Breaking Dormancy in Red Raspberries for Greenhouse Production

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Additional index words. *Rubus idaeus*, chilling units, flower initiation

Abstract. Experiments were conducted to determine the chilling temperature and length of time required to break dormancy in red raspberry (*Rubus idaeus* L.). Five weeks of 7 °C with no light was sufficient to break dormancy in ‘Autumn Britten’, ‘Nova’, ‘Polana’, and ‘Tulameen’, while at least 8 weeks were needed for ‘Titan’. Comparisons with various chilling unit models allowed a model to be developed that could account for the observed chilling variation. In this model, each chilling hour was weighted as follows: below 5.6 °C = 1; 5.7 to 8.0 °C = 0.5; 8.1 to 11 °C = 0; 11.1 to 13 °C = –0.5; and >13 °C = –1. Plants of ‘Nova’ and ‘Tulameen’ chilled before flower initiation occurred, broke dormancy, and the resulting lateral branches remained vegetative. When the plants were fruited in the greenhouse, we were able to produce a second crop on the fruiting canes when the lateral branches that had fruited were removed. These experiments show that raspberries can be manipulated so that plants chilled in mid-September in the Northern Hemisphere can be induced to fruit by the beginning of January.

Most red raspberries fruit in midsummer, although there are a few fall-fruited cultivars. In Europe, raspberries are now commercially produced in greenhouses during the winter, and fruit is produced by various techniques from late March until the end of December (Carew et al., 2002b; Dale et al., 2001, 2002; Dijkstra and Scholtens, 1993; Pritts et al., 1999).

Since 1992, we have been developing systems to grow raspberries in greenhouses in Ontario. We used potted plants whose flower buds had been initiated and their dormancy requirement fulfilled outdoors to produce a crop consistently from late March (Dale et al., 2002). Similarly, in New York, plants moved into the greenhouse in late December fruited from late February (Pritts et al., 1999).

Several cultivars have potential for greenhouse culture in northern North America. ‘Tulameen’ is suitable for the main spring crop because it has high yields, large berries, and excellent fruit quality and flavor (Pritts et al., 1999). ‘Nova’ fruits 1 week earlier than ‘Tulameen’ and can precede ‘Tulameen’ in

a double-cropping system, while ‘Autumn Britten’ and ‘Polana’ are early fall-bearing cultivars that have potential for the fall crop (Dale et al., 2001).

Detailed information is needed on dormancy of red raspberries grown in greenhouses to optimize the scheduling of successive crops and so maximize yield. If the dormancy requirements are not completely filled, raspberries develop fewer laterals, which take longer to fruit (Jennings, 1988). Plants that have completed their dormancy grow rapidly and produce high yields in the shortest possible time. In a year-round greenhouse production system, this allows the most fruiting cycles to be used to maximize the yields.

Bud dormancy in raspberries can be broken and lateral branches induced to flower by an inductive period of 1 week at 10 °C (50 °F) and 9-h days followed by 6 weeks at 3.3 °C (38 °F) and no light (Williams, 1960). However, the length of the inductive period depends on the size of the cane; those with more than 30 nodes require no inductive period. Jennings (1964) found that 6 weeks at 7.2 °C (45 °F) with 9 h light was sufficient to break bud dormancy and to induce lateral branches to flower. He used this information to develop a dormancy model for raspberries adapted from the peach model (Richardson et al., 1974), which weighted different chilling temperatures, giving the greatest weight to 3.0 to 5.6 °C (personal communication). Jennings et al. (1986) showed considerable variation between cultivars in their chilling requirements.

Two experiments were done to determine what chilling treatments would be required to fruit raspberries in a greenhouse before mid-March. In the first, the previously reported chilling temperatures were tested and, in the second, the length of time required to break dormancy was investigated.

Experiment 1. Chilling Temperatures

Rooted cuttings of two summer-bearing raspberry cultivars, ‘Titan’ and ‘Nova’, were planted in 3.8-L grow bags in a mixture of peat, vermiculite, perlite, dolomitic limestone, and bentonite clay (Professional Mix VPW 30, ASB Greenworld, Mt Elgin, Ont., Canada) on 3 May 1997. They were grown in the greenhouse until 18 July and then moved outside. These plants were at least 1.2 m tall and had one or two canes. In both cultivars, buds were dissected weekly from 19 Aug. and examined to determine when flower bud initiation had occurred according to the methods used by Dale and Daubeney (1987). Both had initiated flower buds by 2 Sept. 1997.

Every 2 weeks from 16 Sept. to 28 Oct., 12 plants of each cultivar were placed in a cooler at either 3 or 7 °C. Six plants from each temperature treatment were moved into the greenhouse after 6 weeks and the other six after 8 weeks. Single plants were placed in a randomized complete-block design of six replicates when they came out of the cooler and trellised. Greenhouse temperature was maintained at 24 °C during the day and night and ranged between a minimum of 14 °C and a maximum of 41 °C. Plants were grown under ambient light conditions with the exception of the period between 3 Nov. and 11 Dec. 1997, when lights were on to give a 12-h photoperiod. The average daily incoming radiation for southern Ontario (Vineland Station) varies between 403 J·cm^{–2}·day^{–1} in December to 2250 J·cm^{–2}·day^{–1} in June, and the average daylength varies between 8.9 h in December to 15.5 h in June (Blom et al., 1985). Pots were trickle-irrigated to runoff twice daily. Plants were fertilized with 85 g of 100-d Nutricote 13–13–13 with micronutrients, placed on the surface of the growing medium. Flowers were pollinated by bumblebees (*Bombus impatiens*). A single hive was introduced once flowering started and replaced when the bee population dropped. Occasionally, bees were absent from the greenhouse for up to 2 weeks. Predominant pests were thrips and spider mites. Spider mites were controlled on a regular basis with *Phytoseiulus persimilis*. Thrips were controlled as necessary with *Amblyseius cucumeris*. The first flush of young primocanes was removed when they reached a height of 15–20 cm.

The number of buds that burst (when the tip of the primary leaf began to emerge) and total nodes per cane were counted for each plant 2 weeks after they were moved into the greenhouse. The dates the first flower opened and first fruit ripened were recorded weekly. Ripe fruit was collected, graded, and weighed twice each week from 5 Jan. 1998 until 27 Aug 1998. The number of fruiting canes per pot were counted. In order to stimulate a second crop, as the laterals finished fruiting, they were counted and removed.

Bud burst was calculated as the number of buds that burst divided by the total number of nodes per cane, expressed as a percentage. Lateral development was calculated as the num-

Received for publication 15 Apr. 2002. Accepted for publication 27 Sept. 2002. We thank Linda Packer, Erica Gunn, and Kristen Bell Samson for their technical support, and Gerarda Darlington for her statistical advice. Financial support for this project was provided by the Ontario Ministry of Agriculture, Food, and Rural Affairs and the Industry Research Assistance Program of the National Research Council.

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ber of laterals divided by the total number of nodes per cane, expressed as a percentage. The number of days to the first open, primary flower and ripe fruit was recorded as the number of days that plants were in the greenhouse until these events occurred. Total yield per pot was divided by the number of fruiting canes to give the yield per cane. The days it took for 5%, 50%, and 95% of fruit to be harvested in the first crop were calculated from the day each treatment was placed in the greenhouse.

Experiment 2. Length of Chilling Treatment

One-year-old bare-root canes of two summer-bearing cultivars, 'Nova' and 'Tulameen', and two fall-bearing cultivars, 'Autumn Britten' and 'Polana', were planted as in Expt. 1 on 15 May 1999. They were grown in the greenhouse until they were transferred into the chilling treatments. Immediately before the plants were chilled, the number of canes in each pot was reduced to one.

Plants of each cultivar were subjected to one of three chilling treatments (chilling stage). One group of plants was moved into a dark cooler at 7 °C on 25 Aug. 1999, and a second group moved into the dark cooler at 7 °C on 22 Sept. 1999. A third group of plants was moved outside on the same day the first group was moved into the cooler. Five plants from each of the first two groups of plants were moved into the greenhouse after 4, 5, 6, 7, or 8 weeks in the cooler and five plants from the outside treatment were brought into the greenhouse after they had received 672, 840, 1008, 1176, or 1344 h of chilling below 7 °C. These times represent the equivalent of 4, 5, 6, 7, or 8 weeks in the cooler. Single plants were placed in a randomized complete-block design of five replicates and trellised. Growing conditions in the greenhouse were similar to those for Expt 1, except that the greenhouse temperature was maintained at 20 °C during the day and night, and ranged between a minimum of 16 °C and a maximum of 35 °C. The young canes were not removed.

Ripe fruit were collected, graded, and weighed twice each week from 8 Nov 1999 until 29 June 2000. After the canes had finished fruiting, the development of the lateral bud at each node on the cane was recorded as follows: 5 = fruiting lateral branch; 4 = vegetative lateral branch; 3 = lateral branch started to extend and then aborted; 2 = lateral bud burst then aborted; 1 = bud dormant; and 0 = bud dead.

Bud burst was calculated as the number of buds burst divided by the total number of nodes per cane, expressed as a percentage. Development for each lateral branch category was calculated as the number of nodes in that category divided by the total number of nodes per cane, also expressed as a percentage. Total yield per cane and average berry weight were calculated. The days until 5%, 50%, and 95% of the fruit were harvested were calculated from the day each treatment was placed in the greenhouse.

In both experiments, data were analyzed by GLM using SAS (SAS Institute, Cary,

N.C.). In Expt. 1, the cultivars were analyzed separately, as all cultivar interactions were significant. The percentages of the different node categories in Expt. 2 were analyzed using an arcsin transformation with the Anscombe substitution. For date of treatment in Expt. 1 and length of chilling in Expt. 2, significant effects were partitioned into their linear, quadratic, and residual components. Where the highest order interaction was significant, the interaction mean square was used as the error for the other effects.

Chilling units were calculated in both experiments using different models. The models used were: 1) cumulative hours below 7 °C; 2) peach chilling model (Richardson et al., 1974), where each chilling hour was weighted as follows (<1.4 °C = 0; 1.5 to 2.4 °C = 0.5; 2.5 to 9.11 °C = 1; 9.2 to 12.4 °C = 0.5; 12.5 to 15.9 °C = 0; 16 to 18 °C = 0.5; >18 °C = -1); 3) blueberry chilling model (Norvell and Moore, 1982), where each chilling hour was weighted as for Richardson et al. 1974 model, except <2.5 °C = 0.5; 4) raspberry model (Jennings, personal communication), where each chilling hour was weighted as follows (<3 °C = 0.5; 3.0 to 5.6 °C = 1; 5.7 to 8.0 °C = 0.5; 8.1 to 11 °C = 0; 11.1 to 13 °C = -0.5; >13 °C = -1); and 5) the raspberry model modified so that <5.6 °C has a weight of 1.0. This weight was changed because in Expt. 2 there were many days when the field-conditioned canes were

exposed to below 0 °C, and the raspberry model could not adequately explain the field dormancy requirement for 'Nova' when compared to its chilling requirement in Expt. 1.

Results

Experiment 1. Chilling Temperatures

Chilled plants produced lateral branches that fruited after ≈2 months in the greenhouse. A second crop, 28% of the first, developed from new lateral branches ≈55 d after the first crop.

First crop. For the first flush of lateral branches that developed, the later the 'Nova' plants were placed in the dormancy-breaking treatments the lower the percentage of fruiting laterals that developed, whereas on 'Titan' the opposite occurred (Table 1). On 'Titan' more fruiting laterals grew after 8 weeks than after 6 weeks in storage (9.3% vs. 6.3%, $P = 0.0001$) and more at 3 °C than at 7 °C (9.3% vs. 6.3%, $P = 0.0001$), whereas in 'Nova' the treatments were similar (32.1%). The effect of these two treatments on 'Titan' was additive, with 3 °C for 8 weeks producing the most fruiting laterals (11.1%). Total yield per cane varied significantly only for the date of treatment. The later dates of treatment gave larger yields per cane (Table 1).

'Nova' fruited ≈10 d earlier than 'Titan'.

Table 1. The effect of date of dormancy-breaking treatment on percent of fruiting laterals developed and yield per cane on 'Nova' and 'Titan' raspberries for the first and second crops.

Date of treatment	Percent of fruiting laterals developed				Yield per cane (g)			
	First crop		Second crop		First crop		Second crop	
	Nova	Titan	Nova	Titan	Nova	Titan	Nova	Titan
16 Sept.	39.2	7.0	4.8	2.3	201	157	86	73
30 Sept.	33.4	7.0	4.9	2.5	150	198	35	83
14 Oct.	27.1	8.3	10.3	3.1	222	243	27	70
28 Oct.	28.8	8.9	9.3	2.4	208	210	23	49
Significance of regression $P =$								
Linear	0.0001	0.03	0.0059	0.69	0.37	0.033	0.0001	0.21
Quadratic	0.058	0.65	0.73	0.35	0.42	0.083	0.0025	0.31

Table 2. Variance ratios (F-ratios) for the analyses of variance of the arcsin transformation with Anscombe's substitution of the mean percentage of lateral branches fruiting and growing vegetatively in four raspberry cultivars chilled at 7 °C at three stages for 4-8 week periods.

Treatment effect	df	Fruiting	Veg. & growing	Veg. & stopped ^z	Buds burst	Dormant ^z	Dead
Replicate	4	5.9***	0.9 ^{NS}	0.3 ^{NS}	0.7 ^{NS}	1.8 ^{NS}	1.3 ^{NS}
Cultivar	3	91.9***	23.1***	0.4 ^{NS}	2.4 ^{NS}	23.3***	1.0 ^{NS}
Chilling stage	2	87.9***	42.4***	45.0***	44.6***	47.4***	2.8 ^{NS}
Cultivar × stage	6	22.2***	9.6***	0.9 ^{NS}	3.8**	9.8***	2.3*
Chilling time							
Linear	1	67.3***	2.5 ^{NS}	21.7***	11.2**	110.6***	8.0**
Quadratic	1	31.1***	0.1 ^{NS}	1.1 ^{NS}	5.9*	26.3***	5.4*
Remainder	2	0.4 ^{NS}	3.8*	1.0 ^{NS}	0.8 ^{NS}	5.3 ^{NS}	3.4*
Cultivar (C) × time	12		1.1 ^{NS}	1.2 ^{NS}		1.7 ^{NS}	0.9 ^{NS}
C × linear	3	3.5*	---	---	1.2 ^{NS}	---	---
C × quadratic	3	2.7*	---	---	6.6**	---	---
C × remainder	6	0.56 ^{NS}	---	---	1.6 ^{NS}	---	---
Stage (S) × time							
S × linear	2	0.1 ^{NS}	0.8 ^{NS}	12.6**	5.2**	10.7*	2.0 ^{NS}
S × quadratic	2	0.9 ^{NS}	6.8***	4.1**	1.9 ^{NS}	7.7*	3.6*
S × remainder	4	6.1***	1.4 ^{NS}	1.4 ^{NS}	1.7 ^{NS}	1.1 ^{NS}	2.7 ^{NS}
C × S × time	24	0.8 ^{NS}	1.3 ^{NS}	1.6**	1.4 ^{NS}	1.9**	0.9 ^{NS}
Error mean square	194	0.012	0.008	0.013	0.014	0.023	0.01

^zWhere the cultivar × stage × time interaction was significant, this interaction mean square was used as the error for the other effects.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 3. Mean percentage of buds at different development stages in chilled at 7 °C at three stages of development for four raspberry cultivars chilled for 4–8 weeks.

	August	September	Field
Fruiting	24	24	39
Vegetative and growing	8	5	1
Vegetative and stopped	11	7	2
Buds burst	17	6	8
Dormant	37	57	50
Dead	2	1	0

The days to 5%, 50%, and 95% of harvest were 75, 89, and 104 d for 'Nova' and 84, 101, and 121 d for 'Titan' ($P=0.0045, 0.0001$, and 0.0001 , respectively). All other treatments did not vary significantly (data not presented). 'Nova' placed in the cooler on 16 Sept. 1997 and stored for 6 weeks until 28 Oct. started fruiting on 5 Jan. 1998, and had 5% of its first crop by 11 Jan. and 95% by 18 Feb. Plants of 'Titan' treated on 28 Oct. 1997 and stored for 8 weeks until 23 Dec. had 5% of the first crop by 14 Mar. and 95% by 22 Apr.

Second crop. 'Titan' averaged 2.6% of lateral branches in the second flush that developed and 'Nova', 7.3%. 'Nova' produced more lateral branches for the later treatment dates (Table 1). All other treatments were similar.

'Titan' had a total yield per cane greater than 'Nova' (68 and 43 gm/cane respectively, $P=0.0025$). All other treatments were similar except that 'Nova' had lower yields on the later dates of treatment (Table 1) and 'Titan' varied only for the storage $\times$ temperature interaction (56, 73, 98, 48 g/cane for 3 °C, 6 weeks; 3 °C, 8 weeks; 7 °C, 6 weeks; 7 °C, 8 weeks, respectively, $P=0.275$).

Experiment 2. Length of Chilling Treatment

When the plants were chilled in August and September, they were growing rapidly and several canes were killed by the chilling treatment. Many of the developing lateral branches had black apices. This death was probably caused by the canes and buds being unable to tolerate the cold air flowing from the cooling coils of the cooling system in the cooler.

The percentage of lateral buds in each development category, from fruiting lateral branches to dead buds, usually varied for chilling stage, duration, cultivar, and the cultivar $\times$ stage, stage $\times$ duration interactions (Table 2). Chilling time usually had significant linear and quadratic components. Chilling stage was the most significant effect. The August treatment had proportionately fewer fruiting lateral branches, more vegetative ones, more buds burst, and fewer dormant buds than the field treatment, while the September treatment was intermediate except that its fruiting lateral branches were similar to the August treatment and it had the most dormant buds (Table 3). In the stage $\times$ cultivar interaction, 'Tulameen' and 'Nova' had proportionately fewer fruiting lateral branches and more vegetative ones in the August and September treatments (Table 4). Otherwise,

Table 4. Mean yield per cane, and the mean percentage of lateral branches fruiting and vegetatively growing in four raspberry cultivars chilled at 7 °C at three stages for 4–8 week periods.

Cultivar	Total yield (g/cane)			Percentage of lateral branches					
				Fruiting			Vegetatively growing		
	Aug.	Sept.	Field	Aug.	Sept.	Field	Aug.	Sept.	Field
Autumn Britten	178	123	256	29	24	45	1	1	1
Polana	137	135	224	46	41	38	5	4	1
Nova	77	135	271	19	22	40	11	8	2
Tulameen	26	136	370	2	9	32	16	9	2
Mean	104	132	280	25	24	39	8	5	1

the other lateral branch categories for 'Autumn Britten', 'Nova', and 'Tulameen' matched the chilling stage means (data not presented). For 'Polana', the most lateral branches fruited in August treatment, the September treatment had intermediate levels, and the lowest levels occurred in the field treatment (Table 4), and the reverse for bud-burst and dormant buds (data not shown). Chilling time resulted in a curvilinear response for the different lateral branch categories, which indicated that all the cultivars had broken dormancy by 6 weeks (data not shown). The plot of the stage $\times$ time interaction indicated for the mean of all cultivars that the maximum number of buds had broken after 5 weeks in the September and field treatments but only after 6 weeks in the August treatment (Fig. 1). For individual cultivars in the August treatment, 'Nova' and 'Tulameen' had completed dormancy after 5 weeks, and 'Autumn Britten' and 'Polana' after 6 weeks (data not shown).

Field-treated plants outyielded the plants placed in the cooler in August and September ($P<0.0001$, Table 4). 'Tulameen' and 'Nova' had lower yields than 'Autumn Britten' and 'Polana' in the August-chilled plants, and 'Tulameen' had higher yields than the other cultivars in the field-treated plants (cultivar $\times$ chilling stage, $P<0.0001$, Table 4). The yields for the August treatments did not vary significantly for the durations studied; the September yields

increased the longer the plants were chilled; and the field-treated plants had maximum yields after 6 weeks chilling (Fig. 2.)

'Autumn Britten', 'Nova', and 'Tulameen' produced larger fruit than 'Polana' (2.40, 2.49, 2.43, and 1.84 g, respectively ($P=0.0001$), and those produced in the field treatment were larger than those produced in the August and September treatments (2.53, 2.15, and 2.20 g, respectively; $P=0.0001$). All other treatment effects were nonsignificant, except that August fruit weights showed a curvilinear response to fruiting duration (2.40, 2.26, 1.81, 2.06, and 2.2 g for 4–8 weeks, respectively; $y = 5.14 - 0.990x + 0.0784 x^2$, $SEb_1 = 0.380$, $SEb_2 = 0.319$).

Mean values for days to 50% harvest were ≈ 18 d later than the days to 5% harvest, except for cultivar means where 'Polana' fruited 9 d before 'Nova' at 5% harvest and 11 d after 'Nova' at 50% harvest. The August-treated plants reached 5% and 95% harvest faster than the September-treated plants, whereas the field-treated plants reached 5% harvest in about the same number of days as the September-treated ones, and reached 95% harvest more slowly (Table 5). 'Polana' varied greatly in the number of days to harvest between the different chilling stages, and August- and September-treated plants of 'Tulameen' reached 5% harvest more slowly than the field-treated ones (Table 5). The longer the field-treated plants were chilled

Fig. 1. Mean percentage of dormant buds in four raspberry cultivars chilled at 7 °C at three stages of development for 4–8 week periods. ♦ represents the values for the August treatment, ■ for the September treatment and ▲ for the field treatment. The regression lines differ significantly ($P=0.05$).

Fig. 2. Mean yield per cane for four raspberry cultivars chilled at 7 °C at three stages of development for 4–8 week periods. ♦ represents the values for August treatment, ■ for the September treatment and ▲ for the field treatment. The regression lines differ significantly from each other. The regression line for the August treatment is not given as the regression coefficients did not differ significantly from 0.

Fig. 3. Mean days to 5%, 50%, and 95% harvest in four raspberry cultivars chilled below 7 °C in the field for 4–8 week periods in 1999. ♦ represents values for 5% harvest, □ for 50% harvest, and △ for 95% harvest.

the more quickly they reached harvest and the shorter the harvest period (Fig. 3), whereas the August- and September-treated plants did not show any particular trend (data not shown).

Plants of 'Polana' chilled in August for 4 weeks were the first to start fruiting on 11 Nov. 1999 and had produced 5% of their yield by 14 Nov. and 95% by 15 Jan. 2000. In the field-treated plants, the earliest to fruit were the 'Autumn Britten', chilled for 5 weeks, where 5% of the fruit were harvested on 2 Mar. 2000 and 95% of the fruit harvested on 8 Apr., while the latest plants were 'Tulameen', chilled for 8 weeks, where 5% of the fruit harvested on 2 Apr. and 95% harvested on 10 May.

Chilling units. The chilling unit models would need to account for the variation in percent lateral development in 'Titan' in Expt. 1, and the chilling stage × time interaction in Expt. 2 where dormancy was considered broken after 6 weeks in the cooler and 5 weeks in the field. Both the Jennings model and the modified model accounted for the variation in Expt. 1, and only the modified model accounted for the variation in Expt. 2, with 504 chilling units after 6 weeks in the cooler and 513 chilling units after 5 weeks in the field (Table 6).

Discussion

These experiments showed that dormancy in raspberries could be broken if plants of 'Autumn Britten', 'Nova', 'Polana', and 'Tulameen' were held at 7 °C for 5 weeks and plants of 'Titan' held for at least 8 weeks. Jennings (1964) broke dormancy when plants were treated at 7.2 °C for 6 weeks, and other research has shown that cultivars do vary in their chilling requirements (Carew et al., 2000b).

Once dormancy was broken, continued chilling enabled the fruit to develop sooner.

Table 5. Mean days to 5% and 95% harvest in four raspberry cultivars chilled at 7 °C at three stages for 4–8 week periods.

Cultivar	Days to 5% harvest ^a				Days to 95% harvest			
	Aug.	Sept.	Field	Mean	Aug.	Sept.	Field	Mean
Autumn Britten	74	81	81	78	110	113	133	119
Polana	65	82	91	79	130	131	167	143
Nova	83	90	92	88	102	114	125	114
Tulameen	113	107	98	106	142	156	147	148
Mean	83	90	91		121	129	143	

^aSignificant levels for cultivar, stage of chilling, and stage of chilling × cultivar for both days to 5% and 95% harvest were $P = 0.0001$.

Table 6. Chilling units for chilling treatments calculated for various models in two experiments to determine dormancy requirements in raspberry.

Experimental conditions		Chilling models				
Temp	Time (wks)	Cumulative hours < 7 °C	Richardson et al., 1974 ^a	Norvell and Moore, 1982 ^b	Jennings (personal comm.) ^c	Modified model ^d
7 °C	6	1008	1008	1008	504	504
	8	1344	1344	1344	672	672
3 °C	6	1008	1008	1008	1008	1008
	8	1344	1344	1344	1344	1344
Field 1999	4	672	700	761	226	371
	5	840	840	941	319	513
	6	1008	885	1045	415	689
	7	1176	893	1133	509	854
	8	1344	890	1325	582	998

^a<1.4 °C = 0; 1.5 to 2.4 °C = 0.5; 2.5 to 9.11 °C = 1; 9.2 to 12.4 °C = 0.5; 12.5 to 15.9 °C = 0; 16 to 18 °C = 0.5; >18 °C = -1.

^bAs for Richardson et al. (1974), except <2.5 °C = 0.5.

^c<3 °C = 0.5; 3.0 to 5.6 °C = 1; 5.7 to 8.0 °C = 0.5; 8.1 to 11 °C = 0; 11.1 to 13 °C = -0.5; >13 °C = -1.

^dAs for Jennings model, except <5.6 °C = 1.

In the second experiment, the number of days to harvest decreased the longer the field plants were chilled. This type of effect has been noted before in raspberry and has been summarized by Carew et al. (2000a), who concluded that chilling removes dormancy and then advances flowering through vernalization.

The responses observed to the various chilling temperatures and durations indicated that

the chilling requirement is more complicated than chilling for a certain time period below a certain temperature. In Expt. 1, the percent lateral development in 'Titan' differed at the two temperatures used, and in Expt. 2 the four cultivars varied in the time required to break dormancy in the August treatment but not when chilled in the field. Chill unit models have been used in other crops to explain

variation in chilling requirements (Carew et al., 2000a; Norvell and Moore, 1982; Richardson et al., 1974). We used the models of Richardson et al. (1974), Norvell and Moore (1982), Jennings (personal communication), and the Jennings's model adapted to put greater emphasis on lower temperatures in an attempt to explain our results. Only the modified model accurately accounted for our variation. Whether this model is the optimum one needs to be verified, but it does tell us that, in raspberry, chilling requirements can be fulfilled at lower temperatures than other crops, such as peach and blueberry.

Dormancy can be broken before flowers are initiated, and this appears to be more easily achieved at higher temperatures. When we chilled the plants of 'Tulameen' and 'Nova' at 7 °C with no light before flower buds had been initiated, we were able to break dormancy without initiating flower buds and the developing lateral branches remained vegetative. In 'Nova', the canes had started to initiate flowers, but the process was incomplete so some lateral branches were floral and some vegetative. We also broke dormancy in juvenile plants of Lauren without initiating flower buds (data unpublished). Williams (1960) induced lateral development without flowers on Malling Promise if juvenile plants with 20 nodes were treated with or without 1 week of 10 °C and 9 h light, followed by 3 weeks of 3.3 °C with no light. Jennings (1964) initiated flowers and broke dormancy with 7 °C and 9 h light. He treated plants that he thought had not started to initiate flowers on 15 Aug 1961, but at the same site Dale and Daubeney (1987) showed that flower initiation had started by 16 Aug. 1982.

Vegetative buds in florican-fruiting cultivars appear to require short days and moderate temperatures to initiate flower buds, at least at some physiological ages. This physiological age requirement can be modified by the climatic conditions before the inductive period. Williams (1960) and Jennings (1964) were able to initiate flowers at 3.3 °C with no light when the canes had at least 30 nodes, but not when the canes were younger. Younger canes required an inductive period of short days and moderate temperatures. In this experiment, mature canes of 'Tulameen' did not initiate flower buds

when treated at 7 °C with no light in August, but the plants were growing in long days and high temperatures immediately before the chilling treatment, higher temperatures than the plants grown by Williams (1960) and Jennings (1964) would have been exposed to before they were treated.

Plants in the greenhouse produced a second crop on the fruiting canes when the lateral branches that had fruited were removed. Since considerable within-cane competition occurs (Dale, 1989), only a fraction of the buds on the canes produce lateral branches. When these branches are removed, the remaining buds can develop lateral branches and, hence, a second harvest. Outside the greenhouse, this does not normally happen as, once fruiting is finished, daylength is decreasing and dormancy is initiated. In the greenhouse, daylength is increasing after fruiting; once the apical dominance of the first set of lateral branches is mechanically removed, the remaining buds are able to develop. However, the total yield of the second harvest was considerably less than the first, so would probably not be harvested commercially.

Canes from the greenhouse-grown plants that were chilled without any pretreatment showed considerable chilling damage, whereas canes that had been grown for a period outside did not. This is a similar experience to that described by Williams (1960), who found that a short period of 10 °C was necessary to harden the plants. Alternately, plants could be hardened outside for a period, where the stresses induced by wind have been shown to harden other species (Salisbury and Ross, 1992). Whether this hardening process would be sufficient to initiate flowering in florican-fruiting cultivars like 'Tulameen' when they were chilled at 7 °C is not known.

These experiments show that raspberries can be manipulated so that fruit can be produced throughout the year. We have shown that plants chilled in mid-September in the Northern Hemisphere can be induced to fruit by the beginning of January. Whether the market demand or the economic potential are present is not known, but further research should allow plants to be manipulated to produce reliably higher yields than those obtained by us in the early part of the year.

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