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Prohexadione-Calcium Inhibits Runner Formation and Enhances Yield of Strawberry

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Abstract

Prohexadione-calcium (ProCa) was evaluated for inhibition of runner formation and plant performance in a modified plasticulture system used for growing strawberries (*Fragaria* × *ananassa* Duch.) in the Northeast using summer planted cold-stored plants. Rates between 62.5 to 189 mg•L^{-1} in multiple applications were evaluated but the rates between 125 and 189 mg•L^{-1} were most effective. ProCa reduced runner formation but initiation of treatments within 3 weeks of planting and 3 sprays applied at 3-week intervals appeared to be necessary for complete runner suppression. The inhibitory effects from an application of ProCa lasted for about 28 days. ProCa decreased petiole growth, runner weight and runner number, but increased root to shoot ratio, the number of branch crowns, the number of inflorescences, and total marketable yield without affecting mean fruit size. The number of fruit harvested early was reduced, peak fruit production was delayed and harvest extended later into the season. The performance of plants treated with ProCa was equal or superior to plants where runners were removed manually during the course of plant growth and development.

The majority of strawberries (*Fragaria*× *ananassa* Duch.) grown in the Northeastern and Midwestern U.S. are grown using the matted row or spaced row system (18). In this system strawberries are planted at wide spacing early in the season. Developing runners and daughter plants fill the allotted space by the end of the summer. While this is a low cost system to start, there are also negative aspects. Weed control is difficult and expensive. The wide row spacing and high ultimate plant density reached make harvesting more difficult and this may result in higher disease and insect pressure. An annual plasticulture system is routinely used in California, Florida and other states in the Southeastern U.S. This system has been modified by earlier planting so that it can be useful in the cooler northern tier of states in the United States (5, 16). Plants are set at a relatively close spacing and the formation of daughter plants is prevented by removing runners. Because of the lateness of the planting weed control is easier and less expensive. Yields tend to be higher, fruit size is larger, harvest is easier and there is less disease pressure. Since planting is done during the summer, the production of runners is favored because of the long days. Consequently, runners must be removed by hand if this system is to be adapted for use in the Northeast and Midwest. Since hand labor is involved to remove runners in this system, it may be prohibitively expensive. This system can be adopted profitably only if runner production can be adequately suppressed. Further, if planting is delayed until later in the summer to avoid prolific runner formation, there is likely to be inadequate plant establishment and crown formation.

The strawberry plant is a shortened stem from which leaves and adventitious roots emerge. Buds located in the axils of the leaves may develop into runners, branch crowns or flower clusters. The organ into which these buds develop into is to a large extent under environmental control (4, 7, 24). Production of runners is favored under the long days of summer and this is reinforced by higher temperatures experienced at this time. Flower formation and the production of branch crowns are favored under short days and cool temperatures.

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Evidence based upon exogenous application and use of biosynthetic inhibitors indicates that gibberellins play a prominent role in determining what structure the axillary buds develop into. Exogenous application of GA results in increased runner production (13, 25, 26). Inhibitors of gibberellin biosynthesis inhibit runner production (1, 2, 8, 14, 15). Gibberellin biosynthesis inhibitors have been used effectively to reduce runner formation. Of the GA inhibitors tested, none is currently registered for use on any small fruit crop. Most are not candidates for registration because they lack efficacy and possess a long half life in the soil, or their use poses environmental concerns.

Prohexadione-calcium (ProCa) is the only remaining gibberellin biosynthesis inhibitor labeled in the U.S. for use on food crops. It is currently registered for use and is commercially sold to control vegetative growth and inhibit fire blight [*Erwinia amylovora* (Burr.) Winslow et al.] in apples, growth control of peanuts and inhibition of lodging in grass grown for seed. Reekie et al. (23) reported that ProCa was useful as a nursery treatment to improve strawberry transplant performance and increase yield. Black (2) reported that ProCa suppressed fall runners of 'Chandler' plug transplants in a cold-climate annual hill production system while increasing fall branch crown formation. Handley et al. (10) reported that ProCa sprays of 200, 400 and 600 mg•L^{-1} on 'Jewel' reduced runner formation and fruit size the following year. Only the 200 mg•L^{-1} rate increased marketable yields. Hytonen et al. (12) showed in 6 experiments over a 5 year period that ProCa at rates of 100 and 200 mg•L^{-1} reduced runner formation in 5 experiments, increased crown branching in 3 experiment which resulted in increased yields of 7 to 53%.

This experiment was initiated with several objectives: (1) to determine if runner formation could be adequately controlled in a plasticulture-type hill system as grown in the Northeast; (2) to evaluate specific effects attributable to ProCa on growth and productivity of strawberries; (3) to determine the ProCa concentration, and optimal number of applications to control runners and improve performance of strawberry cultivars typically grown in the Northeastern U.S.

Materials and Methods

Plot location. All experiments were done on a commercial strawberry farm located in Whately, Mass (42.4'N, 72.6'W). The soil was a Hadley fine sandy loam (pH 6.2). Prior to planting, the land had been in a cover crop of winter rye in the previous year.

Experimental design and plot layout. Dormant bare-root plants were set in double rows with a spacing between rows of 45 cm and the spacing of plants within the row was 24 cm. Double rows were separated into 6-plant plots that were separated by 4-plant buffers. In each experiment there were 6 blocks (replications) and within each block there were eight 6-plant plots. Treatments were randomly assigned within each block. The total plant population was approximately 44,500 plants•ha^{-1} (18,000 plants•ac^{-1}).

'Darselect' 2006. A block of 'Darselect' strawberries planted using cold stored dormant plants on 25 June was selected and used in 2006. On 30 July the first ProCa treatment was applied. The plants in two plots were assigned to receive 62.5 mg•L^{-1} ProCa, another two designated to receive 125 mg•L^{-1} ProCa, the plants in another two plots were designated to have runners removed by hand and the last two plots were untreated and served as the controls. Immediately prior to the first ProCa application 2 runners per plot were tagged and measured in plots designated to receive the two rates of ProCa and also in the untreated control plots. Measurement of tagged runners and counting of runners continued at 3-day intervals for 15 days. Plants that received ProCa initially on 30 July were treated again on 18 August and 6 September. Runners were removed on plants in plots designated to have runner removed on 18 August, 13 September and 27 October.

'Jewel' 2007. A block of 'Jewel' strawber-

ries was selected for use in 2007. Cold stored dormant plants were set on 1 July and the first ProCa sprays were applied on 1 August. ProCa at 125 mg•L^{-1} and 189 mg•L^{-1} was applied to different pairs of plots as described previously. Similar ProCa applications were made on the ProCa plots on 22 August. A third application of ProCa was made on 16 September with 1/3 of the earlier ProCa rate applied. At this time plants previously sprayed with 125 mg•L^{-1} and 189 mg•L^{-1} were sprayed with 42 mg•L^{-1}and 63 mg•L^{-1}, respectively. Runners were removed on the designated plots on 22 August, 19 September and 27 October. Two plots were untreated and served as the controls. The number of runners on each plant was recorded weekly from 8 August to 27 October.

'Jewel' 2008. Plants used in this experiment were set on 1 July. Since runners had started to emerge at the time of the first ProCa application, an earlier initial application was decided upon. On July 18 it was judged that leaf area had developed and expanded to the extent that sufficient ProCa would be absorbed. Two rates of ProCa, 83 and 166 mg•L^{-1} were used. Each rate of ProCa was applied once, twice or three times to different plots at 3 week intervals. There were 2 untreated plots that served as the controls for the 2 rates of ProCa.

Destructive harvest. In 2007 and 2008 one of the duplicate plots of each treatment was harvested at the end of October. After carefully digging up the plants in a plot, soil was washed from the roots, and then plants were allowed to drip dry. Runners were removed from each plant and the total number per plot was recorded. The length of the runner to the first daughter plant was measured on 30 randomly selected runners per plot. Six leaves were removed from each plant and the petiole length of each was measured from the attachment at the crown to the leaf blade. The remaining leaves were removed from the plants and then all leaves were counted and recorded. The length of the root system was measured. The number of branch crowns was recorded. Fresh weights were taken on leaves, roots and crowns and then they were place in a drying oven set at 50° C and dried to a constant weight. The fresh weight of all plant material removed from each plot was determined by adding the weight of all plant components, including runners and daughter plants.

Harvest of fruit. Harvest started when the first fruit colored enough to be harvested commercially. Harvest was discontinued when fruit size dropped below a commercially acceptable level (mean fruit size below 8 g). Fruit was harvested twice a week. All fruit from each plot were harvested and separated into marketable and unmarketable fruit categories. The number of fruit in each category was counted and the marketable fruit were weighed. Unmarketable fruit were not weighed since some were damaged by birds or growth was affected by *Botrytis* infection. Fruit were harvested in 2007 from 11 June to 13 July and in 2008 the harvest season was 17 June to 11 July.

ProCa application. ProCa was applied in a dilute application using a hand pump sprayer as the proprietary product Apogee (BASF, Corporation, Research Triangle Park, NC). In addition to the appropriate amount of ProCa placed in the tank, Quest water conditioner, a proprietary water conditioner blend of ammonium salts of polyacrylic, hydroxycarboxylic and phosphoric acid (Helena Chemical Co., Colliersville, Tenn.) was added at a rate of 5 ml•L^{-1} and Regulaid surfactant (Kalo Inc., Overland Park, Kan.) was added to make a final surfactant concentration of 0.1%.

Runner removal. Runner removal was one of the treatments used in 2006 and 2007. All runners were removed and counted from these plants at 3 times after planting. All runners were removed from all plants at the end of the season in late October and counted.

Flower truss removal. All infloresences were removed from all plants at the time of the first ProCa application. After that, flowers were removed weekly as they emerged.

Counting of runners. Runners were counted at the time of the initial ProCa application and then weekly until the end of October in 2007 and 2008. A stolon was counted as a runner when it had grown to a length of 3 cm or more.

Counting flowering trusses. The year following treatment all flowering trusses were counted in each plot when fruit were just starting to enlarge.

Statistical analysis. The experiments were set up using a randomized complete block design. Statistical analysis was done using analysis of variance (SAS, Cary, NC) to determine effects of treatments. Regression analysis was done to determine the effect of ProCa concentration or number of applications.

Results

'Darselect' 2006. At the time of the initial ProCa application on 1 August runner production had just started with an average of 0.5 runners per plant that had emerged (Fig. 1). In subsequent days runner production on untreated control plants continued, but on ProCa treated plants emergence of runners was slowed but not stopped. This reduction in runner production by ProCa was significant beginning 6 days after the initial application. At the end of October differences in runner production between control and ProCa treated plants persisted (Table 1). Total runners produced on plants where runners were removed manually was significantly higher than on control and ProCa treated plants. Growth of runners treated with ProCa was significantly reduced within 3 days of application and complete growth suppression occurred within 9 to 12 days after application (Fig. 2).

Treatment effects on plant growth and development were documented on harvested plants at the end of October. ProCa at 125 mg•L^{-1} caused an increase in the number of branch crowns; whereas, there were no differences among the other treatments (Table 1). The length of roots was comparable among treatments. The number of leaves per plant was increased by ProCa 125 mg•L^{-1} compared with the control. Runner length and petiole length of plants treated with ProCa were significantly reduced. Plant components were separated into runners, crowns,

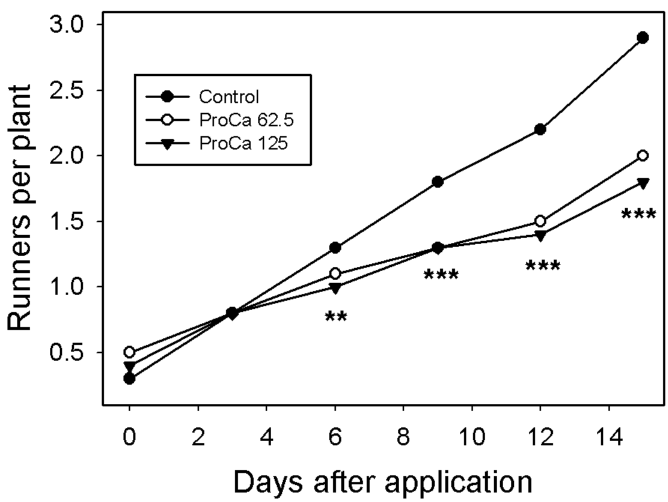

Fig. 1. The emergence of runners for the 15 days immediately following ProCa application on 'Darselect' strawberries. Treatments significantly different at P=0.01 (**) or P=0.001 (***).

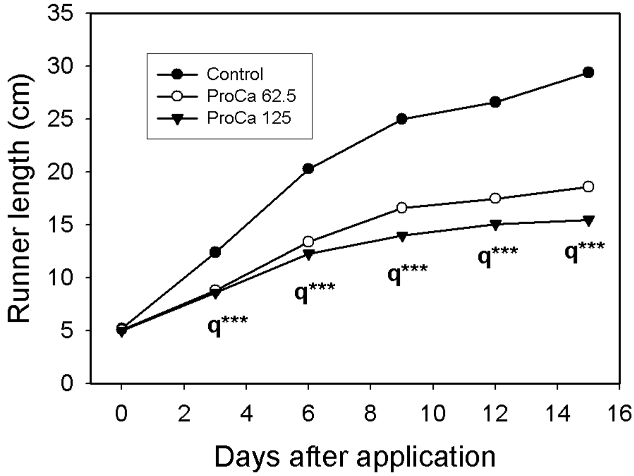

Fig. 2. Growth of individually tagged runners for the 15 days immediately following ProCa application on 'Darselect' strawberries. The response to ProCa concentration was quadratic and significant at P=0.001 (q***).

Table 1. Effect of prohexadione-calcium (ProCa) application on growth characteristics of 'Darselect' strawberries in 2006.

Treatment[z]	Runners per plant (no)	Crowns per plant[x, w] (no)	Root length (cm)	Leaves per plant (no)	Runner length (cm)	Petiole length (cm)
Control	9.8 b	2.3 b	23.0 a	20.2 b	44.9 a	17.7 a
ProCa 62.5 mg•L^{-1}	7.1 c	2.6 b	24.7 a	21.7 ab	11.0 c	11.7 c
ProCa 125 mg•L^{-1}	5.8 c	4.0 a	22.9 a	25.3 a	7.4 d	8.9 d
Runner removal[y]	14.5 a	2.6 b	23.3 a	23.4 ab	34.8 b	16.2 b
Significance						
Treatment	***	***	NS	*	***	***
ProCa	***	***	NS	**	***	***
Linear	***	***	NS	***	***	***
Quadratic	NS	**	NS	NS	***	**

[z] Treatments applied 30 July, 18 August, and 6 September. Strawberries planted 25 June, 2006.
[y] Runners were removed 18 August, 13 September, and 28 October.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS,*,**,***Non-significant or significant at P = 0.05, 0.01, or 0.001, respectively.

roots and leaves and fresh and dry weights were taken (Table 2). ProCa plants treated with 125 mg•L^{-1} increased crown weight and reduced runner weight and leaf weight relative to control plants. Crown and leaf weight were increased on plants where runners were removed by hand relative to the control plants.

ProCa treatment in 2006 increased the number of flower trusses, total number of marketable fruit, total number of marketable and unmarketable fruit and total weight of marketable fruit in 2007 (Table 3). Flowering and yield on plants treated with ProCa 125 mg•L^{-1} and plants where runners were removed was comparable except that there were more marketable fruit on plants receiving ProCa 125 mg•L^{-1}. The time of ripening was altered by ProCa. Significantly more fruit were harvested from the control plants and those where runners were removed during the first week of harvest (Table 4). Conversely, yield of marketable fruit on ProCa treated plants was greater at the end of the harvest period.

'Jewel' 2007. At the time of the first application of ProCa, runner production was just starting (Fig. 3). On control and runner removal plants the production of runners proceeded at an average rate of 1.5 runners per plant per week. Measurable reduction of runner production was noted 1 wk after initial

Table 2. Effect of prohexadione-calcium (ProCa) application on fresh weight and dry weight of 'Darselect' strawberries in 2006.

Treatment[z]	Runner total[x, w] FW (g)	Crowns per plant FW (g)	Crowns per plant DW (g)	Roots per plant FW (g)	Roots per plant DW (g)	Leaves per plant FW (g)	Leaves per plant DW (g)
Control	280.8 a	17.9 c	5.0 c	10.7 b	3.3 b	106.0 b	27.4 b
ProCa 62.5 mg•L^{-1}	209.3 b	20.4 bc	5.4 bc	13.8 a	3.5 ab	91.4 bc	23.4 bc
ProCa 125 mg•L^{-1}	142.7 c	23.1 ab	6.1 b	14.8 a	3.5 ab	81.0 c	20.9 c
Runner removal[y]	36.3 d	25.3 a	6.8 a	13.8 a	4.1 a	145.3 a	39.9 a
Significance							
Treatment	***	***	***	*	NS	***	***
ProCa	***	***	**	**	NS	*	**
Linear	***	***	***	**	NS	**	**
Quadratic	NS	NS	NS	NS	NS	NS	NS

[z] Treatments applied 30 July, 18 August, and 6 September. Strawberries planted 25 June, 2006.
[y] Runners were removed 18 August, 13 September and 28 October.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS,*,**,***Non-significant or significant at P = 0.05, 0.01, or 0.001, respectively.

Table 3. Effect of prohexadione-calcium (ProCa) application in 2006 on yield and fruit size of 'Darselect' strawberries in 2007.

Treatment[z]	Flower trusses[x, w] (no/plant)	Total yield marketable fruit (no/plant)	Mean fruit weight marketable fruit (g/fruit)	Total yield marketable & unmarketable fruit (no/plant)	Total yield marketable fruit (g/plant)
Control	4.3 b	25.8 c	18.5 a	28.4 c	476 c
ProCa 62.5 mg•L^{-1}	5.1 b	33.6 b	17.8 ab	36.2 b	592 b
ProCa 125 mg•L^{-1}	7.4 a	40.9 a	16.8 b	44.4 a	683 a
Runner removal (3x)[y]	6.7 a	35.2 b	17.5 b	40.0 ab	615 ab
Significance	***	***	**	***	***
ProCa	***	***	*	***	***
Linear	***	***	**	***	***
Quadratic	NS	NS	NS	NS	NS

[z] ProCa treatments applied 30 July, 18 August and 6 September, 2006.
[y] Runners were removed 18 August, 13 September, and 27 October 2006.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS,*,**,***Non-significant or significant at P = 0.05, 0.01, or 0.001, respectively.

Table 4. Effect of prohexadione-calcium (ProCa) application in 2006 on the cumulative yield (weight) of marketable 'Darselect' strawberries in 2007.

	Weight of marketable fruit/plant (g)									
	June						July			
Treatment[z]	12[x, w]	15	19	22	26	29	3	6	10	13
Control	13 a	39 a	102 a	186 ab	259 b	320 b	371 b	402 b	459 c	476 c
ProCa 62.5 mg•L^{-1}	1 b	6 b	57 b	156 b	267 b	365 ab	446 ab	497 a	562 b	592 b
ProCa 125 mg•L^{-1}	0 b	3 b	64 b	151 b	280 ab	385 ab	495 a	561 a	649 a	683 a
Runner Removal[y]	8 a	29 a	112 a	212 a	323 a	408 a	489 a	545 a	597 ab	615 ab
Significance	***	***	***	***	NS	NS	**	**	***	***
ProCa	**	***	*	NS	NS	NS	*	**	***	***
Linear	***	***	**	NS	NS	NS	**	***	***	***
Quadratic	*	*	NS	NS	NS	NS	NS	NS	NS	NS

[z] ProCa treatments applied 30 July, 18 August and 6 September, 2006.
[y] Runners removed 18 August, 13 September and 27 October, 2006.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS,*,**,***Non-significant or significant at P = 0.05, 0.01, or 0.001, respectively.

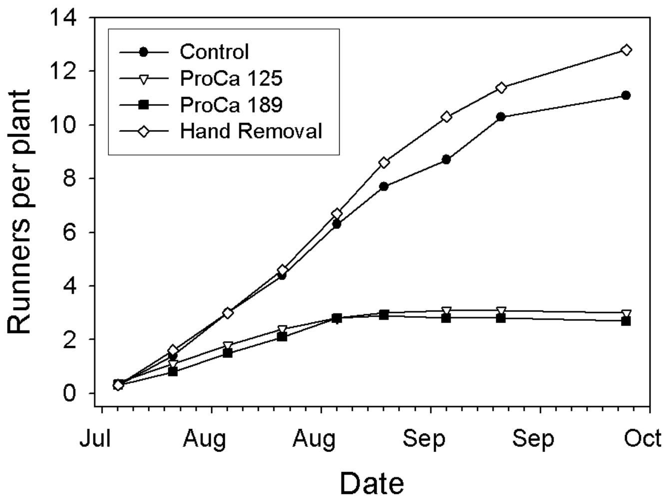

Fig. 3. Runner emergence in 'Jewel' strawberries as a result of 3 ProCa applications made at 3 week intervals and hand removal of runners at 3 timings. Differences in runner production between ProCa-treated plants and the control was significant at P=001 starting on 8 August and differences between runner removal and control were significant starting on 4 September.

application and a significant reduction documented 2 wks after initial application. Runner production on treated plants proceeded at a much reduced rate for an additional 2 wks. From 4 wks after the initial application to early October no additional runners were produced on ProCa-treated plants. There were no differences between rates of ProCa. Removal of runners during the season resulted in more runners being produced than on the control plants and this response was statistically significant starting on 4 September.

ProCa significantly increased the number of branch crowns on each plant to the level comparable to the runner removal treatments (Table 5). The average number of runners on ProCa treated plants was comparable for both concentrations used and considerably less than on the control plants. Fewer runners on the runner removal treatment were the result of runner removal earlier in October. ProCa reduced runner length and petiole length but increased the number of leaves per plant. No treatment affected root length. ProCa reduced the total fresh weight of runners (Table 6). Fresh and dry weight of crowns was comparable for ProCa treated plants and runner removal and these were all greater than the control plants. Fresh and dry weight of leaves was similar for control plants and those treated with ProCa but these were less than the runner removal treated plants.

Table 5. Effect of prohexadione-calcium (ProCa) application on growth characteristics of 'Jewel' strawberries in 2007.

Treatment[z]	Runners per plant (no)	Crowns per plant[x, w] (no)	Root length (cm)	Leaves per plant (no)	Runner length (cm)	Petiole length (cm)
Control	11.6 a	2.2 b	34.1 a	23.4 c	35.0 a	14.2 a
ProCa 125, 125, 42 mg•L^{-1}	3.2 b	7.2 a	32.6 a	47.4 a	7.8 c	8.9 c
ProCa 189, 189, 63 mg•L^{-1}	3.3 b	7.6 a	30.8 a	46.5 a	6.9 c	8.5 c
Runner removal[y]	1.4 c	7.6 a	33.1 a	36.8 b	26.7 b	12.7 b
Significance						
Treatment	***	***	NS	***	***	***
ProCa	***	***	NS	***	***	***
Linear	***	***	NS	***	***	***
Quadratic	***	***	NS	***	***	***

[z] ProCa treatments applied 1 August, 22 August and 16 September, 2007. Strawberries were planted 25 June, 2007.
[y] Runners were removed 22 August, 19 September and 27 October.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS,*,**,***Non-significant or significant at P = 0.05, or 0.001, respectively.

Table 6. Effect of pprohexadione-calcium (ProCa) application on fresh weight and dry weight of 'Jewel' strawberries in 2007.

	Runner total[x, w]	Crowns per plant		Roots per plant		Leaves per plant	
Treatment[z]	FW (g)	FW (g)	DW (g)	FW (g)	DW (g)	FW (g)	DW (g)
Control	438.8 a	22.3 b	5.8 b	26.8 b	5.6 a	109.5 b	27.9 b
ProCa 125, 125, 42 mg•L^{-1}	132.8 b	38.8 a	9.7 a	36.7 a	6.1 a	120.8 b	29.2 b
ProCa 189, 189, 63 mg•L^{-1}	120.8 b	38.3 a	9.2 a	35.7 a	5.8 a	115.8 b	28.4 b
Runner removaly	27.6 c	41.6 a	9.5 a	35.7 a	6.8 a	168.9 a	45.4 a
Significance							
Treatment	***	***	***	*	NS	***	***
ProCa	***	***	***	***	NS	NS	NS
Linear	***	***	***	***	NS	NS	NS
Quadratic	***	***	***	***	NS	NS	NS

[z] ProCa treatments applied 1 August, 22 August and 16 September, 2007. Strawberries were planted 25 June, 2007.
[y] Runners were removed 22 August, 19 September and 27 October.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS,*,**,***Non-significant or significant at P = 0.05, or 0.001, respectively.

Table 7. Effect of Prohexadione-calcium (ProCa) application in 2007 on yield and fruit size of 'Jewel' strawberries in 2008.

Treatment[z] (mg•L^{-1})	Flower trusses[x,w] (no/plant)	Total yield marketable fruit (no/plant)	Mean fruit weight marketable fruit (g/fruit)	Total yield marketable & unmarketable fruit (no plant)	Total yield marketable fruit (g/plant)
Control 0	7.3 c	54.4 c	11.3 c	61.6 c	663.0 b
ProCa 125	24.4 a	84.6 a	13.3 a	116.4 a	919.4 a
ProCa 189	22.1 a	84.2 a	13.1 ab	111.6 a	917.6 a
Runner removal (3x)[y]	14.6 b	67.9 b	12.1 b	93.6 b	750.3 b
Significance	***	***	***	***	***
ProCa	***	***	**	***	***
Linear	***	***	**	***	***
Quadratic	***	**	**	***	**

[z] ProCa treatments applied as a dilute spray on 1 August, 22 August and 16 September, 2007.
[y] Runners removed 22 August, 19 September and 27 October, 2007.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS, *, **, *** Non-significant or significant at P = 0.05, 0.01, or 0.001, respectively.

Table 8. Effect of prohexadione-calcium (ProCa) application in 2007 on the number of marketable fruit of 'Jewel' strawberries harvested at individual harvests in 2008.

Treatment[z]	Marketable fruit harvested (number/plant)[x, w]							
(mg·L^{-1})	June					July		
	17	20	23	27	30	3	7	11
Control 0	4.8 a	6.2 a	7.2 a	7.8 c	8.5 b	7.1 b	9.1 c	3.7 b
ProCa 125	0.0 c	2.7 b	5.4 a	10.9 a	14.7 a	16.6 a	21.0 a	13.4 a
ProCa 189	0.3 c	3.1 b	7.0 a	11.5 a	15.9 a	16.2 a	20.3 a	10.1 a
Runner removal (3x)[y]	2.4 b	5.1 a	5.1 a	9.2 b	12.8 ab	13.2 a	13.8 b	6.3 b
Significance	***	***	NS	***	*	***	***	***
ProCa	***	***	NS	***	*	***	***	***
Linear	***	***	NS	***	**	***	***	**
Quadratic	**	**	NS	*	NS	*	**	***

[z] ProCa treatments applied as a dilute spray on 1 August, 22 August and 16 September, 2007.
[y] Runners removed 22 August, 19 September and 27 October, 2007.
[x] Mean separation within columns by Duncan's multiple range test, P = 0.05.
[w] NS, *, **, *** Non-significant or significant at P = 0.05, 0.01, or 0.001, respectively.

ProCa increased the number of flower trusses on each plant and the number of flower trusses on ProCa treated plants was about 3 times as many as those on the untreated control (Table 7). There were approximately 50% more flower trusses on ProCa treated plants than the plants where periodic hand removal of runners was practiced. ProCa increased the number of marketable fruit, the number of marketable and unmarketable fruit and the weight of marketable fruit. Mean fruit size over the season was higher on the ProCa treated plants and those where runners were removed than on control plants. Fewer fruit were harvested on ProCa treated plants early in the season (Table 8). The delay in fruit ripening appeared to be about 6 days. More fruit were harvested from the ProCa treated plants on the last 2 harvests, providing further evidence that ProCa does delay ripening.

'Jewel' 2008. The first runners emerged about 5 wks after the dormant bare root plants were set and 18 days after the first ProCa spray. Runners started to emerge on plants treated once with either 83 or 166 mg•L^{-1} ProCa between 14 and 22 August, and 22 and 28 August, respectively (Figure 4 A and B). Runners on plants treated twice with either rate of ProCa started to grow between 4 and 11 September, about a month after the last application. The dominant factor ultimately controlling runner production appears to be the number of ProCa applications (Table 9). The concentration effect on number of runners produced was not significant but the interaction between concentration and number applications was. It appears that ProCa concentration is not important when only one application is made since runner growth per plant is comparable. However, if 2 or 3 applications are made, the higher rate of ProCa is more effective at inhibiting runner emergence. Once the inhibitory effects of ProCa wore off, rapid growth of runners was recorded. Mean runner length on plants treated twice with either the 83 or 166 mg•L^{-1} rate was 41.0 and 20.3 cm, respectively. Plants receiving 3 application of ProCa at the 83 mg•L^{-1} rate had runner length of 3.7 cm, which is considered very short. Plants receiving 3 applications of ProCa at 166 mg•L^{-1} had no runners thus there were no runners to measure. Application of ProCa in 2008 increased the number of flowering trusses in 2009. The number of applications was highly significant but the concentrations appeared to be far less important since the concentration effect was significant only at the P=0.08 percent level.

Discussion

One of our objectives in this investigation was to reduce or eliminate runner production in strawberries with the use of ProCa. Runner production was reduced on 'Darselect' in 2006 and on 'Jewel' in 2007 by 28 to 41% and 73 to 74%, respectively. In the experiment conducted in 2008 on 'Jewel', runner productions was suppressed by 6 to 100% depending upon the concentration of ProCa applied and the number applications made. Three applications made at 3 week intervals were required for maximum runner suppression and these repeat applications were more

Table 9. Effect of time of prohexadione-calcium (ProCa) application on the number of runners, length of runner and daughter plants per runner in 2008.

Treatment[z]	Concentration (mg·L^{-1})	Number of applications	Runners per plant[y]	Runner length (cm)	Daughters per plant	2009 Flower trusses per plant
Control	---	0	5.1	79.3	2.0	2.3
ProCa	83	1	4.4	70.7	1.9	3.0
ProCa	83	2	2.0	41.0	1.5	4.1
ProCa	83	3	0.6	3.7	1.0	4.8
Control	---	0	5.1	73.6	1.9	3.0
ProCa	166	1	4.8	61.2	1.8	4.6
ProCa	166	2	0.6	20.3	1.2	5.1
ProCa	166	3	0.0	0.0	0.0	
Significance						
ProCa Concentration			NS	**	**	NS (0.08)
ProCa Number of Applications			***	***	***	***
Conc. x Number of Applications			**	**	**	NS

[z] ProCa treatments applied on 18 July, 8 August, and 28 August.
[y] NS, **, ***Non-significant or significant at P = 0.01 or 0.001, respectively.

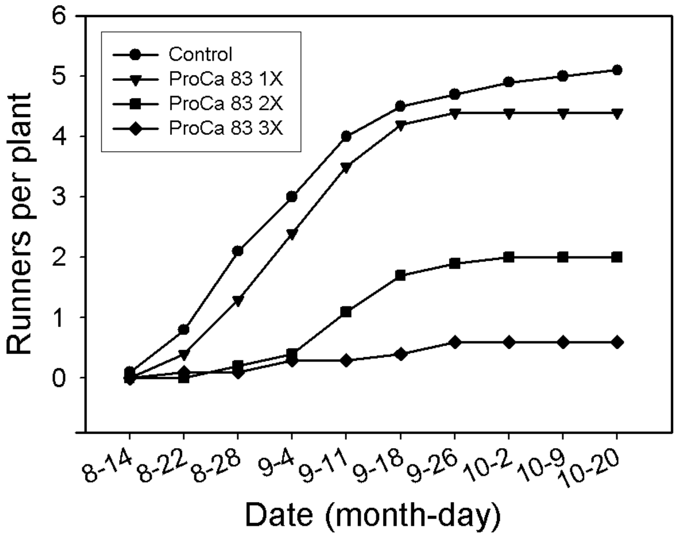

Fig. 4A. Runner emergence in 'Jewel' strawberry as a result of ProCa applications of one to three times. Applications were made initially on 18 July, and where appropriate, were again applied on 7 August and 28 August. Significant differences between the control and ProCa 1x persisted from 22 August and differences between ProCa 2x and 3x applications became significant on 11 September.

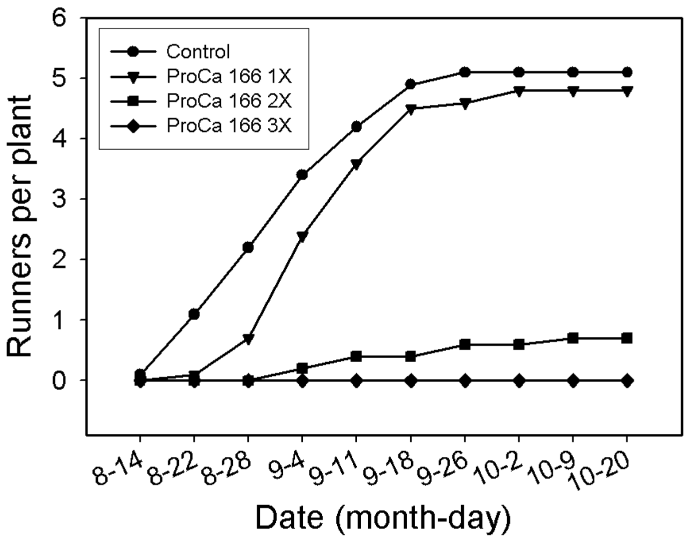

Fig. 4B. Runner emergence in 'Jewel' strawberry as a result of ProCa applications of one to three times. Applications were made initially on 18 July, and where appropriate, were again applied on 7 August and 28 August. Significant differences between the control and ProCa 1x occurred on 28 August and between ProCa 2x and 3x on 11 September and these differences persisted to the end of the season.

important than the concentration of ProCa applied. While Hytonen et al. (12) reported runner reduction with just one application, Black (2), Handley et al. (10), Reekie and Hicklenton (20), and Reekie et al., (22) reported the greatest reduction in runner formation occurred following 3 applications of ProCa.

The time interval between planting and the initial ProCa application appears to play a significant role in effective runner control, although this variable was not tested in this investigation. In 2006 runners were emerging at the time of initial application, which was about 5 wks after planting. The initial application in 2007 was approximately the same time after planting but the first runners did not develop until after application. In 2008 the initial application was made 18 days after planting and the first runners did not appear until nearly 3 weeks later. Runner emergence after application was recorded in 2006 and it showed that after application there was inertia in runner emergence that required at least 15 days to essentially stop runner formation. In 2008 when ProCa was applied on 'Jewel' at least 15 days before emergence of the first runners, it was possible to completely suppress runner formation.

Visually, the runner reduction on ProCa treated plants was much more impressive than the actual numbers may indicate. A runner was defined as a stolon that was 3 cm long or longer. The average length of ProCa treated runners was considerably shorter than the untreated control plants. For example, plants receiving 125 mg•L^{-1} ProCa in 2006 and 2007 had average runner lengths of 8.9 cm and 7.8 cm, respectively. Frequently, at the end of the season it was difficult to differentiate between a large daughter plant located at the end of a very short runner and a large branch crown on the mother plant.

A positive relationship exists between the number of branch crowns, flower trusses and total yield per plant while a negative relationship exists between the number of runners per plant and the above-mentioned parameters. It appears that ProCa, by inhibiting runner formation, is increasing the number of potential buds that develop into inflorescences and branch crowns. In both 'Darselect' and 'Jewel', ProCa increased linearly the number of inflorescences and branch crowns and total yield.

The rates of ProCa reported to control runner formation fall within a range from 60 mg•L^{-1} to 600 mg•L^{-1} (2, 10, 12, 20). In this investigation, 62.5 mg•L^{-1} on 'Darselect' did reduce the number of runners and increase yield relative to the control, but higher rates were more effective. Reekie and Hicklenton (20) applied ProCa at rates of 62.5, 125 and 250 mg•L^{-1} and reported that the number of application was more important than the ProCa concentration, which is similar to our findings for 'Jewel' in 2008. Black (2) concluded that 60 mg•L^{-1} was too low and suggested that repeat applications of 240 mg•L^{-1} may be most appropriate for runner suppression. Handley et al. (10) reported that rates above 200 mg•L^{-1} resulted in no increase in marketable yield and concluded that 200 mg•L^{-1} or less may provide an effective means of reducing runner production. While rates of 100 and 200 mg•L^{-1} reduced runner formation and increased crown branching, the 200 mg•L^{-1} rate most consistently increased the number of inflorescences and yield (9, 12).

There is a concern that treatments or conditions that result in the formation of too many branch crowns may lead to reduced fruit size (17). The system used in this investigation, including the use of cold stored plants, plant spacing and planting time near 1 July, was intended to optimize, by the end of the growing season, plant size and branch crown formation while reducing as much as possible runner formation. Plants treated in 2006 with 125 mg•L^{-1} ProCa produced 4.0 crowns per plant and plants treated with 125 and 189 mg•L^{-1} ProCa in 2007, produced 7.2 to 7.6 crowns per plant, respectively. On plants treated in 2006 and harvested in 2007 fruit weight was reduced slightly compared with the control but not when compared with the plants where runners were removed manually. On plants treated with ProCa in 2007 and harvested in 2008, the size of fruit harvested from plants receiving both rates of ProCa was higher than fruit harvested from the control plants and comparable to plants where runners were removed by hand. We conclude that a reduction in fruit size will not occur if ProCa applications are made in the range of 125 to 189 mg•L^{-1} to reduce runner formation.

ProCa is a gibberellin biosynthesis inhibitor that blocks the conversion of GA_{20} to GA_1 (19). Hytonen (11) reported with the strawberry cultivar 'Korona' nearly a 50% reduction in GA_1 and a corresponding buildup of GA_{19} and GA_{20} in plants within 2 days of ProCa application. Therefore, the reduction in runner growth recorded 3 days after ProCa application in this investigation can be explained by the rather rapid reduction in GA_1 levels. The length of time ProCa remains in the strawberry plant is less clear and the effective period of time is undoubtedly influenced by temperature, day length and growth potential and the physiological response being monitored. In this investigation one application of ProCa on 18 July was sufficient to inhibit runner emergence to 14 August (27 days) with 88 mg•L^{-1} and to 22 August (35 days) with the 166 mg•L^{-1}. A second application of ProC was made on 7 August and runner control was maintained for both ProCa rates for about another 28 days. Reekie and Hicklenton (20) reported that the inhibition of petiole growth was lost about 3 wks after application. Black (2) successfully controlled runner production with multiple applications made at 3-wk intervals and in this investigation no lapses in runner control were observed when 3 treatments were applied at 3 week intervals. We conclude that applications made at 3 week intervals are sufficient to maintain and reinforce inhibition of GA biosynthesis.

ProCa delayed the time of ripening. More strawberries were harvested from control plots for the first 7 days in 2007 and for 6 days in 2008. Hytonen et al. (12) reported that the time of flowers opening was concentration dependent with 100 mg•L^{-1} ProCa having no effect and the first flowers opening on plants treated with 200 mg•L^{-1} being delayed by about 7 days. Reekie et al. (21) reported early fruit production on strawberry plants treated with ProCa in Nova Scotia and then planted in an annual hill system in Florida. Therefore, it appears that the influence of ProCa on the time of ripening is complex and is influenced by ProCa concentration, environmental conditions and the system being used.

The influences of ProCa on plant development and morphology were large and consistent with those reported for mother plants by Black (2) and Hytonen et al. (12), and for daughter plants by Reekie and Hicklenton (20), and Reekie et al. (21, 22). ProCa increased the number of branch crowns per plant (2, 9,12) root fresh weight and root to shoot ratio (22). ProCa reduced petiole length (12, 21, 22), runner length (22), and the number of daughter plants per runner (22).

Growth control in apple is accomplished using multiple ProCa applications (6). The first application is always made at the highest rate and subsequent applications use lower rates. This was done because there is a higher propensity in apple to grow early rather than later in the season. In many respects the situation with strawberry may be analogous. The long days and higher temperatures favor runner production. As temperatures cool and day length shortens, natural runner production slows. In 2007 the third application of ProCa was made at 1/3 the rate used in the previous sprays (42 and 63 mg•L^{-1}) with no resultant loss in runner suppression. Future investigations with ProCa on strawberries may explore the feasibility of using tiered rates over time to control runner emergence. Perhaps, under these environmental conditions less GA is produced, thus requiring less ProCa.

Results reported in this investigation confirm that an annual hill type hill system is a very viable system to grow strawberries in the Northeast of the United States and perhaps other places that have a similar climate provided that runners can be economically managed. A typical strawberry grower using the plasticulture system in North Carolina plants at a density of 44,500 plants•ha^{-1} (18,000 plants•ac^{-1}) and typical yields are 19,054 to 20,174 kg•ha^{-1} (17,000 to 18,000 lb•ac^{-1}) (17). In this investigation plants were set at approximately 44,500 plants•ha^{-1} (18,000 plants•ac^{-1}). Yield in 2007 on plants treated with 125 mg•L^{-1} ProCa was 33,800 kg•ha^{-1} (30,000 lb•ac^{-1}) and in 2008 yields were 40,500 kg•ha^{-1} (36,000 lb•ac^{-1}), thus confirming the productivity of this system in the Northeast. The ability to control runners, increase branch crown number, inflorescence number and final total yield without reducing average fruit size makes ProCa a very viable tool/method to grow strawberries in the Northeastern U.S.

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