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Production of high-yielding raspberry long canes: The way to 3 kg of fruit per cane

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SUMMARY
Experiments were conducted on-Station and in growers' nurseries with the aim of developing cheap techniques for the production of pot-grown raspberry long canes with high yield potential. In an earlier paper, we reported the feasibility of producing raspberry long canes with a yield potential of > 3 kg fruit per cane. The experiments presented here confirm that such high yields can be achieved on a regular basis, even when applying intensified and cheaper production techniques. Thus, the pot size could be reduced from the previous 3.5 l, to 2.5 l and the plant spacing could be decreased from 200 cm × 20 cm, to 100 cm × 20 cm without loss of cane yield potential. Even at a plant spacing of 55 cm × 20 cm, canes with a yield potential close to 3 kg per cane were produced. It was also shown that, during the cropping year, an additional one or two new canes with the same high yield potential could be raised concurrently with flowering and fruiting of the old cane, without a significant loss of yield on the old fruiting cane. When two canes were produced and cropped in each pot, either as two separate canes or as forked single shoots with two canes, yields of almost 4 kg per pot were achieved. However, as in our earlier experiments, long canes with such high yield potentials could only be produced under greenhouse conditions in the cool Norwegian environment. These experiments confirm the feasibility of producing raspberry long canes with yield potentials of ≥ 3 kg fruit per cane on a regular basis, even with intensified and cheaper production techniques.

In response to increasing consumer demands for fresh fruit throughout the year, protected cultivation of raspberry for an extended marketing season has increased markedly over recent decades (Oliveira *et al.*, 1998; Brennan *et al.*, 1999; Dale, 2008). One technique that has been developed for this purpose is the so-called "long cane production system" (Carew *et al.*, 2000; Pitsioudis *et al.*, 2002; Raffle, 2004; Heiberg *et al.*, 2008; Sønsteby *et al.*, 2009). This technique involves the production of long canes with flower buds in one season, followed by cold storage and forcing for berry production in the following season. By varying the duration of cold storage, and hence the time of forcing, the harvest season can be varied widely. Pot-grown plants are commonly used for this purpose, but bare-root plants grown in the field have also been used with variable results. Poor root systems, with an increased risk of dehydration of the roots and canes during storage and establishment, and small canes with a poor flowering potential, have limited fruit yields to a few hundred grams per cane using the latter technique (Brennan *et al.*, 1999; Raffle, 2004).

The environmental control of growth and development in biennial-fruiting red raspberry (*Rubus idaeus* L.) is now quite well understood (see Heide and Sønsteby, 2011) and offers excellent prospects for controlled management of the plant via manipulation of temperature and day-length conditions. While vegetative growth requires long days (LD) and increases with increasing temperature, the initiation of flower buds in biennial raspberry has an upper temperature limit at approx. 15ºC (Williams, 1960; Sønsteby and Heide, 2008). At this critical temperature, flower initiation occurs only in short days (SD) with a critical photoperiod of 15 h, while, at temperatures ≤ 12ºC, floral initiation also takes place in LD. Therefore, successful long cane production requires a seasonal temperature programme that provides an adequate temperature for vigorous cane growth during early- and mid-Summer, followed by reduced temperatures during late-Summer and Autumn, to ensure early and adequate flower formation.

In an earlier paper (Sønsteby *et al.*, 2009), we reported the successful production of pot-grown long canes of 'Glen Ample' raspberry, with yield potentials of well over 3 kg fruit per cane. Plants with such a high yield potential were obtained both at the Experimental Station and in two growers' nurseries. However, it was found that, in the cool Norwegian environment, canes with such a high yield potential could only be produced on a regular basis in a greenhouse. Only in years with exceptionally warm Summers could canes with a yield potential of ≥ 3 kg be produced outdoors. Otherwise, plants produced in plastic greenhouses consistently out-yielded those produced outdoors by approx. 1 kg per cane. Regression analyses revealed that high yields were associated with cane architecture traits such as cane height, the number and length of laterals, and a low proportion of dormant buds. The single, most important component was the length of the flowering laterals, which accounted for 82% of the yield variation. Since

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lateral length increases from the tip towards the base of the cane in raspberry plants, cane heights in excess of 2 m were required to attain maximum yields. The uppermost nodes, with their short and low-yielding laterals, could then be removed by tip pruning, leaving only the lower buds with the potential to develop long and high-yielding fruiting laterals.

However, since these high-yielding plants were grown in large 3.5 l pots at a spacing of 200 cm × 20 cm in plastic greenhouses during the Summer, they were quite expensive to produce. It was therefore important to attempt to reduce the cost of production by reducing both the inter-plant spacing and pot size. In our production and cropping system, only one cane was allowed to develop in each pot, while all additional shoots (i.e., root suckers) were weeded-out in both years in order to optimise the light conditions for the fruiting cane. It was therefore of interest to explore whether more than one cane with a high yield potential could be produced per pot, and also, whether a new cane with a high yield potential could be produced in the second season by allowing a new shoot to develop in each pot concurrently with fruit development on the fruiting cane. We were also interested in exploring the effect of Autumn temperature on the earliness and abundance of flowering and fruiting on such canes. Finally, we wanted to compare the performance of two of the most popular raspberry cultivars for fresh consumption in this production system. Here, we report the results of a series of experiments in which various production components were varied with the aim of optimising a protocol for the production of raspberry long canes with a high yield potential.

MATERIALS AND METHODS

Plant material and cultivation

The raspberry cultivar ‘Glen Ample’, which is presently the standard cultivar for fresh markets in Scandinavia and the UK, was used in all experiments. In addition, the cultivar ‘Tulameen’, which is sometimes preferred for its excellent taste, was included in one experiment to compare its performance.

Plants were produced and cropped as described by Sønsteby *et al.* (2009), except that all plants were produced in 2.5 l pots instead of in 3.5 l pots. Plants were raised and produced both on-Station at Bioforsk Apelsvoll in central South–East Norway (61ºN), and in two commercial growers’ nurseries at Brekke in Sogn (61ºN) and at Sandane in Nordfjord (62ºN) on the West coast of Norway. The yield potential of the canes was assessed by cropping on-Station after cold-storage at −2ºC over the Winter in the dark. Plants were propagated in early-May in greenhouses at approx. 20ºC by rooting of adventitious shoots from cold-stored root material. After rooting and growth to approx. 20 cm in height, all plants were transplanted separately into 2.5 l pots in late-May and, from mid-June, were cultivated further, as described for each Experiment. A coarse-textured sphagnum peat growth medium (Gartnerjord, LOG, Oslo, Norway) with a pH of 5.8 was used throughout. Plants were fertigated daily via an automatic feeding system throughout the production season with a complete fertiliser solution consisting of a 2:3 (w/w) mixture of Superba Red™ (7-4-22 NPK + micronutrients) and Calcinit™ (15.5% N and 19% Ca) both from Yara International (Oslo, Norway) and having an electric conductivity (EC) of 1.1 – 1.8 mS cm^{-1}. Before cold storage in late-November/early-December, tall canes were decapitated at 200 cm, and again at 160 cm after cold storage. Canes shorter than 160 cm were tipped only in the Spring by removing the uppermost 2 – 3 cm of the shoot. In each cropping year, plants were removed from cold storage in early-June, transplanted into 7.5 l pots and cropped in an open Haygrove plastic tunnel, as described by Sønsteby *et al.* (2009). During the cropping season (June – October), plants were fertigated with the above-mentioned Superba Red™/Calcinit™ nutrient solution, starting with an EC of 1.0 mS cm^{-1}, until mid-Summer when the concentration was increased to an EC of 2.0 mS cm^{-1} for the rest of the season.

Description of the various Experiments

The first Experiment (Expt. 1) examined the effect of Autumn temperature on the cessation of growth, flowering, and fruit yield in ‘Glen Ample’ plants raised on-Station by standard procedures in a greenhouse with a minimum temperature of 18ºC. On 18 August, when the plants had reached a height of 192 cm, and had an average of 34 nodes, the plants were moved into the phytotron at the Norwegian University of Life Sciences (59º40’N) and grown-on in daylight compartments under natural day-length conditions and temperatures of 9º, 12º, 15º, or 18ºC for 8 weeks (three replicates of five plants at each temperature). An additional group of 15 plants was left in an open plastic tunnel at Bioforsk Apelsvoll during the same period with daily average maximum, mean, and minimum temperatures of 22.1ºC, 13.8ºC, and 8.5ºC, respectively. After completion of these temperature treatments (on 13 October), all plants were moved back to Apelsvoll and left to mature and harden under natural outdoor conditions (average daily mean temperature 3.0ºC) until they were moved into the cold store on 1 December.

The effects of more than one shoot per pot were examined in ‘Glen Ample’ plants in Experiment 2. In the first year, plants were raised in a plastic greenhouse according to our standard regime, with one shoot per pot. After tipping and cold storage, the plants were transplanted into 7.5 l pots (one per pot) and cropped in an open, Haygrove plastic tunnel in the usual way, with the exception that the plants were divided into three groups in which zero, one, or two additional shoots, respectively, were allowed to develop in each pot concurrently with flowering and fruit development on the fruiting cane. At the end of the season, the old shoots were removed and the plants were tipped and cold-stored over the Winter. Finally, the plants were allowed to fruit a second time, as described above.

In a related Experiment 3, single-cane or double-cane (forked) ‘Glen Ample’ plants were produced in greenhouses at Bioforsk Apelsvoll and at Brekke, and outdoors at Sandane, for comparisons of yield potential and cropping performance. In the greenhouses, temperatures were maintained above 18ºC, while the average daily mean outdoor temperature at Sandane during June – September was 13.3ºC. At all locations,

FIG. 1
Illustration of raspberry long cane production at different planting densities (row spacings). From left to right: 160-cm, 100-cm, and 55-cm row spacing. The photographs were all taken on 29 September, when the shoots had ceased growing.

rooted plants were planted singly in 2.5 l pots in late-May and moved to their growing sites in early-June. Following a "soft pinch" at a height of 20 cm, the plants were allowed to develop one or two shoots per plant. After over-wintering in cold-storage, the plants were cropped in an open, Haygrove tunnel in the usual way.

Experiment 4 tested the effect of plant density on the growth and yield potential of 'Glen Ample' plants grown in a glasshouse at a grower's nursery at Brekke in Sogn. The plants were propagated and fertilised according to our standard practice. On 15 June, the plants were placed in rows across the 12 m-wide glasshouse with mid-point, row-to-row spacings of 160 cm, 100 cm, and 55 cm, respectively. There were five pots m^{-1} within the rows (see Figure 1). Each treatment consisted of three rows, of which only internal plants in the middle row were used for monitoring growth and assessments of yield potential. Diurnal fluctuations in photosynthetic photon flux (PPF) densities above and at the base of plants at the 100 cm and 55 cm row spacings were recorded using an automatic SpectroSense2+ SKL 908 light meter (Skye Instruments Ltd., Llandrindod Wells, UK) over an 18-d period from 12 – 30 August. The ratio of red (R) to far-red (FR) light radiation reaching ground level mid-way between two rows at the 100-cm spacing was also recorded during the same period using a Skye Instruments SKR 110/SS2 sensor.

Experiment 5 compared the growth and yield performance of long canes of the cultivars 'Glen Ample' and 'Tulameen' produced in a plastic greenhouse or outdoors at Sandane.

Experimental design and data collection

All experiments had a factorial randomised block design, with three randomised blocks and five plants per treatment. Shoot growth was monitored by weekly measurements of plant height, and counting of leaf numbers. Ripe berries were harvested three-times per week, and the weight and number of berries were recorded. At the end of each harvest season, fruiting cane architecture was registered by recording fruiting cane heights, as well as the numbers and lengths of fruiting laterals.

Data were subjected to analyses of variance (ANOVA) by standard procedures using the MiniTab® Statistical Software programme package (Release 15: Minitab Inc., State College, PA, USA). Percentage values were always subjected to an arc sin transformation before ANOVA.

RESULTS

Effects of Autumn temperature (Expt. 1)

When raspberry plants were exposed to a range of temperatures from 18 August, further shoot growth ceased within 2 weeks at 9ºC, while at 12ºC, 15ºC, and 18ºC, growth continued for 3, 4, and 6 weeks, respectively (Figure 2). As a result, mean growth increments after 6 weeks varied from 14.5 cm to > 65 cm, while the addition of new nodes varied from six at 9ºC to almost 13 nodes at 18ºC (Table I). However, after tipping to 160 cm in height, the number of nodes remaining was approx. 26 in plants at all temperatures. The early cessation of growth at low temperatures was accompanied by early leaf abscission (Table I).

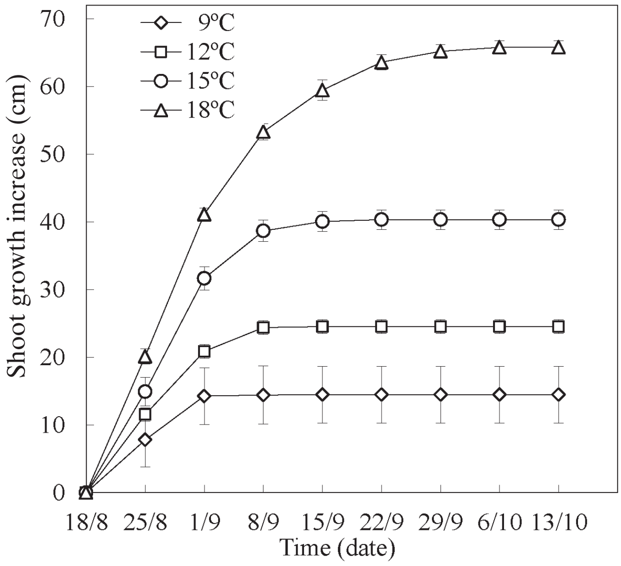

FIG. 2
Time-courses of cumulative shoot growth increments and the time of growth cessation in 'Glen Ample' raspberry plants grown under natural long-day conditions at various temperatures, as indicated. Values are means ± SE of three replicates with five plants in each treatment (Expt. 1).

When cropped in the following season, plants grown at low Autumn temperatures had consistently and significantly earlier flowering and fruit maturation, a higher percentage of fruiting nodes, and larger numbers of fruit per cane and per lateral, while the lengths of their fruiting laterals were reduced (Table II). However, due to a marked negative correlation between fruit number and fruit weight, harvested fruit yields were not significantly different in plants grown at the various Autumn temperatures, but remained more or less constant at between 2.8 – 2.9 kg per cane, regardless of temperature conditions. Plant structure, earliness, and the yield of plants grown at ambient Apelsvoll temperatures were similar to those of plants grown at a constant 15ºC.

Effects of additional shoots in each pot (Expts. 2 and 3)

At end of the first growing season, the plants in Experiment 2 had reached an average height of 224 cm, with an average of 45 nodes. The cropping results in Table III show that yield was not significantly reduced when one or two additional shoots were allowed to develop in each pot concurrently with flower and fruit development. Similarly, the numbers and sizes of harvested fruit were not significantly influenced by the presence of additional shoots. Likewise, mean heights and the numbers of nodes on the additional shoots recorded at the end of the season were not significantly different in pots with one or two additional shoots (Table III).

When the resulting new plants were cropped after cold storage in the usual way in the third season, pots with one cane yielded approx. 3 kg, as usual (Table IV). However, because of the complexity and crowded nature of the fruiting plants, it was not possible to distinguish fruit on the individual canes in pots with two canes, but the two canes combined yielded a total of 3.7 kg per pot, with an equivalent increase in fruit number. The earliness of flowering and fruiting, as well as fruit size, were not significantly different in plants with one or two canes (Table IV).

In agreement with earlier findings (Sønsteby *et al.*, 2009), the single-cane plants produced in the greenhouses in Experiment 3 reached a height of ≥ 2 m at the end of the season, while those grown outdoors ended-up at a height of approx. 1.5 m (Figure 3). Dual-cane plants were always significantly shorter, and produced fewer nodes, than single-cane plants, both in the greenhouses and outdoors (Table V). These differences in shoot height were also reflected in the

TABLE I
Effects of Autumn temperature on shoot height and structure of 'Glen Ample' plants (Experiment 1)

Temperature (ºC)	Final shoot height (cm)	Growth increment (cm)[‡]	Final no. of nodes	Node increment[‡]	Remaining nodes after tipping	Leaf abscission at the end of treatment (%)
9	205.5 c[†]	14.5 c	41.1 c	6.0 b	26.1 a	43.7 a
12	217.1 bc	24.5 c	41.0 c	6.5 b	26.1 a	33.1 b
15	233.4 b	40.3 b	43.2 bc	8.2 b	26.0 a	22.2 c
18	256.6 a	65.8 a	47.1 a	12.7 a	25.3 a	19.7 c
Ambient	260.4 a	68.4 a	45.2 ab	11.2 a	25.0 a	20.0 c
Mean	234.6	36.3	43.5	8.4	25.7	29.7
Probability levels of significance (ANOVA)	< 0.001	< 0.001	0.001	< 0.001	ns	< 0.001

[‡]Increment after 6 weeks of culture.
[†]All values are means of three replications, with five plants in each treatment. Mean values in the same column followed by different lower-case letters are significantly different ($P \leq 0.05$) for the different temperature treatments. ns, not significant.

TABLE II
Effects of Autumn temperature on earliness and fruit yield of 'Glen Ample' long canes (Experiment 1)

Temperature (ºC)	Days to anthesis	Days to first harvest	Fruit yield (g cane^{-1})	No. of berries cane^{-1}	Fruit weight (g)	No. of berries lateral^{-1}	Fruiting nodes (%)	Lateral length (cm)
9	35.0 c[†]	62.3 c	2,897 a	597 a	4.9 c	26.0 ab	88.1 a	58.0 c
12	36.9 c	66.3 c	2,837 a	553 a	5.1 c	24.7 abc	86.1 a	64.2 bc
15	44.8 b	74.0 ab	2,828 a	476 b	6.0 b	21.7 bc	84.4 a	71.7 ab
18	50.9 a	79.7 a	2,885 a	421 b	6.8 a	22.0 c	75.7 b	78.2 a
Ambient	44.1 b	73.7 b	3,020 a	599 a	5.0 c	28.4 a	84.4 a	70.3 ab
Mean	42.3	71.2	2,893	529	5.6	24.6	83.7	68.5
Probability levels of significance (ANOVA)	< 0.001	< 0.001	ns	< 0.001	< 0.001	0.003	0.001	< 0.001

[†]All values are means of three replications, with five plants in each treatment. Mean values in the same column followed by different lower-case letters are significantly different ($P \leq 0.05$) for the different temperature treatments. ns, not significant.

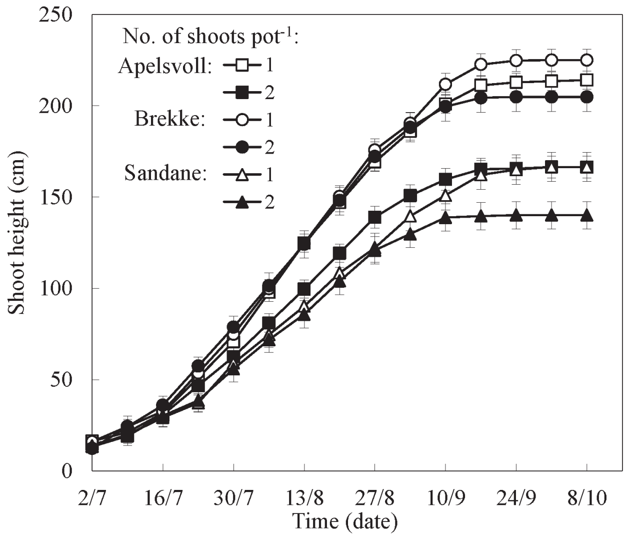

FIG. 3
Time-courses of cumulative shoot growth in 'Glen Ample' raspberry plants bearing one (open symbols) or two (closed symbols) canes when grown in greenhouses at Apelsvoll or at Brekke, or outdoors at Sandane. Values are means ± SE of three replicates with five plants in each treatment (Expt. 3).

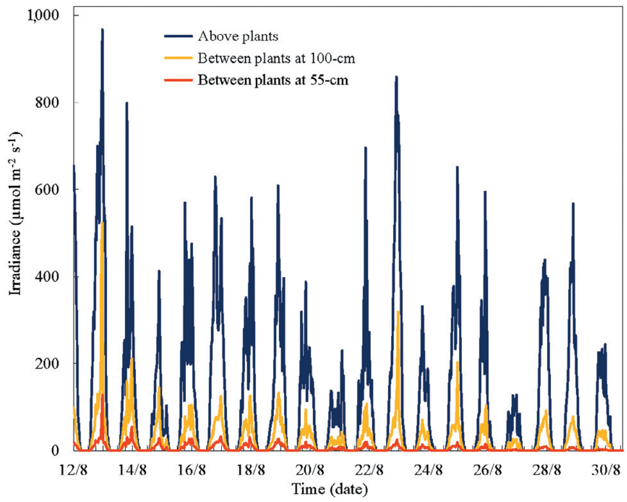

FIG. 4
Diurnal fluctuations in photosynthetic photon flux densities above, and at the base of raspberry plants grown at 100-cm or 55-cm row spacings over an 18-d period in late-August, when the plants had reached a height of approx. 2 m (Expt. 4).

significant differences in fruit yield when plants were cropped in the following season. Thus, the single-cane plants produced in greenhouses at Bioforsk Apelsvoll and at Brekke yielded 2.9 and 3.3 kg fruit plant^{-1}, respectively; while the same type of plant grown outdoors at Sandane yielded approx. 2.0 kg plant^{-1} (Table V). The corresponding yields for dual-cane plants were approx. 3.6 and 4.0 kg plant^{-1} at Apelsvoll and Brekke, respectively; while dual-cane plants produced outdoors at Sandane yielded 2.6 kg plant^{-1}. Numbers of harvested berries varied in a similar way among the various plant types. While fruit size did not vary significantly between plants from the different growing locations, single-cane plants had slightly larger fruit than dual-cane plants at all locations and under all growing conditions (Table V).

Effects of plant density (Expt. 4)

The diurnal PPF densities recorded at the lower part of plants grown at 100 cm or 55 cm row spacings, are presented in Figure 4 and show marked reductions in light flux with increased plant density. It was also shown that, on sunny days, due to the preferential filtration of red light (R) by the leaf canopy, the R:FR ratio of light reaching the lower part of plants between rows at 100-cm spacing was reduced from the usual value of 1.0 – 1.2 in unfiltered sunlight (Smith, 1982) to approx. 0.6 (Figure 5). However, in the early afternoon (between 14.00 – 17.00 h), when the incident solar radiation was parallel to the row orientation, the R:FR ratio increased to a maximum of 0.9 at approx. 15.45 h. On overcast days, the R:FR ratio remained more-or-less constant at 0.8 throughout the day.

Initially, plants at the 160-cm row spacing elongated slightly less than those grown at higher density; but, after

TABLE III
Effects of allowing additional shoots to develop in each pot during the cropping season on the size of the new shoots, and on fruit yield and fruit size on the cropping cane (Expt. 2)

No. of additional shoots	Fruit yield (g cane^{-1})	No. of berries cane^{-1}	Berry weight (g)	Mean length of additional shoots	Node number of additional shoots
0	2,753[†]	455.4	6.2	–	–
1	2,541	426.9	6.1	177.9	33.1
2	2,577	416.0	6.4	183.6	32.1
Mean	2,624	432.8	6.2	180.8	32.6
Probability levels of significance (ANOVA)	ns	ns	ns	ns	ns

[†]All values are means of three replications, with five plants in each treatment. ns, not significant.

TABLE IV
Earliness and fruit yields of additional long canes developed concurrently with fruiting of the old cane during the previous raising season (Expt. 2)

Additional canes per pot	Days to anthesis	Days to first harvest	Fruit yield (g pot^{-1})	No. of berries pot^{-1}	Fruit weight (g)	Fruit per lateral	Lateral length (cm)
1	39.1 a[†]	68.0 a	2,962 a	549.1 b	5.4 a	37.3 a	59.3 a
2	39.2 a	68.7 a	3,725 a	710.1 a	5.3 a	46.0 a	66.1 a
Mean	39.2	68.4	3,344	629.6	5.4	41.7	62.7
Probability levels of significance (ANOVA)	ns	ns	ns	0.05	ns	ns	ns

[†]All values are means of three replications, with five plants in each treatment. Mean values in the same column followed by a different lower-case letter are significantly different ($P \leq 0.05$). ns, not significant.

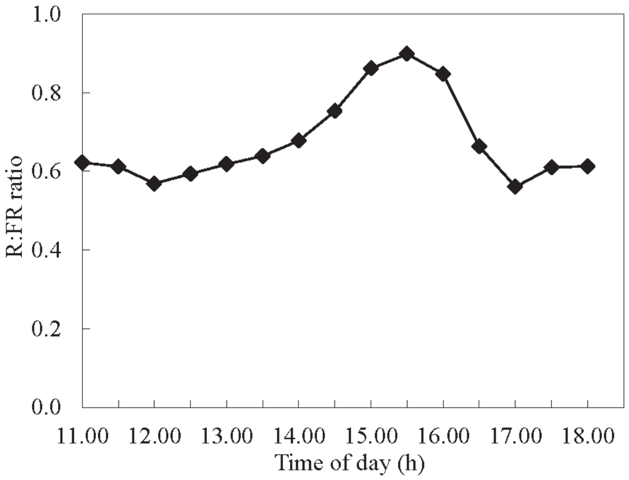

Fig. 5
Daytime changes in the red:far-red (R:FR) light ratio of canopy-filtered light reaching the base of 2 m-tall raspberry plants grown at a 100-cm inter-row spacing. Changes were recorded during a typical sunny day in August (Expt. 4).

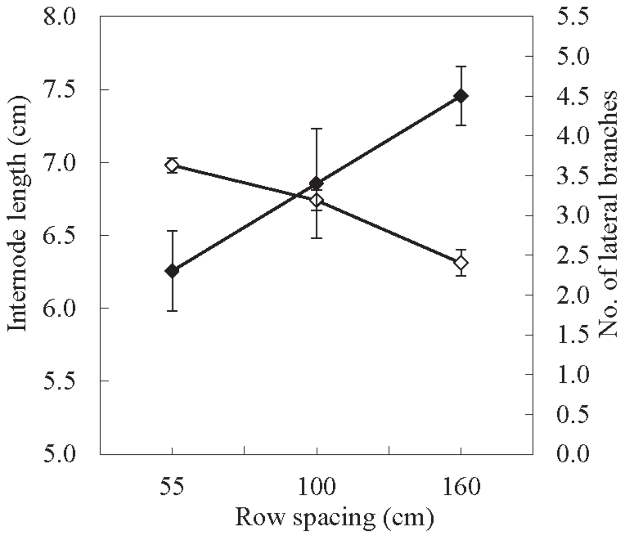

Fig. 6
Effects of inter-row spacing (at 55, 100, or 160 cm) on internode length (open symbols) and lateral branching (solid symbols) of greenhouse-grown 'Glen Ample' raspberry plants. Values are means ± SE of three replicates with five plants in each treatment (Expt. 4).

approx. 7 weeks, the growth rates equalised, so that at the end of the season there were no significant differences in the heights of plants grown at the different plant densities (Table VI). However, the average internode length increased with increasing plant density, resulting in more slender plants with reduced numbers of nodes. Thus, at a height of 2.0 m, plants at the 160 cm row spacing had an average of 32 nodes, while this was reduced to 30 and 28.5 nodes, respectively, in plants grown at the 100 cm or 55 cm row spacings (*cf.* Figure 6). Another effect of planting density was a tendency to increase lateral branching in plants at an increasing spacing (Figure 6). In order to avoid branched canes, such lateral branches must be removed by pinching, which represents an additional labour cost. Pinching can be done in two very different ways, either by removing the entire lateral shoot, or by leaving a few nodes at the base. With the former method, we observed that a fruiting lateral would usually develop from one of the two axillary buds in the following year; while, if the

Table V
Structure and yield of 'Glen Ample' plants with one or two canes per pot when grown in greenhouses at Bioforsk Apelsvoll and at Brekke, or outdoors at Sandane (Expt. 3)

Location	No. of shoots per plant	Fruit yield (g plant^{-1})	No. of berries plant^{-1}	Berry weight (g)	Shoot height (cm)‡	Fruiting shoot (cm)¶	Mean no. of nodes‡
Apelsvoll	1	2,999†	502	6.0	170	160	30.1
	2	3,570	636	5.7	162	160	25.9
	Mean	3,285	569	5.9	166	160	28.0
Brekke	1	3,355	568	6.2	235	160	26.1
	2	3,975	692	5.6	205	160	24.9
	Mean	3,665	630	5.9	220	160	25.5
Sandane	1	2,076	313	6.0	167	160	27.3
	2	2,577	396	5.8	142	140	26.7
	Mean	2,327	355	5.9	155	150	27.0
Probability levels of significance (ANOVA)							
Source of variation							
Location (A)		< 0.001	< 0.001	ns	< 0.001	< 0.001	0.03
No. of shoots (B)		0.004	0.004	0.03	< 0.001	< 0.001	0.01
A × B		ns	ns	0.001	0.03	< 0.001	ns

†All values are the means of three replications, with five plants in each treatment. ns, not significant.
‡Before tipping.
¶After tipping at 160 cm.

Table VI
Effects of plant density during the raising season on shoot size and subsequent yield of 'Glen Ample' raspberry plants (Expt. 4)

Row spacing (cm)	Days to anthesis	Day to first harvest	Yield (g plant^{-1})	Harvested berries plant^{-1}	Berry weight (g)	Tot. no. of nodes	Final shoot height (cm)
160	55.2 a†	87.3 b	3,141 ab	540.9 a	5.8 b	26.3 a	254.9
100	55.1 a	89.3 ab	3,170 a	517.5 ab	6.1 a	24.5 b	260.9
55	57.3 a	92.0 a	2,947 b	472.8 b	6.2 a	23.8 b	253.7
Mean	55.9	89.5	3,086	510.4	6.0	24.9	256.5
Probability levels of significance (ANOVA)							
	ns	0.05	0.03	0.02	0.02	0.002	ns

†All values are the means of three replications, with five plants in each treatment. Mean values in the same column followed by different lower-case letters are significantly different ($P \leq 0.05$). ns, not significant.

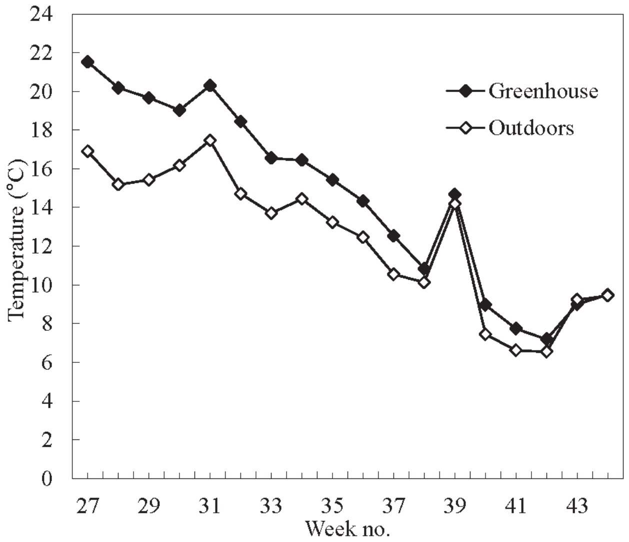

FIG. 7
Average daily mean temperatures during the growing season in a plastic greenhouse or outdoors at Sandane in Experiment 5.

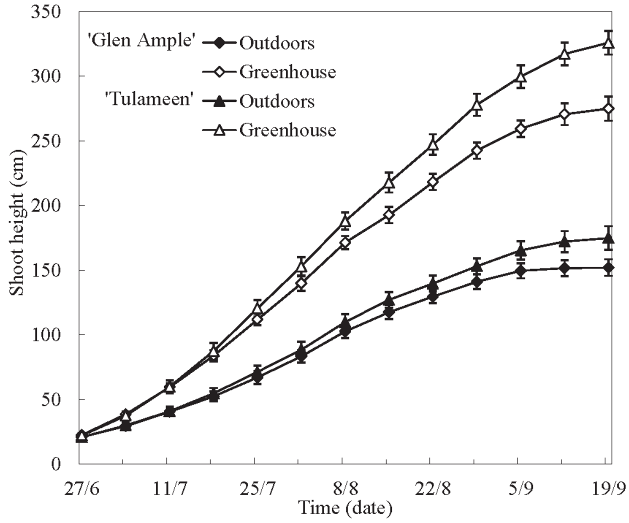

FIG. 8
Time-courses of cumulative shoot growth in 'Glen Ample' and 'Tulameen' raspberry plants grown in a greenhouse or outdoors at Sandane. Values are means ± SE of three replicates with five plants in each treatment (Expt. 5).

lateral shoots were pinched above the two basal leaves, a forked branch with two fruiting laterals would develop. The latter method thus resulted in an additional lateral branch with more flowers and fruit, and is therefore recommended as the better method.

The data in Table VI demonstrate that, after tipping to 160 cm in height, the remaining numbers of nodes per plant decreased with increasing planting density, resulting in a small but significant reduction in the number of fruiting nodes. There was also a small time delay in flowering and fruit maturation with increasing planting density (with only the latter being significant). However, fruit yields plant^{-1} and the numbers of harvested fruit plant^{-1} were not significantly reduced when the row spacing was reduced from 160 cm to 100 cm, while both parameters were slightly, but significantly, reduced when the row spacing was further reduced to 55 cm. Thus, plants grown at 160 cm or 100 cm row spacing produced > 3 kg fruit plant^{-1}, while those grown at a 55 cm row spacing yielded slightly less than 3 kg plant^{-1}. Nor was there any negative effect of increased plant density on fruit size, which was, in fact, significantly larger in plants raised at higher density (Table VI).

Comparison of 'Glen Ample' and 'Tulameen' (Expt. 5)

Plants were propagated in May and transplanted into 2.5 l plastic pots in the usual way. In the last week of June, one-half of the plants of each cultivar were moved outside for cultivation during the rest of the season, while the other half remained in the greenhouse until the end of October. These plants were then also moved outside for maturation and hardening. Plants were grown at a spacing of 160 cm × 20 cm at both sites. The daily mean temperatures in the greenhouse and outdoors during the intervening period are shown in Figure 7. In early-December, the plants were transported to Apelsvoll and moved into the cold store, where they remained until 15 May, when they were transplanted into 7.5 l pots and transferred to an open plastic tunnel, and allowed to fruit in the usual way.

Plants of both cultivars elongated more rapidly at elevated temperatures in the greenhouse; while, under both temperature conditions, 'Tulameen' plants had significantly higher growth rates than those of 'Glen Ample' (Figure 8). While the numbers of nodes were significantly higher in plants grown in the greenhouse, there was no significant difference in the numbers of nodes between the two cultivars (data not shown). When the plants were allowed to fruit in the following season, anthesis and fruit maturation in both cultivars were approx. 1 week earlier in plants raised outdoors, an effect that was also observed and discussed by Sønsteby *et al.* (2009). Overall, however, fruit harvesting started approx. 1 week earlier in 'Glen Ample' than in 'Tulameen' plants (Table VII). The difference in cane heights at the end of the first season were paralleled by consistently higher fruit yields in the taller plants produced in the greenhouse. However, despite 'Tulameen' having significantly taller canes than 'Glen Ample', the latter always out-yielded 'Tulameen' by approx. 0.5 kg plant^{-1}, indicating the inherently greater yield potential of 'Glen Ample' (Table VII). However, since 'Tulameen' plants had a significantly larger proportion of flowers and fruit that did not reach maturity before harvesting was terminated in October, the difference in yield between the two cultivars was, at least in part, a result of later fruit maturation in 'Tulameen'. Also, while fruit size was slightly, but significantly, larger in plants produced outdoors in both cultivars, there was no significant difference in overall fruit size between the two cultivars. The lengths of flowering and fruiting laterals were significantly (P = 0.008) greater in plants produced in the greenhouse and, overall, the laterals were also significantly (P = 0.003) longer in 'Tulameen' than in 'Glen Ample' plants (data not shown).

DISCUSSION

The results shown here clearly demonstrate and confirm that, with proper management, pot-grown raspberry long canes with a yield potential of 3 kg fruit per cane can be produced reliably and reproducibly (*cf.* Sønsteby *et al.*, 2009). It was also confirmed that, in

TABLE VII
Earliness and fruit yields of 'Glen Ample' and 'Tulameen' raspberry long canes produced in a greenhouse or outdoors at Sandane (Experiment 5)

Cultivar	Site of production	Days to anthesis	Days to first harvest	Yield (g cane^{-1})	No. of berries cane^{-1}	Berry weight (g)	No. of fruit not harvested	Tot. no of fruit cane^{-1}
'Glen Ample'	Outdoors	46.9 b[†]	79.0 a	2,713 b	416.9 b	6.5 a	98.3 a	515.2 a
	Greenhouse	53.3 a	87.7 a	3,253 a	536.8 a	6.1 b	144.3 a	681.1 a
	Mean	50.1	83.3	2,983	476.8	6.3	121.3	598.2
'Tulameen'	Outdoors	47.6 b	89.0 a	2,160 b	345.1 b	6.3 a	211.3 a	566.4 a
	Greenhouse	56.1 a	94.3 a	2,769 a	453.9 a	6.1 b	289.3 a	743.2 a
	Mean	51.9	91.7	2,464	399.5	6.2	250.3	649.8
Probability levels of significance (ANOVA)								
Source of variation								
Site of production (A)		0.003	ns	0.02	0.01	0.02	ns	ns
Cultivar (B)		0.03	0.003	0.002	0.002	ns	0.004	0.08
A × B		ns	ns	ns	ns	ns	ns	ns

[†]All values are the means of three replications, with five plants in each treatment. Mean values in the same column followed by a different lower-case letter are significantly different ($P \leq 0.05$) for the main effect of production site. ns, not significant.

the cool Norwegian environment, the tall plants that are required for such high yields can only be produced in a greenhouse. The smaller plants produced outdoors, consistently yielded 0.6 – 1.0 kg less fruit per cane (Table V; Table VII; Sønsteby *et al.*, 2009). On the other hand, it was found that, in this environment, there was no yield benefit of artificially reducing the Autumn temperature below the ambient level in order to promote floral initiation, although this significantly increased the number of harvested berries and advanced the dates of flowering and fruit maturity in the following season.

In previous experiments on the production of high-yielding long canes (Sønsteby *et al.*, 2009), plants were grown in 3.5 l pots at a spacing of 200 cm × 20 cm, and no more than one shoot was allowed to develop in each pot during the propagation season or the cropping season. In the present Experiments, however, we used 2.5 l pots and varied the row spacing and the number of shoots per pot. The results showed that a reduction in pot size to 2.5 l had no negative effects on cane height or on yield potential. Experience from preliminary small-scale trials also suggested that, with the use of an automatic fertigation system, pot size may be reduced further to 2.0 l without significant reductions in plant size or yield potential. It was also demonstrated that plants with a yield potential of > 3 kg fruit per cane were routinely obtained when the plant spacing was reduced from 200 cm × 20 cm, as used by Sønsteby *et al.* (2009), to 160 cm × 20 cm, or even to 100 cm × 20 cm (Table VI), despite marked reductions in photosynthetic photon flux (PPF) densities and the R:FR ratio of the light reaching the lower part of the plants under such increased planting densities (Figure 4; Figure 5). In fact, fruit yields of almost 3 kg per cane were obtained even when the plant spacing was reduced to 55 cm × 20 cm (Table VI). Apparently, light conditions in the lower part of the plant are less important, so long as the upper part of the plant receives adequate light. An additional observation was that the canopy did not close before the plants reached a height of approx. 1.5 m, even at the lowest row spacing (see Figure 1). Furthermore, no significant reduction in yield of the cropping shoot was observed when one or two new shoots were allowed to develop concurrently with flowering and fruiting on the old cane (Table III). At the same time, the new shoots achieved a full yield potential of approx. 3 kg per cane in the following season (Table IV). This permitted harvesting of a heavy fruit crop and the simultaneous production of new high-yielding canes in the same pot in a single growing season. An additional 1.0 kg of fruit per pot could be obtained if two canes were allowed to develop to maturity in each pot. Such dual-cane plants regularly yielded almost 4 kg of fruit, regardless of whether they consisted of two separate shoots or a single, forked shoot with two canes (Table IV; Table V). These results demonstrate that, by applying such methods of intensification, the cost of production of high-yielding raspberry long canes can be reduced significantly without loss of their previously reported high yield potential (*cf.* Sønsteby *et al.*, 2009).

Comparing the performance of 'Glen Ample' and 'Tulameen' revealed their similar temperature requirements. Thus, both cultivars grew taller and achieved significantly higher yield potentials when raised in a greenhouse compared with outdoor conditions. However, 'Glen Ample' consistently out-yielded 'Tulameen', by approx. 0.5 kg fruit per cane, regardless of growing conditions. Flowering and fruit maturation were also approx. 1 week earlier in 'Glen Ample' than in 'Tulameen' (Table VII). As previously reported for 'Glen Ample' (Sønsteby *et al.*, 2009), the dates of flowering and fruit maturation were advanced by approx. 1 week in both cultivars in plants produced outdoors compared with greenhouse-produced plants. This effect was associated with delayed flowering of the long and fruitful laterals developing after decapitation of the taller canes (*cf.* Sønsteby *et al.*, 2009). Because of its superior earliness and fruit yields, its firm fruit and longer shelf-life, 'Glen Ample' is an excellent cultivar for greenhouse production for the fresh market, despite the fact that 'Tulameen' is considered to have a superior flavour (Finn *et al.*, 2008).

In conclusion, the present results demonstrate and confirm the feasibility of producing raspberry long canes with a yield potential of ≥ 3 kg fruit per cane on a regular basis. The key to such an achievement is producing tall, strong canes ≥ 200 cm in height. When these tall plants are cut-back to 160 cm in height before forcing, they produce only long fruiting laterals with heavy flowering and fruiting (*cf.* Sønsteby *et al.*, 2009). These results also outline intensified production techniques that combine reduced costs of production with the maintenance of a high yield potential.

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