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Floricane yield and berry quality of seven primocane red raspberry (*Rubus idaeus* L.) cultivars

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A B S T R A C T

Primocane raspberry (*Rubus idaeus* L.) may produce crop on the lower part of the cane during the second year of its' growth cycle, if the canes are retained over winter. We aimed to evaluate the floricane cropping potential and berry quality in seven primocane raspberry cultivars, which are too late for fall cropping in the Northern growing conditions. Long cane plants of these cultivars were produced, overwintered, and grown like floricane cultivars in a high tunnel. Harvesting floricane crop started in mid-June, and the length of the summer cropping season was between eight to 10 weeks. 'Joan J' and 'Imara' were the earliest cultivars, and 'Autumn Bliss' was the latest. Total floricane yield in most cultivars was between 1.7 to 2.0 kg/cane. 'Autumn Treasure' yielded significantly less, and 'Autumn Bliss' produced 2.5 kg berries /cane. The average berry size was 5 g, except in 'Autumn Bliss' and 'Autumn Treasure', which had smaller berries. The highest sugar content was observed in 'Kwanza' berries and the lowest in 'Polka'. High throughput phenotyping proved an effective tool for determining berry shape and color. 'Kwanza' berry color was the reddest, yellowest and lightest of all cultivars. Based on our results, growing primocane raspberry cultivars as long cane plants for production of summer crop is more reliable than growing them as fall cropping in short growing season conditions. The cultivars 'Imara' and 'Kweli' were the most promising in our experiment; they had a high yield potential and excellent berry quality.

1. Introduction

Raspberry (*Rubus idaeus* L.) cultivars can be divided into floricane-fruiting and primocane-fruiting types (Heide and Sønsteby, 2011). In floricane-fruiting cultivars the canes are kept for two years. During the first year the canes that are called primocanes grow vegetatively until floral induction in the fall. The canes produce fruit in the summer of the second year and are then called floricanes. Primocane-fruiting cultivars go through this whole cycle during one growing season producing fruit usually late in the fall on primocanes. Long cane plants that are used in planting especially in high tunnel and substrate culture, are plants of floricane cultivars with initiated flower buds, lifted and placed into frigo-storage at the end of their first year.

While primocane-fruiting cultivars initiate flowers regardless of day length and temperature; in floricane-fruiting types, flowers are initiated under short days and low temperatures (Jennings, 1988; Sønsteby and Heide, 2009; Hodnefjell et al., 2018). In fact, the crucial difference between these two types of raspberries is that, in floricane-fruiting cultivars, floral initiation is followed by the onset of bud dormancy, whereas in primocane-fruiting cultivars flower development directly follows floral initiation (Heide and Sønsteby, 2011). However, the separation between these two different life cycles is not distinct; a few floricane varieties produce a small amount of crop at the tips of the canes during their first season (Carew et al., 2000; Hodnefjell et al., 2018). Similarly, not all the lateral buds in a primocane variety produce crop in the first year, but the buds in the lower part of the cane may break and fruit in the second year of the cane's growth cycle, if the canes are retained over winter. This characteristic allows double cropping of the primocane varieties, since the upper part of the cane produces crop on a primocane, while the lower part behaves like a floricane variety. Hanson et al. (2019b) showed that double cropping increased total yields of several primocane cultivars in a short growing season area, in Michigan, USA.

'Polka' is one of the earliest primocane varieties (Danek, 2002), and so far the only one that may be commercially grown and successfully cropped in the high latitude conditions of Finland (north of 60°N) during favorable growing seasons. A few techniques are available to accelerate flowering and fruiting, such as covering a field with rowcovers before cane emergence (Pritts et al., 1992) or using high tunnels (Demchak,

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2009; Hanson et al., 2011; Fernandez and Perkins-Veazie, 2013). Still, yield production on primocanes occurs too late under northern conditions, and a majority of cropping potential is usually lost due to fall frost. After the autumnal equinox, day length shortens rapidly, and even though growth-promoting temperatures could be maintained, the scarcity of light would restrain the ripening of berries. Furthermore, berry quality does not develop well under the low-light conditions prevailing in the fall. Artificial lighting could be used to overcome this problem. However, as high tunnels are usually simple structures with no advanced technology, and as tunnel plastic is often removed for winter, artificial lighting is not a feasible solution.

Many of the newly released raspberry cultivars are primocane-fruiting and have high yield potential as well as excellent berry quality. One option to overcome the challenges of a short growing season is to grow the promising primocane varieties as floricane varieties in a biennial system for summer cropping.

The aim of our study was to evaluate the summer cropping potential and berry quality of seven primocane raspberry cultivars, which are too late for fall cropping in high-latitude growing conditions.

2. Materials and methods

2.1. Plant material and growing conditions

The experiment was conducted at the University of Helsinki research field in Viikki (60°13′ N; 25°1′ E) during growing seasons 2015 and 2016 using seven primocane raspberry cultivars: ‘Autumn Bliss’, ‘Autumn Treasure’, ‘Imara’, ‘Joan J’, ‘Kwanza’, ‘Kweli’, and ‘Polka’. Long cane plants of these primocane varieties were raised in a high tunnel during summer 2015 and cropped during the following growing season.

The tunnel (8 m W × 35 m L × 4 m H) was oriented South-to-North and covered with clear polyethylene (Folitec UV M 42, Folitec, Westerburg, Germany). The tunnel floor was covered with white woven polypropylene fabric (MyPex®). The tunnel was ventilated mainly through the tunnel doors at either end. Information on the temperature and humidity conditions of the tunnel was collected by two EL-USB-2-LCD RH / TEMP Data Loggers (Lascar Electronics, Wiltshire, UK).

The plants were received from two commercial nurseries (Savonlinnan taimisto, Savonlinna, Finland; R.W. Walpole, Norfolk, UK) on 27 May 2015, and planted in 10-L pots (Aeroplas, PD Zevenaar, Netherlands) filled with peat (OPM 630 W, Kekkilä Oy, Vantaa, Finland). In total 84 plants (12 plants of each cultivar) divided into three rows (blocks) (four plants of each cultivar in a block) spaced 2.4 m apart were grown in the tunnel. Plant spacing within a row was 0.4 m. The plants were fertigated through drip irrigation three times a day with a 0.01% compound fertilizer, Taimi-Superex (NPK 19–4.4–20.2 plus microelements) (Kekkilä Oy, Vantaa, Finland), from 16 May through 5 June, and with a mixture of Taimi-Superex and Turve-Superex (NPK 12–4.7–27.1 plus microelements) (0.08%) from 6 June through 19 August. Two primocanes per pot were allowed to grow.

The tunnel plastic was removed on 19 November 2015. On 2 December, the number of lateral shoots that had produced fall crop was recorded, and the primocanes were tipped at about 150 cm height. The plants were laid down on the MyPex® fabric and covered with several layers of acryl cover to protect against frost.

The following spring, the plants were placed into the high tunnel and the tunnel plastic was installed on April 29, 2016. The experiment now consisted of 55 plants, 5 to 12 plants of each cultivar, because a few plants had to be discarded from the experiment due to damage caused by voles. The plants were grown in three rows (blocks), with a row spacing of 2.4 m, and a plant spacing of 0.5 m within a row. The number of plants of each cultivar per block was between one to four. The plants were pruned to retain one long cane (floricane) per pot for yield production, and one new primocane per pot was allowed to grow during the experiment for observation of the timing of the fall crop. The rest of the new emerging primocanes were removed from the pots throughout the growing season. A bumblebee hive (Minipol, Koppert Biological Systems, Romulus, MI, USA) was placed in the tunnel to ensure pollination on 1 June 2016.

Plants were fertigated through drip irrigation three times daily for 10 min (one drip provided 330 ml water in 10 min) with a compound fertilizer, Taimi-Superex (NPK 19–4.4–20.2 plus microelements) (Kekkilä Oy, Vantaa, Finland), from 17 May through 31 May, with a mixture (1:1) of Taimi-Superex and Turve-Superex (NPK 12–4.7–27.1 plus microelements) from 1 June through 31 July, and with Flower-Superex (NPK 11–3–26) from 1 August through 16 August. The conductivity of the fertigation solution was 1.02 mS cm^{-1}. In May, 9 × 1 g of YaraLiva™ Calcinit™ (N 15.5, Ca 19) (Yara, Oslo, Norway) per plant and 4 × 1 g Taimi-Superex per plant were given as additional fertilization.

Substrate conductivity (EC) was measured three times during the 2016 season in all pots (Grodan Water Content Meter, WC / EC / T, Grodan, KD Roermond, Netherlands). It was 1.2 (± 0.1) mS cm^{-1} in May, 1.5 (± 0.2) mS cm^{-1} in June, and 2.0 (± 0.6) mS cm^{-1} at the end of July.

Soap (Mäntysuopa, Henkel Norden Oy, Stockholm, Sweden) in 2% solution was used to control small raspberry aphid (*Aphis ideaei*). Biological pest control included *Neoseiulus cucumeris* to control thrips, *Neoseiulus californicus* and *Phytoseiulus persimilis* to control spider mites, and BerryProtect tubes containing different species (*Aphidius ervi, A. matricariae, A.colemani, Ephedrus cerasicola, Praon volucre, Aphelinus abdominalis*) were used to control aphids (Biotus Oy, Forssa, Finland).

2.2. Measurements

During summer cropping, raspberry fruit were harvested three times a week, and weighed and counted to determine total yield and the number of berries per cane. Once a week during harvest, concentration of soluble solids (SS) and titratable acidity (TA) in the berries were measured. Berries were pressed with a hand-held potato presser through a filter cloth to obtain 20 to 40 ml of filtered juice. SS (°Brix) was measured with an analogical refractometer (Master, Atago, Japan). To measure TA, a 5.0 g aliquot of clear fruit juice was added to 25 ml of ultra-pure water in a decanter. The pH was then measured with a Metrohm 744 pH meter (Metrohm AG, Herisau, Switzerland). Using a buret, the amount of 0.1 M NaOH needed to reach a pH of 8.1 was quantified and the concentration (w/w) of citric acid in the sample juice was calculated; three moles of NaOH is required to neutralize 1 mole of citric acid.

The shelf life of berries was determined at two temperatures using Weiss Bio 2000 (+4 °C) and Weiss Bio 1300 (+21 °C) (Weiss Umwelttechnik GmbH, Reiskirchen-Lindenstruth, Germany) growth chambers. Before the start of the experiment, the growth chambers and all the supplies were carefully disinfected. Six homogeneous berries per cultivar from each of the three blocks were placed on plastic trays so that they did not touch each other. Berries were stored at + 4 °C and + 21 °C and evaluated daily for deterioration. Moldy, dry, or leaking berries were discarded. The estimates for the length of shelf life (time in days until 50% of the berries had been discarded) were calculated using logit models (Lindén et al., 1996) and PROBIT procedure of the SAS 9.4 software (SAS 9.4, SAS Institute Inc.).

The plant phenotyping facility at the University of Helsinki Viikki campus (http://blogs.helsinki.fi/nappi-blog) was used for morphometric characterization of berries in different cultivars. Six berries from each of the three blocks per cultivar were collected in the middle of the harvest season on 13 July, and imaged in a 6-well plate (TC Plate 6 Well, Standard, F; Sarstedt AG & Co. KG, Germany) with the PSI PlantScreen™ RGB imaging system (Aptina GigE uEye UI-5580SE-C/M - 5 Megapixels QSXGA Camera with 1/2″ CMOS Sensor). The images were processed with MorphoAnalyzer version 1–0–5–1 (Photon Systems Instruments, spol. s r.o., Czech Republic) and TomatoAnalyzer version 4.0 (Brewer et al., 2006).

Beginning of fall cropping in the cultivars was recorded. Then, the dry weight of the plants, for the canes and lateral shoots separately, was determined at 80 °C for 7 d

2.3. Statistical analysis

The experiment was set up as an RCBD with three blocks. The data were analyzed with ANOVA using the SPSS software (IBM SPSS Statistics 22), or the GLM procedure of the SAS 9.4 software (SAS 9.4, SAS Institute Inc.). Data for berry quality measurements from different dates were pooled and the means were used in the analyses. Cultivar means were separated using Tukey's test at a significance level of $P < 0.05$. Correlation co-efficients between yield and vegetative growth parameters, and between berry area and berry weight, were calculated using the CORR procedure of SAS.

3. Results

3.1. Yield

'Joan J' and 'Imara' were the first cultivars to be harvested beginning on June 15 and 16, respectively (Fig. 1). The latest summer cropping season was observed in 'Autumn Bliss'. The length of the summer cropping period in all the cultivars was between 54 and 70 d. In several cultivars fall crop on primocanes overlapped the summer cropping period. In fall cropping 'Polka' was the earliest, and 'Kwanza' the latest.

Total berry yield per cane was between 1.7 to 2.0 kg in all cultivars except 'Autumn Bliss' (2.5 kg / cane) and 'Autumn Treasure' (0.7 kg / cane) (Fig. 2A). In most cultivars, except 'Autumn Bliss' and 'Joan J', the peak in weekly yield was observed at the beginning of the harvest period (Fig. 3). This was mainly because the average berry size decreased as the harvest season proceeded (data not shown). The proportion of discarded berries was 14% (w/w) in 'Autumn Treasure' and 'Kwanza', 9% in 'Polka', and 6% or less in all other cultivars (Fig. 2C). Most of the discarded berries in 'Kwanza' were either crumbly or split. Total yield in primocane cultivars correlated significantly with lateral shoot dry weight and total plant dry weight, but not with cane dry weight (Table 1).

3.2. Berry quality and characteristics

The average berry weight was about 5 g in all other cultivars except 'Autumn Bliss' and 'Autumn Treasure', which had significantly smaller berries (Fig. 2B). 'Kwanza' berries were highest in sugar and highest in titratable acidity, and the lowest sugar and TA concentration were recorded in 'Polka' fruit (Table 2). The lowest sugar to acid ratios were observed in 'Autumn Treasure' and 'Joan J', whereas 'Kwanza' and 'Kweli' berries had the highest sugar to acid ratios. The shelf life of berries was between 2 and 4 d at room temperature (21 °C), and between 8 and 12 d at refrigerator temperature (+4 °C), and was significantly affected by the cultivar. At both storage temperatures, 'Kwanza' berries had the longest shelf life.

Berry shape was characterized using morphometric parameters from the PSI PlantScreen™ RGB imaging system software (Fig. 4) and morpho- and colorimetric parameters from TomatoAnalyzer software. The projected berry area (in pixels) was smallest in 'Autumn Bliss', followed by 'Autumn Treasure' (Fig. 5A). Eccentricity value, which corresponds to elliptical shape, was highest (most elliptical) in 'Autumn Treasure' (Fig. 5B). Medium eccentricity was observed in 'Joan J' and 'Polka', whereas the rest of the cultivars were rounder in shape. Similar morphometric results were obtained from the TomatoAnalyzer software (data not shown). There was a highly significant correlation between berry weight and berry area as measured with phenotyping ($r = 0.795$, $p<0.001$). However, looking at the scatter plot of berry weight vs. berry area (not shown) and Fig. 5, we notice that in 'Autumn Treasure', the cultivar that had the highest eccentricity values, berry area measurement, would overestimate berry size.

'Kwanza' berries were the reddest of all cultivars (Figs. 6A and C). Additionally, 'Kwanza' berry color was the lightest (Fig. 6B), and yellowest (Fig. 6D).

4. Discussion

Growing primocane raspberry cultivars as long cane plants for summer cropping proved a feasible alternative for producing fruit yield on cultivars that possess the desired berry quality or agronomic traits, but yield too late on primocanes. Floricane yields were relatively high, between 1.7 to 2.0 kg per cane for most cultivars, and the quality of the harvested crop was very good. Based on the results presented here and

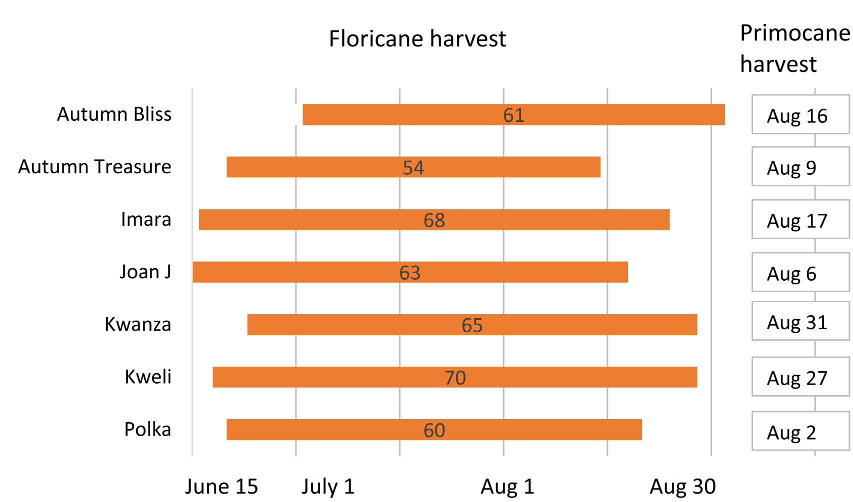

Fig. 1. The timing of summer crop, the length of the harvest period (d), and the date for the beginning of the fall crop in primocane raspberry cultivars grown in a high tunnel.

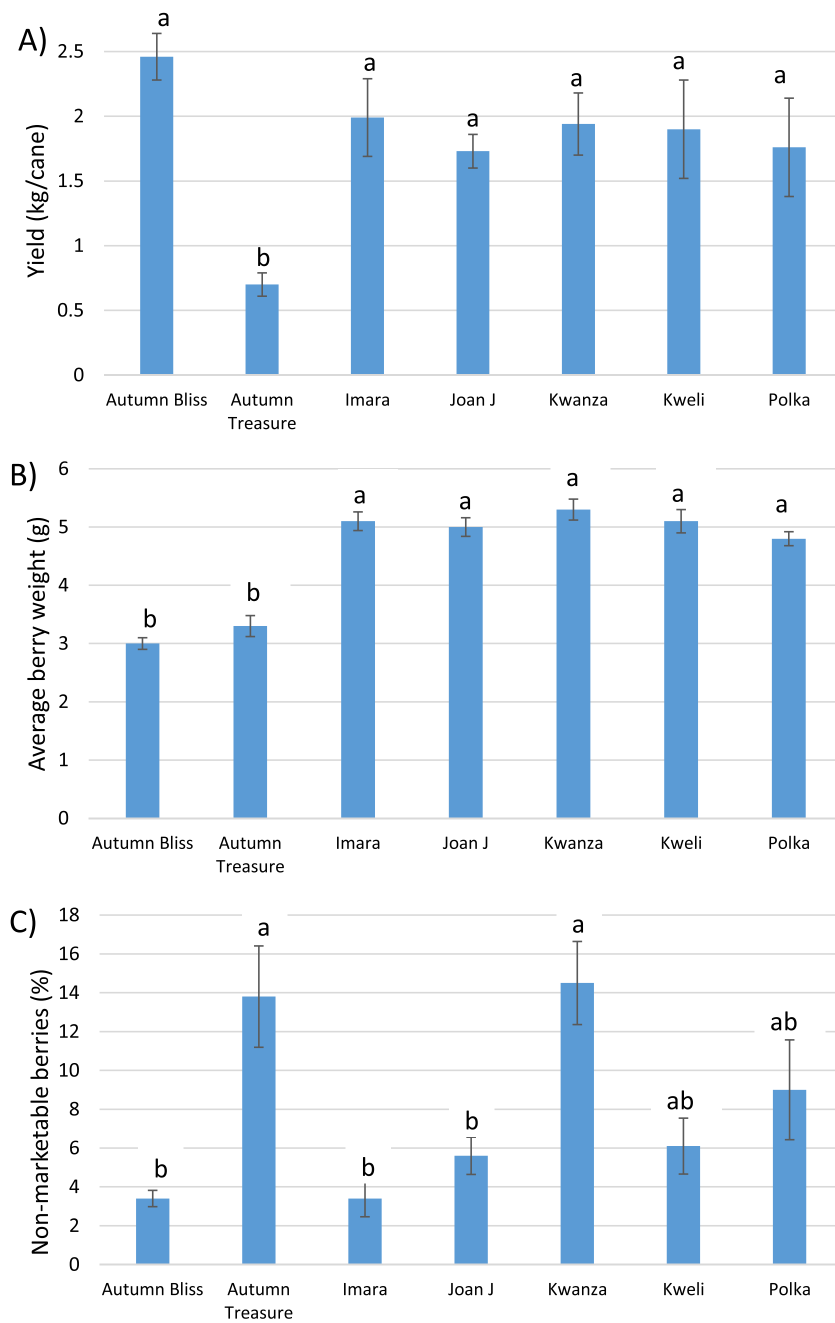

Fig. 2. Total berry yield (A), average berry weight (B), and the proportion (w/w) of discarded berries (C) in primocane raspberry cultivars grown in a high tunnel for summer cropping. The vertical bars represent ± SEM (n = 5–12). Values marked with the same letter are not significantly different at $p < 0.05$ by Tukey's test.

our earlier report on the growth habit of these cultivars (Palonen and Laine, 2020), 'Imara' and 'Kweli' were the most promising cultivars for long cane production; they had a good growth habit, high yield potential, large fruit, and excellent berry quality and shelf life. 'Imara' and 'Kweli' have also been reported to be the best suited cultivars for double-cropping in a high tunnel in Michigan (Hanson et al., 2019a). There, the floricane yields of 'Imara', 'Kwanza', and 'Kweli' averaged 1.43 kg and 0.87 kg per plant (two canes) in two years (Hanson et al., 2019a), while the same cultivars yielded 1.94 kg per cane, on an average, in our study. On the other hand, the primocane fruit yield per pot was 1.5 kg for 'Kweli', 1.2 kg for 'Imara', 1.0 kg for 'Autumn Bliss', 0.9 for 'Joan J', and 0.7 kg for 'Polka' under polyethylene rain cover (umbrella) in Switzerland (Andrianjaka-Camps et al., 2016), while the average primocane fruit yields per plant of 0.64 kg for 'Autumn Bliss' and 'Polka', and 0.29 kg for 'Autumn Treasure' were reported by Sønsteby and Heide (2010).

In double-cropping of several cultivars as potted plants, the highest total yields per plant (primocane and floricane) were reported for 'Imara' (2.69 kg) and 'Kweli' (2.94 kg) (Hanson et al., 2019a). We only recorded the amount of the previous year primocane crop in 'Polka' in the same plants, and it was 1.49 kg/plant (two canes). Hence, the total yield potential for a single 'Polka' cane was 2.5 kg, and only 30% of it was realized in the first year. As the primocane crop in the other cultivars of our study is significantly later, we may expect an even lower percentage of yield potential being realized during the first year for them.

Variation between the cultivars in the timing of the summer crop was smaller (16 d) than the variation in the beginning of the fall crop (29 d)

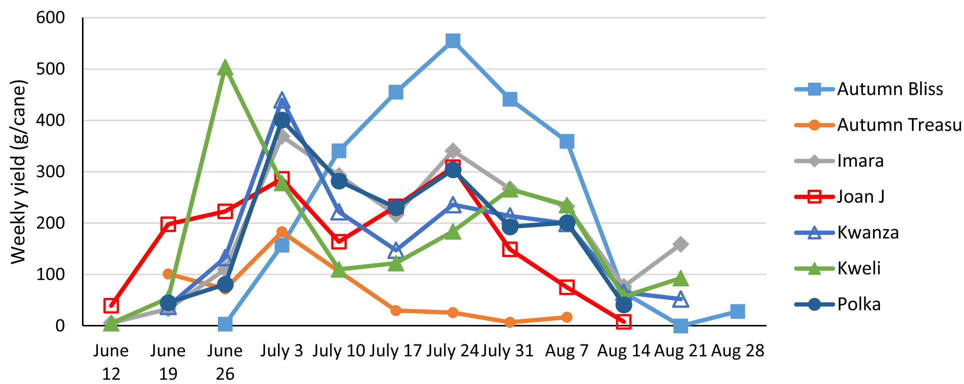

Fig. 3. Weekly marketable floricane berry yield of seven primocane raspberry cultivars grown in a high tunnel for summer cropping during 2016.

Table 1
Pearson correlation coefficients between the yield and vegetative growth parameters in seven primocane raspberry cultivars grown for summer cropping in a high tunnel. ($n = 55$).

	Total yield	Cane DW	Laterals DW	Total plant DW
Cane DW	n.s.			
Laterals DW	0.843 * [z)]	0.802 *		
Total plant DW	0.777 *	0.873 *	0.992 **	
Cane diameter	n.s.	0.882 **	0.923 **	0.947 **

[z)] *, ** = significant at $p < 0.05$ and $p < 0.01$, respectively.

Table 2
Concentration of soluble solids (SS) and titratable acidity (TA), sugar to acid ratio, and the length of shelf life in summer crop berries of primocane raspberry cultivars grown in a high tunnel. Values marked with the same letter are not significantly different at $p < 0.05$ by Tukey's test.

	SS (°Brix)	TA (%)	Sugar to acid ratio	Shelf life (d)	
				+21 °C	+4 °C
Autumn Bliss	9.8 bc	1.89 bc	5.2 bc	3.2 abc	9.7 ab
Autumn Treasure	8.8 ab	1.95 bc	4.5 a	4.1 bc	9.6 ab
Imara	9.1 ab	1.82 b	5.0 ab	3.3 bc	10.5 ab
Joan J	8.7 ab	1.94 bc	4.5 a	3.0 ab	8.0 a
Kwanza	12.2 d	2.08 c	5.9 c	4.2 c	11.9 b
Kweli	10.6 c	1.85 b	5.7 c	2.9 ab	10.5 ab
Polka	8.3 a	1.49 a	5.5 bc	2.0 a	9.6 ab
P	< 0.001	< 0.001	< 0.001	< 0.001	0.009

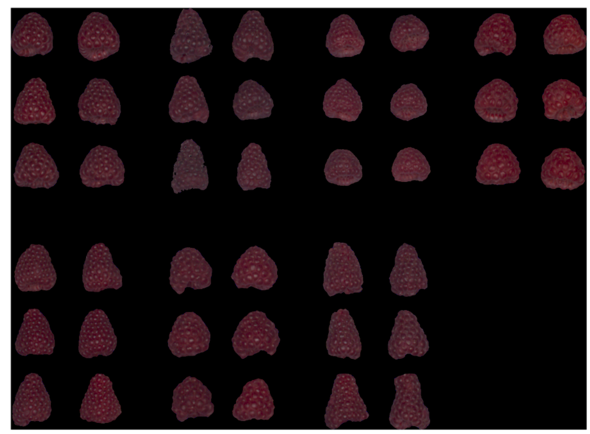

Fig. 4. Example of PSI system processed RGB image with background excluded. The cultivars from left to right; upper row: 'Imara', 'Joan J', 'Autumn Bliss' and 'Kwanza', lower row: 'Polka', 'Kweli' and 'Autumn Treasure'.

in the same plants. The harvest time was similar to the floricane fruiting cultivars (e.g. 'Glen Ample', 'Glen Dee', and 'Maurin Makea') grown in the same high tunnel (data not shown). We were not able to conclude on the effect of retaining the floricanes on the timing of primocane crop, but in the study by Hanson et al. (2019b) retention of floricanes did not affect primocane harvest times. During the previous year, when these plants were grown with primocanes only, the fall crop harvest started on 16 August in 'Polka' and two weeks later in 'Autumn Bliss'. Yearly variation in the timing of harvest season is usually large.

The length of the summer cropping period in our study was eight to 10 weeks, which is comparable to the duration of the fall crop in several primocane cultivars in a high tunnel (Sønsteby and Heide, 2010; Weber, 2018). Summer cropping started first in 'Joan J' and 'Imara', while 'Autumn Bliss' was the latest cultivar. Similarly, in a study of Hanson et al. (2019b), the floricane crop of 'Joan J' started, on an average, 9 d earlier than in 'Polka'.

Generally, the timing of the floricane crop did not correlate with the timing of the primocane crop. In all cultivars except 'Kwanza' and 'Kweli', the summer cropping period overlapped with the fall cropping of primocanes in the same pots. This overlapping of floricane and primocane crops was not observed by Hanson et al. (2019b). The earliness of 'Polka' (Danek, 2002) was confirmed in the present study, as primocane fruit harvest began first in 'Polka' on August 2, followed by 'Joan J' and 'Autumn Treasure' soon thereafter. 'Autumn Bliss' and 'Imara' were medium in earliness, starting fall cropping in mid-August, while the latest cultivars were 'Kweli' and 'Kwanza', which started fall production only at the end of August. Interestingly, in the study by Sønsteby and Heide (2010), conducted in high latitude conditions, 'Autumn Bliss' was the earliest in cropping followed by 'Polka' one week later.

Contrary to what is sometimes stated, that floricane fruit would be of inferior quality to primocane fruit, we observed the floricane fruit to be large and sweet with an acceptable shelf life. The amount of discarded berries was low, except in 'Autumn Treasure' and 'Kwanza'. In addition to genetics, berry quality is largely influenced by growing conditions and cultivation practices. Floricane fruit size in our study was comparable to primocane fruit size reported by Andrianjaka-Camps et al. (2016) for 'Autumn Bliss', 'Joan J', 'Imara', and 'Kweli'. 'Polka' fruit, on the contrary, were larger, 4.8 g, in our study as compared to 3.68 g reported by Andrianjaka-Camps et al. (2016), or 2.84 g reported by Weber (2018). 'Joan J' fruit were also larger, 5.0 g, as compared to the study of Weber (2018), where 'Joan J' in ground primocane fruit in a high tunnel weighed 2.89 g. Sønsteby and Heide (2010) report significantly higher weights of 5.6 g, 5.8 g, and 7.0 g for the primocane fruit of 'Autumn Bliss', 'Autumn Treasure', and 'Polka', respectively. Floricane fruit size in the relevant cultivars has only been reported by Hanson

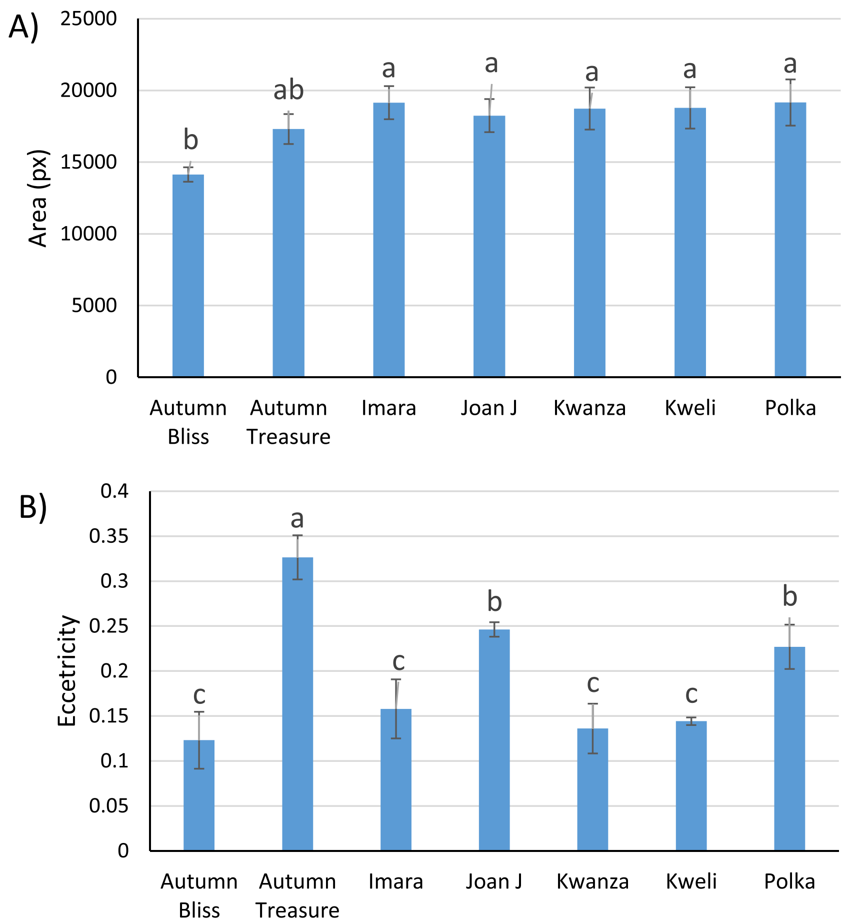

Fig. 5. Area (A) and eccentricity (B) of a berry image in seven primocane raspberry cultivars grown as long cane plants for summer cropping. The vertical bars represent ± SD ($n = 3$). Values marked with the same letter are not significantly different at $p < 0.05$ by Tukey's test.

et al. (2019a), who observed a berry size of 3.6 g for 'Imara' and 'Kweli', and 4.2 g for 'Kwanza' plants grown in pots in a high tunnel, while we observed the berries of 'Imara' and 'Kweli' to weigh 5.1 g and 'Kwanza' 5.3 g.

No findings on the sugar content (°Brix) in 'Imara', 'Kwanza', and 'Kweli' could be found in the literature. °Brix value for 'Kwanza' was notably high, 12.2%, in our study. 'Kwanza' berries were also high in acidity. 'Kwanza' and 'Kweli' were among the cultivars that had the highest sugar to acid ratio. Interestingly, 'Polka' berries were the lowest in both sugars and acidity. 'Kwanza' berries were also distinctive in color, being the reddest, yellowest and lightest of all cultivars. It is notable, however, that as much as 14% of 'Kwanza' berries had to be discarded, as they were either crumbly or split.

High throughput phenotyping proved an effective tool for determining berry shape. However, this technique may not be used to directly estimate berry weight (g) based on the berry area, as berry shape affected the size of the projected berry area. The PSI PlantScreen™ RGB imaging system did, however, provide a fast and efficient tool for determining berry color. This feature might be used more extensively e. g. in post-harvest research or in defining harvest maturity. As automatization will inevitably become more common in horticulture, there are numerous potential applications for colorimetric measurements to determine sufficient maturity stage for harvest.

For the purpose of designing cultivation systems and to exploit the full yield potential of raspberry canes, it is important to understand how the presence of floricanes affects primocane productivity and vice versa. As raspberry is a source-limited plant, competition between vegetative canes, fruiting canes and the root system is present (Carew et al., 2000). The three major assimilate sinks during the season are the fruit, primocane and root growth. Roots act as a source in the beginning of the season, supporting primocane growth and the outgrowth of the fruiting laterals on floricanes (Fernandez and Pritts, 1993; Alvarado-Raya et al., 2007). Later, during the onset of fruiting, roots become a sink for carbohydrates, and then both primocanes and floricanes act as carbohydrate sources for the root system. There seems to be no direct translocation of the assimilates between primocanes and floricanes (Alvarado-Raya et al., 2007). Several studies confirm that removing primocanes from a biennial cultivar increases floricane yield (e.g. Freeman et al., 1989). In a so-called biennial or alternate-year cropping system, the competition between the two types of the canes may be reduced by growing them in alternate years, and this has been observed to increase the yield in the cropping year (e.g. Clark, 1984), or to decrease yields in the long term due to declining plant vigor (Dalman, 1991), possibly because of carbohydrate depletion in the roots. Sønsteby et al. (2018) stated that there is no significant yield increase in the biennial cropping system, when the amount of yield was observed per cane. According to Fernandez and Pritts (1996) the two types of canes compete for light rather than for carbohydrates. These experiments have been conducted under field conditions, and little information is available on the performance of containerized plants in a high tunnel environment. According to Hanson et al. (2011; 2019b), neither the amount of fall crop nor primocane growth was affected by the presence of floricanes in high tunnel production.

Long cane plants of a few primocane varieties are now also commercially available. However, if a grower decides to raise the long cane plants on the farm, the cultivars must have adequate winter hardiness, or there have to be storage rooms with temperature control. Overwintering the plants in pots also poses a risk of root damage, since

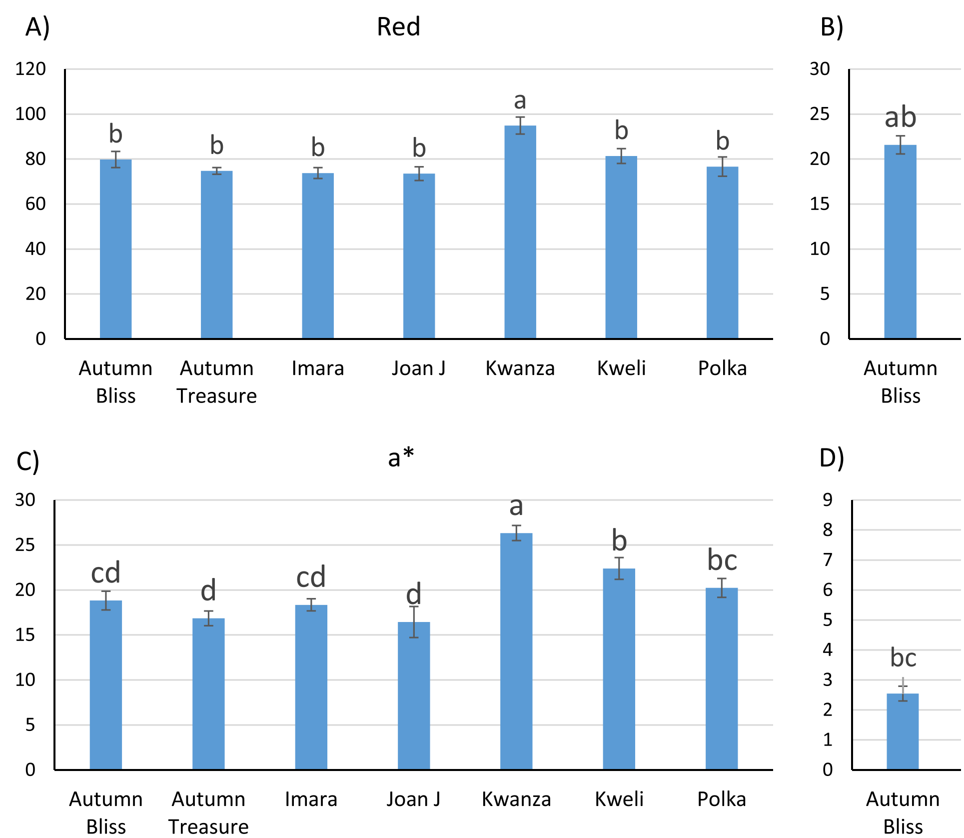

Fig. 6. Average Red value (A) and CIE values L* (B), a* (C) and b* (D) of berry image area pixels in seven primocane raspberry cultivars grown as long cane plants for summer cropping. The L* (lightness) value ranges from 0 = black to 100 = white, the a* value ranges from negative for green to positive for red, and b* value ranges from negative for blue to positive for yellow. The vertical bars represent ± SD (n = 3). Values marked with the same letter are not significantly different at $p < 0.05$ by Tukey's test.

plant roots are always more susceptible to frost injury than shoots or canes (Pellett, 1971). As the low number of dormant buds is the most important single factor contributing to high yields in primocane varieties (Sønsteby and Heide, 2010), the opposite would be beneficial for a high summer crop in the same varieties. We observed the highest number of nodes producing fall crop in 'Polka' and the lowest in 'Kwanza'(Palonen and Laine, 2020), although the yield was similar in these cultivars. Generally, flowering and fruiting in primocane raspberry are promoted by high temperature (Sønsteby and Heide, 2010). Hence, when raising long cane plants of primocane raspberry for summer crop next year, relatively low temperature would be a benefit. At intermediate temperatures, the number of dormant buds in 'Polka' was increased under SD conditions as compared to LD (Sønsteby and Heide, 2009). Furthermore, not all primocane cultivars are suitable for long cane production (Palonen and Laine, 2020), and the plant density also has a role in reducing lateral development in the first year.

Based on the results presented here, we can conclude that growing primocane raspberry cultivars as long cane plants for summer cropping is a feasible option to overcome the challenges of a short growing season. Relatively high floricane yields with excellent fruit quality were observed in our study.

CRediT authorship contribution statement

Pauliina Palonen: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft, Supervision, Funding acquisition. **Tuomo Laine:** Methodology, Investigation, Formal analysis, Writing – review & editing. **Katriina Mouhu:** Methodology, Investigation, Formal analysis, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors have no competing interests to declare.

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