatures in high tunnels compared with outdoor control plots but no increase in minimum temperatures inside of high tunnels. Temperature differences (Δ) were calculated as daily maximum (or minimum) air temperature in tunnels minus maximum (or minimum) air temperature in control plots. Sidewalls of the high tunnels remained open from 15 May on.

Yield data. Fruit set was calculated as the number of flowers that produced a ripe fruit divided by the number of flowers on that inflorescence $\times 100\%$ using the same inflorescences as those monitored for flower development (see previously). In 2007, all ripe fruits were harvested weekly for 6 weeks beginning 23 Apr. Both cultivars were harvested individually and total fruit fresh weight was recorded. No ripe fruit was obtained in 2008.

Fruit size. Approximately 150 g of fruit from each harvest was weighed and photographed with a digital camera. The fruits were then frozen at -20°C for subsequent quality analysis. Photographs were processed with image analysis software (Assess; APS, St. Paul, MN) to determine the number and diameter of the berries. Approximately 100 berries were counted and measured per subsample. Average diameter and weight per berry were calculated.

Soluble solids. Ten grams of frozen fruit were thawed, macerated, and filtered through two layers of cheesecloth. Juice was then filtered through a Whatman number 1 filter paper under vacuum. The sample was analyzed for soluble solids with a digital refractometer (PR-32 α ; ATAGO USA, Bellevue, WA).

Anthocyanin content. Total monomeric anthocyanin content was determined using the pH differential method as described by Rodriguez-Saona and Wrolstad (2001) and Lee et al. (2005). Absorbance at 520 nm was measured with a spectrophotometer (Spectronic Genesys 2; Thermo Fisher Sci., Waltham, MA). Because the anthocyanin composition of the fruit was unknown, the molecular weight of cyanidin-3-glucoside (449.2 g/mol) and a molar extinction coefficient of 26,900 were used in the calculations (Moyer et al., 2002). Fruit anthocyanin concentrations are expressed as milligrams of cyanidin-3-glucoside equivalents per gram fresh weight.

Experimental design and data analysis. The study used a completely randomized design with a split plot (cultivar) with four main treatments, two replicates, and repeated measures (harvests). The four treatments consisted of three different dates (15 Dec., 2 Jan., and 16 Jan.) at which the high tunnels were closed and a control treatment without a tunnel. The study was conducted in the 2006–2007 and 2007–2008 growing seasons. Treatment effects were analyzed using analysis of variance (ANOVA) and linear regression (SAS 9.0; SAS Institute, Cary, NC). When ANOVA indicated significant effects ($P < 0.05$), means were separated using Duncan's multiple range test. In addition, the correlations between tunnel closure date and yield, fruit set and yield, and harvest time and fruit quality were tested using linear regression.

Results

Environmental effects. The high tunnels affected air and soil temperatures similarly in both years. Because temperatures in tunnels

that were closed later quickly resembled those in earlier closed tunnels, only data from the 2006–2007 growing season and from the control and 15 Dec. treatments are shown (Figs. 1 and 2). Maximum daily air temperature was consistently increased in all tunnels by 3 to 15 $^{\circ}\text{C}$ as compared with the outdoor control plots (Fig. 1). After opening tunnel sidewalls on 15 May, air temperatures inside the tunnels were similar to those outdoors. Daily minimum air temperatures were not raised and temperatures inside tunnels actually dropped slightly below ambient on numerous nights (Fig. 1). Propane heaters

successfully increased air temperature inside tunnels, raising them as much as 5 to 6 $^{\circ}\text{C}$ above ambient (Fig. 1). Daily minimum soil temperatures were increased by all tunnel treatments. Warming of the soil by 5 to 7 $^{\circ}\text{C}$ occurred within 1 to 2 weeks of tunnel closing. Tunnel soil temperatures were 2 to 8 $^{\circ}\text{C}$ higher than control plots throughout January, February, and March. In April, the control soil temperatures started to increase and equalized with tunnel soil temperatures by mid-May. During summer months (June to August), soil temperatures in control plots were 2 to 5 $^{\circ}\text{C}$ higher than in the tunnels (Fig. 2).

Fig. 2. Effects of high tunnels on minimum and maximum soil temperatures during the 2006–2007 growing season. Only two treatments are shown but similar trends were observed in all high tunnels after closing them. Error bars indicate SD. Bars not shown are within the limits of the symbol. Note the warming of soil temperatures in the high tunnels above those in outdoor control plots during winter and cooling of the soil in the high tunnels during summer. Temperature differences (Δ) were calculated as daily maximum (or minimum) soil temperature in the tunnels minus maximum (or minimum) soil temperature in control plots. Sidewalls of the high tunnels were permanently opened on 15 May.

Year 2007 was a difficult year for many fruit growers in the southeastern United States. A very warm March was followed by hard freezes on 6 and 7 Apr. (-5°C) in an event known as the Easter freeze of 2007 (Warmund et al., 2008). These freeze events destroyed 100% of the developing fruit in the control plots, whereas the tunnel-grown berries survived as a result of heating of the tunnels with propane heaters.

Flower and fruit development. There was an interactive effect of tunnel closure date and cultivar on the date of Stage 1 in 2007 and 2008 (Fig. 3). In 2007, 'Emerald' plants in high tunnels closed on 15 Dec. and 2 Jan. reached Stage 1 on 12 Jan. compared with 31 Jan. in outdoor control plots, an advancement of 19 d. Date of first 'Emerald' flower in the 16 Jan. closure treatment was not significantly earlier than in control plots. In 2007, Stage 1 of 'Jewel' was advanced by 28 to 36 d in all tunnel treatments as compared with the control, but 'Jewel' reached Stage 1 30 to 50 d later than 'Emerald' (Fig. 3).

In 2008, the 15 Dec. tunnel closure generated earlier 'Emerald' flowering than the outdoor control by 17 d, but Stage 1 occurred later than in 2007 (6 Feb. in 2008 compared with 12 Jan. in 2007). Stage 1 of 'Jewel' was advanced by 20 to 24 d in all tunnel treatments compared with the controls. The large difference in the date of Stage 1 between the two cultivars in the first

year (36 d) was reduced to only 7 d in 2008 (Fig. 3).

Treatment effects were observed in both years on the date of Stage 5, just after petal drop and before fruit expansion. In 2007, 'Emerald' reached Stage 5 in the 15 Dec. and 2 Jan. treatments 38 and 44 d earlier than the control, respectively. Although the date of Stage 1 for 'Emerald' was not earlier than the control in the 16 Jan. treatment, Stage 5 was advanced by 30 d. 'Jewel' reached Stage 5 22 to 29 d earlier in the high tunnels than in control plots (Fig. 3). In 2008, fruit of both cultivars in high tunnels also reached Stage 5 earlier than their outdoor counterparts. In 'Emerald', date of Stage 5 in the 15 Dec. and 2 Jan. treatments occurred on 26 and 29 Feb., respectively. This was earlier than the 16 Jan. treatment (11 Mar.), which in turn was earlier than the outdoor control (21 Mar.) (Fig. 3).

In 2007, 'Emerald' required ≈ 105 d to develop from a Stage 1 bud to a ripe fruit (Stage 8), whereas 'Jewel' required ≈ 80 d irrespective of tunnel closure date (Fig. 4). The duration of fruit development in the high tunnels could not be compared with that in outdoor control plots, because no ripe fruit developed outdoors. During 2008, fruit set was not achieved on tagged inflorescences (data not shown) inside tunnels. On 25 Mar. 2008, the minimum temperatures dropped well below the predicted minimum (3°C) and reached -5°C inside of the high tunnels.

Because the predicted minimum was 3°C , the heaters were not turned on. Most flowers inside the tunnels were at Stage 5 at that time, which is the most vulnerable stage for freeze damage (Longstroth, 2002), and fruit development in the high tunnels stopped at this point.

Vegetative development. In 2007, there was no interactive effect of treatment and measurement date on light interception, so only main effects are shown (Fig. 5). The lack of an interactive effect indicates that light interception, an indicator of plant size, was consistently higher in the tunnels (average of 39%) than in the control plots (31%) (Fig. 5). As expected, canopy light interception increased throughout the growing season. Light interception was low and stable in February and March but increased to over 40% by early April, indicating the onset of rapid vegetative growth (Fig. 5). In 2008, there was an interactive effect of treatment and measurement date on light interception. Light interception was similar in all treatments early in the growing season (27 Jan. and 1 Mar.) and late in the season (25 June) but was higher in all of the tunnel treatments compared with control on 20 Mar. and 1 May, indicating more rapid vegetative growth in the tunnels than outdoors (data not shown).

Yield. In 2007, low, early yields were achieved with the use of the high tunnels. Harvesting began on 23 Apr., when an average of 40 g/plant was harvested in the high tunnels (Fig. 6). Early yields (23 and 30 Apr., 7 May) were similar in all tunnel treatments, but both the 2 Jan. and 16 Jan. closure dates resulted in higher yields on 14 May than the 15 Dec. closure date. On 21 May, yield with the 16 Jan. closure date was higher than with the 15 Dec. closure date (Fig. 6). All developing fruits and flowers in the control plots succumbed to freeze damage.

Total yields in 2007, averaged over both cultivars, were 121, 236, and 367 g/plant in the 15 Dec., 2 Jan., and 16 Jan. closure dates, respectively. There were no significant differences in total yield among tunnel treatments as a result of the large variation between replicates, particularly within the 15 Dec. closure date. One of the two tunnels of this treatment had very low fruit set (4%) and yield, possibly as a result of low bumblebee activity in that tunnel. Regression indicated that later tunnel closure resulted in higher yields for 'Emerald' ($r^2 = 0.74$, $P = 0.03$) but not for 'Jewel' (Fig. 6). Fruit set was highly correlated with yield (Fig. 7).

In 2008, there was no fruit set inside any of the high tunnels, likely as a result of freeze damage. There was a low yield of late berries from the outdoor control plots. Two freeze events affected the 2008 crop. A freeze (-11°C in unheated tunnels, -9°C outdoors) on 3 Jan. 2008 was severe enough to damage swollen, undifferentiated 'Emerald' flowers. On 25 Mar., temperatures dropped below the predicted minimum and reached -5°C inside of the high tunnels. The flowers were at a vulnerable development stage, just after petal drop and before fruit expansion, and no

Fig. 3. The effect of high tunnel closure dates on the flower development of southern highbush blueberry cultivars Emerald and Jewel blueberries. Cultivar and high tunnel closure date affected date of Stage 1 (individual flowers can be differentiated) and Stage 5 (petal abscission) during both years of the study ($P < 0.05$). Means with the same letter are not different according to Duncan's multiple range test.

Fig. 4. The effect of high tunnel closure dates on time from the appearance of individual florets (Stage 1) to ripe fruit (Stage 8) of 'Emerald' and 'Jewel' blueberries. The two cultivars differed in the time required from floral initiation to fruit ripening ($P < 0.05$), but high tunnel closure date had no effect. Fruit did not reach Stage 8 in the control plots as a result of the 2007 Easter freeze. Means with the same letter are not different according to Duncan's multiple range test.

Fig. 5. Average light interception by blueberry crops during the growing season as affected by high tunnel closure date (left, averaged overall measurements dates) and changes in light interception during the growing season (right, averaged overall treatments). Light interception was higher in all high tunnel treatments as compared with the control ($P < 0.05$) and increased throughout the season ($P < 0.05$). Means with the same letter are not different according to Duncan's multiple range test ($P = 0.05$).

Fig. 6. The effect of high tunnel closure date on the temporal distribution (left, averaged over both cultivars) and total yield (right, averaged over tunnel closure and harvest dates) of two blueberry cultivars. There was an interactive effect of high tunnel closure date and harvest date on yield/plant. Means within a harvest date with the same letter are not significantly different according to Duncan's multiple range test ($P = 0.05$). Total yield of 'Emerald' increased with later high tunnel closure dates, whereas 'Jewel' yield was unaffected. As a result of freeze damage, there was no yield in the outdoor control plots.

further fruit development was observed after this date. Thus, freeze protection is a critical need for early blueberry production in high tunnels. Similarly, all developing fruit was lost in the high tunnels in the 2008–2009 growing season. Although not part of this study, the high tunnels were managed similarly in 2008–2009 as in the previous two seasons, and the heaters did not provide adequate freeze protection to allow fruit to fully develop.

Fruit quality. Tunnel closure date had no discernible effect on soluble solids or anthocyanin content of the fruit. 'Emerald' had higher soluble solids (12.81 °Brix) than 'Jewel' (11.5 °Brix). Soluble solid content was consistent throughout the harvest period with a range of 11 to 13 °Brix (Table 1; Fig. 8), values normal for southern highbush blueberries grown in high tunnels (Ozeki and Tamada, 2006). Higher anthocyanin concentrations were found in 'Emerald' (1.01 mg·g⁻¹) than in 'Jewel' (0.83 mg·g⁻¹) (Table 1). Anthocyanin concentrations increased throughout the harvest season ($r^2 = 0.98$, $P < 0.001$), from 0.66 mg·g⁻¹ on 23 Apr. to 1.18 mg·g⁻¹ on 28 May (Fig. 8). The fruits of the two cultivars were similar in size, averaging 1.14 g/berry with a diameter of 9.7 mm. Berries in the 16 Jan. closure date were heavier (1.26 g/berry) than those in the 15 Dec. (1.09 g/berry) and 2 Jan. closure dates (1.07 g/berry).

Discussion

The high tunnels affected microclimatic conditions in distinct, consistent ways that induced changes in the flowering and vegetative development of blueberry plants. The high soil and daytime air temperatures facilitated early floral and fruit development. An unforeseen result was the reduction in soil temperature in the tunnel treatments during the hot summer months, when soil temperatures reached superoptimal levels (30 to 35 °C) in the control plots. This reduction in soil temperature in the tunnels was likely the result of increased shading of the pine bark beds by the larger plants inside of the tunnels. This reduction in soil temperature in high tunnels may be beneficial, because root and shoot growth of southern highbush blueberry are reduced at high substrate temperatures and cultural practices that cool the soil during summer may be beneficial for blueberry growth (Spiers, 1995).

Interestingly, the high tunnels did not provide freeze protection. Anecdotal accounts suggested that high tunnels retain heat at night, but this was not the case. On numerous nights, minimum temperatures inside of high tunnels fell 1 to 5 °C below ambient (Fig. 1). Albright et al. (1989) predicted that temperatures under row covers with high long-wave radiation transmittance, low ventilation, and high surface-to-volume ratio will drop below ambient as a result of radiative cooling and lack of convective air movement. The plastic cover used in this study was not treated to block long-wave

Fig. 7. The effect of fruit set on yield of high tunnel-grown blueberries. Percent fruit set correlated strongly with yields. Fruit set was low and yields were low with early tunnel closure dates, whereas later closure dates generated higher percent fruit set and higher yields. Fruit set and yield data were averaged over both cultivars and data represent the averages per tunnel.

Table 1. A comparison of two high tunnel-grown blueberry cultivars with respect to yield and fruit quality characteristics.^z

Cultivar	Yield (g/plant)	Fruit set (%)	Soluble solids (°Brix)	Anthocyanin concn (mg·g ⁻¹)	Fruit size (g/berry)
Emerald	314 a	22.6 b	12.8 a	1.01 a	1.14 a
Jewel	168 a	73.5 a	11.6 b	0.82 b	1.16 a

^zAll data are from the 2006–2007 growing season and are averaged overall harvest dates because of the absence of an interaction between harvest date and cultivar. Significant differences between cultivars were detected with Duncan's multiple range test ($P = 0.05$) and are noted by different letters.

Fig. 8. Blueberry fruit quality characteristics throughout the harvesting season. Harvest date affected soluble solids and anthocyanin concentration. Means with the same letter are not significantly different according to Duncan's multiple range test ($P = 0.05$). Regression analysis showed that anthocyanin content increased linearly with harvest date.

radiation, and the tunnels met the other criteria as well. Our previous finding that high tunnels lose more heat on clear than on cloudy nights (Ogden and van Iersel, 2008) further emphasizes the importance of radiative cooling in the energy balance of high tunnels. Greenhouse plastics designed to block long-wave radiation may be more effective at reducing radiative heat loss from high tunnels. However, we found that a larger high tunnel with a long-wave-blocking plastic (Luminance THB; BPI Agri, Leominster, UK) in south Georgia also did not provide freeze protection (Krewer et al., 2009). The effects of tunnels on air temperature were reflected in leaf and bud temperatures with the daily minimum leaf and bud temperatures

being lower in high tunnels than outdoors (Ogden et al., 2009). In addition to radiative heat loss from high tunnels, pine bark beds lower air temperatures at the plant level by as much as 2.9 °C (Lyrene and Williamson, 2004). Cooling by pine bark beds may be more pronounced inside high tunnels as a result of a lack of convective heat exchange with the surrounding air.

The lack of freeze protection from the high tunnels poses a problem for early blueberry production at locations where freeze events during flower and fruit development are common. Blueberry flowers become increasingly susceptible to freeze damage as their development progresses. A Stage 1 flower can withstand temperatures of –2.2 to –3.8 °C,

whereas a Stage 5 flower is susceptible to damage at –0.5 °C (Longstroth, 2002). Thus, freeze protection is critical to the successful high tunnel production of southern highbush blueberry. Although higher daytime temperatures, which speed up plant growth and development, are the main benefit of high tunnels, an additional benefit is that high tunnels make heating a feasible option for freeze protection. Heating prevented freeze damage in our high tunnels during the 2007 Easter freeze, whereas all outdoor fruits were lost. Similar results were seen on a commercial blueberry farm in south Georgia (our unpublished results).

The tunnels advanced the dates of first flower and petal drop of both cultivars compared with their outdoor counterparts. There was much variation in flower development between the two growing seasons, likely the result of weather differences. Hicklenton et al. (2004) and Renquist (2005) have reported similar variability. The number of days from the appearance of individual flowers to ripening (80 to 105 d) was similar to those reported by Ciordia et al. (2006) for southern highbush cultivars in high tunnels. Although 'Emerald' flowered earlier, its longer development time (Fig. 4) delayed ripening so that it coincided with that of 'Jewel'. Cultivars with a short fruit development period should enable early yields while reducing the period that freeze protection is needed.

Poor synchronization of flower development between cultivars can be problematic in southern highbush blueberry production. Southern highbush blueberry cultivars possess varying degrees of self-incompatibility and benefit from cross-pollination. Benefits of cross-pollination include rapid fruit development, enhanced seed production, and large berry size (Mainland, 1984; Sampson and Spiers, 2002; Williamson and Lyrene, 2004b). 'Emerald' and 'Jewel' were selected for this study based on their synchronization of flowering in south Georgia. Interestingly, in 2007, the cultivars were poorly synchronized in their flowering times, which may have resulted in little cross-pollination, especially with early tunnel closing dates (Fig. 3). Perhaps as a result, fruit set during Spring 2007 was low with the 15 Dec. closure (22%), whereas it increased to 68% with the 16 Jan. closure date. The larger fruit size with the 16 Jan. closure date also may have been the result of more effective cross-pollination. The large difference in time of flowering was not seen in 2008. It is not clear how the difference in age between the cultivars, or the fact that they had been planted recently, may have affected the flowering in 2007. Nonetheless, careful cultivar selection will be important for production of southern highbush blueberries in high tunnels because high yields depend on good fruit set (Fig. 7).

Most cultivars require more chilling for vegetative than for reproductive bud break (Gough, 1994). Thus, floral bud break normally precedes vegetative bud break (Maust et al., 1999). If the reproductive chilling requirement is met, but the vegetative requirement

is not, floral and fruit development may be negatively impacted as a result of a lack of leaves to provide carbohydrates for fruit growth. Newly forming leaves initially act as sinks, using up carbohydrate reserves and competing with fruits (Darnell, 1991). A delay in the onset of vegetative growth resulting from a lack of chilling would only exacerbate this problem. This situation may occur during mild winters in the southeast United States (Mainland, 1984; Williamson et al., 2002) and could be worsened by closing a high tunnel too early, potentially preventing the accumulation of chill hours. The situation is further complicated by the fact that some negation of chilling may occur if high temperatures occur during critical months (Lyrene and Williamson, 2004) as is likely in high tunnels. Although the plants in the 15 Dec. and 2 Jan. closure dates flowered earlier than those in the 16 Jan. closure date, vegetative growth was initiated at similar times in all tunnel treatments. This suggests that synchronization between vegetative and reproductive growth may be disrupted by using an early tunnel closure date.

The increase in anthocyanin content of the fruit over the course of the growing season (Fig. 8) suggests that there may be some loss of quality in early-ripened southern highbush blueberry, although other compounds, including other phenolics, also contribute to blueberry antioxidant strength (Beccaro et al., 2006).

Conclusion

High tunnels modified microclimatic conditions, which resulted in early flower and fruit development and advanced vegetative growth. However, the lack of freeze protection provided by the high tunnels made heating of the high tunnels necessary. In both 2008 and 2009 (the year after this study), the high tunnel crops were lost because of freeze damage. Poor synchronization of flowering, especially in 2007, may also have contributed to low yields. Because growth and development of southern highbush blueberry are closely tied to temperature, microclimatic manipulation can be used to promote out-of-season production. However, effective freeze protection and methods to ensure good fruit set will be necessary to allow early blueberry production in high tunnels.

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