Evaluating High Tunnel and Field Performance of Early Ripening Blueberry Cultivars in Central Alabama

By

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Abstract

Rabbiteye blueberry (*Vaccinium virgatum*) predominantly makes up blueberry production in Alabama. These blueberries typically ripen later in the season toward the end of May and June when market prices are low. Production of southern highbush blueberries (*Vaccinium corymbosum* L.) has great potential to increase market price and give local growers a competitive edge by producing earlier yields. However, risk of spring frost damage will be the most limiting factor for Alabama growers and adequate frost protection will be crucial. 13 one-yr-old southern highbush cultivars grown in 2.84 L containers and 2 rabbiteye cultivars were planted under high tunnel and in open field in Apr. 2022. Blueberry plants were evaluated for berry yield, timing of first berry harvest and peak harvest, individual berry weight and soluble solid content during the 2023 growing season. The high tunnel production system increased monthly maximum air temperature by 0.9 to 5.9 °C, monthly average air temperature by 0.2 to 10 °C, and minimum monthly air temperatures by 0.3 to 0.8 °C. The high tunnel also increased monthly maximum soil temperature up to 1.4 °C higher than the field, monthly average soil temperature up to 1.7°C higher than the field, and minimum monthly soil temp by 0.3 to 11.8 °C compared to the field. Photosynthetically active radiation (PAR) at noon had an average reduction of 15.8% in the high tunnel for 2022 and an average reduction of 24.5% in the high tunnel compared to the field in 2023. All southern highbush cultivars produced first berry harvests in the month of April for both field and high tunnel locations in 2023. The two rabbiteye cultivars both produced first berry harvests in the month of May for both field and high tunnel. Total berry yield ranged from 12.74 g to 607.08 g in the high tunnel while 1.56 g to 159.49 g in field for 2023. ‘Krewer’ produced the greatest average single berry weight (3.2 g) in the high tunnel and ‘Titan’ did in the field (2.5 g). ‘Titan’ also produced berries with the greatest soluble solid content for both high tunnel and field

(15.7% brix and 16.5% brix, respectively). Plant canopy volume (PCV) was 1.65 times greater in the field compared to the high tunnel in 2022, and 1.02 times greater in the high tunnel than field in 2023. Rabbiteye cultivars 'Krewer' and 'Titan' were among the cultivars with the greatest chlorophyll content values throughout the study. Growing southern highbush blueberries under high tunnel advanced blueberry bloom up to 19 days at 10%, 26 days at 50%, and 17 days at 90%, while also advancing first blueberry harvest dates up to 20 days when compared to field production and therefore may serve as a potential production system for early ripening blueberries in central Alabama.

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List of Abbreviations

°C	Degrees Celsius
kg	Kilogram
g	Gram
cm	Centimeter
m	Meter
L	Liter
N	Nitrogen
PAR	Photosynthetically Active Radiation
PPF	Photosynthetic Photon Flux
RH	Relative Humidity
PCV	Plant Canopy Volume
dm^3	Decimeters cubed
SSC	Soluble Solids Content
d	Days
FDP	Fruit development period

CHAPTER I

Literature Review

Vaccinium

Blueberries are a member of the Ericaceae family (Austin, 1994), and are of the genus *Vaccinium* (Trehane, 2004). This genus consists of around 450 species that are distributed worldwide and are commonly found in areas that possess acidic soils (Trehane, 2004). It is thought that the first species of blueberries to be managed were the lowbush species *Vaccinium angustifolium* Ait. and *Vaccinium myrtilloides* Michx. (Eck and Childers, 1996). This belief is held because in eastern North America, the native Americans would burn wild stands of lowbush blueberries to increase their fruit production. Eventually, in the 19th century, European settlers moved in and began to manage the wild stands in the same way (Eck and Childers, 1996). Cultivation of rabbiteye blueberries began near the end of the 19th century (Mowry and Camp, 1928), while Elizabeth White and F.V. Coville are credited with beginning the cultivation of northern highbush blueberries in the early 1900s (Eck and Childers, 1996). The first southern highbush blueberries, based mainly on *V. corymbosum* and *V. darrowi*, were developed by breeders R. Sharpe and W. Sherman and released by the University of Florida in 1975 (Strik, 2006).

Today, in the United States, the most used species for commercial production of blueberries are the lowbush (*Vaccinium angustifolia* Aiton), rabbiteye (*Vaccinium virgatum* Reade), and highbush species (*Vaccinium corymbosum* L.) (Austin and Bondari, 1993). Lowbush blueberry production is geographically limited by its high chilling requirement (Yarborough, 2012), so most commercial lowbush blueberry production occurs in the state of Maine within the

United States and in certain southeastern provinces of Canada (Strik and Yarborough, 2005). Rabbiteye blueberries are native to the southeastern part of the United States and are well adapted to the mild climate (Austin, 1994). Rabbiteye blueberries are the most prominent species grown in the southeastern area because of their tolerance to a mild climate, relatively low chilling requirement that ranges from 300 to 700 hours (Retamales and Hancock, 2012), as well as other benefits such as the possibility of minimal insect and disease control (Esendugue et al., 2008). Highbush blueberries are also native to North America and happen to be the most widely produced native species in the United States (Nesom, 2002). Highbush blueberries can be further split into northern, southern, or intermediate types depending on chill requirements and winter hardiness (Retamales and Hancock, 2012). Northern highbush blueberries are adapted to cold mid-winter temperatures that reach below -20°C and grow anywhere that there are 800 to 1000 hours of chilling available (Retamales and Hancock, 2012). Southern highbush on the other hand does not tolerate winter temperatures much below freezing and has a chill requirement that ranges from 150 to 800 hours depending on the cultivar (Retamales and Hancock, 2012). The southern highbush blueberry was developed by making multiple interspecific crosses between northern highbush and a variety of low-chill *Vaccinium* species (Nishiyama et al., 2021). The introduction of the southern highbush species allows for blueberry production in much warmer areas, like the south, while also possessing the fruit quality that is highly desirable of its highbush parent (Eck, 1988).

Establishment and Production Considerations

There are many factors that growers must consider for successful orchard establishment. Among these factors is selecting a proper location. Blueberries have shallow, fibrous root systems that grow best in well-drained, sandy soils that possess adequate amounts of organic matter (Stafne et al., 2020). Proper soil drainage is essential to sustain blueberry plants. If the water table does not drain to a depth of at least 60.96 cm below the soil surface after a heavy rain, the land is too wet for blueberry production (Puls, 1999). However, raised planting beds with a height of 20.32 to 30.48 cm can be used in slightly wet areas to aid in compensation for the lack of drainage (Stafne et al., 2020). Land topography is another important factor to consider in site selection. It is important to select land that is located on open, elevated sites. This type of location provides the land with the ability to drain excess water, as well as cold air, while also creating a less favorable environment for diseases (Puls, 1999). Reducing the risk of cold air settling is of key importance in the spring when low-chill, early-ripening rabbiteye and southern highbush blueberry cultivars are beginning to bloom and produce fruit (Stafne et al., 2020). Ideal sites for blueberry production consists of virgin soils that have not been farmed before (Fonsah et al., 2008), while old pasture sites or farmland with a pH below 5.5 could be acceptable (Stafne et al., 2020). Sites that are not ideal for blueberry production include recently cleared and burned land as these areas often have high amounts of minerals and salts, as well as a higher pH that could prove detrimental to plants (Stafne et al., 2020).

Blueberries perform best in soils that have a pH of 4.2-5.5, and blueberry growth is often stunted and development delayed when production occurs outside of this range (Puls, 1999). Production in a soil pH below 4.2 can result in nutrient issues, such as nutrient toxicities of manganese and aluminum, or even nutrient deficiencies of calcium, magnesium, copper, boron, and molybdenum (Puls, 1999). On the other hand, iron deficiency symptoms are usually apparent when the soil pH is at or above 5.5. Iron deficiency is characterized by the presence of interveinal chlorosis, or yellowing between leaf veins, of young leaves (new growth). This deficiency presents itself when the pH is above 5.3 on many southern highbush cultivars because the iron present in the soil is in an unavailable form and cannot be taken up by the plant (Krewer and NeSmith, 2006). To amend soils with a high pH, it is recommended to add and incorporate elemental sulfur to the soil. To adjust soils with too low of a pH, add and incorporate dolomitic or calcitic lime (Spiers et al., 1985). The existence of organic matter in soil is of great importance. Soil organic matter provides essential nutrients as it is broken down by microbes, provides habitat for beneficial soil organisms that help fight pests and disease, creates better soil texture, holds water in sandy soils, aids in the drainage of clayey soils, and increases cation exchange capacity (Sawyer, 2021). Common materials added to the soil to increase organic matter in blueberry production includes milled pine bark and peat moss (Himelrick et al., 2002; Puls, 1999; Stafne et al., 2020). It is recommended that soil amendments should be applied six months to one year before planting (Puls, 1999).

It is known that blueberries evolved in areas of low nutrient content, so it is possible for them to survive with a low level of fertilization. However, for increased growth of young plants and greater yields of older plants, a fertilization program is necessary – especially for southern highbush blueberries. Blueberries are a salt-sensitive plant and are often killed by over-fertilization or using the wrong type of fertilizer when they are younger. Fertilizer form is important for blueberry production. Nitrogen in the ammonium form is preferred over the nitrate form (Krewer and NeSmith, 2006). Fertilizer is normally applied to blueberries in the spring when growth begins and again after harvest. However, if fertilizer is to be injected into the irrigation system, it should be done on a weekly basis throughout the growing season (Stafne et al., 2020). For both southern highbush and rabbiteye blueberries during the first year of establishment, Smith and Jacobs (2019) recommend a total of 24.5 kilograms (kg) of nitrogen (N) per acre for plants originally in pots at a spacing of 3.7x0.9 meters (m). Granular fertilization during the establishment year can be split into 4 applications of 6.3 kg N or 6 applications of 4 kg N, while fertigation, which is fertilizing through irrigation, is applied at 0.9 kg N weekly for 27 weeks (Smith and Jacobs, 2019). During years 2 and 3, again for both southern highbush and rabbiteye, 40 kg of total N is recommended. Four applications of granular fertilizer equates to 10.2 kg N per application, while 6 applications of granular fertilizer requires 6.8 kg N. Fertigation over the span of 27 weeks in years 2 and 3 requires 1.4 kg N weekly (Smith and Jacobs, 2019). Finally, after year 3, plants are considered to be at maturity. From then on, southern highbush and rabbiteye blueberries require 45.4 kg of total N each season for commercial production. For granular application, 11.3 kg N is to be applied at budbreak, 11.3 kg N is to be applied 4 weeks after budbreak, and 7.7 kg N is to be applied in three separate applications during postharvest. Fertigation will consist of 1.5 kg N weekly for 27 weeks. (Smith and Jacobs, 2019). Slow-release forms of nitrogen are also available in an ammonium sulfate or sulfur-coated urea form.

For pollination, most *Vaccinium* species normally exhibit partial to complete self-incompatibility (Chaves and Lyrene, 2009). However, evidence shows that highbush blueberries can range from self-compatible (Ehlenfeldt, 2001), partial to completely self-incompatible (Chaves and Lyrene, 2009), parthenocarpic (Ehlenfeldt and Vorsa, 2007), or have earlier ripening berries of larger size with higher fruit set when cross-pollinated (Chaves and Lyrene, 2009) depending upon the cultivar grown. Therefore, pollination recommendations for highbush blueberries should be made based on cultivar-specific requirements. Rabbiteye blueberries, however, are either partially or completely self-incompatible. Hence, rabbiteye cultivars require cross-pollination – a transfer of pollen from one cultivar to another cultivar – to ensure an adequate fruit set (Himelrick et al., 2002). Taber and Olmstead (2016) also determined that in most cases cross-pollination resulted in improved fruit set, fruit weight, and seed number while decreasing the time to harvest in their observations of 13 southern highbush blueberry cultivars, ultimately concluding that interplanting with unrelated cultivars that share a similar window of bloom time, remains the best recommendation to ensure an early, high yield.

The act of pollination is mainly carried out by insects, predominantly bees (Mackenzie, 1997). This is because blueberry pollen is sticky and relatively heavy, so it cannot be moved around easily by the wind like tree pollen. The bell shape of the flower and the position of flower parts also affect the efficiency of pollination. Because of the shape and position of flower parts, pollen cannot fall directly onto a receptive stigma (Yarborough, 2006). Therefore, multiple visits from bees ensures that an ample amount of pollen is moved from flower to flower in order to fertilize blueberry ovules. There are many species of bees, such as bumble bees and solitary bees that are native pollinators of blueberry plants in North America, some species even pollinate blueberries solely (Yarborough, 2006). Most commercial blueberries are pollinated by honeybees, however, there is a possibility that honeybees may prefer other flower sources in range of the intended crop and depart (Batra, 1997). Bees pollinate by carrying pollen on their bodies from flower to flower and leave some behind when probing for nectar. Another way bees pollinate is through sonication. Bumblebees do this by vibrating the flower with their flight muscles as they collect pollen, ultimately shaking the pollen loose from the flower's anthers (Yarborough, 2006). Small production areas may be effectively pollinated by only native bees, but larger areas may require assistance and the placement of honeybee hives to ensure adequate pollination for fruit set.

Proper pruning of blueberries ensures that the plants will become well-established and correctly maintained (Yarborough, 2006). Winter is the best time of the year to do annual pruning once blueberries have lost their leaves and entered dormancy (Yarborough, 2006; Kichler, 2022). Winter pruning for mature plants involves removing shoots at the ground that make the crown of the plant too wide, low-lying branches, and canes that cross others. Larger, older canes should be removed to open the center of the plant, create better air flow, and encourage the development of new fruiting wood. Twiggy clumps of growth and canes that are too tall should also be removed (Kichler, 2022). The pruning of young blueberry plants differs in the first few years from the pruning of mature blueberry plants. Young plants should always be cut back 1/2 to 2/3 of height at the time of planting and all flower buds removed in the first year to promote establishment and vegetative growth. Plants will be allowed to keep some flower buds in year two, but branches that are low-lying, weak, or cross-over should be removed. By year three, the bush should be well-established and able to produce a significant crop (Kichler, 2022). Pruning from year three on will follow the instructions for mature plants that were listed earlier. Blueberry plants may also be pruned over the summer, immediately after harvest, but no later than the beginning of August. This ensures that the plant has ample time to produce new wood that is mature enough to develop fruit buds for the next spring's crop (Stafne et al. 2020).

Rabbiteye blueberries are relatively free of disease problems compared to highbush cultivars, but do occasionally suffer from Botryosphaeria stem blight (*Botryosphaeria dothidea* and other spp.) and certain leaf spot diseases. Southern highbush blueberries are often more susceptible than rabbiteye to fungal, algal, bacterial, and viral diseases. Common fungal diseases of southern highbush include septoria leaf spot (*Septoria albopunctata*), rust (*Naohidemyces vaccinii*), anthracnose leaf spot (*Colletotrichum gloeosporioides*), target spot (*Corynespora cassiicola*), and powdery mildew (*Microsphaera vaccinii*) (Phillips et al., 2019). Management of fungal diseases relies heavily on maintaining good cultural practices. Cultural practices that can help lessen the likelihood and severity of fungal leaf diseases include using drip irrigation compared to overhead, maintaining and pruning bushes to create airflow, and implementing sanitation practices. Fungicide applications can also be made, although it is recommended to practice proper integrated pest management practices and avoid using only one fungicide or active ingredient. There is only one algal disease that impacts southern highbush production, algal stem blotch (*Cephaleuros virescens*). Algal stem blotch is caused by a parasitic green alga and is thought to enter the plant through natural wounds or openings from pruning (Phillips et al., 2019). Important viruses and bacterial pathogens of concern for blueberries include blueberry red ringspot virus, blueberry necrotic ring blotch virus, bacterial leaf scorch (*Xylella fastidiosa*), and bacterial wilt (*Ralstonia solanacearum*) (Phillips et al., 2019).

Some major insect pests of blueberries include the blueberry maggot (*Rhagoletis mendax*), Blueberry gall midge *(Dasineura oxycoccana*), cranberry tipworm (*Dasineura oxycoccana*), spotted wing drosophila (*Drosophila suzukii*), and Japanese beetle (*Popillia japonica*). Common minor pests include blueberry aphids (*Illinoia pepperi*), leaf-footed bugs (*Leptoglossus* spp.), cranberry weevil (*Anthonomus musculus*), blueberry bud mites (*Acalitus vaccinii*), and scale insects (Liburd and Arevalo, 2006; Steck, 2000).

Weed management is the most important during the first two years of establishing a blueberry planting (Stafne et al., 2020). When young blueberry plants are not fully established, they are most susceptible to weed competition. Competition between plants and weeds affects the blueberry's ability to uptake water and nutrients, as well as interfering with spatial resources and the amount of sunlight it can receive (NeSmith and Krewer, 1995). Weed competition can result in stunted growth and increased plant mortality, and prove to be a nuisance when harvesting or completing tasks of orchard maintenance. Lastly, weeds also possess the potential to reduce the aesthetic appeal of an orchard. The aesthetic appeal may not be important to commercial producers but could be of concern for pick-your-own operations that deal directly with the public.

While effective weed control begins 6-12 months before planting by using a combination of herbicides and cultivation, there are some management practices available after planting. Undesirable vegetation in blueberry orchards can be managed using mechanical practices, such as tillage or hand weeding, but tillage should be done carefully to avoid causing damage to the very shallow root systems of blueberries (Himelrick et al., 2002). A thick layer of mulch may also help control weed pressure, conserve moisture, maintain proper soil acidity, and supply organic matter. Organic materials such as well-rotted saw dust, woodchips, pine straw, pine bark, peanut hulls (Himelrick et al., 2002) and pecan shells (Hoppers et al., 2018) may be used as a mulching source. Examples of inorganic mulches include gravel, chipped rubber, plastic, or landscape fabric. However, with using black plastic or landscape fabric as weed mat soil temperature is a key concern. Blueberries have fine, fibrous root systems that are primarily concentrated near the upper portions of the soil profile, which makes the plant more susceptible to drought and higher soil temperatures. Spiers (1995) found that a negative correlation exists between a soil temperature increase from 16 to 38 °C, indicating that blueberries would respond more favorably to cultural practices that lower soil temperature during the warmer growing season. Herbicides may also be used in the management of weeds in a blueberry orchard. When using herbicides, it is always important to follow label instructions carefully and use caution when spraying. Shielded sprayers are best used and spraying on windy days should be avoided. A list of pre-emergence herbicides, post-emergence herbicides, and herbicide programs can be found in the Southeast Regional Blueberry Integrated Management Guide (2023).

Benefits of Growing Highbush Blueberries

Reasons for growers to be interested in producing southern highbush blueberries, beyond climate suitability, can be directly linked to the marketability of the fruit produced. As discussed previously, southern highbush blueberries have a relatively low chilling requirement that allows for early bloom periods. This ultimately results in much earlier harvest times when held in comparison to what is historically grown across the southern region of the United States, rabbiteye blueberries (Stringer et al., 2009). Thus, the earliness of fruit production allows for the opportunity for regional growers to compete in a more lucrative fresh blueberry market (Stringer et al., 2009). For example, producers from the state of Florida acquire nearly twice the price for fresh market blueberries when compared to other states' growers because of the ability to produce in an early harvest window (Eklund, 2016). This early harvest window occurs when blueberry market prices peak during March and April, and before the prices decrease in May, June, and July (Evans and Ballen, 2014). While earliness does help create a competitive edge in the market, fruit quality also plays a great role in marketability. Furthermore, recent surveys show that consumers consider fruit quality to be the most important attribute of fresh market blueberries (Gallardo et al., 2018; Gilbert et al., 2014). Specifically, what consumers have been found to desire the most are berries with sweet and intense flavor, whereas fruit with bad texture characteristics were the most undesirable (Gilbert et al., 2014). These characteristics are qualities that have been taken into consideration across many blueberry breeding programs and are descriptive of many southern highbush cultivars in the market today. In fact, the fruit quality characteristic of firmness has the potential to play an important role in aiding in labor costs. Labor cost and availability are some of the chief concerns of blueberry growers, so the potential for using mechanical harvesters for the fresh market is enticing (Fonsah et al., 2008). Machine, or mechanical, harvest has been used since the mid-twentieth century for lowbush blueberry, highbush blueberry, and rabbiteye blueberry, however the harvested fruit are almost always destined for processed blueberry products because of the potential for fruit damage which ultimately leads to reduced marketability and postharvest shelf life (Olmstead et al., 2013). Nonetheless, newer harvest technologies and cultivars are becoming more available and future studies could show a difference. The older harvesters with side-slapper finger units have been replaced with newer dual vertical-shaft vibrating finger units that function to shake the canopy (Mainland, 1993) as well as over-the-row machine harvester designs with shakers, catcher plates, and conveyor belts (Olmstead et al., 2013). Firm fruit texture increases the likelihood of mechanically-harvested fresh-packed blueberries to be received by buyers with acceptable fruit quality; hence, blueberries that possess the characteristic of a firm fruit texture are incredibly important (Sargent et al., 2013). Southern highbush blueberry cultivars with firm fruit quality that have high potential to be mechanically harvested include University of Florida cultivar releases ‘Bluecrisp’, ‘Indigocrisp’, and ‘Keecrisp’ (Blueberry Breeding and Genomics Lab, n.d.).

Production

Global production of blueberries continues to expand as more and more countries go into production. Between the years 2010 and 2019, global production of blueberries more than doubled, increasing from 439,000 metric tons to almost 1.0 million (United States Department of Agriculture, 2021). According to Brazelton and Strik (2007), highbush blueberries are produced across North America, Europe, South America, Asia, as well as in South Africa, Australia, and New Zealand. Recent data shows that not only is the United States the largest blueberry-producing country, but also among the top consumers. However, it is important to note that Peru is the world's leading exporter and the fourth-largest producer behind the United States, Canada, and Chile (United States Department of Agriculture, 2021).

There are 26 states within the U.S. that commercially produce blueberries, however more than 98 percent of that production happens within 10 states. Major state producers include Oregon, Washington, Georgia, Michigan, California, New Jersey, North Carolina, Florida, Texas, and Minnesota (U.S. Highbush Blueberry Council, n.d.). Of the southeastern region, Georgia and Florida are the two most productive states. In 2019, Georgia had 21,700 acres of blueberry production, while Florida had 5,100 acres (United States Department of Agriculture, National Agricultural Statistics Service, 2020). According to data taken in 2017, the state of Alabama had a total of 834 acres of blueberries (United States Department of Agriculture, National Agricultural Statistics Service, 2017). Because of favorable environmental conditions, southern highbush grow well in regions of southeastern Georgia and in Florida. Alabama's environmental conditions are not quite as favorable with increased likelihood of spring frosts, perhaps warranting the use of a protective structure such as a high tunnel.

Production Challenges

Spring frost is the most limiting factor for blueberry production in the southeast. Cold damage to small fruit crops occurs commonly and can cause major economic losses (Warmund et al., 2008). A frost occurs when the air temperature measures less than or equal to 0 °C (32 °F) and ice crystals form on the surface of the plant (Snyder et al., 2005). There are two separate types of freezes that could occur: advective and radiative. Advective freezes occur when a large mass of cold air moves into a region with windy atmospheric conditions. These windy conditions cause cool air to mix in the upper atmosphere resulting in temperatures that could be less than 0 °C (32 °F) and freeze protection measures are often not effective (Snyder et al., 2005).

Conversely, radiative freezes occur on calm, clear nights with little to no wind. During radiative freezes temperatures from the day measure above freezing causing the ground to absorb heat from the sun. During the night, the heat from the ground radiates back into the atmosphere resulting in the ground cooling once more. As the ground cools, the cold air forms a layer under the warm air creating an inversion (Langstroth, 2015). Heaters, wind machines, irrigation, and row covers are all means of freeze protection. All freeze protection practices come with benefits and disadvantages. Heaters perform well but are mostly designed to run on oil or fuel. With the current cost of fuel, this may not be an attractive strategy for protection for farmers. Wind machines work best in radiative events by mixing the warm and cool air for a net benefit of warmer air at the canopy level. Overhead irrigation has the potential to be the cheapest option but is not always feasible. Overhead irrigation functions as freeze protection by replacing heat lost from the plant as the applied water turns to ice. As the water turns to ice, it releases latent heat at the plants surface in a process called latent heat of fusion. However, for this to work water has to be continuously applied at an adequate rate until freezing temperatures subside (Smith et al., 2023). The part that is not always feasible, or can be limiting with running overhead irrigation, is having access to enough water to effectively prevent damage in the orchard. Row covers can be placed directly over the crop and have been used to increase the air temperature under the cover compared to the outside temperature with varying success (Smith et al., 2023). Using a combination of the frost protective measures mentioned above could also be beneficial to producers.

High Tunnels

High tunnels are structures made from pipe or galvanized tubing that are covered in a single or double layer of plastic. These structures differ from greenhouses in that they have no electrical service, automated ventilation, or heating (Lamont, 2009). High tunnels are passively heated and cooled. Passive heating and cooling is obtained by rolling up or down the side walls of the structure. High tunnels can range in size and shape and are used in protected culture all around the world. High tunnels have been extensively used in Europe and the Middle East for the production of vegetables, cut flowers, and other high-value horticultural crops (Wells and Loy, 1993; Wittwer and Castilla, 1995). Recently, an interest in the production of small fruits under high tunnels has taken off. In the United States and Canada, producers are using high tunnels to grow raspberries, blackberries, strawberries, and blueberries (Demchack, 2009).

Production under high tunnels can provide many benefits to the grower. High tunnels allow for some control over environmental conditions such as wind, moisture, temperature, and light intensity, and the ability to lower the rates of some weeds, insects, and diseases (Wells and Loy, 1993; Wittwer and Castilla, 1995). In Japan, Tamada and Ozeki (2012) found that high tunnels help prevent fruit cracking, which is normally caused by rainfall on ripe berries. Similarly, Lang (2013) found this to be true for protecting ripening cherries under high tunnel in Michigan. Not only can high tunnels prevent damage from wind and rain, but also shelter plants to avoid damage from hail or even prevent feeding damage from birds. Another benefit that is highly sought after with protected culture is the prevention of freeze or frost damage. In a study on strawberries in Kansas, Kadir et al. (2006) found the microclimate of a high tunnel to protect strawberry crowns from winter cold damage. High tunnels also elevate air temperature which in return increase growing degree days. An increase in growing degree days can extend a growing season into early spring, advance blooming, and expedite fruit ripening (Li and Bi, 2019). In a Chilean high tunnel study, Retamal-Salgado et al. (2015) found the high tunnel to reduce photosynthetically active radiation by an average of 25% in sunny conditions which can favor leaf stomatal conductance in blueberry plants. Common concerns of high tunnel production include cost, labor, and high-temperature stress on plants, where the addition of shade cloth might be recommended.

Production of small fruit can also be successful in high tunnels in other ways. In raspberries, high tunnel production allowed growers to extend the crop's season into colder, non-traditional production months and access off-season markets to obtain higher prices (Demchack, 2009; Gaskell, 2004). Lang (2009) studied the performance of cherry under high tunnel and found that a warmer, wind-protected environment resulted in more rapid, healthier plant growth as well as fruit with larger sugar concentrations and of greater size when covering trees compared to open field production. Kadir et al. (2006) and Salame-Donoso et al. (2010) demonstrated that strawberry leaf area and number, shoot biomass, and soluble solid content improved when grown under high tunnels.

Previous studies with southern highbush blueberry conducted in Italy, Portugal, and Japan demonstrated that production could range from 1 week to 1 month earlier when grown under high tunnels compared to open-field production (Baptista et al., 2006; Ciordia et al., 2002; Ozeki and Tamada, 2006). Similarly, Santos and Salame-Donoso (2012) found that fruit earliness was increased by almost 4 weeks under high tunnel in Florida, while Li and Bi (2019) found that southern highbush blueberry harvest could be increased to as early as April in Mississippi, 4 to 5 weeks earlier than their traditional open-field production of rabbiteye blueberries. Ogden and van Iersel (2009) found that high tunnels could advance dates of first flower and petal drop of two southern highbush cultivars in Georgia, however the high tunnel did not provide adequate freeze protection. Ogden and van Iersel (2009) experienced the opposite of what is commonly observed. Instead of retaining heat at night, minimum temperatures inside the high tunnel would drop 1 to 5 °C below ambient temperatures. They believe the polyethylene film lost heat throughout the night due to radiative cooling and a lack of convective air movement. In addition, Ogden and van Iersel (2008) also found that high tunnels lose more heat on clear nights in comparison to cloudy nights, which further emphasizes the importance of radiative cooling and the balance of energy in high tunnel production. A lack of freeze protection for earlier flowering blueberry cultivars is a major problem for locations that suffer from late spring frost events. Blueberries become more susceptible to cold damage as flower bud development progresses (Spiers, 1978). Critical temperatures for flower buds begin at stage 2, when plants are considered to be in bud swell and can usually tolerate temperatures of -12 to -9 °C (Michigan State Univ. Ext., n.d.). Whereas plants that are in stage 7, petal fall, are likely to be damaged at 0 °C (Michigan State Univ. Ext., n.d.). Ogden and van Iersel (2009) suggest the use of cost-efficient heaters, such as propane heaters, be used in conjunction with high tunnels to mitigate frost damage. In contrast, Li and Bi (2019) found that the high tunnel used in their study did provide some frost protection by increasing the minimum air temperature inside the high tunnel up to 3.0 °C during freeze events when compared to ambient air temperature outside the structure. Li and Bi (2019) believe this difference may be due to having a larger sized high tunnel compared to the high tunnel used by Ogden and van Iersel (2009) as well as opening of the high tunnel sides when daytime temperatures reached higher than 4.4 °C compared to leaving the high tunnel closed on 15 Dec., 2 Jan., and 16 Jan. and not opening until temperatures exceeded 16 °C. While Santos and Salame-Donoso (2012) also reported that their high tunnel provided freeze protection, but in conjunction with overhead irrigation. The high tunnel also decreased the amount of water needed for freeze protection. As far as fruit quality, Ogden and van Iersel (2009) found no observable effect on soluble solids or anthocyanin content of fruit between high tunnel closing dates.

Cultivar descriptions

'Arcadia' is a mid-season southern highbush blueberry released by the University of Florida's Institute of Food and Agricultural Sciences (UF/IFAS) blueberry breeding program in 2015 (Blueberry Breeding and Genomics Lab, n.d.). 'Arcadia' produces a large-sized fruit with medium color and a less than ideal fruit firmness. The lack of fruit firmness as well as the spreading structure of the plant, make 'Arcadia' a less than likely candidate for machine harvesting (Blueberry Breeding and Genomics Lab, n.d.). However, when grown in evergreen production systems, 'Arcadia' has the possibility of a very long harvest window (Blueberry Breeding and Genomics Lab, n.d.). 'Arcadia' has a chill requirement of less than 200 hours and 50% harvest can be seen around the end of April in regions of central Florida (Florida Foundation Seed Producers, Inc., n.d.) The average soluble solids content for 'Arcadia' is 11.3° brix and the average berry weight is 2.4 g (Blueberry Breeding and Genomics Lab, n.d.). While no known insect damage has been observed to date, 'Arcadia' has shown disease susceptibility toward *Ralstonia* (Blueberry Breeding and Genomics Lab, n.d.).

'Avanti' is another southern highbush cultivar that was released by the University of Florida's blueberry breeding program in 2015 (Blueberry Breeding and Genomics Lab, n.d.). 'Avanti' is a low-chill, early flowering and ripening cultivar that has a chilling requirement of 100 hours (Florida Foundation Seed Producers, Inc., n.d.). These plants produce a sweet, firm berry with a small, dry picking scar. No data has been recorded yet for machine harvestability, but the characteristic of berry firmness suggests a great possibility (Blueberry Breeding and Genomics Lab, n.d.). Fruit size starts out as medium but may become smaller toward the end of the season (Florida Foundation Seed Producers, Inc., n.d.) ‘Avant’ has an average soluble solids content of 12.0° brix and an average berry weight of 2.2 g (Blueberry Breeding and Genomics Lab, n.d.). Known disease and insect damage recorded by the Blueberry Breeding Genomics Lab includes algal stem blotch and southern red mite damage.

‘Bluecrisp’, is a southern highbush cultivar released by the University of Florida’s blueberry breeding program in 1999 (Lyrene, 1999). ‘Bluecrisp’ displays medium to high vigor and has a growth habit that ranges from upright to spreading. The chilling requirement for plants of ‘Bluecrisp’ need approximately 400 hours below 7 °C for spring blooming and leafing. In north-central Florida, ‘Bluecrisp’ has a 60-day ripening period after bloom (Lyrene, 1999). The average mid-harvest date for this cultivar occurs on May 2nd in Gainesville, Florida, but to achieve this ‘Bluecrisp’ must be planted with other cultivars to encourage cross-pollination since it is only partially self-compatible (Lyrene, 1999). Fruit of ‘Bluecrisp’ are large, sweet, crisp textured berries that are excellent for shipping (Blueberry Breeding and Genomics Lab, n.d.). ‘Bluecrisp’ had an average berry weight of 1.28, 0.94, and 1.52 g in 2006, 2007, and 2008, respectively (Andersen et al., 2008). Likewise, in 2006, 2007, and 2008, ‘Bluecrisp’ had an average soluble solid content of 15.2, 13.3, and 16.3 °brix (Andersen et al., 2008).

‘Chickadee’, a southern highbush cultivar, introduced by the blueberry breeding program at the University of Florida in 2010, is a very early season producer with high-quality fruit that is perfect for Florida’s market window (Blueberry Breeding and Genomics Lab, n.d.). The plant possesses a strong, upright growth habit with a narrow base and is highly vigorous (Lyrene, 2010). The chill requirement for ‘Chickadee’ is 100 hours and plants have a low to medium degree of self-fruitfulness. The mean date for first harvest occurs on April 5th, mid-harvest occurs on April 15th, and last harvest on April 25th in central Florida (Lyrene, 2010). Fruit harvested from ‘Chickadee’ is very firm, sweet with low acidity, and has good texture (Lyrene, 2010). The average soluble solids content for fruit of ‘Chickadee’ is 10.5° brix and the average berry weight is 2.1 g (Blueberry Breeding and Genomics Lab, n.d.). ‘Chickadee’ tends to have a thin canopy and may not respond well to hard pruning once it matures as well as an above-average tendency to topple over when using overhead irrigation as freeze protection (Blueberry Breeding and Genomics Lab, n.d.; Lyrene, 2010).

‘Colossus’, a cross between unpatented parents, ‘FL08-35’ and ‘FL04-103’, is a southern highbush blueberry cultivar released by the University of Florida in 2021 (Lyrene and Olmstead, 2021). ‘Colossus’ possesses a semi-bushy to semi-upright growth habit and requires 150 hours of chilling (Lyrene and Olmstead, 2021). ‘Colossus’ has a low to medium degree of self-fruitfulness and appears to be tolerant of spider mites (Lyrene and Olmstead, 2021). ‘Colossus blooms somewhat later but has a short bloom to ripening period with very well-concentrated ripening and early natural leafing. Fruit is also very firm with an average soluble solids content of 12.3° brix and an average berry weight of 2.8 g (Blueberry Breeding and Genomics Lab, n.d.).

‘Farthing’ is another southern highbush cultivar that was released out of the University of Florida in 2007 (Lyrene, 2008). ‘Farthing’ is a highly vigorous cultivar with a growth habit that is characterized by an upright and spreading architecture. This cultivar produces a dense canopy with a medium to high tendency toward evergreeness (Lyrene, 2008). ‘Farthing’ has a chilling requirement of 300 hours below 7 °C with a cold hardiness to -3 °C when flowers and fruit are present. According to its patent, ‘Farthing’ produces 2267.96 to 4535.92 g of berries per bush on plants that are 3 years old and older in northeast Florida (Lyrene, 2008). ‘Farthing’ has a mean date of April 20th for its first commercial harvest, a mean date of May 4th for mid-harvest, and a mean date of May 20th for last harvest. Fruit of ‘Farthing’ have a medium cluster tightness, highly firm fruit, a sweet, subacid flavor, and good texture with small seeds (Lyrene, 2008). The average soluble solids content of 'Farthing' is 11.8° brix and the average berry weight is 2.2 g (Blueberry Breeding and Genomics Lab, n.d.). 'Farthing' has a self-fruitfulness rating that is higher than most southern highbush blueberry cultivars from Florida (Lyrene, 2008). 'Farthing' is susceptible to algal stem blotch disease and some susceptibility to midge injury has been observed (Blueberry Breeding and Genomics Lab, n.d.).

'Gumbo' is a southern highbush blueberry cultivar released by the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) and Mississippi Agricultural and Forestry Experiment Station in 2018 (Stringer et al., 2018). 'Gumbo' is characterized by having very high vigor and a growth habit of moderately spreading with the tendency for multiple canes to sprout from the ground (Stringer and Draper, 2018). Another plant characteristic for growers to be aware of is the surface texture of 'Gumbo's' canes. The surface texture of canes that are less than 3 years old are smooth, but canes that are 3-4 years old can exhibit a rough texture with flaking bark. However, as the canes get older, they become nearly smooth once again (Stringer and Draper, 2018). 'Gumbo' has a chilling requirement of approximately 350-400 hours below 7 °C. This cultivar has a low to moderate degree of self-compatibility and should be grown with other cultivars. 'Gumbo' begins flowering around March 3rd in south Mississippi, reaches 50% bloom on March 17th, and 90% bloom by March 27th. 'Gumbo' has a fruit development period of 60 to 65 days and on average has 10% ripe berries on May 11th, 50% on May 22nd, and 90% ripe by June 1st (Stringer and Draper, 2018). Fruits of 'Gumbo' have good firmness, mild flavor, soluble solids content of 11.6° brix, and average berry weight of 2.1 g (Stringer and Draper, 2018). 'Gumbo' has shown to be more tolerant to septoria leaf spot when compared to other southern highbush cultivars (Stringer and Draper, 2018).

‘Indigocrisp’ is a southern highbush blueberry cultivar released by the University of Florida in 2013. ‘Indigocrisp’ has medium plant vigor, an upright growth habit, and a low to medium tendency towards evergreeness (Lyrene, 2015). ‘Indigocrisp’ has a chilling requirement of 300 hours below 7 °C and a mean date of 50% bloom on February 13 in central Florida (Lyrene, 2015). The mean date of first commercial harvest for ‘Indigocrisp’ is April 15th, while the mean date for mid-harvest is April 25th, and the mean date of last harvest is May 5th. Fruit of ‘Indigocrisp’ are extremely firm, sweet with very low acid, and a very crisp texture with small seeds (Lyrene, 2015). ‘Indigocrisp’ has an average soluble solids content measurement of 12.1° brix and an average berry weight of 2.5 g (Blueberry Breeding and Genomics Lab, n.d.). This cultivar has a known disease susceptibility to botryospheria stem blight (Blueberry Breeding and Genomics Lab) and phytophthora root rot (Lyrene, 2015).

‘Keecrisp’ is also a southern highbush blueberry cultivar that was released by the University of Florida in 2016. ‘Keecrisp’ has great plant vigor with an upright growth habit (Lyrene and Olmstead, 2017). ‘Keecrisp’ has a requirement of 300 hours below 7 °C to fulfill chilling and break dormancy. ‘Keecrisp’ has a low to medium degree of self-fruitfulness and therefore should be planted with other southern highbush varieties to promote cross-fertilization and ensure fruit set. 50% harvest occurs May 5th in Citra, Florida for this cultivar and fruit is very firm, has a sweet flavor with a low acid ratio, and crisp, crunchy texture (Lyrene and Olmstead, 2017). The average fruit soluble solid content is 12.1° brix and berry weight average is 2.5 g (Blueberry Breeding and Genomics Lab, n.d.). According to the plant patent, ‘Keecrisp’ appears to be tolerant to stem blight and root rot, but does experience leaf spots common to other blueberry varieties. ‘Keecrisp’ also experiences susceptibility towards common insects and mites, such as spotted wing drosophila, blueberry gall midge, and blueberry bud mite (Lyrene and Olmstead, 2017).

‘Krewer’ is a new rabbiteye blueberry cultivar released by the University of Georgia in 2017. ‘Krewer’ has a growth habit that is highly vigorous and strongly upright (NeSmith, 2017). ‘Krewer’ exhibits a high crop yield that averages 6803.89 to 9071.85 g of fruit per plant for plants that are 4 years and older. This rabbiteye cultivar has a chill requirement of 400 to 450 hours and a date of 50% bloom on March 16th in southern Georgia and March 24th in middle Georgia (NeSmith, 2017). According to the plant patent, ‘Krewer’ has a small degree of self-compatibility and a fruit development period of 74 to 84 days (NeSmith, 2017). Fruit of ‘Krewer is very large (~3.0 g) with good texture, good flavor, and a medium to high seed abundance. The average soluble solids content for ‘Krewer’ is 12.9% brix (NeSmith, 2017). While, in a cultivar trial at Auburn University’s Chilton Research and Extension Center, ‘Krewer’ exhibited an average soluble solids content of 13.2° brix in the year 2020, and a mean berry size of 3.0 g (Coneva, 2021).

‘Legacy’ is a southern highbush blueberry cultivar that was released by the USDA-ARS in conjunction with the New Jersey Agricultural Experiment Station, Rutgers University in 1993. ‘Legacy’ is vigorous in growth with an upright plant structure (USDA-ARS, 2016). The chill requirement for ‘Legacy’ is estimated to be 700 to 800 hours with first bloom beginning April 1st in southeastern North Carolina (Cline, 2011). In southeastern North Carolina first harvest occurs around May 30th to June 3rd. Fruits of ‘Legacy’ are medium sized, light blue, and firm with excellent flavor (Cline, 2011). Carter et al. (2002) found that berry weight of ‘Legacy’ remained similar from year to year and tended to have smaller berries. Average single berry weight of

‘Legacy’ weighs 1.1 g (Carter et al., 2002). ‘Legacy’ has been observed to be susceptible to blueberry stem canker disease, *Botryospheria cortices*. Irrigation and selective pruning is advised to manage this disease (Cline, 2011).

‘Meadowlark’, a southern highbush blueberry cultivar, was released by the University of Florida in 2010. Plants of ‘Meadowlark’ are highly vigorous with a strongly upright growth habit (Lyrene, 2010). ‘Meadowlark’ has a chilling requirement of 200 hours below 7 °C and a low to medium degree of self-fruitfulness. In northeast Florida, ‘Meadowlark’ produces 5 to 8 pounds of berries per bush once mature. The first date of commercial harvest for ‘Meadowlark’ is April 10^{th}, mid-harvest occurs on April 24^{th}, and last harvest takes place on May 5^{th} (Lyrene, 2010). Flower and fruit clusters on ‘Meadowlark’ are very open and loose due to long pedicles and peduncles, which is a characteristic given by the presence of sparkleberry (*Vaccinium arboreum*) in the cultivar’s genetic makeup (Blueberry Breeding and Genomics Lab, n.d.). Fruits from ‘Meadowlark’ have a mild flavor with a good balance between sugar and acid. Soluble solids content averages 10.9° brix and fruits have high firmness (Blueberry Breeding and Genomics Lab, n.d.). ‘Meadowlark’ berry weight ranges from 2.1 to 3.0 g, but averages 2.5 g (Blueberry Breeding and Genomics Lab, n.d.). ‘Meadowlark’ shows susceptibility to bacterial leaf scorch and blueberry red ringspot virus but appears to have above-average resistance to root rot and stem blight (Blueberry Breeding and Genomics Lab, n.d.; Lyrene, 2010).

The southern highbush cultivar ‘New Hanover’ was released by North Carolina State University in 2007 with a requirement of 500 to 600 chilling hours (National Cooperative Extension, 2019). ‘New Hanover’ has a semi-upright growth habit and produces flowers that are self-fertile (Ballington and Rooks, 2009). In North Carolina, date of first bloom occurs on March 5^{th} and 50% bloom occurs on April 1^{st}, while fruit ripening occurs early to mid-May (National

Cooperative Extension, 2019; Ballington and Rooks, 2009). Fruits of ‘New Hanover’ range in size from large to very large and have very good firmness and flavor (National Cooperative Extension, 2019). ‘New Hanover’ has an average weight per berry at 2.0 g (Ballington and Rooks, 2009).

‘Optimus’ is a southern highbush blueberry cultivar released by the University of Florida in 2020 that has high plant vigor and a semi-upright growth habit (Lyrene and Olmstead, 2020). ‘Optimus’ requires 200 hours of chilling and has a low to medium degree of self-fruitfulness. The mean date for mid-harvest on ‘Optimus’ is April 11th in central Florida and mature plants yield an average of 6.7 pounds of fruit per plant (Blueberry Breeding and Genomics Lab, n.d.; Lyrene and Olmstead, 2020). Fruit harvested from plants of ‘Optimus’ have an average soluble solids content of 12.3° brix, are sweet with a hint of acid, have an average berry weight of 1.7 g, and are medium sized with good texture (Blueberry Breeding and Genomics Lab, n.d.).

Finally, ‘Titan’ is a rabbiteye blueberry cultivar that was released by the University of Georgia in 2014. ‘Titan’ has a semi-upright growth habit and is highly vigorous. To exit dormancy and induce flowering and leafing, ‘Titan’ requires 500 to 550 hours of chilling at or below 7 °C (NeSmith, 2014). Plants of ‘Titan’ exhibit a low degree of self-compatibility and should be planted with other cultivars to ensure cross-pollination. ‘Titan’ has a fruit development period of 73 to 77 days with an average first date of harvest on May 25th for southeast Georgia and June 12th for middle Georgia (NeSmith, 2014). Berries are large with sweet flavor. In a study conducted at the Chilton Research and Extension Center in Alabama, the average soluble solids content measured 12.0° brix in the year 2020 and 12.3° brix in the year 2021 with an overall mean berry weight of 2.9 g (Coneva, 2021). There have been no notable disease resistances or susceptibilities, however, ‘Titan’ is very susceptible to fruit cracking under wet conditions (NeSmith, 2014).

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CHAPTER II

Evaluating High Tunnel and Field Performance of Early Ripening Blueberry Cultivars in Central Alabama

Introduction

Blueberry (*Vaccinium* spp.) is an important small fruit crop for the United States. In 2021, United States blueberry growers led the world in total volume of blueberry production with a total harvest of 774.1 million pounds (Morgan, 2022). While blueberry bushes possess the ability to be grown all over the United States, there are only a total of 26 states that commercially produce blueberries (U.S. Highbush Blueberry Council, n.d). The majority of this production occurs in just 10 states. These states geographically span from coast to coast and aid in providing fresh blueberries for market from April through October along with other regions of North America. (U.S. Highbush Blueberry Council, n.d.). Currently, fresh blueberries are imported from South America to the U.S. once North American production slows to fill the gap and allow for year-round availability; this mainly occurs from November to March (U.S. Highbush Blueberry Council, n.d.). Evans and Ballen (2014) reported that blueberry market prices peaked and dropped twice throughout the year, with the highest wholesale blueberry prices occurring early in the season from March to April and then again later from September to October. In the southeast United States, Florida and Georgia growers primarily produce southern highbush blueberries (*Vaccinium corymbosum* L. interspecific hybrids) for the early spring market window to garner higher wholesale prices compared to summer prices.

Meanwhile, Alabama produces blueberries on a total of 834 acres (USDA, 2017), much of which is supported by the cultivation of rabbiteye blueberries (*Vaccinium virgatum* A.). The rabbiteye blueberry ripening period generally occurs from late May to July, aligning with peak domestic blueberry production. Unfortunately, this also leads to a sale window with some of the lowest market prices (Evans and Ballen, 2014). A potential solution to meeting an earlier market window and allowing regional growers to compete for higher prices could be through the production of southern highbush blueberries. Southern highbush cultivars have a relatively low chilling requirement that ranges from 150 to 800 hours (Retamales and Hancock, 2012). The low-chill requirement of many southern highbush cultivars allows for flowering and fruiting to occur much earlier in the season, but increases the risk of spring frost injury. Due to the increased risk of spring frost injury inherent in southern highbush production, blueberry producers in Alabama and Mississippi primarily grow the later flowering rabbiteye blueberries.

While the solution may seem to be to continue to primarily grow the later flowering rabbiteye blueberry species, avoid the risk of freeze damage, produce a later crop and receive lower market prices, that is not always guaranteed. In some years Alabama blueberry producers can benefit from mostly growing rabbiteye blueberries. For example, in 2022, growers in southwest Alabama avoided spring frost injury and had an outstanding crop compared to some of their contemporaries in neighboring states like Florida and Georgia (Thompson, 2022). However, in 2023, those same growers in southwest Alabama suffered from devastating sub-freezing temperatures in March that ultimately resulted in crop failure (Thompson, 2023).

The ultimate solution would be to provide adequate freeze protection using effective passive and active systems. Passive protection includes proper attention to site selection, soil type, cultivar selection, nutrition, orchard floor management, pruning, application of chemical growth regulators, and plant covers. While active practices include wind displacement devices, heating, and irrigation (Powell and Himelrick, 2000).

Another option for frost protection that is of recent interest is the use of a high tunnel. High tunnels are structures made from pipe or galvanized tubing that are covered in a single or double layer of plastic. These structures differ from greenhouses in that they have no electrical service, automated ventilation, or heating (Lamont, 2009). High tunnels are passively heated and cooled by rolling up or down the side walls of the structure. In addition, portable heaters can be incorporated into high tunnels effectively to avoid injury during potentially damaging freeze events (Ogden and van Iersel, 2009).

Production under high tunnels can provide many benefits to the grower. High tunnels allow for some control over environmental conditions such as wind, moisture, temperature, and light intensity, and the ability to lower the rates of some weeds, insects, and diseases (Wells and Loy, 1993; Wittwer and Castilla, 1995). In Japan, Tamada and Ozeki (2012) found that high tunnels help prevent fruit cracking, which is normally caused by rainfall on ripe berries. Similarly, Lang (2013) found this to be true for protecting ripening cherries under high tunnel in Michigan. In a study on strawberries in Kansas, Kadir et al. (2006) found the microclimate of a high tunnel to protect strawberry crowns from winter cold damage. In raspberries, high tunnel production allowed growers to extend the crop’s season into colder, non-traditional production months and access off-season markets to obtain higher prices (Demchack, 2009; Gaskell, 2004). Lang (2009) studied the performance of cherry under high tunnel and found that a warmer, wind-protected environment resulted in more rapid, healthier plant growth as well as fruit with larger sugar concentrations and of greater size when covering trees compared to open field production.

In southern highbush blueberry, previous studies from Italy, Portugal, and Japan show that production could be from 1 week to 1 month earlier when grown under high tunnels compared to open-field production (Baptista et al., 2006; Ciordia et al., 2002; Ozeki and

Tamada, 2006). Similarly, Santos and Salame-Donoso (2012) found that fruit earliness was increased by almost 4 weeks under high tunnel in Florida, while Li and Bi (2019) found that southern highbush blueberry harvest could be increased to as early as April in Mississippi, 4 to 5 weeks earlier than their traditional open-field production of rabbiteye blueberries.

The production of some southern highbush blueberries cultivars under high tunnels has been studied in many surrounding states, such as Georgia (Ogden and van Iersel, 2009), Florida (Santos and Salame-Donozo, 2012), and Mississippi (Li and Bi, 2019) with varying results. There are many recently released and older southern highbush cultivars that may be feasible for either field or high tunnel production in central Alabama that have not been evaluated in this region. The objective of this study was to evaluate the performance of 15 early ripening blueberry cultivars, 13 southern highbush cultivars and 2 rabbiteye cultivars, when grown for 2 years under high tunnel and field conditions in central Alabama.

Materials and Methods

Site Description

In March of 2022, a field and high tunnel planting of early ripening blueberry cultivars was installed at Auburn University's E.V. Smith Research Center at the Plant Breeding Unit in Tallassee, Alabama (latitude: 32.4967N. longitude: 85.8905W). The primary soil type consisted of Kalmina loamy sand with an initial pH of 5.6 (Auburn University Soil, Forage, and Water Testing Laboratory, Auburn, AL). The land was previously used for row crop production.

Site Preparation

Site preparation began in January of 2022 prior to the installation of the high tunnel. Soil was amended by incorporating elemental sulfur and 15 cm of pine bark. Raised beds were then pulled at a height of approximately 15.2 cm and top dressed with an additional 2 cm of pine bark before being covered by black landscape fabric. Soil tests, taken 8 months after soil amendments were made, showed the amendments lowered the soil pH from 5.6 to around 4.8 to 5.2 (Auburn University Soil, Forage, and Water Testing Laboratory, Auburn, AL). The raised beds ran north to south and were 29.26 m long under the high tunnel and 56.69 m long in the field. The raised beds were spaced 2.4 m apart measured from center to center of bed. This spacing allowed for four raised beds to be pulled under the high tunnel, while two raised beds were pulled in the field. Plants were spaced 0.91 m apart within the rows. Planting holes in landscape fabric were created by cutting an x with hot knives to ensure the fabric would not fray. Irrigation was installed above the landscape fabric, assigning one micro emitter head per plant and spaced approximately 10.2 cm from the base of each plant. Each drip emitter delivered 1.9 L $hour^{-1}$. Plants used in this study consisted of one-year-old 2.84 L (1 trade gal) southern highbush blueberry (*Vaccinium corymbosum* L. interspecific hybrids) cultivars 'Arcadia', 'Avanti', 'Chickadee', 'Farthing', 'Gumbo', 'Indigocrisp', 'Keecrisp', 'Legacy', 'Meadowlark', 'New Hanover', and 'Optimus' (Island Grove Ag Products, Winter Haven, FL), and two rabbiteye blueberry (*Vaccinium virgatum*) cultivars, 'Krewer' and 'Titan' (Bottoms Nursery, Concord, GA). Southern highbush cultivars 'Bluecrisp' and 'Colossus' (Island Grove Ag Products, Winter Haven, FL) were also planted in this study, but were younger plants and therefore much smaller in size when held in comparison to the one-year-old southern highbush and rabbiteye cultivars (Fig. 2.1).

The high tunnel installation was completed in March of 2022. The high tunnel (Atlas Greenhouse, Alapaha, GA) had a gothic arch design and was covered with a single layer of 0.15 mm clear polyethylene plastic. The high tunnel was positioned on a north/south longitudinal axis, and its dimensions were 9.1 m W x 29.3 m L x 4.3 m H. The high tunnel was equipped with side curtains that ran the total length of the structure as well as 4.9 m W x 2.4 m H front curtains that rolled up to allow for passive cooling.

Crop Management

All blueberry plants were pruned back 1/2 to 2/3 of their height at the time of planting in the first year. All flower buds and blooms were removed upon planting as well to encourage vegetative growth and aid in establishment. Additional pruning occurred in November of 2022 to remove any low-lying, weak, unproductive shoots for the next year. In the second year, 2023, a few excessively tall shoots were pruned shorter to avoid any breakage due to weight in June. Irrigation was scheduled to occur three times a day at 45-minute periods during the spring and summer months. Irrigation events were lowered down to twice a day during the winter season when plants were dormant. For fertilization, ammonium sulfate was injected through the irrigation system at bi-weekly intervals starting in March and continuing until September in both 2022 and 2023 in accordance to commercial recommendations made by Smith and Jacobs (2019).

Three separate freeze events occurred in the spring of 2023 where the high tunnels were closed. On 14 March, the high tunnel was closed at 2:00 p.m. and opened again on 15 March at 9:00 a.m. once temperatures had risen above freezing. It was observed that temperatures in the high tunnel dropped slightly lower than temperatures in the open field for part of the night and during the early morning hours. The next high tunnel closing occurred on 18 March. Although field and high tunnel data logger records showed temperatures never dropped below freezing, proactive actions were taken. On 18 March, plots were irrigated in an effort to soak the soil area surrounding each blueberry plant to create a warmer environment at ground level. Next, the high tunnel was closed around noon and two propane heaters were placed in the high tunnel in center isle approximately 4 m from each end and turned on from 9:00 p.m. until the high tunnel was opened on 19 March at 9:00 a.m. the next morning. The last closing occurred on 19 March where the same proactive steps were taken. Plots were irrigated, the high tunnel was closed at 2:00 p.m., and propane heaters were turned on at 7:00 p.m. until 9:00 a.m. the next day. On 20 March at 9:00 a.m., the high tunnel was opened back up.

Experimental Design

These two studies, open field and high tunnel, were conducted over the span of two years from the beginning of 2022 until the end of 2023. Both field and high tunnel plots were planted in a randomized complete block design with eight blocks. There were 15 treatments (13 southern highbush cultivars and 2 rabbiteye cultivars) with one single-plant replication per block. Both field and high tunnel contained 120 plants each, totaling 240 plants combined.

Data Collection

Environmental data was taken from both field and high tunnel locations and analyzed periodically through the use of SpecWare 9 Basic software (Spectrum Technologies, Inc., Aurora, IL). Environmental data was recorded by three different data loggers in both locations, all of which were Watchdog data loggers (Spectrum Technologies, Inc., Aurora, IL). All loggers were placed in radiation shields at 60.96 cm above the raised beds. The Watchdog 1425 logger recorded photosynthetically active radiation (PAR, PPF, $\mu mol \cdot m^{-2} \cdot s^{-1}$) and ambient temperature. The Watchdog A-125 logger recorded ambient temperature and soil temperature. The soil probe was buried at a depth of 10 cm. The Watchdog A-150 logger recorded ambient temperature and relative humidity (RH, %). Data loggers were placed inside the center of the two interior beds of the high tunnel, while also located in the very center of the high tunnel itself. Likewise, the data loggers were also placed in the very center of the two open field beds. All data loggers were set to record every 30 minutes.

Monthly growing degree days (GDDs) were estimated for each month starting in May of 2022 and ending in September of 2023. This was done by using the formula from Li and Bi (2019) where (monthly average temperature – base temperature) x the number of days in a month. The base temperature used in this study was 7 °C (Kovaleski et al., 2015; NeSmith, 2012; NeSmith and Bridges, 1992).

Plant growth was measured monthly from June to Sept. in 2022 and 2023 by measuring plant height from the crown to the top of the main shoot, and by taking cross-sectional measurements parallel and perpendicular to the raised bed for plant width. This was conducted for each plant in the field and under the high tunnel. From these measurements plant canopy volume (PCV, dm^3) was calculated using the equation for the volume of an elliptical cone; $V = p \cdot d^2 \cdot h/6$ (NASA, 2021; Marino et al., 2014).

From June to October of 2022 and then June to September of 2023, leaf chlorophyll content was nondestructively measured bi-weekly using a Minolta Chlorophyll Meter SPAD-502 (Minolta, Tokyo, Japan). Three of the most recently matured leaves from the middle portion of the shoot were measured. SPAD measurements were recorded for each plant in the field and under the high tunnel.

Phenological development was monitored every two days during the weekdays, beginning in January of 2023. Three shoots of each plant in the field and under the high tunnel were flagged using orange tape and numbered. The following stages were recorded using the scale illustrated in the work of Spiers (1978): 1 = no visible swelling; 2 = visible swelling, scales separating; 3 = scales separated, parts of flower visible; 4 = bud scales abscised, distinguishable individual flowers; 5 = individual, distinctly separated, unexpanded flowers; 6 = corollas completely expanded; 7 = petal fall. Percent bloom was also recorded for each plant in the field and high tunnel. These recordings were visually made when plants exhibited 10%, 50%, and 90% open flowers.

Berries were harvested early in the morning beginning on 20 Apr. and continuing to 16 Aug. by hand picking from the bush straight into a labeled plastic bag, and then placed immediately into a cooler. Berries were then transported in the cooler from the research station to the lab, where each berry for every cultivar picked per block was counted and weighed (total weight, g) on an A&D ej-610 scale (Ann Arbor, MI). From this yield per plant, total yield per location, and single berry weight was calculated. Yield data was only available for year 2023.

Fruit soluble solid content (SSC) was measured at each harvest date using three ripe berries from each plant with a digital refractometer (PAL-1 pocket refractometer, ATAGO U.S.A., Inc., Bellevue, WA). Soluble solids content was recorded for both field and high tunnel locations.

Statistical Analysis

An analysis of variance was performed on monthly yield, total yield, single berry weight, SSC, PCV, and SPAD values for both field and high tunnel locations using a Generalized Linear Mixed Model (GLIMMIX) as well as the LSMeans procedure and Tukey test for pairwise mean comparison in SAS version 9.4 (SAS Institute, Carey, NC).

Results

Environmental conditions

Air temperature. The high tunnel raised monthly maximum air temperature by 0.9 to 5.9 °C, average air temperature by 0.2 to 1.0 °C, and minimum air temperature by 0.3 to 0.8 °C compared with open field air temperature in Tallassee, AL (Fig. 2.2). From Apr. 2022 to Sept. 2023, lowest open field temperatures occurred in Nov. 2022 (-2.5 °C), Dec. 2022 (-7.0 °C), Jan. 2023 (-1.7 °C), and Mar. 2023 (-1.0 °C). The high tunnel resulted in monthly minimum temperatures of -1.8 °C in Nov. 2022, -7.1 °C in Dec. 2022, -1.6 °C in Jan. 2023, and -0.6 °C in Mar. 2023. The greatest maximum air temperatures occurred during June (37.9 °C), July (36.4°C), Aug. (37.0 °C) and Sept. (36.7 °C) for the field in 2022. While May (37.4 °C), June (41.1 °C), July (38.9 °C), Aug. (40.0 °C), and Sept. (38.9 °C) were the hottest months for the high tunnel in 2022. Maximum temperatures for the hottest months of 2022 differed by 2.2 °C to 3.2 °C between the field and high tunnel location. In 2023, the hottest months of the year occurred in May (35.3 °C), June (37.5 °C), July (38.9 °C), Aug. (40.6 °C), and Sept. (37.1 °C) for the field. Likewise, for the high tunnel, the hottest months in 2023 were May (36.6 °C), June (40.3 °C), July (41.1 °C), Aug. (43.1 °C), and Sept. (39.3 °C). Maximum temperatures for 2023 differed by 1.3 °C to 2.8 °C between field and high tunnel. The high tunnel only slightly raised monthly maximum, average, and minimum air temperatures in comparison to open field conditions.

Air temperature during freeze events. After a test run of closing the high tunnel in Jan., when temperatures were going to be low but not below freezing, it was noticed that minimum temperatures in the high tunnel were slightly lower than open field temperatures (data not reported). The high tunnel minimum temperatures were again slightly lower compared to field conditions when closed for a freeze event on 14-15 Mar. (Table 2.1). Hence, two propane heaters were used in high tunnels for all subsequent freeze events. When high tunnel was closed on 18-19 Mar. for a potential freeze event, there was no temperature increase detected by the temperature data loggers with the addition of the propane heaters, though temperatures did not drop below 2.6 °C (Table 2.1). However, during the third and final closing on 19-20 Mar., the recorded temperature data indicated that the propane heaters did slightly increase the air temperature in the high tunnel when compared to the open field. Air temperature was held above 0.0 °C from 5:00 a.m. to 8:00 a.m on 20 Mar. with the addition of propane heaters.

Soil temperature. Similarly, in comparison to open field conditions, the high tunnel raised monthly maximum soil temperature by 0 to 1.4 °C, average soil temperature by 0 to 1.7 °C, and minimum soil temperature by 0.3 to 11.8 °C (Fig. 2.3). Lowest open field soil temperatures occurred Oct. 2022 (8.0 °C), Dec. 2022 (4.6 °C), and Apr. 2023 (5.7 °C). The high tunnel resulted in monthly minimum soil temperatures of 16.1 °C in Oct. 2022, 5.8 °C in Dec. 2022, and 17.6 °C in Apr. 2023. Soil temperatures were only slightly higher in the high tunnel compared to the open field for the majority of the study. The high tunnel, however, did increase soil temperatures during the coldest months.

Photosynthetically Active Radiation (PAR). PAR in the high tunnel at noon was less than 1000 $\mu mol \cdot m^{-}2 \cdot s^{-1}$ in Nov. and Dec. 2022 as well as Jan., Feb., and Mar. 2023. Open field PAR at noon was only less than 1000 $\mu mol \cdot m^{-}2 \cdot s^{-1}$ in Dec. 2022 and Jan. 2023 (Fig. 2.4). The months with the highest PAR were June 2022 and Aug. 2023 for open field conditions. July 2022 and Aug. 2023 were the months with the highest PAR for the high tunnel. The reduction of PAR in the high tunnel ranged from 0.7% (July) to 32.8% (Dec.), with an average of 15.8% reduction for 2022. July PAR readings are similar due to data logger recording error. PAR values at noon were less variable for 2023 and ranged from 19.7% (Feb.) to 31.6% (Sept.). The average percent of PAR reduction for 2023 was 24.5%.

Growing Degree Days

Due to slightly elevated air temperature compared to the open field, the high tunnel accumulated 3,673 growing degree days (GDDs) from May to Dec. in 2022 and 4,021 GDDs from Jan. to Sept. in 2023 (Table 2.2). The open field accumulated 3,505 GDDs from May to Dec. 2022 and 3,858 GDDs from Jan. to Sept. 2023. The high tunnel accumulated higher monthly GDDs than the open field by 6 to 28 GDDs from May 2022 to Sept. 2023. Compared with the open field, the high tunnel accumulated 168 more annual GDDs from May to Dec. in 2022 and 163 more GDDs from Jan. to Sept. in 2023.

% Bloom, cumulative chill hours, and fruit growing period

In 2023, all cultivars in the high tunnel experienced 10% bloom dates during Feb. (Table 2.3). The only cultivar in the field to not have a 10% bloom date in Feb. was 'Titan' (Mar. 1). The high tunnel advanced dates of 10% bloom from 2 to 19 d when compared to the field. 'Gumbo' was the cultivar with the greatest advancement in 10% bloom date compared to field grown 'Gumbo' plants (19d). 'Farthing', 'Indigocrisp', 'Krewer', and 'Legacy' had no advancement of 10% bloom dates; the dates were the same for both locations.

The majority of cultivars grown under high tunnel and in open field experienced dates of 50% bloom in the month of Feb. (Table 2.3). The high tunnel advanced the date of 50% bloom from 0 to 16 days compared to the dates of 50% bloom in the field. 'Arcadia' reached 50% bloom in high tunnel 16 d prior to 50% bloom in field location, while 'Indigocrisp' and 'Krewer' reached 50% bloom at the same time for both locations.

All cultivars in the field had 90% bloom dates in March, while the high tunnel had dates in Feb. and Mar. (Table 2.3). The high tunnel advanced dates of 90% bloom by 0 to 17 d. The only cultivar that had no difference in 90% bloom date between locations was 'Krewer'.

From Oct. 2022 to Feb. 2023, the high tunnel cumulated a total of 705 chill hours, while the field cumulated a total of 743.5 chill hours. In this study chill hours were counted as hours of temperatures between 0 to 10 °C.

Fruit development period (FDP) was calculated in this study from the number of days between 10% bloom and the first harvest date of cultivars in the field and high tunnel (Table 2.3). Differences in FDP between high tunnel and field ranged from 2 to 21 days. The FDP for 'Legacy' was the same in the field and high tunnel. Interestingly, 'Gumbo' had a shorter FDP (13 d) in field compared to high tunnel. It is important to note that for first harvest in the field, 'Gumbo' only had an average of 11 berries per plant while high tunnel 'Gumbo' had an average of 121 berries picked on its first harvest date (data not reported). FDP for 'Keecrisp' was 1 day shorter in the field than high tunnel and 'New Hanover was 2 days shorter in the field than the high tunnel.

Date of first berry harvest

Harvest was only recorded for the second year, 2023, to encourage vegetative growth and aid in establishment of the plants in the first year. The first harvest occurred on 20 Apr. 2023 for both field and high tunnel locations. In the high tunnel, cultivars 'Avanti', 'Chickadee', 'Colossus', 'Farthing', 'Indigocrisp', 'Keecrisp', and 'Optimus' were the first to produce ripe fruit (Table 2.4). The first cultivar to be harvested in field location was 'Chickadee', however this first harvest date only produced a small amount of fruit. Overall, first berry harvest was earlier for cultivars grown under the high tunnel when compared to the open field. Cultivars 'Gumbo' and 'New Hanover' had first harvests 6 d earlier in the high tunnel than the field. Cultivars 'Farthing' and 'Bluecrisp' had the greatest difference in days between first harvests for the high tunnel and field with 20 d and 18 d, respectively. Most cultivars grown under high tunnel had first harvests 8 d earlier than the field ('Avanti', 'Indigocrisp', 'Keecrisp', 'Krewer', and 'Titan'). However, 'Chickadee' and 'Legacy' had no advancement in time of first harvest under the high tunnel. Cultivars 'Colossus', 'Meadowlark', and 'Optimus' did not produce any fruit in the field for the 2023 harvest season due to freeze damage. Freeze damage also caused field yields to be much lower than high tunnel yields.

Peak harvest

In 2023, high tunnel grown cultivars 'Avanti', 'Chickadee', 'Colossus', 'Indigocrisp', and 'Meadowlark' all produced the earliest peak harvests on 28 Apr. (Table 2.4). Field grown cultivars 'Chickadee', 'Indigocrisp', and 'Keecrisp' produced the earliest peak harvests on 11 May. High tunnel grown cultivar 'Avanti' produced a peak harvest with the greatest difference in days (18 d) prior to field grown 'Avanti'. High tunnel 'Gumbo', 'Keecrisp', and 'New Hanover' produced peak harvests with the least amount of days between locations (6 d). For most cultivars ('Arcadia', 'Bluecrisp', 'Chickadee', 'Farthing', and 'Indigocrisp'), the high tunnel advanced peak harvest dates by 12 d when compared to the field. Three cultivars ('Krewer', 'Legacy', and 'Titan') had earlier peak harvest dates in the field rather than the high tunnel. However, 'Titan' was the only cultivar to have a higher peak harvest yield for the field in conjunction with the earlier peak harvest date. 'Krewer' and 'Legacy' had an earlier peak harvest date in the field, but had greater peak harvest yield in the high tunnel. Peak harvest yield ranged from 0.7 g ('Chickadee') to 100.2 g ('Titan') per plant in the open field, while the high tunnel's peak harvest ranged from 9.9 g ('Colossus') to 202.7 g ('Krewer') per plant. Field cultivars 'Colossus', 'Meadowlark', and 'Optimus' did not produce any yield in the year 2023 due to freeze injury that occurred in March.

Blueberry yield

There was a total of 16 berry harvests during the 2023 growing season, beginning on 20 Apr. and continuing to 16 Aug. 2023. Total berry yield was greatest in the high tunnel due to late spring freeze events that occurred in March (Tables 2.5, 2.6). Field grown plants experienced more injury from these spring frosts compared to plants grown in high tunnel, that resulted in much lower yields (Fig. 2.5). 'Avanti' (67.5 g), 'Chickadee' (57.6 g), 'Colossus' (11.2 g), and 'Meadowlark' (110 g) all had their greatest early yields in the month of April (Table 2.5). While the majority of the rest of the cultivars grown under high tunnel experienced their greatest yields in the month of May. For the month of May, under the high tunnel, 'New Hanover' had the greatest yield of 346.9 g, which was statistically similar to 'Gumbo' (340 g), 'Legacy' (268.9 g), 'Farthing' (247.5 g), 'Keecrisp' (222.9 g), and 'Indigocrisp' (173.3 g). Rabbiteye cultivars 'Krewer' (532.5 g) and 'Titan' (258.9 g) produced their greatest yield in the month of June. Overall, for the high tunnel, the highest yield occurred in the month of June for 'Krewer'. In the field, 'Arcadia', 'Chickadee', 'Farthing', 'Gumbo', 'Indigocrisp', 'Legacy', and 'Optimus' had their greatest yields in the month of May (Table 2.6). 'Legacy' (61.8 g) and 'Gumbo' (53.5 g) had greater yields for the month of May compared to other cultivars. In June, field rabbiteye cultivars 'Krewer' and 'Titan' produced their greatest yields, with 'Titan' producing the greatest yield in June (130.7 g). The last cultivars to produce their greatest yields in the field were 'Avanti', 'Bluecrisp', and 'Keecrisp' in the month of July. This is unusual for these cultivars, as they are considered to be earlier fruiting cultivars and is likely the result of secondary flowering and fruiting that occurred after plants sustained damage from cold temperatures in March.

Total yield varied greatly between locations. In the high tunnel, the greatest total yield was produced by ‘Krewer’ (607.1 g), with ‘Gumbo’ (469.1 g), ‘Legacy’ (394.4 g), ‘New Hanover’ (364.8 g), ‘Titan’ (359.9 g), and ‘Farthing’ (356.2 g) having comparable total yields (Table 2.5). ‘Titan’ (159.5 g) had the greatest total yield in the field, followed by ‘Legacy’ (93 g) and ‘Gumbo’ (61.8 g) (Table 2.6). The high tunnel ranged in having greater total yields by 67.8 g (‘Bluecrisp’) to 582.5 g (‘Krewer’) compared to the open field.

Individual berry weight

The test of fixed effects showed a significant interaction between location in 2023 (*P* value <.0001). The high tunnel was significantly different than the field for effect on average individual berry weight. The greatest individual berry weights for cultivars ‘Avanti’, ‘Bluecrisp’, ‘Farthing’, ‘Indigocrisp’, ‘Keecrisp’, ‘Meadowlark’, ‘New Hanover’, and ‘Optimus’ occurred in the month of April for the high tunnel (Table 2.7). ‘Chickadee’ averaged the same individual berry weight for April and May in the high tunnel. Average individual berry weights in the following months were lower for these cultivars. A handful of cultivars exhibited greater individual berry weights during peak production in the month of May. These cultivars were ‘Arcadia’, ‘Krewer’, ‘Legacy’, and ‘Titan’. Average individual berry weights of these cultivars lessened in the following months as well. ‘Gumbo’ had the greatest average individual berry weight in July under the high tunnel. Overall, berry weight was greatest for ‘Krewer’ (3.1 g) and ‘Titan’ (2.9 g).

Individual berry weights for open-field production were only recorded for the months of May and June due to the sample size of each cultivar. In May, 'Titan' had the greatest average individual berry weight (2.9 g) and in June both 'Krewer' and 'Titan' had the greatest average single berry weight (2.3 g). Overall, between both months, 'Titan' had the greatest average individual berry weight (2.9 g).

Blueberry soluble solid content (SSC)

The fixed effect test showed significant interaction (*P* value 0.038) between location for SSC. 'Titan' (15.7 %) berries had the greatest average SSC in the high tunnel compared to all other cultivars, followed by 'Keecrisp' (14.5 %) and 'Krewer' (14.6 %) (Table 2.9). 'Avanti', 'Bluecrisp', 'Chickadee', 'Colossus', 'Farthing', 'Gumbo', 'Indigocrisp', 'Legacy', 'Meadowlark', 'New Hanover', and 'Optimus' all had similar SSC that ranged from 11.8 to 13.3 % brix. The cultivar with the lowest SSC was 'Arcadia' (11.4 %), though similar to total SSC for 'Chickadee', 'Colossus', 'Meadowlark', and 'Optimus'.

High tunnel cultivars 'Arcadia', 'Chickadee', 'Colossus', 'Krewer', 'Meadowlark', and 'Titan' all had the highest monthly average soluble solids content during the time of their peak harvests (Table 2.9). 'Bluecrisp' and 'Optimus' had the highest soluble solid measurements early in the season during the month of April, while 'Gumbo', 'Indigocrisp', and 'Legacy' had higher SSC or soluble solids content in June. Some cultivars produced flowers for a second time and were allowed to fruit again, resulting in a higher soluble solids content much later in the season. Cultivars that experienced this characteristic were 'Avanti', 'Farthing', and 'Keecrisp'.

In the field, ‘Titan’ (16.5 %) and ‘Krewer’ (15.8 %) produced the highest total SSC (Table 2.10). ‘Keecrisp’ had among the greatest SSC in each month it was harvested. All other cultivars in the field ranged in SSC from 11.1 (‘Chickadee’) to 14.5% brix (‘Keecrisp’).

Only four cultivars from the field produced the highest soluble solids content during their peak harvest dates – ‘Arcadia’ (11.3 % brix, May), ‘Krewer’ (15.8, June), ‘New Hanover’ (12.5 % brix, May), and ‘Titan’ (17.3, June) (Table 2.10). ‘Chickadee’ and ‘Indigocrisp’ had the highest soluble solids content early in the season, during April, while ‘Gumbo’ and ‘Legacy’ produced their highest soluble solids content around mid-season in June. Like the high tunnel, cultivars ‘Avanti’, ‘Bluecrisp’, ‘Farthing’, and ‘Keecrisp’ produced flowers and fruit for a second time in the season and resulted in higher soluble solids contents in July and August.

Plant canopy volume

Due to the amount of variability, many of the cultivars had similar PCV throughout the study (Tables 2.11 and 2.12). Cultivars ‘Bluecrisp’ and ‘Colossus’ started out smaller in size than all other cultivars at the very beginning of the study. The PCV measurements are very indicative of this throughout both years in both locations. ‘New Hanover’ tended to have the largest PCV in the high tunnel for 2022, though similar to all other cultivars with “a’s” such as ‘Chickadee’, ‘Gumbo’, ‘Keecrisp’, ‘Legacy’, ‘Optimus’, and ‘Titan’. Total PCV was 1.65× greater in the field and significantly different from the high tunnel by the end of the 2022 season (*P* value 0.0001). ‘Bluecrisp’ had the greatest difference in PCV between the field and high tunnel with a total PCV 3.9× greater in the field than the high tunnel. ‘New Hanover’ had the lowest difference in PCV between field and high tunnel with a PCV that was 1.2× greater in the field than high tunnel.

In the second year, 2023, total PCV was significantly different in the high tunnel (*P* value 0.0002) with a PCV 1.02× greater in the high tunnel compared to the field. However, certain cultivars did still produce greater PCVs in the field. These cultivars were ‘Bluecrisp’ (1.01× greater), ‘Colossus’ (2.39× greater), ‘Gumbo’ (1.0× greater), ‘Krewer’ (1.18× greater), ‘Legacy’ (1.08× greater), ‘New Hanover’ (1.11× greater), and ‘Titan’ (1.13× greater). While cultivars ‘Arcadia’ (1.12× greater), ‘Avanti’ (1.15× greater), ‘Chickadee’ (1.39× greater), ‘Farthing’ (1.04× greater), ‘Indigocrisp’ (1.03× greater), ‘Keecrisp’ (1.03× greater), ‘Meadowlark’ (1.07× greater) and ‘Optimus’ (1.24× greater) produced greater PCVs in the high tunnel.

Chlorophyll content

In 2022, there was a significant difference between locations (*P* value 0.0154). The Field was significantly different. However, in 2023, there was no significant difference between locations. The two rabbiteye cultivars ‘Krewer’ and ‘Titan’ tended to have among the highest chlorophyll level throughout the study, while ‘Legacy’ and ‘Optimus’ tended to have the lowest (Table 2.13 and 2.14). ‘Legacy’ SPAD values averaged lower in the high tunnel for the months of July and Aug. in 2022 and 2023. Field grown ‘Legacy’ experienced a similar drop in SPAD values in the month of Aug. each year. High tunnel ‘Optimus’ also had lower SPAD value averages in Aug. of 2022 and 2023. SPAD value averages tended to be greatest in the high tunnel for the month of Sept. in both years. In 2022, ‘Indigocrisp’ and ‘Keecrisp’ had their greatest average SPAD values in Sept. under the high tunnel. In 2023, under the high tunnel, ‘Arcadia’, ‘Avanti’, and ‘Bluecrisp’ had their greatest SPAD value averages in Sept.. In 2022 high tunnel cultivars ‘Gumbo’, ‘Indigocrisp’, ‘Keecrisp’, and ‘Meadowlark’ had similar SPAD values to that of the rabbiteye cultivars. For the field in 2022, ‘Indigocrisp’ and ‘Keecrisp’ had similar SPAD values to the rabbiteyes. For both locations in 2023, ‘Chickadee’, ‘Colossus’, ‘Farthing’, ‘Gumbo’, ‘Indigocrisp’, and ‘Keecrisp’ had similar SPAD values to the rabbiteye cultivars.

Discussion

Environmental conditions varied between locations. The most notable difference being between monthly maximum air temperatures in the high tunnel and open field. Li and Bi (2019) reported similar results stating that the major temperature differences occurred with elevated maximum temperatures in Jan. to June. Li and Bi (2019) also saw a similar trend of elevated minimum temperatures during some of the coldest months of their study. However, in this study minimum air temperatures between locations did not show great differences, but even so were slightly higher within the high tunnel for the majority of the length of the study.

A lack of freeze protection for earlier flowering blueberry cultivars is a major problem for locations that suffer from late spring frost events. Blueberries become more susceptible to cold damage as flower bud development progresses (Spiers, 1978). Critical temperatures for flower buds begin at stage 2, when plants are considered to be in bud swell and can usually tolerate temperatures of -12 to -9 °C (Michigan State Univ. Ext., n.d.). Whereas plants that are in stage 7, petal fall, are likely to be damaged at 0 °C (Michigan State Univ. Ext., n.d.). During the first freeze event on 15 Mar. the only cultivars in the high tunnel that had not made it completely through the last stage of the bud scale rating were 2 cultivars of ‘Gumbo’ (one branch in stage 7 and 5, respectively), 2 cultivars of ‘Legacy’ (both with single branches in stage 7), and 1 plant of ‘New Hanover’ (two branches in stage 6 and 7, respectively) (data not reported). For the 17 of Mar. only 1 plant of ‘Gumbo’ (one branch, stage 6) and 1 of ‘New Hanover’ (two branches, stage 7) had not made it through the bud development stages in the high tunnel. Lastly, on 20

Mar. in the high tunnel only 1 plant of ‘Legacy’ was in stage 6 and 1 bush of ‘New Hanover was in stage 7. All other cultivars in the high tunnel had made it through all stages and past petal fall with developing green fruit. In the field on the 15 Mar. One plant of ‘Arcadia’, 1 of ‘Bluecrisp’, 4 of ‘Gumbo’, 2 of ‘Krewer’, 4 of ‘Legacy’, 1 of ‘New Hanover’, and 4 of ‘Titan’ were all still in various bud stages (stage 5 to 7). By the last freeze date, 20 Mar., only 3 plants of ‘Gumbo’, 1 of ‘Legacy’, and 1 of ‘New Hanover’ ranged in bud development stages from 5 to 7. Like the high tunnel, most cultivars in the field had already made it past petal fall and had green fruit at the time of the three freeze events in Mar. Longstroth (n.d.) reports that green fruit are the most tender plant parts and can be damaged by temperatures just below freezing. No frost covers or propane heaters were placed with blueberry cultivars in the field for all freeze events, leading to fruit damage that ultimately caused yield reductions.

Ogden and van Iersel (2009) reported that the high tunnels in their study did not provide adequate frost protection on their own and temperatures inside fell 1 to 5 °C below ambient temperature. Ogden and van Iersel (2009) predict that this occurred in their study due to high long-wave radiation transmittance, low ventilation, and a high surface to volume ratio. In previous findings, Ogden and van Iersel (2008) state that high tunnels also lose more heat on a clear night rather than a cloudy one. Similarly, the minimum temperatures within the high tunnel of this study were lower compared to open field during freeze events. To aid in frost protection, in conjunction with the high tunnels, Ogden and van Iersel (2009) incorporated the use of propane heaters which aided in preventing damage during the 2007 Easter freeze. Although the temperature data in this study does not show great differences between open field temperature and temperature in high tunnel with heaters, the heaters did aid in providing freeze protection with the high tunnel. Temperatures in the high tunnel do not show great differences between the field likely due to the fact that the heaters were placed approximately 10 m away from the data loggers.

Because black landscape fabric was used as a weed mat in both field and high tunnel locations, soil temperature was monitored regularly. Too high of soil temperatures were a concern for both locations, but even more so in the high tunnel. Blueberries have fine, fibrous root systems that are primarily concentrated near the upper portion of the soil profile, making them more susceptible to drought at higher temperatures. Spiers (1995) found that a negative correlation exists between a soil temperature increase from 16 to 38 °C, thus indicating that blueberries would respond more favorably to cultural practices that lower soil temperature during the warmer parts of the growing season. In this study maximum soil temperatures never reached above 36.6 °C throughout both years of the study. Additionally, monthly maximum soil temperatures stayed below monthly maximum air temperatures consistently throughout the study. Li and Bi (2019) also recorded monthly average PAR at noon, and found that PAR in the high tunnel was less than 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during the winter and early spring months. This aligns well with the PAR results of this study. In this study PAR was measured in the high tunnel as well as the field and proved to have an overall higher PAR reading in the field. This is likely a result of the high tunnel diffusing sunlight that shines through the plastic covering that surrounds it. Maynard and O'Donnell (2019) state that a single layer of plastic may only transmit 88 to 92 % of PAR under ideal conditions. Similarly, Retamal-Salgado et al. (2015) reported that an average of 25% difference in light interception occurred between his high tunnel and field locations. In this study, the high tunnel experienced 15.8% average PAR reduction in 2022 and 24.5% average PAR reduction in 2023 when compared to the open field.

In this study, the high tunnel accumulated 168 more annual GDDs from May to Dec. in 2022 and 163 more GDDs from Jan. to Sept. in 2023. Li and Bi (2019) reported a similar finding due to elevated temperatures within the high tunnel. NeSmith and Bridges (1992) demonstrated that chill hours and heat units, or GDDs, both control time of flowering after dormancy requirements are met. Thus, if a high tunnel can increase heat units, or growing degree days, the potential for advanced blooming and expedited fruit ripening is high. Li and Bi (2019) found this to be true in their study when the use of a high tunnel advanced first berry harvest to the first week of April during both growing seasons in Mississippi. Ogden and van Iersel (2009) found that the use of a high tunnel advanced floral and fruit development in Georgia. Santos and Salame-Donoso (2012) also reported similar results where a high tunnel progressed bloom stages in Florida. Recently, Zimeri (2023) reported evidence of accelerated phenological development in 3 southern highbush cultivars under high tunnel in Alabama. In this study 10%, 50%, and 90% bloom dates were accelerated by the high tunnel for most cultivars, with the exception of the rabbiteye cultivar ‘Krewer’. Tamada and Ozeki (2012) found that date of 50% flowering was advanced about 26 to 40 days in an unheated plastic house compared to field production in Japan. Tamada and Ozeki (2012) also calculated fruit growing period (from 50% flowering to 50% harvest time) and found that fruit growing interval of all blueberry cultivars from their study had a tendency to be longer in the unheated house than the field. This could possibly explain why the flower development period of ‘Gumbo’, ‘Keecrisp’, ‘New Hanover’, and ‘Titan’ was greater in the high tunnel.

In this study, the first harvest dates for the majority of the southern highbush cultivars planted in the high tunnel occurred toward the end of April. Southern highbush cultivars ‘Star’, ‘Emerald’, and ‘Rebel’, which are considered to be standard cultivars, have similar first berry harvest dates from early to late April in open field conditions in northeastern Florida and south central Georgia (Lyrene, 2008; Lyrene and Sherman, 2000; NeSmith, 2008). According to the plant patent, ‘Indigocrisp’ has a mean date of 15 April for first harvest in Florida (Lyrene, 2015). Similarly, in this study, southern highbush cultivar ‘Indigocrisp’ had its first harvest on 20 April in the high tunnel.

Monthly yield was the highest in May for all cultivars except ‘Avanti’, ‘Chickadee’, ‘Colossus’, ‘Krewer’, ‘Meadowlark’, and ‘Titan’. This is likely due to differences between cultivar, chilling, and time of flowering. High tunnel yields suffered drastically from freeze damage in the spring, so a comparison of yield would not be accurate.

Single berry weights of ‘Bluecrisp’, ‘Krewer’, and ‘Titan’ from the high tunnel were all very close to what has been previously recorded for field production of these varieties. High tunnel ‘Bluecrisp’ in this study had an average single berry weight of 1.6 g in May and Andersen et al. (2008) recorded ‘Bluecrisp’ to have an average single berry weight of 1.52 g in the year 2006. High tunnel grown ‘Krewer’ has an average single berry weight of 3.2 g for the month of May and has been previously recorded to have a mean berry size of 3.0 g (Coneva, 2021). ‘Titan’ in the high tunnel, from this study, had an average single berry weight from the month of May as 2.6 g, while ‘Titan’ has been recorded to have a mean berry weight of 2.9 g (Coneva, 2021). All other cultivars had smaller single berry weights than what is recorded in the literature. With time and establishment, it is possible that single berry weights will reach what is considered average for each cultivar as maturity is reached.

Average SSC of high tunnel grown ‘Keecrisp’ was 14.5 % brix for the harvest season of this study. The Blueberry Breeding and Genomics Lab (N.d.) report that ‘Keecrisp’ has an average SSC of 12.1 % brix. Another high tunnel grown cultivar with a higher than reported average SSC was ‘Krewer’ at 14.6 % brix. NeSmith (2017) reported ‘Krewer’ to have an average SSC of 12.9. However, another study from Alabama reports a more similar SSC for ‘Krewer’ at 13.2 % brix (Coneva, 2021). Coneva (2021) also reported that ‘Titan’ averaged 12.3 % SSC in the 2021 season, but in this study the high tunnel grown ‘Titan’ averaged 15.7 % SSC. All other cultivars averaged similar SSC to what has been previously reported (Blueberry Breeding and Genomics Lab, n.d.).

During the first growing season, it is possible that the cultivar ‘Legacy’ exhibited the highest PCV in the high tunnel at the beginning of the season due to the wide branching nature of its growth. ‘New Hanover’ became the cultivar with the greatest PCV next for a similar reason, an increased growth in plant height and width. ‘Bluecrisp’ and ‘Colossus’ remained the cultivars with the smallest PCV due to the difference in size from the beginning. In the second year of high tunnel growth measurements, ‘Optimus’ became the cultivar with the largest PCV also due to its wide growth habit and ‘Colossus’ remained the smallest. It is also possible that ‘Meadowlark’ had lower PCV’s due to its upright growth habit. PCV measurements differ in size from June to Sept. in the high tunnel during 2023 for cultivars ‘Gumbo’, ‘Keecrisp’, ‘Krewer’, ‘Legacy’, ‘New Hanover’, and ‘Titan’ due to pruning very tall, lanky canes shorter in July and Aug. New shoots and canes that were unpruned quickly grew between measurements in Aug. and Sept. to allow for large plant canopies. A few plants of ‘Colossus’ under the high tunnel in 2023 were also pruned slightly toward the end of Aug. due to death of canes.

Differences in chlorophyll content most likely result due to differences among cultivars. However, it is possible that some of the differences occur because of cultivar and location interaction. Tateno and Taneda (2007) state that plants under full sun conditions tend to have a higher photosynthetic capacity. However, Zimeri (2023) determined that overall diurnal photosynthetic rate was greater under high tunnel conditions with an average of 22% less direct light interception compared to open field when using the same type of high tunnel in the present study. Chlorophyll plays an important role in photosynthesis by trapping light energy, so plants with leaves containing greater chlorophyll content might have greater rates of photosynthesis. In this study, 2022, was the only year with significant differences between locations.

Conclusion

Overall, there was a greater fruit yield in the high tunnel as opposed to the field. This can be directly correlated to the fact that the high tunnels serve as a more protective means from freeze damage. Because of the possibility of spring frost, it is not recommended that southern highbush be planted in central Alabama without means of protection. However, my findings suggest, that in conjunction with heaters, high tunnels can protect from the susceptibility of spring frost which provides a possible solution to the problem as well as offers a possibility of earlier fruit production. Our study, along with Ogden and van Iersel (2009), determined that the high tunnels alone may not work sufficiently in event of a freeze. However, propane heaters appeared to be a cost effective solution and provide significant protection. Another study done by Santos and Salame-Donoso (2012) found the use of overhead irrigation in conjunction with high tunnel production can provide protection with the added benefit of lower water use rates. Another finding in this study was that the high tunnel did advance blueberry bloom and ripening. Due to freeze events, FDP may be inconclusive in the field. However, it does appear that ripening was advanced and much earlier compared to traditional rabbiteye field production. Initially, it was found that growth measurements were greater in the field, but in the second year of the study the high tunnel caught up. One of our concerns at the beginning of the study was the black landscape fabric that was used as weed mat because of the potential of hotter air and soil temperatures in the high tunnel during the summer months. Although temperatures did not appear damaging, the younger plants in the high tunnel may have experienced more stress. For example, the cultivar ‘Colossus’ was one of the youngest plants put in for this study and did not establish and grow well under high tunnel as compared to the field. Based off the results of these first few years of establishment and one season of production, potential early, high-performing cultivars for fruit production in the high tunnel include ‘Arcadia’, ‘Chickadee’, and ‘Meadowlark’, as well as ‘Farthing’ and ‘New Hanover’. Cultivars that performed the best in the field for fruit production include ‘Gumbo’, ‘Legacy’, and ‘Titan’.

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Figure 2.1. Initial plant size of ‘Bluecrisp’ and ‘Colossus’ prior to planting at E.V. Smith R.C. in Tallassee, AL.

Figure 2.2. Monthly maximum, average, and minimum air temperature in the high tunnel and open-field at E.V. Smith R.C., Tallassee, AL. from April 2022 to September 2023. High tunnel and field air temperature was recorded by Watchdog A125 A-series data loggers and a 1425 1000 series micro station (Spectrum Technologies, Inc., Aurora, IL).

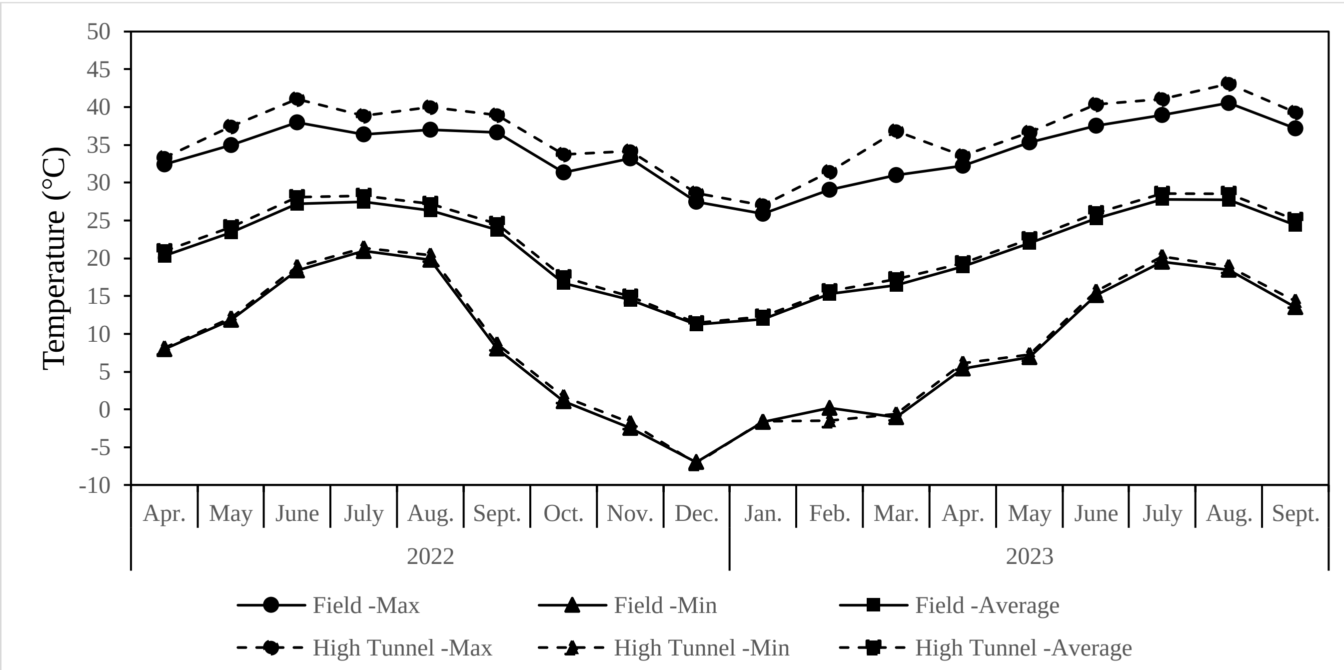

Table 2.1. Dates and comparison of temperatures during freeze events of spring of 2023 at E.V. Smith R.C in Tallassee, AL.

		Temperature (°C)				Temperature (°C)				Temperature (°C)	
Date	Time	Field	High Tunnel	Date	Time	Field	High Tunnel	Date	Time	Field	High Tunnel
3/14/2023	2:00 PM	15.5	30.4	3/18/2023	2:00 PM	15.1	36.8	3/19/2023	2:00 PM	11.8	14.4
3/14/2023	3:00 PM	15.8	35.4	3/18/2023	3:00 PM	14.1	28.8	3/19/2023	3:00 PM	12.1	33.6
3/14/2023	4:00 PM	14.9	31.0	3/18/2023	4:00 PM	13.4	20.8	3/19/2023	4:00 PM	12.2	33.3
3/14/2023	5:00 PM	13.1	21.4	3/18/2023	5:00 PM	13.4	19.8	3/19/2023	5:00 PM	11.8	27.9
3/14/2023	6:00 PM	10.5	10.9	3/18/2023	6:00 PM	12.5	15.8	3/19/2023	6:00 PM	10.4	18.9
3/14/2023	7:00 PM	8.3	6.7	3/18/2023	7:00 PM	11.8	12.6	3/19/2023	7:00 PM	8.1	*9.5
3/14/2023	8:00 PM	6.4	4.7	3/18/2023	8:00 PM	11.0	11.4	3/19/2023	8:00 PM	7.0	*6.4
3/14/2023	9:00 PM	6.0	4.0	3/18/2023	9:00 PM	10.8	*11	3/19/2023	9:00 PM	5.7	*4.3
3/14/2023	10:00 PM	4.5	3.5	3/18/2023	10:00 PM	10.6	*10.9	3/19/2023	10:00 PM	5.1	*3.7
3/14/2023	11:00 PM	3.2	2.6	3/18/2023	11:00 PM	10.0	*10.5	3/19/2023	11:00 PM	4.8	*3.4
3/15/2023	12:00 AM	3.9	2.3	3/19/2023	12:00 AM	9.3	*9.0	3/20/2023	12:00 AM	4.2	*3.0
3/15/2023	1:00 AM	2.1	1.7	3/19/2023	1:00 AM	9.2	*9.1	3/20/2023	1:00 AM	3.5	*2.7
3/15/2023	2:00 AM	1.5	1.3	3/19/2023	2:00 AM	7.9	*7.6	3/20/2023	2:00 AM	2.5	*2.3
3/15/2023	3:00 AM	1.1	0.8	3/19/2023	3:00 AM	6.9	*6.3	3/20/2023	3:00 AM	1.5	*1.7
3/15/2023	4:00 AM	1.5	0.9	3/19/2023	4:00 AM	5.4	*4.2	3/20/2023	4:00 AM	0.6	*1.0
3/15/2023	5:00 AM	0.1	0.0	3/19/2023	5:00 AM	4.9	*3.2	3/20/2023	5:00 AM	-0.2	*0.3
3/15/2023	6:00 AM	-0.4	-0.6	3/19/2023	6:00 AM	4.2	*2.6	3/20/2023	6:00 AM	-1.0	*0.1
3/15/2023	7:00 AM	2.1	9.6	3/19/2023	7:00 AM	3.3	*2.8	3/20/2023	7:00 AM	-0.7	*0.3
3/15/2023	8:00 AM	8.8	9.8	3/19/2023	8:00 AM	4.8	*8.3	3/20/2023	8:00 AM	0.9	*10.7

3/15/2023	9:00 AM	11.4	11.5	3/19/2023	9:00 AM	6.9	*8.1	3/20/2023	9:00 AM	5.6	*21.0

* Indicates times when two propane heaters were used inside high tunnel.

Figure 2.3. Monthly maximum, average, and minimum soil temperature in the high tunnel and open-field at E.V. Smith R.C. in Tallassee, AL from April 2022 to September 2023. High tunnel and field soil temperature was recorded by Watchdog A125 A-series data loggers (Spectrum Technologies, Inc., Aurora, IL).

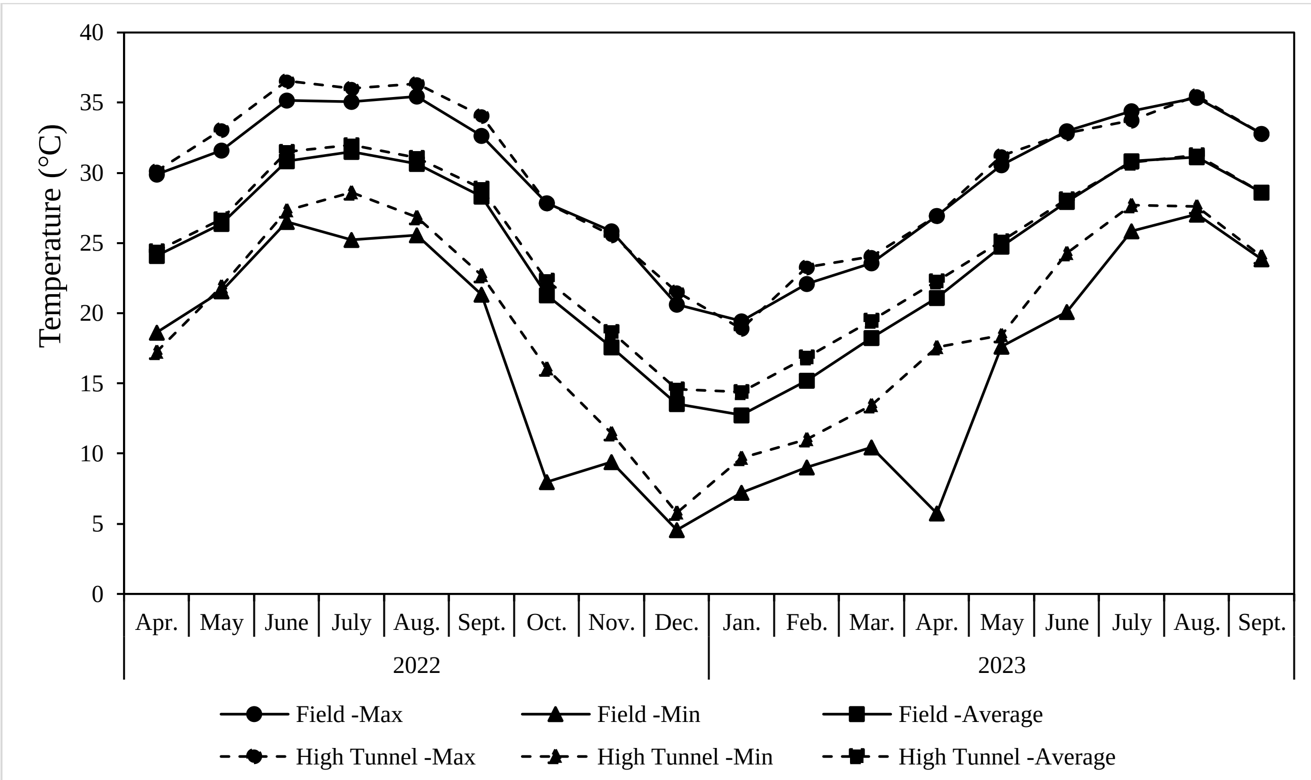

Figure 2.4. Photosynthetically active radiation (PAR) at noon averaged over a month in high tunnel and open-field at E.V. Smith R.C. in Tallassee AL from April 2022 to September 2023. PAR was recorded by Watchdog 1425 1000 series micro stations in both high tunnel and field locations (Spectrum Technologies, Inc., Aurora, IL).

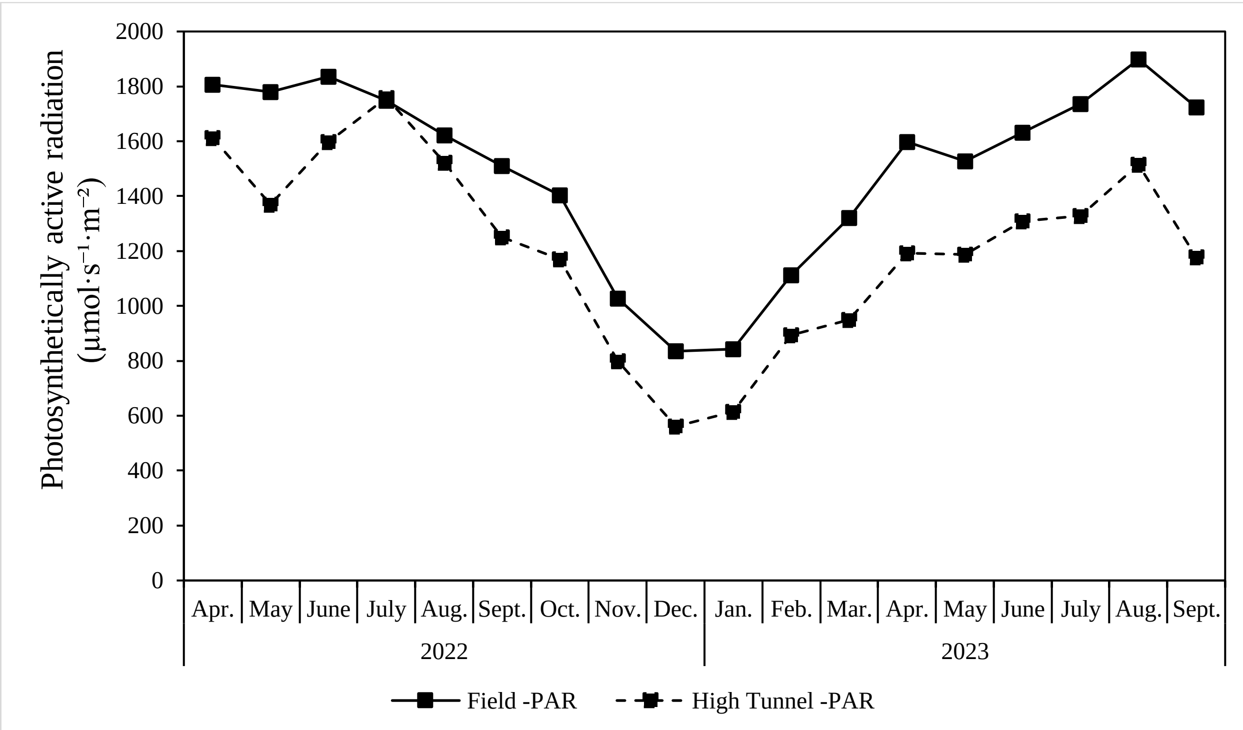

Table 2.2. Monthly growing degree days (GDDs) accumulated in the high tunnel and open-field at E.V. Smith R.C. in Tallassee, AL.

			High Tunnel[y]		Open Field	
Year	Month	No. of days in the month	Monthly avg. temp. (°C)	Monthly GDDs	Monthly avg. temp. (°C)	Monthly GDDs
2022	May	31	24.1	530	23.4	508
2022	June	30	28.1	633	27.2	606
2022	July	31	28.3	660	27.5	636
2022	August	31	27.2	626	26.3	598
2022	September	30	24.5	525	23.7	501
2022	October	31	17.5	326	16.7	301
2022	November	30	14.9	237	14.5	225
2022	December	31	11.4	136	11.2	130
2023	January	31	12.2	161	12.0	155
2023	February	28	15.6	241	15.3	232
2023	March	31	17.2	316	16.4	291
2023	April	30	19.4	372	18.9	357
2023	May	31	22.5	481	22.0	465
2023	June	30	26.0	570	25.3	549
2023	July	31	28.6	670	27.8	645
2023	August	31	28.5	667	27.7	642
2023	September	30	25.1	543	24.4	522

[y]Monthly GDDs were calculated as GDDs=($T_{monthly\ average}$ - T_{base}) x number of days in a month. T_{base} = 7°C for southern highbush blueberries.

Monthly growing degree days (GDDs) accumulated in the high tunnel and open field.

Table 2.3. Cumulative chill hours, dates of 10%, 50%, and 90% flowering, and fruit growing period during 2023 for several southern highbush blueberry cultivars and two rabbiteye blue berry cultivars under high tunnel and in field at E.V. Smith R.C. in Tallassee, Alabama.

	High Tunnel				Field			
Cultivar	10%	50%	90%	Fruit growing period[y]	10%	50%	90%	Fruit growing period
Arcadia	Feb.6	Feb. 8	Feb. 17	81	Feb. 17	Feb. 24	Mar. 1	83
Avanti	Feb. 6	Feb. 8	Feb. 24	73	Feb. 8	Feb. 17	Mar. 1	79
Bluecrisp	Feb. 17	Feb. 24	Mar. 6	70	Feb. 27	Mar. 6	Mar. 13	79
Chickadee	–	Feb. 8	Feb. 17	–	Feb.6	Feb. 17	Mar. 1	73
Colossus	Feb. 8	–	Feb. 17	71	Feb. 27	Mar. 1	Mar. 6	–
Farthing	Feb. 8	Feb. 17	Mar. 3	71	Feb. 8	Feb. 27	Mar.8	92
Gumbo	Feb. 8	Feb. 27	Mar. 8	86	Feb. 27	Mar. 6	Mar. 20	73
Indigocrisp	Feb. 22	Feb. 27	Mar. 3	57	Feb. 22	Feb. 27	Mar. 8	65
Keecrisp	Feb. 8	Feb. 17	Mar. 6	71	Feb. 17	Feb. 27	Mar.13	70
Krewer	Feb. 17	Feb. 27	Mar. 8	89	Feb. 17	Feb. 27	Mar. 8	97
Legacy	Feb. 27	Mar. 1	Mar. 8	73	Feb. 27	Mar. 6	Mar.13	73
Meadowlark	Feb.6	Feb. 8	Feb. 17	73	Feb. 8	Feb. 17	Mar.1	–
New Hanover	Feb. 8	Feb. 17	Mar. 6	79	Feb. 17	Feb. 27	Mar. 13	77
Optimus	–	Feb. 8	Feb. 17	–	Feb. 8	Feb. 17	Mar. 1	–
Titan	Feb. 17	Mar. 1	Mar. 13	89	Mar. 1	Mar. 8	Mar. 20	85
Chill hours[z]	705				743.5			

[z]Chill hours were determined as hours between 0 to 10 °C from Oct. of 2022 through Feb. 2023.

[y]Fruit growing period was calculated as days from date of 10% bloom to first harvest date.

Table 2.4. Date of first berry harvest, peak harvest, and average peak harvest yield of 13 southern highbush cultivars and 2 rabbiteye cultivars (‘Krewer’ and ‘Titan’) grown under high tunnel and in open-field at E.V. Smith R.C. in Tallassee, AL.

Cultivar	Location	Date of first harvest	Date of peak harvest[y]	Peak harvest yield (g per plant)
		2023	2023	2023
Arcadia	High Tunnel	28-Apr	5-May	56.2
	Field	11-May	17-May	1.3
Avanti	High Tunnel	20-Apr	28-Apr	180.2
	Field	28-Apr	17-May	7.0
Bluecrisp	High Tunnel	28-Apr	5-May	36.2
	Field	17-May	17-May	1.9
Chickadee	High Tunnel	20-Apr	28-Apr	29.3
	Field	20-Apr	11-May	0.7
Colossus	High Tunnel	20-Apr	28-Apr	9.9
	Field	–	–	–
Farthing	High Tunnel	20-Apr	5-May	117.6
	Field	11-May	17-May	1.1
Gumbo	High Tunnel	5-May	11-May	125.2
	Field	11-May	17-May	28.6
Indigocrisp	High Tunnel	20-Apr	28-Apr	92.0
	Field	28-Apr	11-May	2.8
Keecrisp	High Tunnel	20-Apr	5-May	121.9
	Field	28-Apr	11-May	3.7
Krewer	High Tunnel	17-May	8-Jun	202.7
	Field	25-May	1-Jun	7.7
Legacy	High Tunnel	11-May	25-May	147.6
	Field	11-May	17-May	31.5
Meadowlark	High Tunnel	20-Apr	28-Apr	61.8
	Field	–	–	–
New Hanover	High Tunnel	28-Apr	11-May	159.4
	Field	5-May	17-May	14.3
Optimus	High Tunnel	20-Apr	5-May	55.9
	Field	–	–	–
Titan	High Tunnel	17-May	16-Jun	35.6
	Field	25-May	1-Jun	100.2

Table 2.5. Cultivar effect on blueberry yield in April, May, June, July, and August, and total yield of southern highbush and Rabbiteye blueberries grown under high tunnel in 2023 at E.V. Smith R.C. in Tallassee AL.

	Berry yield, g / plant, 2023					
Cultivar	April	May	June	July	August	Total
Arcadia	7.4 b	106.1 bcde	–	–	–	113.4 cde
Avanti	67.5 ab	32.3 de	–	30.6 a	2.56 b	132.9 cde
Bluecrisp	8.6 b	50.1 cde	11.5 c	5.3 a	–	75.5 de
Chickadee	57.6 ab	19.1 e	–	–	–	76.7 de
Colossus	11.2 b	1.6 e	–	–	–	12.7 e
Farthing	82.6 ab	247.5 abc	12.9 c	8.8 a	4.32 b	356.2 abcd
Gumbo	–	339.5 a	10.3 c	18.2 a	101.12 a	469.1 ab
Indigocrisp	106.5 a	173.3 abcde	7.2 c	1.7 a	–	288.7 bcde
Keecrisp	31.3 ab	222.9 abcd	12.0 c	29.7 a	20.32 b	316.3 bcd
Krewer	–	67.2 cde	532.5 a	7.4 a	–	607.1 a
Legacy	–	268.9 ab	124.3 bc	1.2 a	–	394.4 abc
Meadowlark	110.0 a	30.9 de	–	–	–	140.9 cde
New Hanover	6.1 b	346.9 a	11.7 c	–	–	364.8 abc
Optimus	62.2 ab	103.0 bcde	2.9 c	–	–	168.1 cde
Titan	–	80.7 bcde	258.9 b	20.3 a	–	359.9 abcd
P Value[y]	<.0001	<.0001	<.0001	0.0042	<.0001	<.0001

[y]Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table 2.6. Cultivar effect on blueberry yield in April, May, June, July, and August, and total yield of southern highbush and Rabbiteye blueberries grown in open-field in 2023 at E.V. Smith R.C. in Tallassee, AL.

	Berry yield, g / plant, 2023					
Cultivar	April	May	June	July	August	Total
Arcadia	–	1.6 cd	–	–	–	1.6 d
Avanti	3.5 a	2.3 cd	–	5.1 a	–	10.9 d
Bluecrisp	–	1.9 cd	–	5.8 a	–	7.7 d
Chickadee	0.6 a	1.4 cd	–	–	–	2.0 d
Colossus	–	–	–	–	–	
Farthing	–	1.8 cd	–	1.5 a	–	3.3 d
Gumbo	–	53.5 a	3.4 bc	5.0 a	–	61.8 bc
Indigocrisp	6.0 a	7.8 bcd	–	–	–	13.8 d
Keecrisp	0.2 a	9.1 bcd	–	9.6 a	0.8 a	19.7 d
Krewer	–	0.9 cd	23.7 bc	–	–	24.6 cd
Legacy	–	61.8 a	31.2 b	–	–	93.0 b
Meadowlark	–	–	–	–	–	
New Hanover	–	23.7 bc	–	–	–	23.7 cd
Optimus	–	–	–	–	–	
Titan	–	28.8 b	130.7 a	–	–	159.5 a
P Value[y]	0.1984	<.0001	<.0001	0.3344	0.4604	<.0001

[y]Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Figure 2.5. Freeze damage to field fruit in March of 2023 at E.V. Smith R.C. in Tallassee, AL.

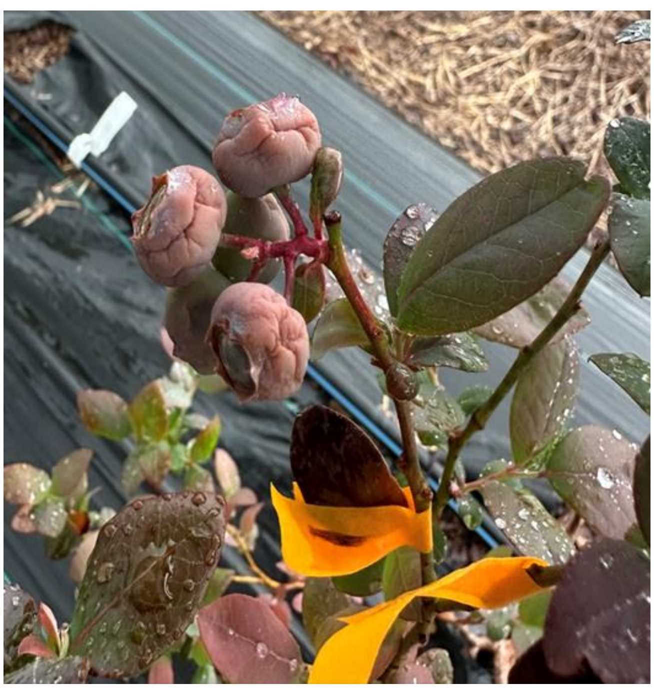

Table 2.7. Effect of cultivar on average individual berry weight in April, May, June, July, and August of southern highbush and rabbiteye blueberries grown under high tunnel in 2023 at E.V. Smith R.C in Tallassee, AL.

	Individual berry weight (g)				
Cultivar	April	May	June	July	August
Arcadia		1.4 bc	–	–	–
Avanti	1.9 ab	1.0 c	–	1.7 a	1.2 b
Bluecrisp	2.3 a	1.7 b	–	1.7 a	–
Chickadee	1.5 ab	1.5 bc	–	–	–
Colossus	1.3 b	–	–	–	–
Farthing	1.7 ab	1.2 bc	0.8 ab	2.0 a	1.7 ab
Gumbo	–	1.1 bc	0.8 ab	1.9 a	1.8 a
Indigocrisp	2.0 ab	1.4 bc	0.7 ab	0.9 ab	–
Keecrisp	1.8 ab	1.3 bc	0.8 ab	1.7 a	1.1 b
Krewer	–	3.1 a	2.5 a	1.4 ab	–
Legacy	–	1.7 b	1.2 ab	–	–
Meadowlark	1.8 ab	1.2 bc	–	–	–
New Hanover	1.6 ab	1.4 bc	1.1 ab	–	–
Optimus	1.6 ab	1.0 bc	0.6 b	–	–
Titan	–	2.9 a	2.0 ab	0.7 b	–
P Value[y]	<.0001	<.0001	<.0001	<.0001	<.0001

[y]Different lower-case letters within a column suggest significant difference indicated by Tukey’s honest significant difference test at $P < 0.05$. Means with the same letters are not significantly different.

Table 2.8. Effect of cultivar on average individual berry weight in May and June of southern highbush and rabbiteye blueberries grown in open-field in 2023 at E.V. Smith R.C. in Tallassee, AL.

	Individual berry weight (g)	
Cultivar	May	June
Arcadia	–	–
Avanti	–	–
Bluecrisp	–	–
Chickadee	–	–
Colossus	–	–
Farthing	–	–
Gumbo	1.5 bc	–
Indigocrisp	0.7 cd	–
Keecrisp	0.8 cd	–
Krewer	–	2.3 a
Legacy	1.8 b	1.2 b
Meadowlark	–	–
New Hanover	1.8 b	–
Optimus	–	–
Titan	2.9 a	2.3 a
P Value[y]	<.0001	<.0001

[y] Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table 2.9. Effect of cultivar on average SSC in April, May, June, July, and August of southern highbush and rabbiteye blueberries grown under high tunnel in 2023 at E.V. Smith R.C. in Tallassee, AL.

	Soluble solids content (% Brix)					
Cultivar	April	May	June	July	August	Mean SSC
Arcadia	11.0 c	11.8 bc	−	−	−	11.4 d
Avanti	13.7 a	12.1 b	−	13.9 abc	14.3 b	13.3 c
Bluecrisp	13.6 ab	13.1 ab	12.8 bc	12.2 d	−	13.0 c
Chickadee	13.2 ab	10.9 c	−	−	−	12.1 cd
Colossus	12.1 abc	11.3 bc	−	−	−	11.8 cd
Farthing	12.3 abc	12.6 b	12.9 bc	14.3 ab	14.4 b	12.8 c
Gumbo	−	12.3 b	14.0 bc	12.5 cd	12.4 c	12.6 c
Indigocrisp	12.0 bc	13.0 ab	14.0 bc	11.2 d	−	12.8 c
Keecrisp	13.5 ab	13.9 a	15.1 ab	15.3 a	16.3 a	14.5 b
Krewer	−	12.9 ab	15.3 ab	13.0 bcd	−	14.6 b
Legacy	−	11.8 bc	14.9 b	13.4 abcd	−	13.2 c
Meadowlark	12.3 ab	11.6 bc	−	−	−	12.0 cd
New Hanover	12.3 abc	12.6 b	13.9 bc	−	−	12.8 c
Optimus	13.1 ab	11.8 bc	12.2 c	−	−	12.2 cd
Titan	−	13.1 ab	16.5 a	14.1 abc	−	15.7 a
P Value[y]	<.0001	<.0001	<.0001	<.0001	<.0001	< .0001

[y] Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table 2.10. Effect of cultivar on average SSC in April, May, June, July, and August of southern highbush and rabbiteye blueberries grown in open-field in 2023 at E.V. Smith R.C. in Tallassee, AL.

	Soluble solids content (% Brix)					
Cultivar	April	May	June	July	August	Mean SSC
Arcadia	–	11.3 bcd	–	–	–	11.3 cd
Avanti	11.4 c	10.5 cd	–	15.2 ab	–	11.8 cd
Bluecrisp	–	12.8 ab	–	15.2 ab	–	13.6 bc
Chickadee	12.8 b	10.3 d	–	–	–	11.1 d
Colossus	–	–	–	–	–	–
Farthing	–	12.8 ab	–	13.2 b	–	12.9 bcd
Gumbo	–	11.7 bc	13.6 c	13.1 b	–	12.0cd
Indigocrisp	12.2 bc	12.0 b	–	–	–	12.0cd
Keecrisp	15.7 a	13.8 ab	–	16.0 a	16.3 a	14.5 b
Krewer	–	–	15.8 b	–	–	15.8 a
Legacy	–	12.3 b	14.5 c	–	–	13.3 bc
Meadowlark	–	–	–	–	–	–
New Hanover	–	12.5 b	–	–	–	12.5 cd
Optimus	–	–	–	–	–	–
Titan	–	14.5 a	17.3 a	–	–	16.5 a
P Value[y]	0.0001	<.0001	<.0001	0.0004	<.0001	< .0001

[y] Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table 2.11. Effect of cultivar and location on plant canopy volume (dm^3) in 2022 at E.V. Smith R.C. in Tallassee, AL.

		Volume (dm^3)			
Location	Cultivar	June	July	Aug.	Sept.
High Tunnel	Arcadia	63.3 abc	109.5 abcd	130.0 abcde	126.7 bcdef
	Avanti	33.7 defg	61.0 bcde	73.5 cdef	74.5 defg
	Bluecrisp	7.0 g	22.3 e	29.5 f	23.0 g
	Chickadee	69.0 ab	127.8 abc	142.8 abcd	165.3 abcd
	Colossus	13.8 fg	230.6 e	32.1 f	30.2 fg
	Farthing	38.4 cdef	73.6 bcde	92.3 bcdef	100.0 bcdefg
	Gumbo	67.2 ab	132.8 ab	162.8 ab	175.3 abc
	Indigocrisp	34.4 defg	64.5 bcde	74.7 cdef	82.7 cdefg
	Keecrisp	66.0 abc	119.4 abc	142.3 abcd	181.7 ab
	Krewer	44.2 bcdef	55.6 cde	66.7 def	64.7 efg
	Legacy	76.6 a	111.5 abcd	133.1 abcd	148.7 abcde
	Meadowlark	26.0 efg	42.4 de	52.2 ef	50.6 fg
	New Hanover	63.0 abc	163.3 a	188.1 a	232.1 a
	Optimus	52.4 abcde	131.6 ab	148.0 abc	176.6 ab
	Titan	60.1 abcd	119.7 abc	140.2 abcd	144.6 abcde
Field	Arcadia	89.1 a	195.9 a	251.1 a	284.4 a
	Avanti	26.0 de	70.1 def	94.8 de	108.2 ed
	Bluecrisp	11.6 e	43.5 ef	79.5 e	90.0 ed
	Chickadee	57.7 abcd	134.7 abcd	81.8 abcd	201.8 abcd
	Colossus	10.1 e	34.7 f	65.0 e	71.2 e
	Farthing	42.4 bcde	114.1 bcde	156.4 abcde	167.6 bcde
	Gumbo	73.8 ab	166.7 abc	214.1 abc	245.3 abc
	Indigocrisp	32.0 cde	83.9 def	122.7 cde	143.1 cde
	Keecrisp	67.7 abc	163.2 abc	233.2 ab	264.6 ab
	Krewer	54.4 abcd	94.2 cdef	153.1 bcde	182.8 abcd
	Legacy	82.1 a	174.1 ab	239.4 ab	275.3 ab
	Meadowlark	27.2 de	54.6 ef	72.4 e	86.6 e
	New Hanover	70.9 ab	189.5 a	235.2 ab	279.1 ab
	Optimus	63.2 abcd	172.3 ab	222.2 ab	263.6 ab
	Titan	72.5 ab	137.1 abcd	225.2 ab	272.4 ab
P value[z]		<.0001	<.0001	<.0001	<.0001

[z]Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table 2.12. Effect of cultivar and location on plant canopy volume (dm^3) in 2023 at E.V. Smith R.C. in Tallassee, AL.

		Volume (dm3)			
Location	Cultivar	June	July	Aug.	Sept.
High Tunnel	Arcadia	475.2 abc	488.5 abc	599.5 abc	716.0 abc
	Avanti	522.2 abc	608.6 ab	695.1 abc	790.8 abc
	Bluecrisp	254.3 bc	300.7 bc	343.6 cd	428.9 cd
	Chickadee	633.0 ab	682.7 ab	837.0 ab	965.4 ab
	Colossus	129.7 c	138.5 c	161.7 d	143.5 d
	Farthing	390.4 abc	489.4 abc	509.1 bcd	599.9 bcd
	Gumbo	635.0 ab	459.7 abc	563.0 abc	732.1 abc
	Indigocrisp	481.2 abc	521.2 abc	538.0 bcd	575.4 bcd
	Keecrisp	578.1 ab	669.9 ab	626.6 abc	796.5 abc
	Krewer	498.5 abc	482.2 abc	563.0 abc	652.2 bc
	Legacy	567.5 ab	433.2 abc	514.7 bcd	688.0 abc
	Meadowlark	312.2 bc	358.0 bc	378.2 cd	441.5 cd
	New Hanover	737.8 a	616.2 ab	680.2 abc	917.8 ab
	Optimus	745.2 a	765.2 a	898.4 a	1105.2 a
	Titan	734.9 a	653.2 ab	534.4 bcd	748.3 abc
Field	Arcadia	539.0 ab	556.7 abcd	604.2 bcd	640.5 bcdef
	Avanti	448.3 abc	562.7 abcd	617.6 bcd	688.9 abcdef
	Bluecrisp	285.6 cd	307.6 cde	371.9 cde	433.2 def
	Chickadee	493.8 abc	585.5 ab	650.5 abc	690.2 abcde
	Colossus	224.7 d	255.8 e	297.5 e	342.4 f
	Farthing	424.9 abcd	466.6 bcde	529.1 bcde	576.6 bcdef
	Gumbo	591.4 ab	625.9 ab	671.4 ab	734.9 abcd
	Indigocrisp	419.7 bcd	485.0 bcde	530.3 bcde	560.2 cdef
	Keecrisp	600.4 ab	676.6 ab	708.1 ab	773.9 abc
	Krewer	573.1 ab	641.1 ab	721.4 ab	771.9 abc
	Legacy	563.4 ab	640.4 ab	698.1 ab	745.8 abcd
	Meadowlark	284.9 cd	299.4 de	343.5 de	411.8 ef
	New Hanover	674.9 a	788.5 a	922.5 a	1015.0 a
	Optimus	493.9 abc	572.1 abc	759.5 ab	890.2 ab
	Titan	661.7 ab	725.3 ab	712.5 ab	842.1 abc
P value[z]		<.0001	<.0001	<.0001	<.0001

[z]Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table. 2.13. Effect of cultivar and location on plant chlorophyll content in 2022 at E.V. Smith R.C. in Tallassee, AL.

		SPAD value			
Location	Cultivar	June	July	Aug.	Sept.
High Tunnel	Arcadia	47.51 ed	45.16 ef	46.72 def	49.93 bcd
	Avanti	46.56 e	45.52 def	44.48 efg	45.95 cd
	Bluecrisp	47.76 cde	47.37 cde	49.84 bcd	52.79 abcd
	Chickadee	51.15 abc	49.34 abc	51.19 abcd	52.90 abc
	Colossus	49.50 abcde	47.18 cde	49.80 bcde	52.37 abcd
	Farthing	47.60 ed	46.86 cde	47.18 def	51.06 bcd
	Gumbo	50.54 abcd	47.82 cde	50.68 bcd	52.97 abc
	Indigocrisp	48.77 abcde	49.36 abc	52.56 abc	58.24 a
	Keecrisp	48.46 bcde	48.94 bcd	53.86 ab	58.18 a
	Krewer	51.66 a	51.31 ab	52.85 abc	54.71 ab
	Legacy	47.11 e	43.04 f	44.02 fg	47.12 cd
	Meadowlark	50.34 abcd	48.01 cde	49.25 cde	50.30 bcd
	New Hanover	47.05 e	47.29 cde	47.55 def	47.05 cd
	Optimus	49.06 abcde	45.36 ef	41.64 g	45.70 d
	Titan	51.42 ab	52.21 a	55.73 a	58.20 a
Field	Arcadia	51.37 abcde	50.43 ab	46.07 cdef	46.63 cdef
	Avanti	48.17 cdef	44.78 ed	44.02 defg	43.84 ef
	Bluecrisp	51.86 abcde	44.73 ed	42.14 fg	44.42 ef
	Chickadee	53.24 abc	47.34 abcde	48.44 abcde	48.07 cde
	Colossus	46.77 def	45.47 cde	47.58 abcde	45.10 def
	Farthing	52.80 abc	48.90 abcd	47.04 bcde	48.22 cde
	Gumbo	52.39 abcd	48.14 abcde	48.78 abcd	49.70 ab
	Indigocrisp	55.79 a	50.71 a	50.66 abc	48.78 cd
	Keecrisp	56.17 a	51.64 a	48.61 abcde	49.27 bcd
	Krewer	50.10 bcde	51.59 a	52.16 a	53.48 ab
	Legacy	43.16 f	45.91 bcde	41.19 g	42.51 f
	Meadowlark	54.36 ab	50.15 abc	46.94 bcde	47.81 cde
	New Hanover	47.79 cdef	43.81 e	44.99 defg	47.35 cde
	Optimus	46.26 ef	43.97 e	43.91 efg	42.76 f
	Titan	52.86 abc	52.04 a	51.01 ab	56.70 a
P value[z]		<.0001	<.0001	<.0001	<.0001

[z]Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at $P < 0.05$. Means with the same letter are not significantly different.

Table. 2.14. Effect of cultivar and location on plant chlorophyll content average in 2023 at E.V. Smith R.C. in Tallassee, AL.

		SPAD value			
Location	Cultivar	June	July	Aug.	Sept.
High Tunnel	Arcadia	47.50 de	45.16 ef	46.72 def	58.24 a
	Avanti	46.56 e	45.53 def	44.48 efg	58.20 a
	Bluecrisp	47.76 cde	47.37 cde	49.84 cde	58.18 a
	Chickadee	51.15 abc	49.36 abc	51.19 abcd	54.71 ab
	Colossus	49.50 abcde	47.18 cde	49.80 bcde	52.97 abc
	Farthing	47.60 de	46.86 cde	47.18 def	52.90 abc
	Gumbo	50.54 abcd	47.82 cde	50.68 bcd	52.79 abcd
	Indigocrisp	48.77 abcde	49.36 abc	52.56 abc	52.37 abcd
	Keecrisp	48.46 bcde	48.94 bcd	53.86 ab	51.06 bcd
	Krewer	51.66 a	51.31 ab	52.85 abc	50.30 bcd
	Legacy	47.11 e	43.04 f	44.02 fg	49.93 bcd
	Meadowlark	50.34 abcd	48.01 cde	49.25 cde	47.12 cd
	New Hanover	47.05 e	47.29 cde	47.55 def	47.06 cd
	Optimus	49.06 abcde	45.36 ef	41.64 g	45.95 cd
	Titan	51.42 ab	52.20 a	55.73 a	45.70 d
P value		<.0001	<.0001	<.0001	<.0001
Field	Arcadia	47.96 ab	46.96 abcd	46.72 cdefg	49.57 abc
	Avanti	46.48 ab	46.49 abcd	45.56 efg	47.03 c
	Bluecrisp	49.56 ab	46.26 bcd	46.94 bcdefg	47.76 bc
	Chickadee	49.06 ab	50.79 a	52.10 abc	57.89 a
	Colossus	47.65 ab	46.64 abcd	50.28 abcde	53.23 abc
	Farthing	48.56 ab	46.62 abcd	48.99 abcdef	52.64 abc
	Gumbo	49.79 ab	50.02 abc	50.68 abcde	50.79 abc
	Indigocrisp	48.11 ab	49.86 abc	52.33 ab	54.16 ab
	Keecrisp	47.83 ab	50.43 ab	52.47 ab	56.33 ab
	Krewer	50.86 a	49.71 abc	51.60 abcd	54.39 ab
	Legacy	45.16 b	43.94 d	43.00 g	44.37 c
	Meadowlark	45.63 ab	48.84 abc	45.89 efg	48.54 bc
	New Hanover	48.01 ab	47.32 abcd	46.67 defg	49.26 abc
	Optimus	46.46 ab	45.69 cd	43.62 fg	48.26 bc
	Titan	49.75 ab	50.61 a	53.47 a	56.14 ab
P value[z]		0.018	<.0001	<.0001	<.0001

[z]Different lower-case letters within a column suggest significant difference indicated by Tukey's honest significant difference test at *P* < 0.05. Means with the same letter are not significantly different.