HIGH TUNNEL RASPBERRY PRODUCTION

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Dedication

To all of my friends and family who have supported me in my endeavors.

Abstract

According to the 2007 USDA-NASS- Agricultural Census (USDA and NASS, 2009) intensive commercial production of raspberries is primarily on the Pacific coast of North America in Oregon, Washington, British Columbia and California. However, there is a demand for locally produced raspberries in Minnesota. Most fresh raspberries come to Minnesota primarily from the West Coast. Locally grown berries could reduce shipping distance but the short growing season in Minnesota limits the feasibility. Lengthening the growing season using high tunnels may be possible. The reason for this project is to ascertain practicality and methodology for the production of organically grown raspberries in Minnesota, using high tunnels.

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Raspberry as a Fruit Crop

Raspberries (*Rubus idaeus*), often called brambles, have perennial roots and biannual shoots referred to as canes. In the first year the canes are referred to as primocanes and in the second year as floricanes (Crandall and Danbery, 1990). The classification of raspberries is by the color of the fruit and the age of the canes on which they produce fruit. The colors of raspberries range from red to black and purple and even yellow. Raspberry cultivars that produce fruit on primocanes are often referred to as primocane-fruiting, ever-bearing or fall-fruiting where as floricane-fruiting raspberries are referred to as summer-fruiting (Bowling, 2000).

The amount of manual labor involved with raspberry production depends on the timing of fruit production. Floricane-fruiting cultivars are biennial requiring a year of cane growth before the canes produce fruit. Primocane-fruiting cultivars produce fruit on the first year canes from late summer through fall. If left alone, the primocanes continue to produce fruit lower on the same canes during the summer of the following year, the canes at that point are called floricanes. If the canes of a primocane-fruiting cultivar are pruned to the ground in early spring of their second year, that year's crop is lost. Although the crop from the floricanes is lost there is the elimination of the costs incurred from carrying the canes through the second year. There is also the reduced risk of winter injury to overwintering floricanes as well as an extended period of harvest for primocane-fruiting cultivars (Pritts and Handley. 1989).

Site Selection, Field Layout and Planting

When preparing a site for raspberry production there are many factors that need to be taken into consideration. Raspberry plants lack vigor under poor soil aeration. As such, special care should be given to soil drainage (Bowling, 2000). For more porous soils, increased irrigation and fertilizer application may be necessary. Sites free from spring frosts and cold winter winds are considered optimal. Testing for the presence of nematodes is necessary to prevent the diseases they can transmit. With the soil tests for nutrient levels, a test for nematodes should be carried out and appropriate measures for fumigation and control taken. Tilling is recommended in the fall prior to planting, with manure applied to adjust soil nutrients to adequate levels. The application of manure or compost is particularly important with soils having low organic matter. The pH should be adjusted to a range of 5.7 to 6.0 (Crandall and Danbery, 1990).

Rows are oriented north/south where possible to optimize light exposure. Row spacing depends on cane vigor. For vigorous raspberries (black and red) spacings of 2.4-3 m between rows is recommended. For less vigorous red raspberry cultivars spacing between rows of 1.8-2.4 m is advised (Crandall and Danbery, 1990). Plant spacing within the row for red raspberries of 60 cm is recommended for both primocane-fruiting and floricane-fruiting cultivars (Bowling, 2000).

Planting can take place at the earliest time that weather conditions allow in the spring. The roots should be sufficiently splayed upon planting. Planting depth should align the crown of the plant at soil level (Crandall and Danbery, 1990).

Fruit Development

The raspberry fruit is classified as an aggregate fruit composed of drupelets. These drupelets adhere to each other with epidermal hairs entangling. Raspberry fruit takes an average of 30 to 36 days after pollination with drupelets tending to ripen together. Fruit development tends to occur in three stages (Jennings, 1988). Following pollination there is a period of rapid growth due to cell division followed by a period of slow embryo development and endocarp maturation, which is then followed by a final stage of rapid growth due to cell enlargement. Each of these stages takes between 10 and 12 days (Hill, 1958).

Cultivars Used in Thesis Research

Autumn Britten (*Rubus idaeus* 'Autumn Britten') was released in 1995 V.H. Knight, E. Keep and J.H. Parker from East Malling, Kent, U.K. (Goulart and Demchak, 1999). It is known to produce a red berry with a weight in excess of 2.5g with yields as high as 2.5t/ha (Hanson, et. al, 2005). The canes of Autumn Britten, grown in open fields, have been recorded as reaching an average height of 1.2 meters (Hanson, et. al, 2005; Goulart and Demchak, 1999).

Caroline (*Rubus ideaus* 'Caroline') was released by Dr. Harry Swartz, University of Maryland, in 1989 (Goulart and Demchak, 1999). It is known to produce a red berry with a weight in excess of 2.5g with yields as high as 6.1t/ha (Hanson, et. al, 2005). Caroline produces fruit later in the season then Autumn Britten, possibly necessitating a need for season extension. The canes of Caroline, grown in open fields, have been recorded as reaching an average height of 1.2 meters (Hanson, et. al, 2005;Goulart and

Demchak, 1999). Caroline has an interesting pattern of growth, producing both tall and short canes, the shorter canes producing fruit before the taller canes (Goulart and Demchak, 1999). The time of 1st harvest also differs between these two cultivars. As the canes matured Caroline consistently reached the point of 5% harvest after Autumn Britten (Dale et al., 2001).

High Tunnels

High tunnels fall under the broader category of plasticulture. Plasticulture is defined as "the science and the technology of the use of plastics in agriculture and horticulture"(Dubois, 1978). The use of tunnels in plasticulture is categorized as the semi-forcing of plants. Semi-forcing is growing crops that are early or late without heat in order to increase yield (Dubois, 1978).

A high tunnel resembles a traditional greenhouse with certain distinctions. A high tunnel is a nonpermanent structure consisting of a series of ribs covered with a greenhouse grade plastic. Not being a permanent structure allows for exemptions in many areas to certain taxes and zoning regulations (Heidenreich et al., 2007). By convention, there is no permanent heating installed in the high tunnel itself. For northern growers, propane heaters, or similar, are often used to marginally increase temperature in the fall to further extend the season. Raising and lowering the sides and end walls provides cooling and aeration for the structure (Lamont et al., 2003).

Climate in a High Tunnel

High tunnels are used to control the environment to maximize production. Often in areas of the world with warm climates, high tunnels are used to reduce wind damage as well as protect the plants from rain. Reducing water on foliage has the added advantage of reducing disease pressure. Controlling temperature, particularly to increase temperature during mid-winter is a second reason cited for high tunnel use (Burkhart and White, 2003).

Environmental parameters that can be controlled include wind, water, and temperature. These environmental factors are controlled to a great extent by adjusting wind and aeration through the raising and lowering of the sides of the structure as well as opening and closing the end walls.

Humidity varies over the course of the day as well. It is greatest at night and lowest during the day. This is a point worth noting since humidity affects transpiration rates and certain diseases (Burkhart and White, 2003). Watering methods that are employed for high tunnel production include hand watering, in ground and overhead sprinklers as well as drip irrigation. Drip irrigation is the most commonly used method of water application due to the many potential benefits it provides. Drip irrigation allows picking to occur while watering; supplies the water directly were it is needed, cutting down on waste and excess weed growth; and keeps the water off of the leaves reducing the disease pressure.

Temperatures are dependent on the amount and intensity of sunlight hitting the structure. As such, there is a predictable cycling of temperature as the day progresses into night and around again. At Pennsylvania State, they found that the average inside vs. outside temperature difference over a 24hr. period tends to be 8.4 °F with most of the heating taking place between 6AM and 2PM. On a bright day there can be a temperature difference of as much as 15-50°F (Burkhart and White, 2003). Temperatures inside vs. outside the high tunnel showed the greatest difference during the day rather than at night where temperatures in and out equalized. Time of year also resulted in variation in temperature. The summer was the peak time for increased temperatures inside compared to out outside of the high tunnel but there was a distinct increase in temperatures inside as compared to outside the high tunnel in winter as well, just less pronounced (Burkhart and White, 2003).

Light Transmittance and Plant Growth

To provide optimal exposure for photosynthetically active radiation (PAR) high tunnel direction should be considered carefully. As a general rule above 40 degrees latitude, the high tunnel should be oriented with the end walls in an east/west direction as well as providing the optimal radiation exposure (Jett et al., 2004).

The quantity and quality of light transmitted through the high tunnel covering both play an important role in the growth and development of the plants. A spectrophotometer is commonly used to measure transmitted light (Kittas and Baille, 1998; Papadakis and Briasooulis, 1998), indicating both wavelength and intensity of the light being transmitted.

Transmission of PAR aids the plant in developing vegetative mass as well as improving fruit productivity, and shortening the time to flowering (Wagner, 1998). This is because light is the principle factor of photosynthesis and photomorphogenesis. Vigor increases with light intensity until the light saturation point for a particular plant is reached (Ingram et al., 2008). The effects of even a slight decrease in photosynthetically active light to the plants being grown can have a pronounced effect. Cockshull et al. (1992) showed a 1% decrease in PAR resulted in a 1% decease in tomato yield (Hunt et al., 1998).

To monitor how the amount of PAR light that is getting through is affecting a plants photosynthetic rate, a method often employed is measuring CO_2 and H_2O level fluctuations in relation to temperature and irradiance. Photosynthetic rate is measured by use of a portable IRGA machine, Infrared Gas Analyzer. The chamber is used to measure differences in concentrations between the gasses entering the chamber holding the sampled area of the leaf and the gasses that leave the chamber. When the levels of these two gasses are compared with the temperature and levels of photosynthetically active radiation the rate of photosynthesis can be calculated (Millan-Almaraz et al., 2009).

Raspberries are known for shifting between sources and sinks of fixed carbon through the course of development. During development, carbon allocation switches from developing shoots and leaves to flowers and fruit (Privè et. al, 1994). This shifting of sources and sinks has been mapped through the application of C^{14}. When new leaves and flowers were present on the same cane at the same time, they were equally treated as sinks. There was a shift in favor of reproductive growth being the predominant sink when fruit set was initiated. Furthermore, the amount of allocation was most closely related to the distance of the leaf to the flowering or fruiting lateral. The closer the leaf is, the more the leaf contributed carbon to developing fruit (Privè et. al., 1994).

There is a similar interplay between the intercepted irradiance and photosynthetically active areas. This is thought to be a difference between primocane and floricane fruiting cultivars. Primocane-fruiting raspberries are expected to not have as much crowding because they don't have the competition between the primocanes and floricanes (Privè et al, 1994). Without the competition they have more their resources available to feed the top one third to one half involved in the production of fruit (Pritts and Handley, 1989).

Diseases and Insects of Raspberries in High Tunnels

There are many different diseases that can infect raspberries. Viral diseases most noted for raspberries of all colors include mosaic virus, leaf curl virus, tomato ringspot virus, and raspberry bushy dwarf virus. Some non-viral diseases that merit mentioning are Anthracnose, *Verticillium albo-atrum* and *Verticillium dahliae* are more prevalent in black and purple raspberries. Spur blights *Didymella applanata* tend to affect primarily red raspberries. Crown gall and root rot are indifferent as to the color of the raspberry (Crandall and Danbery, 1990).

One disease that merits special discussion is fruit rot, *Botrytis cinerea*. It affects red, purple and black raspberries equally. The infection occurs on the fruit or less commonly on the cane (Crandall and Danbery, 1990). Many different fungi cause fruit rot but Botrytis is the most important. The means of infection are by airborne spores infecting the flowers. The hyphae grow down to the ovary alongside the pollen tubes. Once the hyphae reaches the ovary it produces an endogenous mycelium, now prepared to attack the fruit once ripe (Jennings, 1988). "Fruit infected by grey mould show a watery rot covered by a grey-brown mass of felt-like hyphai" (Jennings, 1988). Grey mold dramatically shortens the shelf life of the fruit post harvest and is particularly common when humid or wet conditions are present during flowering of fruit ripening (Jennings, 1988). Normally, the mold does not form on fruit connected to the canes unless the fruit is over ripe. The exception, again, comes with particularly wet years (Bowling, 2000). In Canada it was found that even when prevalence is low in the field 64-93% of the fruit picked developed fruit rot within 40 to 60 hours post harvest (Freeman, 1965)

Disease is a matter of concern in high tunnel production because field practices don't necessarily translate well to high tunnel practices. Rotation practices should be observed as well as removing all plant debris after harvest. The time of most concern for disease exposure is during times when the sidewalls are down. The lack of airflow and high humidity can result in condensation forming on the foliage optimizing the likelihood of infection. A similar result can be found with plant densities getting too high. With this, there is overlapping of plant tissues resulting in a localized high humidity again promoting infection. With all these points, scouting is the means by which problems are identified and dealt with early before they become a problem (Backman, 2003).

For further information on diseases and pests of raspberries, *Raspberries and Blackberries: Their Breeding Diseases and Growth* by D.L. Jennings (1988) is recommended.

The three insects monitored most often by researchers at Pennsylvania State were whiteflies, aphids and mites (Thomas et al., 2003). Heidenreich et al. (2007) found two spotted spider mites and Japanese beetles and recommend most pest problems encountered with high tunnels can be controlled by biological control coupled with soft pesticides. For biological control, there are many predatory insects available with selection dependent on the pest (Thomas et al., 2003).

The application procedures for pesticides tend to be intermediate between procedures for field application and for greenhouse application. Application is dependent on the amount of ventilation of the high tunnel. If the sides are open and ventilation is at a maximum then application methods mimic field applications. If the sides are closed the methods should be more in line with greenhouse practices.

The use of a high tunnel helps with control of detrimental insects. By being able to close the high tunnel, growers can work to keep detrimental insects out, be able to use gentler pesticides, and could contain the release of beneficial insects. The use of beneficial insects is a form of biological control. Such a biological pest control is achieved by two means, by controlling the environment with the aim of isolating and enhancing the existing antagonists and by introducing the antagonists (Lind et al., 2003).

The fertilizers applied tend to be dependent on the intended use and the means of application. There are organic fertilizers intended for soil conditioning. These serve the role of increasing the humus content of the soil. There are fertilizers that are intended for supplying nutrients, varying from application to the soil surface to application as a foliar fertilizer (Lind et al. 2003). For the applications of fertilizers such as manure fertilizer should be applied to the middle of the row in late fall through early winter (Crandall, 1995)

The Consideration for High Tunnel Use in Raspberry Production

The use of high tunnels in raspberry production has been known to produce high yields. The yield is 2-3 times what could be expected in comparable field plots. There is also the potential to grow cultivars that would otherwise not be hardy to Minnesota (Demchak, 2009).

Pests of special concern for high tunnel raspberry production are two-spotted spider mite and Japanese beetles. In both cases, there are biological controls available as long as they are applied at or below threshold. Diseases that have posed special concern for high tunnel raspberry production are many but two of particular concern are the mildews and rusts. Powdery mildew is a fungus caused by the fungus *Sphaerotheca maculari,* appearing as a white powdery patch covering the plant. To help prevent powdery mildew, plantings should not be located near wild brambles and assure adequate ventilation occurs within the high tunnel. In more severe cases, a fungicide might be required. Rusts require two hosts to complete a life cycle of which spruce tend to be a common intermediate. Care should be taken to not locate the high tunnel near any stands of spruce. A point that was brought up earlier is the concern about gray mold. The concern was that in particularly wet year there is going to be gray mold developing on the fruit rendering it unfit for sale. It is felt at this point that the use of high tunnels can reduce this but to what extent is unknown (Pritts et al., 2006).

The final point is the season extension of raspberry production by the use of high tunnels. There are two categories of season extension, early and late season. Early season is beneficial to both floricane and primocane-fruiting raspberries and involves the closing of the high tunnel early in the season, warming the environment around the plants and providing them with a head start. Late season extension is particularly useful for the primocane-fruiting cultivars; extending the season at the end fruit harvest is prolonged.

Hypothesis

The purpose of this study is to ascertain if there are differences between the raspberry cultivars Autumn Brittan and Caroline each grown at two initial in-row plant spacings of 45 or 60 cm grown in a high tunnel. The hypothesis is that there is no difference in growth parameters of these two cultivars at either in-row plant spacing.

High Tunnel Raspberry Production

Introduction

According to the 2007 USDA-NASS- Agricultural Census (USDA and NASS, 2009) intensive commercial production of raspberries is primarily on the Pacific coast of North America in Oregon, Washington, British Columbia and California. However, there is a demand for locally produced raspberries in Minnesota. Most fresh raspberries come to Minnesota primarily from the West Coast. Locally grown berries could reduce shipping distance but the short growing season in Minnesota limits the feasibility. Lengthening the growing season using high tunnels may be possible. The reason for this project is to ascertain practicality and methodology for the production of organically grown raspberries in Minnesota, using high tunnels.

Primocane-fruiting raspberries produce fruit on first year canes. However, there is considerable difference between cultivars of primocane-fruiting raspberries. For instance, Autumn Britten has been reported to produce berries that are larger then Caroline but, Caroline produces a higher yields per year then Autumn Britten (Goulart and Demchak, 1999; Dale et al., 2001; Hanson et al., 2005).

High tunnels are non-permanent structures and usually are not heated unlike greenhouses (Lamont et al., 2003). This combined with the fact that high tunnels cost considerably less then greenhouses makes high tunnels much more attractive to small-scale producers. There are many reasons for the interest in high tunnel production in northern climates such as allowing winter-tender cultivars to survive, and may increase the quality and quantity of produce by reducing wind damage and keeping rain off plants (Pritts et al., 2006; Demchak, 2009). Last and by no means least is season extension. High tunnels have been known to elevate the daytime temperatures inside of the structure by an average of 8.4°F (Burkhart and White, 2003). The increase in temperature has extended the number of frost-free days by as much as 40 days in Kentucky (Bomford et al., 2007). Although the increase in temperature could extend late season production the shortened photoperiod could result in an end to fruit production in some primocane-fruiting cultivars (Privè et al., 1997). For all of these reasons there is a benefit to high tunnel production in northern climates and a need to explore this production system in Minnesota. The purpose of this study was to determine if cultivars and/or initial plant spacing would effect growth parameters and yield of primocane-fruiting raspberries.

Materials and Methods

The high tunnel planting was established in the spring of 2008 on the University of Minnesota St. Paul campus, 45° north latitude 93° west longitude. The soil is a Waukegan silt loam with a pH of 7.2 and an organic matter content of 5.3%. Before planting, the soil was amended with compost from the University of Minnesota. Analyses conducted prior to compost addition indicating the nitrogen level at 8.4ppm, Olsen phosphorus at 140ppm, Bray 1 phosphorus greater than 100ppm, and potassium greater than 300ppm. All of these levels, with the exception of the nitrogen, were adequate for raspberry production. After adjustment with compost the nitrogen level had risen to 46 ppm, adequate for raspberry production.

The high tunnel is a Quonset-style covered in a 6 mm polyethylene plastic, with dimensions of 14.4 m long by 9.1 m wide and 3.7 m tall. The high tunnel contained 3 rows, 11m in length, oriented in an east/west direction. A weed suppressive black woven landscape fabric was used between the rows with a 60 cm weed-free border maintained around the tunnel.

The experimental design was a 2X2 factorial with three replications. Primocane-fruiting cultivars, Autumn Britten (AB) and Caroline (CAR) were the main factors with plants spaced at either 45 cm (45) or 60 cm (60). The 45 cm treatments contained six plants for a plot length of 225 cm; the 60 cm treatments contained 4 plants with plots 183 cm long. Rows were replicates. Each row contained the four treatments randomly arranged into four plots. One meter was maintained between each plot within each row.

Planting occurred on 15 May 2008 using bare-rooted plants. The primocanes were allowed to grow without thinning or trellising during the summer of 2008, year one of the study. During the second year, 2009, the primocanes were thinned to 6-8 per 30 cm of row and the spacing maintained throughout the growing season by hand removing primocanes as they emerged. The primocanes were trellised on 15 July, 2009.

Pest management was carried out using guidelines set forth by ATTRA (ATTRA, 2010). A drip irrigation system was installed at the time of planting. Soil moisture levels were monitored and kept at or above 30 centibars during the growing season. The high and low temperatures inside of the structure were recorded daily from 26 Oct. 2009 to 1 Dec. 2009.

Primocane height and number of nodes were recorded weekly from 30 July 2008 to 22 Oct. 2008 of the first year. Measurements were taken weekly 20 May 2009 through 20 July 2009 then twice more on 20 Aug. 2009 and 20 Oct. 2009 of the second year. During year one, one primocane was labeled and measured on each plant, for a total of 60 samples across the experiment. During the second year, five canes were selected at random for each plot for each date. Through the growing season the height of the primocane was measured from the ground to the apical bud. Number of nodes was also recorded for each primocane starting at ground level proceeding to the node containing the smallest true leaf discernable. Laterals exceeding 12.7 cm were counted at the end of the growing season.

Harvest data collected included total weight of fruit and total number of berries per plot. Berry production occurred during year two of the study. The first harvest occurred on 31 July 2009 with harvest done as often as needed, but at least twice weekly.

Samples were collected 3 times per season for postharvest observations. For each experiment, fruit was harvested and promptly transported to cold storage at 3°C. In the first experiment, six berries from each treatment in each row were collected, rinsed in water, the inside and outside dried with a paper towel and placed in egg cartons. The cartons sprayed with Lysol 24 hours prior to the berries being placed in the cartons. Observations were made daily for evidence of infection with *Botrytis cinerea*. This experiment was replicated twice. The first observations were made from 24 Aug. 2009 to 24 Sep. 2009 and from 24 Sep. 2009 24 Oct. 2009.

The second postharvest experiment began 26 Oct. 2009 and ended on 2 Nov. 2009. Ten berries of each cultivar were selected at random from across all plots. The berries were collected, rinsed in water, the inside and outside dried with a paper towel and were placed in washed plastic ice cube trays consisting of twelve wells, six containing individual fruit and six filled with 3-5 ml of water. The trays were wrapped in clear plastic, sealed and placed in 3C. Fruit were monitored and photographed daily. Berries were rated on a scale of 0-5: 0 equated with no visible infection and a rating of 5 equated to 100% fruit surface was covered with hyphai.

To determine photosynthetic rates, three primocanes of each cultivar were selected from the second replication located in the center of the high tunnel. The primocanes were selected based upon the identification of the first visible unopened flower buds at the apical tip of the primocane. The measurements of Autumn Britten were conducted on 13 Sep., 27 Sep. and 30 Sep. 2009. The measurements of Caroline were conducted on 20 Sep., 4 Oct., and 7 Oct. 2009.

Photosynthetic measurements were taken with the LI-COR LI-6400 Portable Photosynthesis System, with an internal light source and a 6 cm^2 cuvette. The cuvette was clamped on the most distal lobe of the youngest fully expanded leaf. The internal light source was set at 1100 lumens with 400 ppm CO_2, at a flow rate of 500 $\mu mol/m^2/sec$ and 75% humidity. Standardization took place prior to a leaf placed in the cuvette. One leaf was measured per date taking 3-5 readings per temperature. Readings were taken at three degree increments of block temperatures ranging from 17°C to 35°C, between 9 AM and 4 PM. Leaf temperature was used in the calculations but block temperature was used while taking the readings due to a greater degree of control. Three to five readings per temperature were taken to accommodate fluctuations in leaf temperature and photosynthetic rate at individual block temperatures.

Statistical analysis was performed using a linear mixed effects model in R (R Development Core Team, 2005; Bates, 2007). Plant spacing and cultivar were treated as fixed effects. The factors, date of data collection as well as the location of each treatment within the high tunnel, were treated as nested random effects. The results of the analysis took into account variation over time for the differences between the treatments. Multiple comparisons of means were done with Tukey's HSD and analysis of variance of cultivar and spacing at the end of the experiment. As a result of the two different kinds of analyses, there might be a significant difference reported over the course of a season between treatments but at the end of the season no significant difference may have been found.

Results

Growth parameters of the two cultivars varied in primocane height and number of nodes during the two years of the study. Although these differences were statistically significant, no significant difference in yield occurred among treatments.

During the year of planting, no significant difference was seen between cultivars but significant differences in height between the two plant spacings and the interaction of cultivar by spacing were noted (Table 1). During year one, number of nodes was significantly different between the cultivars, plant spacing, and the interaction between cultivar by spacing (Table 1).

Primocane height in year one varied among treatments. AB (45) produced the shortest primocanes (Table 2). Average primocane height through year one depicts a divergence between AB (45) and AB (60) in mid August (Fig. 1). The difference in growth was also observed when number of nodes was plotted with AB (45) having significantly fewer nodes than AB (60) and CAR (45) (Fig. 2).

As the plants matured in year two, significant differences between cultivars, plant spacing, as well as the interaction between cultivar by spacing appeared (Table 1). Once again differences in height and number of nodes for AB (45) and AB (60) occurred (Fig. 3 & Fig. 4).

There was a significant difference in height at the end of the second growing season between AB (45) and CAR (60) with the other treatments intermediary. The number of nodes at the end of the 2^{nd} year followed primocane height with AB (45) having significantly fewer nodes then CAR (60). Again, AB (60) and CAR (45) were intermediate in node number (Table 2).

Fruit harvest occurred in the second year of the study. Yield, recorded weekly, was not significantly different between cultivars, plant spacing, or the interaction between cultivars by spacing (data not shown). Additionally, no significant difference was found in the number of berries or mean berry weight by cultivar, plant spacing or the interaction term between cultivar and spacing (data not shown). A significant difference in mean berry weight between cultivars occurred (p<0.001) but not between plant spacings or interaction. AB (60) produced the berries with the largest mean weight (3.2g) with the smallest mean weight per berries being produced by CAR (60) (2.5g). AB (45) and CAR (45) were intermediate (Table 3).

Autumn Britten had the first fully opened flowers on July 2, 2009, 14 days before Caroline. Autumn Britten started to produce fully ripened fruit on July 31, 2009, 17 days before Caroline. This difference in timing of development between cultivars continued with time of peak harvest of about 2 weeks (Fig. 5) and time of 50% harvest being 2 weeks (Fig. 6). Caroline was harvested through the first freeze (October 9, 2009) while Autumn Britten harvest was completed on October 9, 2009. Harvest continued after the first freeze for Caroline but a marked decline in yield and marketable fruit was noted. The harvest of Caroline was completed on October 23, 2009. We observed Caroline had more unopened flowers with a lesser degree of senescing prior to the end of the growing season compared to Autumn Britten. Berry size decreased over the course of the season with a large drop in size being noted around the time of first freeze (Fig. 7).

We investigated shelf life of raspberry fruit growing under high tunnels. In the two experiments lasting 4 weeks each, no significant differences between the two cultivars were observed (data not shown). The berries from both cultivars showed signs of fungal hyphai presence between 24 and 48 hrs after harvest.

There was a significant difference in photosynthetic rate between the two cultivars (p<0.001) over the range of leaf temperatures from 17°C and 35°C. The leaf temperature was used instead of the more consistent block temperature in the representation of photosynthetic rates due to the temperature of the leaf having a more direct affect on the rate of photosynthesis. The R2 for Autumn Britten was 0.25 for the polynomial equation $y= 0.0056x^2-0.453x+14.373$ (Fig. 8). No maximum photosynthetic rate was calculated for Autumn Britten because of the small R^2 value. The temperature of maximum photosynthetic rate calculated for Caroline was derived from the derivative of the equation for the trend line, $y=-0.0338x^2+1.4742x-5.16$, $R^2=0.63$ (Fig 9). The calculated maximum photosynthetic rate for Caroline was 21.8°C.

Discussion

High tunnels are used in northern climates, such as New York, Michigan and Minnesota, as a means of season extension. Primocane-fruiting raspberries are well suited for high tunnel production due to the high value and the potential to produce berries into the fall. In our study growth parameters of height and number of nodes were recorded over 2 years as well as yield parameters of weight, number and weight of berries taken during the second growing season. Although significant differences in growth parameters between cultivars were recorded, no significant differences in yield occurred.

We report significant differences in height and number of nodes in the establishment year as well as the first year of harvest between the cultivars. Despite differences initial plant spacing and in growth parameters, no significant differences in yield parameters were measured. Studying field-grown primocane-fruiting cultivars in southern Michigan, Hanson et al. (2005) found Caroline produced significantly higher yields by weight then Autumn Britten. Goulart and Demchak (1999) in a field trial of 9 primocane-fruiting raspberries in Pennsylvania also reported Caroline produced over twice the yield, by weight, as Autumn Britten. The differences in yield among these studies and ours may be, in part, due to the difference in age of the planting. In a greenhouse trial of various cultivars of primocane-fruiting raspberry, including Caroline and Autumn Britten, Dale et al. (2001) concluded within the first few years, yield between the two cultivars were equivalent. This suggests, given time, the raspberry cultivars grown in our experiment may show a divergence in yield that would be expected given the results from experiments done on more established plantings.

The greater mean weight per berry of Autumn Britten compared to Caroline in our experiment may be attributable to the inherent differences in cultivar. Autumn Britten has been recorded as producing larger fruit then Caroline in other studies (Dale et al., 2001; Goulart and Demchak, 1999). In the experiment by Dale et al. (2001), raspberries grown in greenhouses over a three year period produced a mean weight per berry for Autumn Britten between 3.0 and 4.0 g and with Caroline averaging between 2.5 and 2.6 g per berry. In the field trial done by Goulart and Demchak (1999) Autumn Britten had a mean berry weight of 2.9g; Caroline had a mean berry weight of 2.5g. The mean berry weight for Caroline from our experiment exceeded the mean berry weight recorded by these other studies. In our study Autumn Britten's mean berry weight was within the range in greenhouse studies of pot cultivated primocane-fruiting raspberries conducted by Dale et al. but far exceeded the mean berry weight found in a field planting by Goulart and Demchak (1999).

Though there was no comparable field plot in our study, as expected yield per meter was greater when compared with other research on field-grown primocane-fruiting raspberries. In the field experiment carried out by Goulart and Demchak (1999), we converted yield measurements from kg/ha to kg per meter of row. For Autumn Britten and Caroline yields were 500g/meter of row and 1100g/meter of row respectively, which were 3-6 times lower than yields we recorded in our high tunnels. Differences in growing conditions obviously had a large impact on yield between our high tunnel and the field results of Goulart and Demchak. Our results suggest a need to carry out future cultivar trials in high tunnels to determine cultivar performance in this type of protected environment.

Autumn Britten was consistently 2 weeks ahead in development compared to Caroline during the first year of production in our study, supporting the work of Dale et al. (2001). The time from anthesis to first harvest in our study was 29 days for Autumn Britten and 32 days for Caroline. Goulart and Demchak (1999) found Caroline took 36 days from bloom to harvest. Interestingly, no difference between the field and high tunnel environments was measured leading us to conclude that temperature may not alter fruit development in these cultivars of primocane-fruiting raspberries.

When the photosynthetic measurements were taken in our study Autumn Britten had completed harvest while Caroline was still producing fruit. S.P. Long (1991) described the effect of elevated temperature on photosynthesis in C3 plants.. The plant's photosynthetic rate increases until it reaches an optimal point after which rubisco's (ribulose-1,5-bisphosphate carboxylase oxygenase) affinity for CO_2 begins to decrease. The resulting decrease in CO_2 uptake reduces the photosynthetic rate. The resulting photosynthetic rate curve is a parabolic, increasing with temperature to the maximum rate then decreasing as temperature continues to rise. The temperature response curve for Autumn Britten at the first date had the expected bell curve. Subsequent measurements taken for Autumn Britten, approximately 2 weeks later, did not follow the expected curve. The temperature response curve for Autumn Britten from 4 Oct., was a decline in photosynthetic rate and the curve from the 7 Oct., was flatter than the temperature response curve recorded on the 20 Sep., 2009. A likely cause for the difference in Autumn Britten temperature response curve among the three dates is senescence of the leaves. A temperature at which Autumn Britten had a maximum photosynthetic rate was not calculated because of the high variability amongst the curves. Privè et al. (1997), showed the photosynthetic rates of primocane-fruiting raspberries cultivars, Autumn Bliss and Redwing raspberries grown in Ontario, didn't change with age until they reached the point of senescence, at which point it declined. The photosynthetic curve for Autumn Britten would suggest Autumn Britten was senescing and might be less suited for late season extension.

In contrast to Autumn Britten, the photosynthetic curves for Caroline were more cons. The temperature maximum for Caroline was higher than the temperature maximum reported for other cultivars. A study by Fernandez and Pritts (1994) found the primocanes of potted Titan raspberries grown in field conditions had a temperature maximum at 15 °C, with the photosynthetic rate declining as the temperature increased. Similar results were found by Privè et al. (1997) in which pot grown Autumn Bliss primocane-fruiting raspberries under field conditions had an optimal photosynthetic rate at 17 °C. In our experiment the temperature of maximum photosynthetic rate was 21.8

°C. The elevated temperature of maximum photosynthetic rate for Caroline may indicate an increased tolerance for the elevated temperatures recorded in high tunnels compared to the field.

Fruit production of Autumn Britten and Caroline can be increased both in quality and quantity by being grown in high tunnels, particularly in our northern climate. The difference between these two cultivars also illustrates the need to test other cultivars of primocane-fruiting raspberries for suitability for high tunnel production systems. We recommend multiple cultivars be grown in high tunnels to effectively extend the growing season. Use of standard field plant spacing of 60 cm at the time of initial planting be considered for primocane-fruiting raspberries grown in high tunnels.

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Tables and Figures

Table 1: The p-values of the height and number of nodes when time is taken into account as a random effect at the end of both year one and two of the study for the two cultivars Autumn Britten (AB) and Caroline (CAR) planted at either 45 or 60 cm initial plant spacing.

Year 1		
	p-values for height (cm)	p-values for # of Nodes
Cultivar	0.1777	0.03000
Spacing	0.0001	0.0074
Interaction	0.0001	0.0229
Year 2		
Cultivar	0.0001	0.0090
Spacing	0.0055	0.0106
Interaction	0.0004	0.0003

Table 2: Mean height and number of nodes at the end of both year one and two of the study for the two cultivars Autumn Britten (AB) and Caroline (CAR) either 45 or 60 cm initial plant spacing. Significant differences between the final heights and number of nodes at ($p \leq 0.05$) are indicated by different letters within each year and within each column.

Year 1		
Cultivar Plant Spacing (cm)	Height (cm)	# of Nodes
AB (45)	72 b	24 b
AB (60)	97 a	30 ab
CAR (45)	87 ab	31 a
CAR (60)	78 ab	30 ab
Year 2		
AB (45)	125 b	30 b
AB (60)	136 ab	31 ab
CAR (45)	146 a	36 a
CAR (60)	136 ab	34 ab

Table 3: End of the second season yield/meter of row for the two cultivars Autumn Britten (AB) and Caroline (CAR) either 45m or 60m initial plant spacing. Significant differences among treatments for total yield, number of berries and mean weight per berry at ($p \leq 0.05$) are indicated by different letters within each column.

Cultivar Plant Spacing (cm)	Weight (g)	Number of Berries	Weight per Berry (g)
AB (45)	3610	1059	3.4 abc
AB (60)	3891	1107	3.5 a
CAR (45)	3695	1182	3.1 bc
CAR (60)	3760	1305	2.9 c

Fig 1: Primocane height during year one for the two cultivars Autumn Britten (AB) and Caroline (CAR) initially planted at either at (45) or (60).

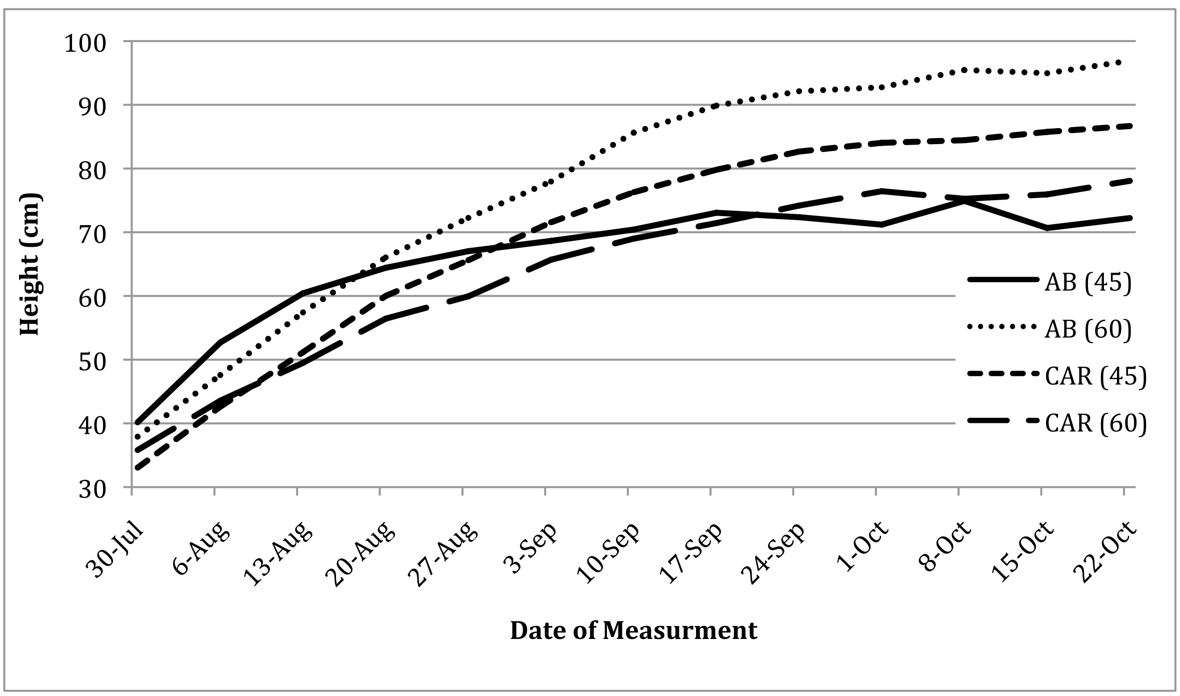


Fig. 2: Number of primocane nodes during year one for the two cultivars Autumn Britten (AB) and Caroline (CAR) either at (45) or (60) plant spacing.

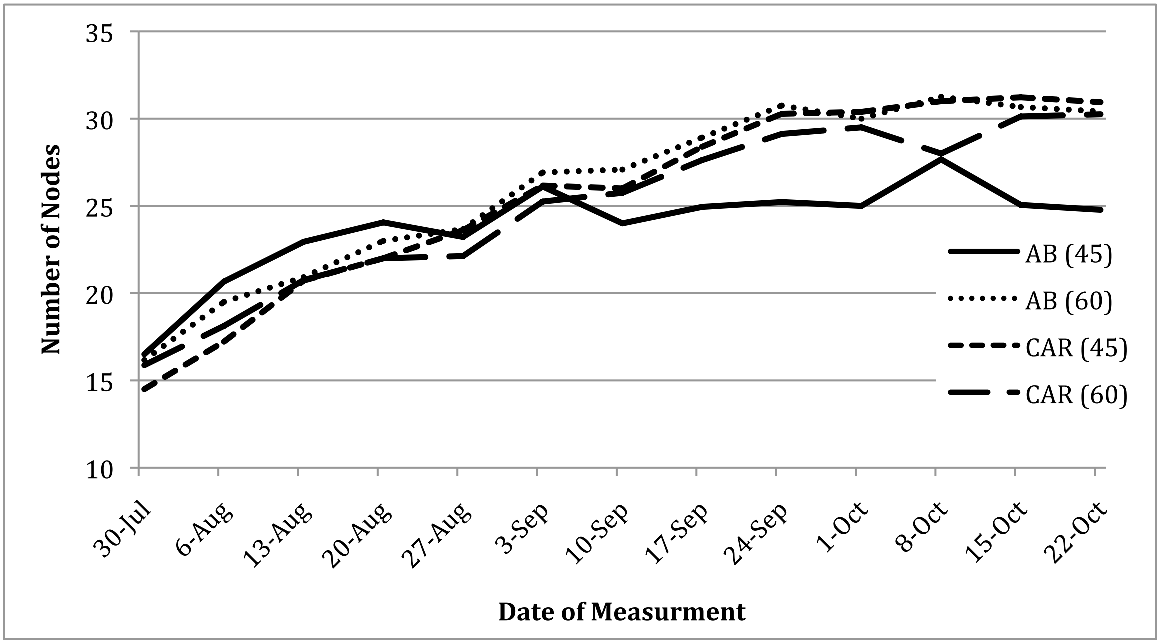


Fig. 3: Primocane height during year two for the two cultivars Autumn Britten (AB) and Caroline (CAR) initially planted at either (45) or (60).

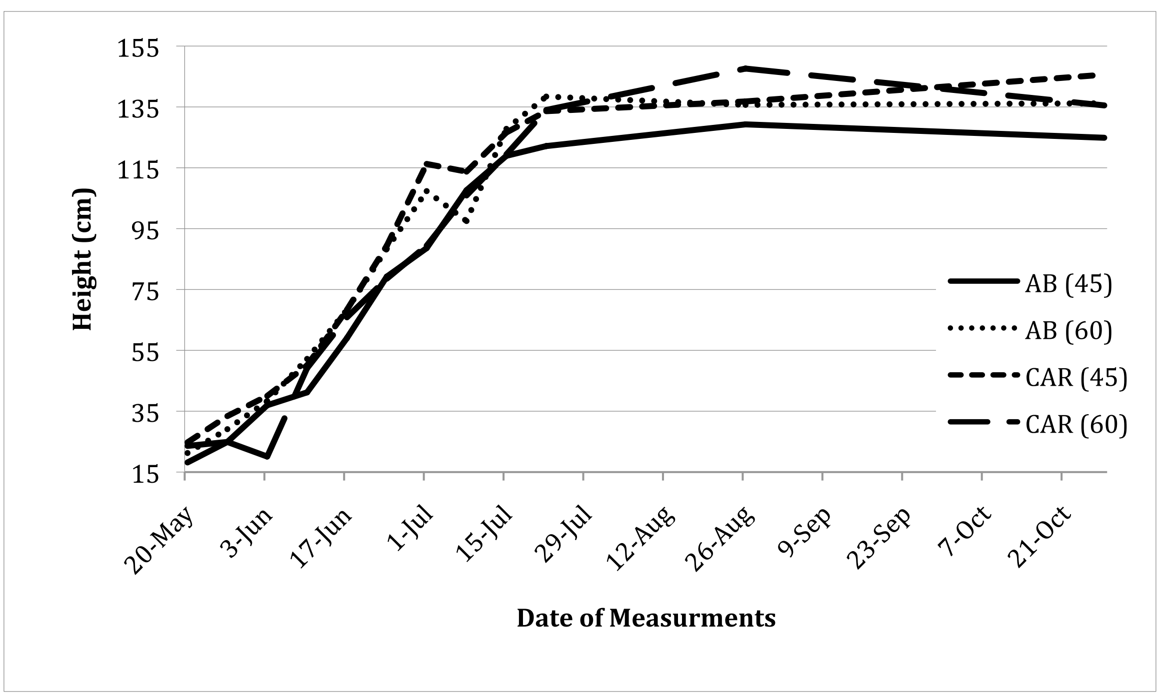


Fig. 4: Number of nodes during year two of the study for the two cultivars Autumn Britten (AB) and Caroline (CAR) either at (45) or (60) initial plant spacing.

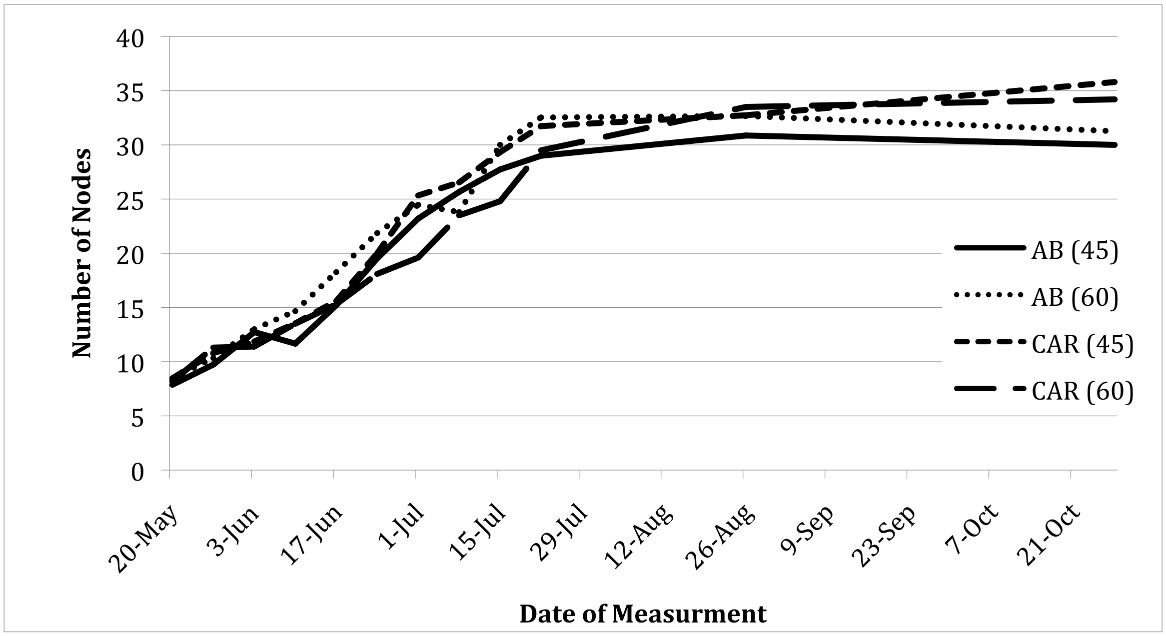


Fig. 5: Fruit harvested per week per meter of row during year two of the study for the two cultivars Autumn Britten (AB) and Caroline (CAR) either at (45) or (60) initial plant spacing.

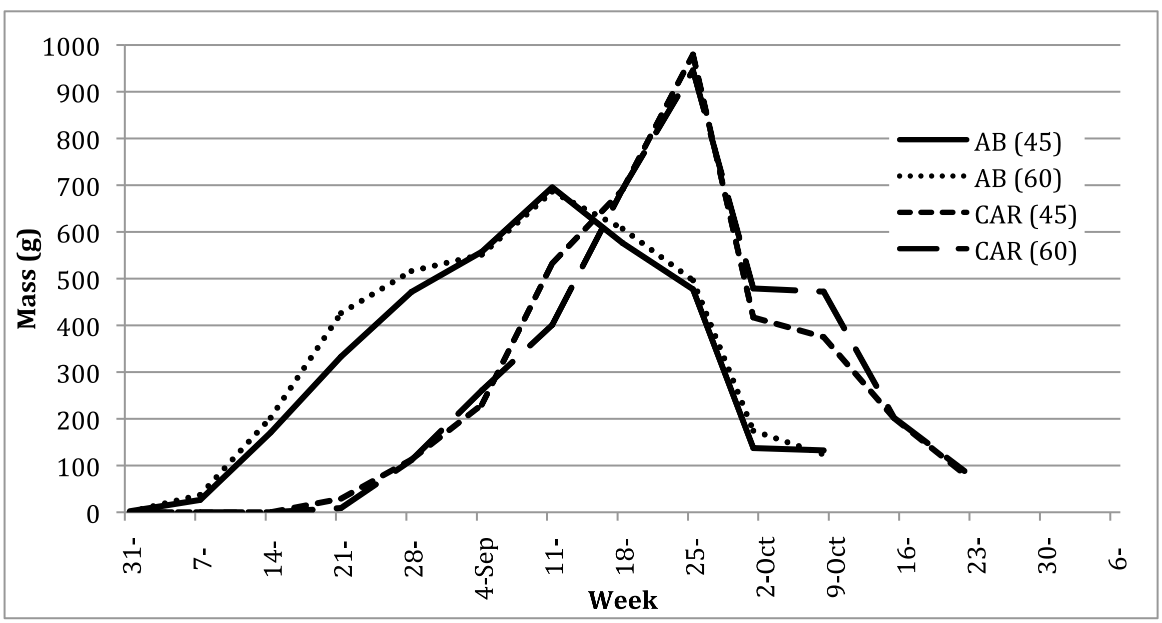


Fig. 6: Percentage of yield by weight per week during year two for the two cultivars Autumn Britten (AB) and Caroline (CAR) either at (45) or (60) initial plant spacing.

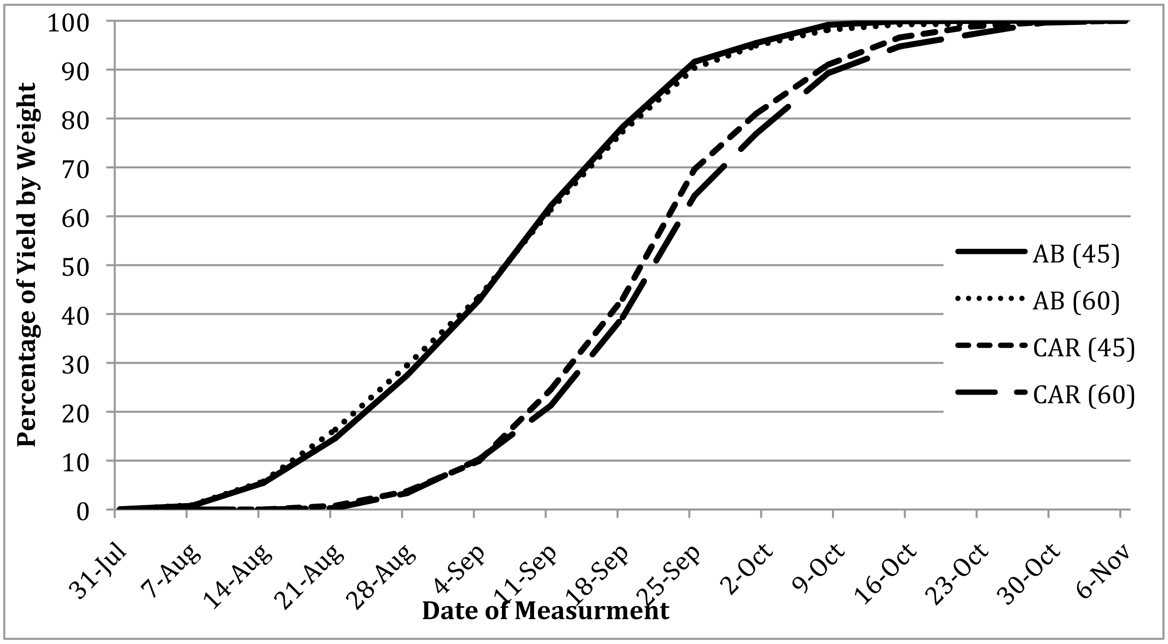


Fig. 7: Mean berry weight per week during year two for the two cultivars Autumn Britten (AB) and Caroline (CAR) either at (45) or (60) initial plant spacing.

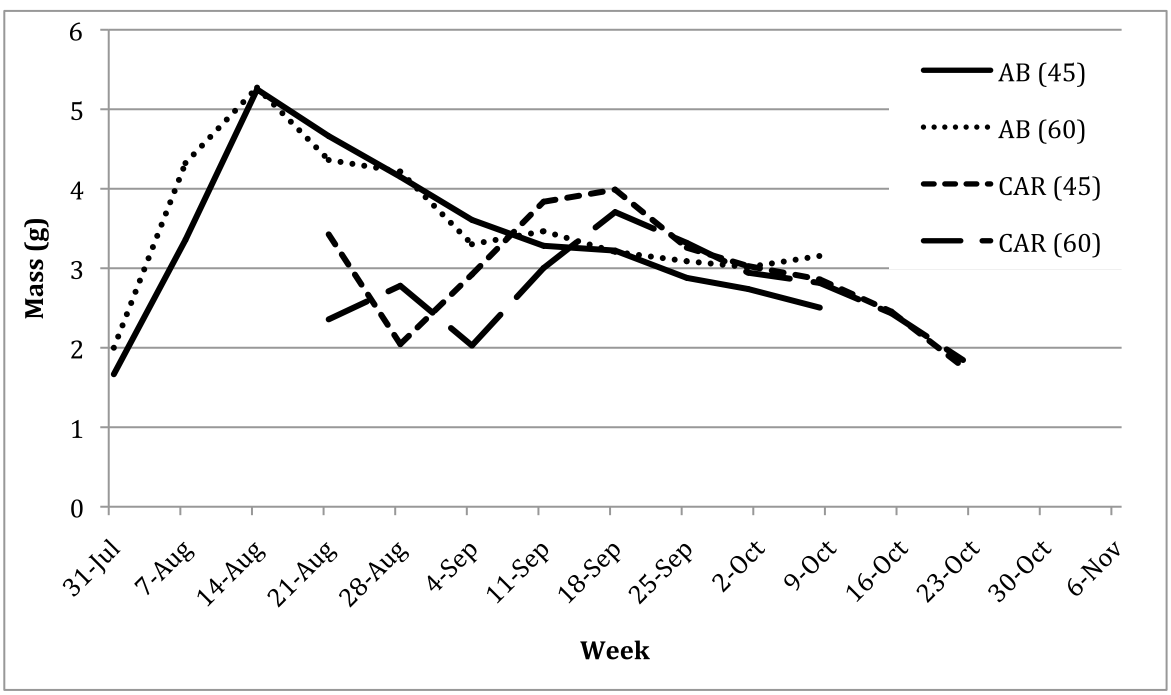


Fig. 8: Composite photosynthetic curve for Autumn Britten (AB). Three dates (1 leaf/primocane and 1 primocane/date) are represented for each temperature.

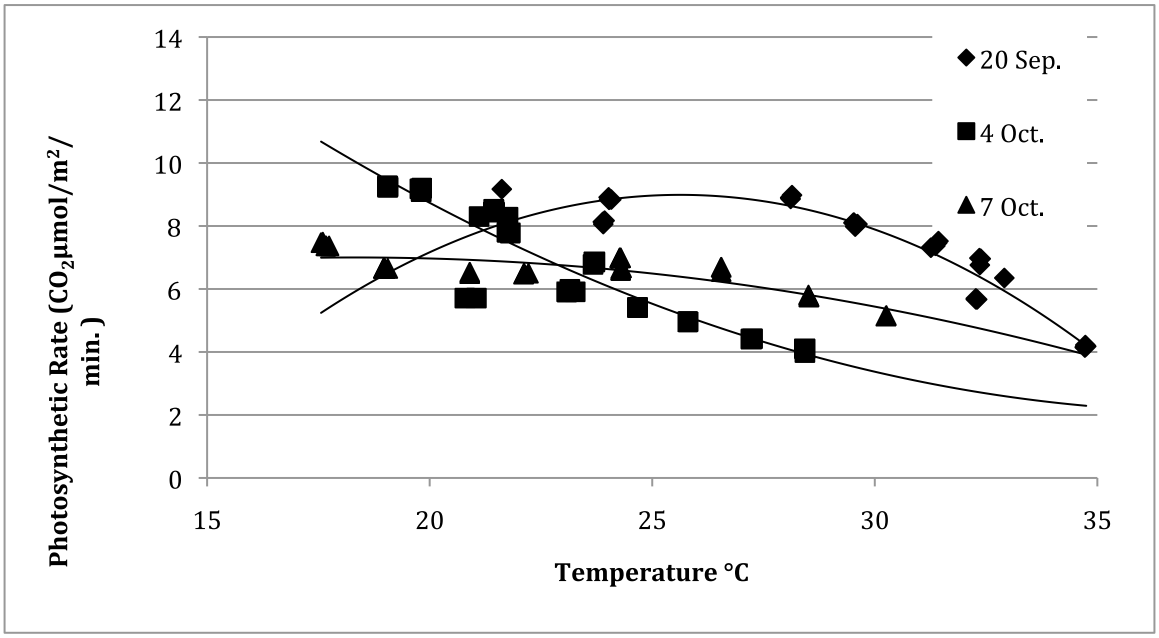
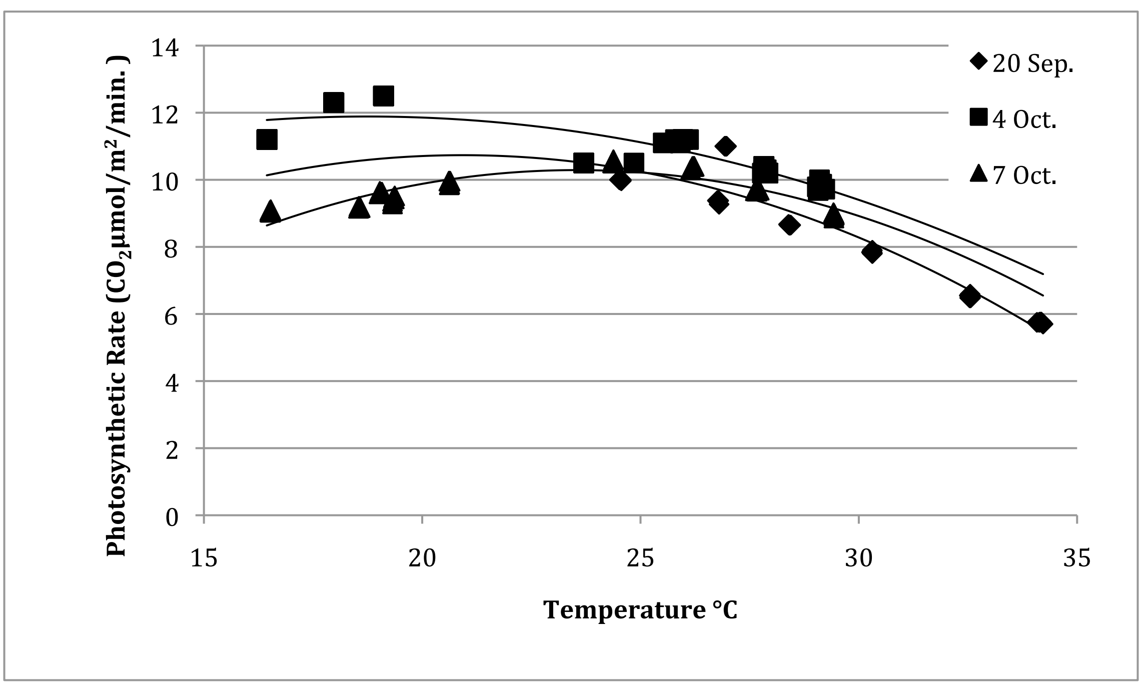


Fig. 9: Composite photosynthetic curve for Caroline (CAR). Three primocanes (1 leaf/primocane and 1 primocane/date) are represented for each temperature.



Appendix

Height Year 1 ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	66.01496	4.461919	585	14.795193	0.0000
Cultivar2	3.49573	2.572949	88	1.358646	0.1777
Spacing2	11.43697	2.734934	88	4.181807	0.0001
Cultivar2:Spacing2	-17.00534	4.128515	88	-4.118997	0.0001

Height Year 2 ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	79.24445	12.722454	528	6.228708	0.0000
Cultivar2	10.63889	2.615215	81	4.068073	0.0001
Spacing2	7.46666	2.615215	81	2.855087	0.0055
Cultivar2:Spacing2	-14.52083	3.922822	81	-3.701629	0.0004

Node Year 1 ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	23.875787	1.2891608	585	18.520410	0.0000
Cultivar2	1.678736	0.7608548	88	2.206381	0.0300
Spacing2	2.219478	0.8097688	88	2.740878	0.0074
Cultivar2:Spacing2	-2.823418	1.2196889	88	-2.314868	0.0229

Node Year 2 ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	20.266667	2.5989393	528	7.798053	0.0000
Cultivar2	1.544444	0.5773337	81	2.675132	0.0090
Spacing2	1.511111	0.5773337	81	2.617396	0.0106
Cultivar2:Spacing2	-3.247222	0.8660004	81	-3.749677	0.0003

Yield, Weight ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	240.19708	65.42583	117	3.671288	0.0004
Cultivar2	6.46033	32.03570	117	0.201660	0.8405
Spacing2	13.26951	32.00448	117	0.414614	0.6792
Cultivar2:Spacing2	-0.09683	48.21271	117	-0.002008	0.9984

Yield, Number ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	69.24105	19.441309	117	3.561543	0.0005
Cultivar2	10.65728	8.385821	117	1.270869	0.2063
Spacing2	2.87825	8.377578	117	0.343566	0.7318
Cultivar2:Spacing2	7.31191	12.620409	117	0.579372	0.5635

Yield, Weight per Berry ANOVA

	Value	Std.Error	DF	t-value	p-value
(Intercept)	2.8008085	0.3037628	117	9.220381	0.0000
Cultivar2	-0.6458532	0.2759937	117	-2.340101	0.0210
Spacing2	0.1881107	0.2757601	117	0.682153	0.4965
Cultivar2:Spacing2	-0.3398528	0.4153550	117	-0.818223	0.4149

The mean height and number of nodes at the end of both year one (Y1) and two (Y2) of the study for the two cultivars Autumn Britten (AB) and Caroline (CAR) either 45 or 60 cm initial plant spacing. The p-value corresponds to variation within each factor for each year.

Year	Factor	Height	Height p-value	Node	Node p-value
Y1	AB	85		27	
	CAR	83	0.7329	31	0.0154
Y2	AB	131		31	
	CAR	141	0.1083	35	0.0016
Y1	45	80		28	
	60	88	0.1072	30	0.0999
Y2	45	136		33	
	60	136	0.8581	33	0.7472

The yield/meter of row/week in year two of the study for the two cultivars Autumn Britten (AB) and Caroline (CAR) either 45 or 60 cm initial plant spacing. The p-values for the comparison between cultivars and spacings for each week are listed below their respective weeks.

	31-Jul	7-Aug	14-Aug	21-Aug	28-Aug	4-Sep	11-Sep	18-Sep	25-Sep	1-Oct	8-Oct	15-Oct	22-Oct
AB (45)	2.19298246	26.4619883	170.614035	333.040936	471.491228	557.45614	695.467836	576.169591	477.192982	137.426901	132.45614		
AB (60)	1.09289617	37.1584699	202.367942	426.229508	516.211293	551.36612	686.156648	606.921676	496.357013	174.499089	123.679417		
CAR (45)	0	0	0	29.0935673	112.719298	230.116959	532.602339	690.204678	979.678363	416.959064	374.853801	201.315789	81.5789474
CAR (60)	0	0	0	9.01639344	111.47541	260.655738	400.819672	691.530055	945.901639	478.961749	472.131148	202.185792	88.2513661
AB/CAR p-valu	0.20334942	0.12048519	0.01793075	0.00290413	0.00021127	0.0006147	0.0017397	0.35324145	0.00346157	0.00118597	0.00655536	0.00010765	0.00015522
45/60 p-value	0.73906133	0.70830415	0.7016646	0.60629605	0.66665814	0.73777882	0.63049645	0.94163152	0.78033877	0.86072702	0.93611769	0.90222914	0.85724312