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Managing Cone Formation and Leader Growth in Fraser Fir Christmas Tree Plantations with Plant Growth Regulators

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Abstract: Early cone formation is a consistent issue in Fraser fir Christmas tree plantations in the eastern United States. Growers must remove cones by hand, resulting in significant labor costs, as cones degrade the aesthetic value of Christmas trees. In this study, we conducted two series of experiments in collaboration with several Christmas tree farms to determine the effectiveness of applying plant growth regulators (PGRs), specifically GA-inhibitors, in reducing cone formation and shoot growth in Fraser fir. In the first experiments we investigated the effectiveness of paclobutrazol, applied as a soil injection or as a foliar spray in reducing cone formation. The highest rate of soil application (300 mL of paclobutrazol per tree) reduced cumulative coning by approximately 38%. Leader growth control of soil applied paclobutrazol increased with application rate. In the second set of experiments, we compared four GA-inhibitors (paclobutrazol, chlormequat chloride, uniconazole-p, daminozide) applied as foliar sprays on coning and leader growth. Overall, paclobutrazol was the most effective compound for reducing coning and shoot growth. The results confirm earlier findings that application of GA-inhibitors can reduce, but not eliminate, coning. Likewise, PGR application can reduce shoot growth and possibly increase tree density but will not eliminate the need for shearing.

Keywords: *Abies fraseri*; precocious coning; paclobutrazol; chlormequat chloride; uniconazole-p; daminozide

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1. Introduction

Early cone production of Fraser fir (*Abies fraseri* (Pursh) Poir.) trees is a major concern for Christmas tree growers in the eastern United States. Individual plantation-grown Fraser fir trees can produce hundreds of cones, and growers have reported over 1000 cones on large trees. Fir cones disintegrate in the fall leaving unsightly cone stalks that reduce the salability of trees (Figure 1). Moreover, developing cones compete for photosynthate reserves and reduce shoot and needle growth if they are not removed [1]. Presently, Christmas tree growers remove cones using picking crews, which has become a major labor expense. In plantations with large trees, pickers use ladders, which creates potential worker safety concerns. Ironically, in native stands Fraser fir trees do not produce cones until trees are 15 years old and usually produce infrequent cone crops [2].

Reproductive development in conifers is controlled by a series of factors including environmental conditions, particularly temperature and tree water stress, and genetic predisposition [3]. Both environmental and genetic control of cone formation are mediated through hormonal signaling within trees [4]. In particular, gibberellic acid (GA) levels are a primary driver of coning in conifers and seed orchard managers often apply GA to induce coning [5,6]. For example, trunk-injection of GA4/7 combined with fertilizer, girdling, and tenting resulted in a 30-fold increase in cone production in Pacific silver fir (*Abies amabilis*

[Douglas ex Loudon] Douglas ex Forbes) [7]. Likewise, endogenous GAs accumulate at the meristem from neighboring tissues immediately prior to strobilus initiation and regulate development of reproductive structures [8]. Based on the stimulatory effect of GA on coning, we hypothesized that application of GA inhibitors to Fraser fir trees may reduce coning. GA inhibitors are used as plant growth regulators (PGRs) to control shoot growth in a range of horticultural applications [9]. In a previous trial in our laboratory, application of paclobutrazol, a GA-inhibitor, reduced coning density (number of cones per tree) by 33% to 54% [10]. Our earlier study focused on application of GA inhibitors on trees that were reproductively mature and had produced cones in previous years. In the current project, we expand this work to include younger trees that are entering reproductive maturity in order to determine if application of GA-inhibitors can delay reproductive onset and further inhibit cone formation. We conducted two sets of experiments in cooperation with operational Christmas tree farms in Michigan. In the first set of experiments, we evaluated the effect of three rates of soil-applied paclobutrazol and a foliar application of paclobutrazol on coning in Fraser fir. In the second set of trials, we evaluated the coning response of Fraser fir trees to several GA-inhibitors applied as foliar sprays. In both sets of trials, we also evaluated leader growth response as reduced shoot growth associated with PGR application could provide an additional benefit to growers by producing denser trees and reducing the need for shearing.

Figure 1. Fraser fir trees produce cones that disintegrate in the fall, leaving unsightly stalks on the tree.

2. Materials and Methods

2.1. Paclobutrazol Trials

We initiated two series of field trials, one series beginning in 2016 and one series beginning in 2017 to investigate the effect of paclobutrazol on coning in Fraser fir. We installed field plots at cooperating farms at four locations in Michigan: Allegan, MI, USA, (Badger Evergreen Nursery); Sidney, MI, USA, (Korson's Tree Farms); Horton, MI, USA, (Gwinn's Christmas Tree Farm); and Manton, MI, USA, (Dutchman Tree Farms). All cooperating farms are commercial Christmas tree farms that produce trees for wholesale and/or retail markets. Trees at all farms were grown on approximately 1.6 m × 1.6 m spacing. All plots were located in operational plantations and growers maintained their standard cultural practices (i.e., weed control, fertilization, shearing), which are typical for Christmas tree farms in the region. Soil characteristics of each site and initial tree data are presented in Table S1.

At each farm we applied paclobutrazol (Cambistat®; Rainbow Ecoscience, Minnetonka, MN, USA) at three rates (100, 200, or 300 mL of ready-to-use product per tree) using a soil injection system (Figure 2). Ready-to-use product was prepared from concentrated product using an 11:1 dilution (*v*:*v*; water:concentrate) as directed by the product label. We also applied paclobutrazol as a foliar spray (Trimtect®; Rainbow Ecoscience, Minnetonka, MN, USA) using a 4:1 dilution (*v*:*v*; water:concentrate). Treatments were applied to six 10-tree row plots (i.e., n = 60 for each treatment at each farm) in a completely randomized design. Soil treatments were applied once (spring 2016 or spring 2017). For the 100 mL and 200 mL treatments, we made two soil injections 8 cm deep on opposite sides of each tree approximately 0.5 m from the trunk. For 300 mL treatments, we made three injections 8 cm deep equally spaced around the tree approximately 0.5 m from the trunk. We used three injections for the 300 mL treatments because product would begin to well up out of the injection site when more than 100 mL was applied per injection. Foliar spray treatments (Trimtect) were applied each spring when current year's terminal shoots had reached approximately 50% of their total growth based on the MSU Fraser fir shoot growth phenology model [https://enviroweather.msu.edu/crops/christmasTrees/fraserfirgrowth] (Accessed on 14 December 2022). Foliar treatments were applied using a standard handpump backpack sprayer annually each spring. For each tree we sprayed the upper half of each tree crown. When spraying trees we made a complete 360° pass around each tree and then reversed direction to minimize spray 'shadows'. All foliar applications were made when the crowns of the trees were dry, wind speeds were less than 2.5 m s^{-1} to minimize drift, and no rain was forecast for the next 24 h. In addition to the three rates of soil application of paclobutrazol and the foliar application of paclobutrazol, a fifth group of plots was not treated (Control).

We evaluated coning, terminal leader growth, and bud density of terminal leaders in the 2016 series of trials at all locations in 2017, 2018, and 2019, and at two locations (Horton. MI USA and Manton, MI, USA) in 2020 (Figure 3). The 2017 series of plots were evaluated in 2018, 2019, and 2020. Coning was evaluated shortly after cone emergence by picking and counting cones on each tree. Leader growth was assessed after shoot growth was complete (late July/August) by measuring total length with a meter stick. We counted vegetative buds along the terminal leader of each tree and calculated bud density (buds cm^{-1}) by dividing the number of buds by the leader length.

2.2. Foliar-Applied PGR Trials

We initiated trials at four locations in Michigan in 2018 to evaluate the effectiveness of foliar-applied PGRs in reducing coning. Mean tree heights ranged between. 1.41 and 1.89 m for the four farms (Table S2). We selected four GA-inhibitors: chlormequat chloride (Citadel®; Fine Americas, Inc., Walnut Grove, CA, USA), uniconazole-p (Concise®; Fine Americas, Inc., Walnut Grove, CA, USA), daminozide (Dazide®; Fine Americas, Inc., Walnut Grove, CA, USA), and paclobutrazol (Trimtect®) (Table S3) based on availability in the horticultural trade and effectiveness in earlier trials with conifers. Each compound was applied to the upper one-half of the tree crowns using a backpack sprayer in early summer as described above. For each compound, the treatments were applied once (1×) or applied twice, one week apart (2×). Each PGR × application combination was applied to five 5-tree row plots (i.e., n = 25 trees) per farm. We repeated all of the foliar PGR treatments on the same trees in summer 2019. We evaluated coning, terminal leader growth, number of vegetative buds, and bud density of trees on each plot in 2019 and 2020.

Figure 2. Paclobutrazol is soil-injected in a Fraser fir plantation using a back-pack injection system.

Figure 3. Research assistants assess coning on Fraser fir Christmas trees.

2.3. Statistical Analyses

For each trial, data were initially analyzed by repeated measures analysis of variance (ANOVA). For tree response variables (cones per tree, leader length, buds per leader, bud density), *Year* × *Treatment* and/or *Year* × *Farm* interaction effects were significant ($p < 0.01$). Subsequently, we analyzed data by *Year* using a two-factor ANOVA to test for *Farm* and *Treatment* effects (Paclobutrazol trials) or a three factor ANOVA test for *Farm*, *Treatment* and *Application* effects (Foliar PGR Trials). *Farm* × *Treatment* interaction effects were significant ($p < 0.01$) for cone density, therefore *Treatment* effects were analyzed by *Farm*. For leader growth and bud density, *Farm* × *Treatment* effects were not significant and data were pooled across *Farms* for analysis and presentation. Where ANOVA indicated significant treatment effects, treatment means were separated using Tukey's HSD test at $p = 0.05$.

3. Results

3.1. Paclobutrazol Trials

Soil application of paclobutrazol significantly ($p < 0.05$) reduced cumulative cone production in both the 2016 trial and the 2017 trial (Tables 1 and 2). Foliar application of paclobutrazol also reduced cumulative cone production (Tables 1 and 2). In the 2016 trial, application of 300 mL of paclobutrazol reduced the cumulative number of cones per tree by 38%. Foliar application of paclobutrazol reduced coning by 28% in the 2016 trial. In the 2017 trial, all soil applied treatments and foliar application of paclobutrazol reduced cumulative coning by 32% or more. The effectiveness of paclobutrazol in controlling cones varied among farms in each trial. In the 2016 studies, maximum effectiveness (greatest % reduction in coning relative to the untreated control) of soil applied treatments ranged from 30% at Allegan to 67% at Sidney. In the 2017 trials, maximum effectiveness of soil-applied treatments ranged from 35% at Allegan to 55% at Horton. In both trials, control of coning from soil application of paclobutrazol lasted three years or longer. Soil application of paclobutrazol in 2016 reduced coning in 2019 (3 years after treatment) by up to 36% across all farms, compared to untreated control trees. Soil application in 2017 reduced coning in 2020 across all farms by 47%. For the two farms in which we were able to evaluate a fourth-year response in the 2016 trial, soil application of paclobutrazol reduced coning by up to 47% at Manton and by up to 59% at Sidney.

Table 1. Mean cone density of Fraser fir trees treated with soil injected or foliar applied paclobutrazol. Soil treatments were applied in 2016. Foliar treatments were applied annually 2016–2018. Figures in parentheses indicate change in means relative to untreated control.

		Cones per Tree Location				
	Treatment	**Allegan**	**Manton**	**Horton**	**Sidney**	**Overall** [1]
2017	Control	47.9 (0.0)	4.1 (0.0)	10.0 (0.0)	3.6 (0.0)	**16.4a (0.0)**
	Soil 100 mL	43.3 (−9.6)	2.8 (−31.7)	10.6 (+6.0)	2.9 (−19.4)	**14.9ab (−9.1)**
	Soil 200 mL	46.8 (−2.3)	2.6 (−36.6)	10.9 (+9.0)	4.3 (+19.4)	**16.2a (−1.2)**
	Soil 300 mL	32.2 (−32.8)	1.7 (+58.5)	7.4 (−26.0)	1.8 (−50.0)	**10.8ab (−34.1)**
	Foliar	27.8 (−42.0)	0.8 (−80.5)	8.3 (−27.0)	1.1 (−69.4)	**9.5b (−42.1)**
2018	Control	84.2 (0.0)	14.6 (0.0)	12.7 (0.0)	19.1 (0.0)	**32.6a (0.0)**
	Soil 100 mL	76.5 (9.1)	12.9 (−11.6)	10.1 (−20.5)	19.1(0.0)	**29.7ab (−8.9)**
	Soil 200 mL	72.2 (14.3)	4.8 (−67.1)	8.7 (−31.5)	12.2 (−36.1)	**24.5abc (−24.8)**
	Soil 300 mL	54.2 (−35.6)	6.2 (−57.5)	6.3 (−50.4)	4.4 (−77.0)	**17.8c (−45.4)**
	Foliar	50.6 (−39.9)	7.9 (−45.9)	8.2 (−35.4)	14.2 (−25.7)	**20.2bc (−38.0)**
2019	Control	87.6 (0.0)	62.9 (0.0)	42.3 (0.0)	42.7 (0.0)	**58.8a (0.0)**
	Soil 100 mL	80.5 (−8.1)	44.5 (−29.3)	29.6 (−30.0)	43.2 (+1.2)	**49.7ab (−15.5)**
	Soil 200 mL	83.8 (−4.3)	33.5 (−46.7)	24.7 (−41.6)	27.2 (−36.3)	**42.3b (−28.1)**
	Soil 300 mL	66.7 (−23.9)	51.4 (−18.3)	18.0 (−57.4)	15.4 (−63.9)	**37.9b (−35.5)**
	Foliar	70.7 (−19.3)	35.8 (−43.1)	28.6 (−32.4)	51.9 (21.5)	**46.7ab (−20.6)**

Table 1. *Cont.*

	Treatment	Cones per Tree Location Allegan	Manton	Horton	Sidney	Overall [1]
2020	Control	NA	46.7 (0.0)	58.8 (0.0)	NA	**NA**
	Soil 100 mL		36.9 (−41.3)	34.1 (−19.4)		
	Soil 200 mL		24.7 (−60.7)	23.9 (−43.5)		
	Soil 300 mL		52.4 (−16.7)	26.7 (−36.9)		
	Foliar		58.6 (−6.8)	31.3 (−26.0)		
Cumulative [2]	Control	219.7 (0.0)	77.3 (0.0)	64.7 (0.0)	65.3 (0.0)	**106.8a (0.0)**
	Soil 100 mL	200.8 (−8.6)	60.1 (−22.1)	50.2 (−22.4)	65.3 (0.0)	**94.1ab (−11.9)**
	Soil 200 mL	202.8 (−7.7)	40.8 (−47.2)	42.5 (−34.3)	43.7 (−33.1)	**82.5abc (−22.8)**
	Soil 300 mL	153.1 (−30.3)	59.3 (−23.3)	31.7 (−51.0)	21.6(−66.9)	**66.4c (−37.8)**
	Foliar	149.1 (32.1)	44.5 (−42.4)	45.6 (−29.5)	67.5 (3.4)	**76.4bc (−28.5)**

NA = plots were harvested in 2019. [1] means followed by the same letter are not different at $p < 0.05$. Mean separation by Tukey's HSD test. [2] sum of 2017–2019 cone counts.

Table 2. Mean cone density of Fraser fir trees treated with soil injected or foliar applied paclobutrazol. Soil treatments were applied in 2017. Foliar treatments were applied annually 2017–2019. Figures in parentheses indicate change in means relative to untreated control.

	Treatment	Cones per Tree Location Allegan	Manton	Horton	Sidney	Overall [1]
2018	Control	2.2 (0.0)	20.8 (0.0)	4.6 (0.0)	17.1 (0.0)	**11.2 (0.0)**
	Soil 100 mL	4.5 (+104.5)	21.5 +(3.8)	2.2 (−52.2)	15.6 (−8.8)	**10.9 (−2.7)**
	Soil 200 mL	6.6 (+200.0)	23.6 (+13.5)	3.5 (−23.9)	8.7 (−49.1)	**10.6 (−5.4)**
	Soil 300 mL	7.0 (+218.2)	11.8 (−43.3)	3.1 (−32.6)	15.0 (−12.3)	**9.2 (−17.9)**
	Foliar	1.1 (−50.0)	21.0 (+1.0)	3.3 (−28.3)	12.8 (−25.1)	**9.5 (−15.2)**
2019	Control	12.8 (0.0)	NA	16.6 (0.0)	56.8 (0.0)	**28.8 (0.0)**
	Soil 100 mL	10.7 (−16.4)		10.1 (−39.2)	36.2 (−36.3)	**19.0 (−34.0)**
	Soil 200 mL	18.5 (+44.5)		8.4 (−49.4)	29.7 (−47.7)	**19.0 (−34.0)**
	Soil 300 mL	13.1 (+2.3)		7.6 (−54.2)	37.5 (−34.0)	**19.4 (−32.6)**
	Foliar	6.3 (−50.8)		7.5 (−54.8)	40.0 (−29.6)	**17.9 (−37.8)**
2020	Control	26.6 (0.0)	NA	20.8 (0.0)	53.7 (0.0)	**33.7a (0.0)**
	Soil 100 mL	11.4 (−57.1)		11.6 (−44.2)	29.9 (−44.3)	**17.7b (−47.5)**
	Soil 200 mL	25.5 (−4.1)		9.3 (−55.3)	35.1 (−34.6)	**23.4ab (−30.6)**
	Soil 300 mL	15.8 (−40.6)		8.4 (−59.6)	31.5 (−41.3)	**18.5b (−45.1)**
	Foliar	11.1 (−58.3)		11.9 (−42.9)	34.5 (−35.8)	**19.2b (−43.0_**
Cumulative [2]	Control	41.0 (0.0)	NA	42.0 (0.0)	127.6 (0.0)	**70.2a (0.0)**
	Soil 100 mL	26.6 (−35.1)		23.9 (−43.1)	77.8 (−39.0)	**42.7b (−39.2)**
	Soil 200 mL	50.6 (−23.4)		21.3 (−49.3)	70.1 (−45.1)	**47.3ab (−32.6)**
	Soil 300 mL	35.6 (−13.2)		19.1 (−54.5)	82.6 (−35.3)	**45.8ab (−34.8)**
	Foliar	18.2 (−55.6)		22.7 (−46.0)	88.2 (−30.9)	**43.0b (−38.7)**

NA = cones were picked before evaluation. [1] means followed by the same letter are not different at $p < 0.05$. Mean separation by Tukey's HSD test. [2] sum of 2017–2019 cone counts.

Soil application of paclobutrazol reduced terminal leader lengths in both the 2016 and 2017 trials (Figure 4). Leader growth control in response to paclobutrazol application generally followed a dose-rate response, with growth reduction increasing with application rate. Maximum reductions in annual leader growth ranged from 2.1 cm in 2018 following 2017 application to 8.1 cm in 2018 for the 2016 application. Foliar application of paclobutrazol significantly reduced leader growth in 4 out of 6 evaluations (Figure 4). Soil application of paclobutrazol increased ($p < 0.05$) bud density of the terminal leaders the year after application (i.e., 2017 bud density for the 2016 application; 2018 bud density for the 2017 application) but did not affect bud density in subsequent years (Table S4). In the 2016 trial, bud density in 2017 was higher ($p < 0.05$) for trees receiving 300 mL of paclobutrazol (0.46 buds cm^{-1}) than for untreated control trees or trees that were treated with foliar paclobutrazol (0.41 and 0.39 buds cm^{-1}, respectively). For trees treated in 2017, treating trees with 200 mL of paclobutrazol increased bud density in 2018 relative to trees that received foliar applications (0.39 vs. 0.35 buds cm^{-1}). In contrast to bud density, the number of buds per leader decreased consistently with paclobutrazol application, with significant treatment effect indicated on 5 of the 6 evaluations (Table S4).

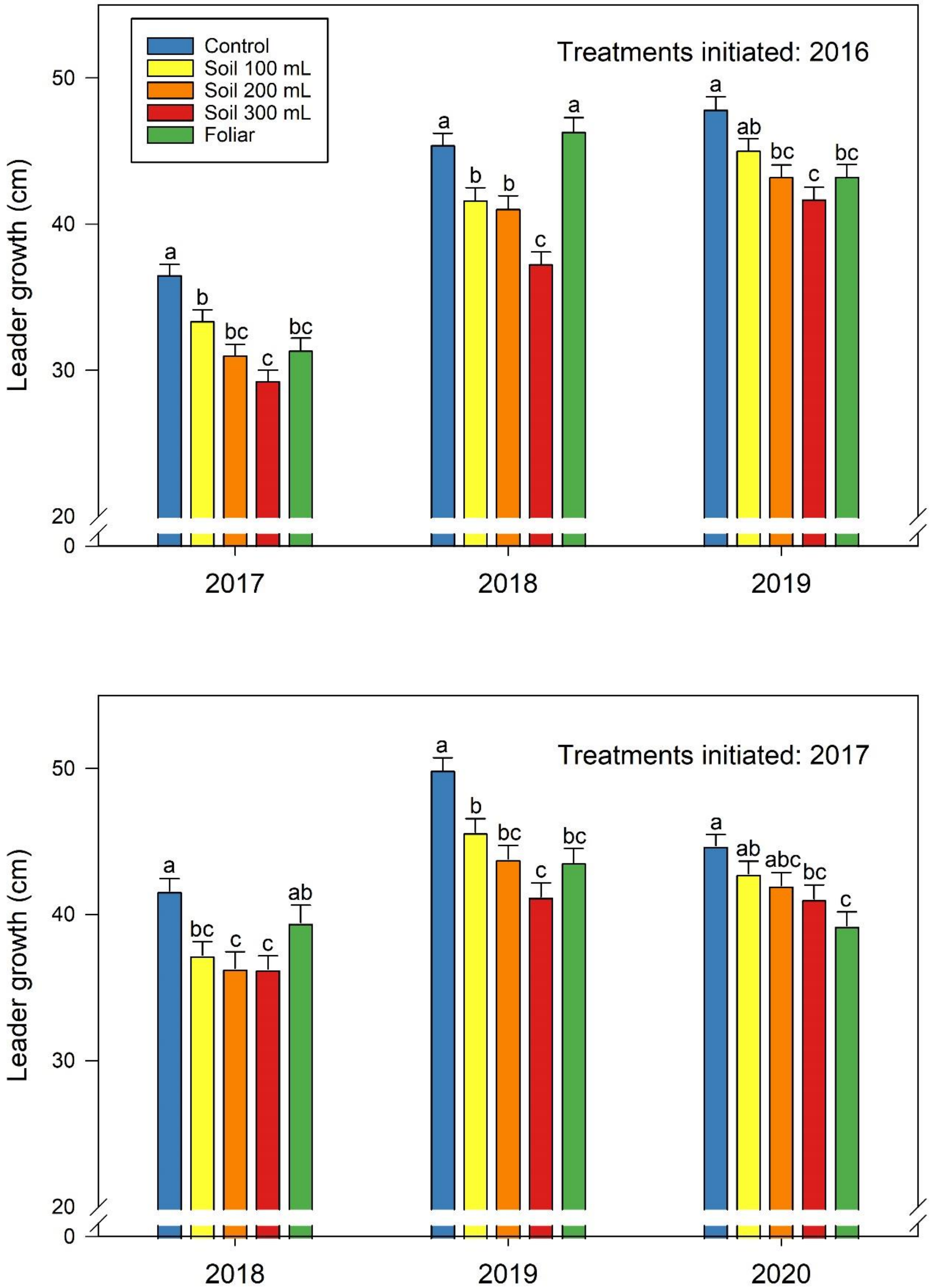

Figure 4. Mean annual leader growth of Fraser fir trees treated with three rates soil applied paclobutrazol, treated with foliar applied paclobutrazol, or left untreated (Control). **Top:** trees treated with soil application in 2016 or foliar-treated annually 2016–2018. **Bottom:** trees treated with soil application in 2017 or foliar-treated annually 2017–2019. Means within a year indicated by the same letter are not different at $p < 0.05$. Mean separation by Tukey's HSD test.

3.2. Foliar-Applied PGR Trial

Foliar-applied PGRs reduced ($p < 0.05$) coning across farms, however repeating applications (i.e., 2× treatments) did not affect ($p > 0.05$) coning. Therefore, we combined the single and repeated application data for analysis and present means for each product. Overall, all of the PGRs reduced cumulative coning (2019 cones + 2020 cones) relative to trees in the untreated control (Table 3). Paclobutrazol reduced cumulative coning by 45% compared to control trees. Efficacy of the products varied among farms. All products significantly reduced coning at Allegan relative to the control. Paclobutrazol reduced coning at Manton in 2020. PGR-treated trees had fewer cones than untreated trees at Sidney but the difference was not significant. Likewise, foliar PGR treatments did not affect coning at Horton in 2019 (Table 3).

Table 3. Mean cone density (cones per tree) of Fraser fir trees treated with four foliar applied plant growth regulators or not treated (control). Treatments were applied annually 2018–2019. Figures in parentheses indicate change in means relative to untreated control.

		Cones per Tree		
Location	**Treatment**	**Cones 2019**	**Cones 2020**	**Cumulative**
Allegan	Control	122.5a (0.0)	122.0a (0.0)	244.4a (0.0)
	Chlormequat chloride	79.4b (−35.2)	71.8b (−41.1)	151.2b (−38.1)
	Uniconazole-p	63.1b (−48.5)	75.1ab (−38.4)	138.2b (−43.5)
	Daminozide	66.9b (−45.4)	67.5b (−44.7)	134.4b (−45.0)
	Paclobutrazol	64.9b (−47.0)	60.9b (−50.1)	125.6b (−48.6)
Sidney	Control	49.8 (0.0)	46.0 (0.0)	95.8 (0.0)
	Chlormequat chloride	30.1 (−39.5)	44.2 (−3.9)	73.5 (−23.3)
	Uniconazole-p	23.5 (−52.8)	43.1 (+6.3)	66.1 (−31.0)
	Daminozide	42.3 (−15.1)	33.8 (−26.5)	76.1 (−20.6)
	Paclobutrazol	34.9 (−29.9)	28.9 (−37.2)	65.3 (−31.8)
Manton	Control	NA	89.3a (0.0)	
	Chlormequat chloride		63.9ab (−28.4)	
	Uniconazole-p		75.7ab (−15.2)	
	Daminozide		67.0ab (−25.0)	
	Paclobutrazol		28.9b (−67.6)	
Horton	Control	38.6 (0.0)	NA	
	Chlormequat chloride	31.2 (−19.2)		
	Uniconazole-p	40.2 (+4.1)		
	Daminozide	52.2 (+35.2)		
	Paclobutrazol	39.9 (+3.4)		
All farms *	Control	**70.8a (0.0)**	**86.8a (0.0)**	**118.4a (0.0)**
	Chlormequat chloride	**46.9b (−33.8)**	**60.0ab (−30.9)**	**80.2b (−32.3)**
	Uniconazole-p	**42.4b (−40.1)**	**65.1bc (−25.0)**	**80.3b (−32.2)**
	Daminozide	**53.8ab (−24.0)**	**56.1bc (−35.4)**	**82.4b (−30.4)**
	Paclobutrazol	**46.5b (−34.3)**	**39.7c (−54.3)**	**64.6b (−45.4)**

* 2019 + 2020 cones for Allegan and Sidney, 2020 for Manton, 2019 for Horton. Means within a column for a given farm that are followed by the same letter are not different at $p < 0.05$. Mean separation by Tukey's HSD test.

Leader growth control with foliar applied PGRs varied among farms as paclobutrazol provided greater growth control at Manton and Allegan than at Horton in 2019. However, paclobutrazol generally provided the greatest growth control overall, and there was a slight, but consistent, additive effect of repeating the applications on leader growth (Figure 5). Two foliar applications of paclobutrazol reduced ($p < 0.05$) the number of buds per leader relative to the control trees in 2020 (Table S5). None of the foliar treatments affected bud density relative to the untreated control trees (Table S5).

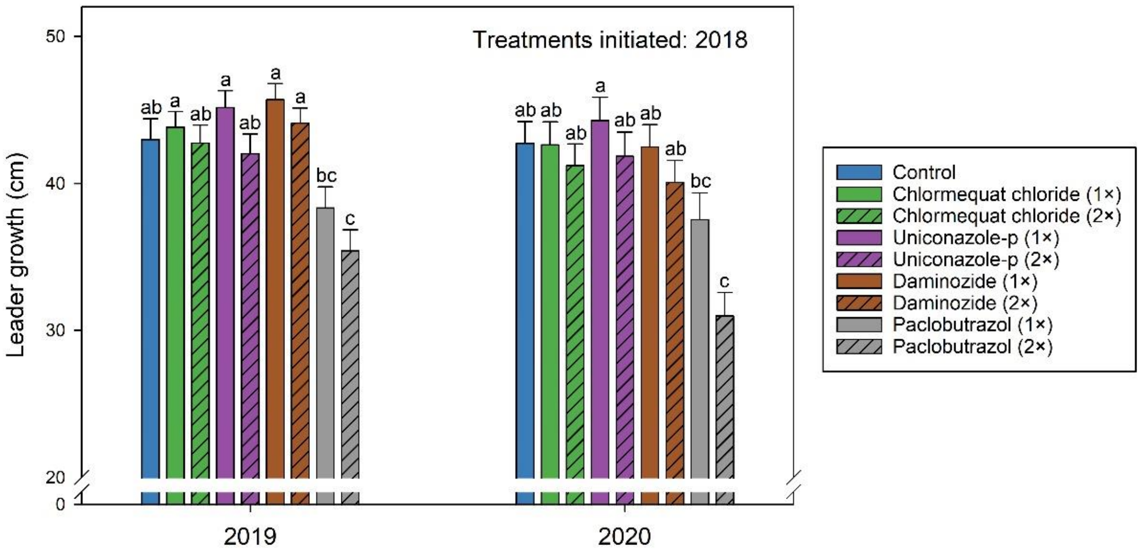

Figure 5. Mean annual leader growth of Fraser fir trees treated with four plant growth regulators or left untreated (Control). Each PGR was applied once (1×) or applied a second time approximately 1 week later (2×). Foliar treatments were applied annually in 2018 and 2019. Means within a year indicated by the same letter are not different at $p < 0.05$. Mean separation by Tukey's HSD test.

4. Discussion

To date, PGRs have not been widely used in Christmas tree culture in North America, although they are applied for height growth control of Christmas trees in Europe and interest is increasing in North America [11–13]. In this trial, we investigated the utility of PGRs, specifically GA-inhibitors, in reducing nuisance cone production in Fraser fir. Gibberellic acid increases cone formation in conifers [3,14], therefore we hypothesized that GA-inhibitors could reduce cone formation. Moreover, GA-inhibitors, particularly paclobutrazol, have been shown to reduce shoot extension in conifers [15,16], which could provide an additional benefit in Christmas tree production by improving tree density and reducing the need for shearing.

As in an earlier trial, soil and foliar applied PGRs reduced coning and shoot elongation [10]. Soil applications of paclobutrazol are particularly promising as a single application may reduce coning for up to four years. The principal limitation of using PGRs to reduce coning is inconsistency of responses among farms and years. For example, in the 2016 trial, trees on the farm with the greatest amount of cones (Allegan) had the smallest proportionate response to PGR application. The site had a very sandy soil, and it is likely trees were under significant water stress. Nonetheless, the high rate of soil applied PGR reduced cumulative coning by 67 cones per tree, or approximately 200,000 cones per hectare, assuming a 1.6 m tree spacing and that all trees produce cones.

Foliar-applied PGRs were effective in controlling cones but results were also variable among farms and years. The variation in response to foliar applied PGRs may be due to variation in timing and tree phenology. We attempted to time applications based on our growth phenology model, in order to apply the GA-inhibitors when shoot growth was 50% complete. This point of shoot development corresponds to the typical start of bud differentiation in firs [17,18]. However, weather conditions after this time could affect persistence of the compounds in the shoots and foliage. Logistically, foliar application may be more limiting than soil application as they need to be repeated each year and spraying is constrained by tree phenology and weather conditions.

Application of paclobutrazol, either as a soil drench or a foliar treatment, reduced terminal leader growth, which can improve tree density. The number of buds per leader also decreased following treatment, resulting no net change in bud density. Thus, application of paclobutrazol is unlikely to substitute for more common forms of chemical leader control in Christmas trees such as naphthaleneacetic acid (NAA) or S-abscisic acid (S-ABA) [11,19].

The cost-effectiveness of PGR applications will largely depend on local farm conditions, especially the amount of cones per tree and cost of labor picking cones. For small, owner-operators that rely on their own labor and have a large cone problem, PGR applications could reduce the amount of time spent picking cones by about 40% and free up time for other tasks. Based on 2022 pricing, concentrated paclobutrazol (22.3% a.i.) retails for approximately USD 200 per gallon (3.7 L). This amount will treat 148 trees, assuming an 11:1 dilution and a rate of 300 mL tree^{-1}, resulting in a product cost of USD 1.35 per tree. Workers can apply soil drenches quickly using appropriately-sized cups and can treat 4 trees per minute, adding USD 0.06 per tree. However, a single soil application of paclobutrazol can reduce coning for three to four years, so the annual cost of cone control with paclobutrazol could be as low as USD 0.35 to USD 0.47 per tree. Growers in regions where labor costs are especially high may consider combining application of PGRs to reducing coning with chemical treatments to eliminate cones that do form [20].

Paclobutrazol also reduced shoot growth and, in some instances, increased bud density. The effect of paclobutrazol on shoot growth is unlikely to have a major impact on the need for shearing – growers typically prune terminal leaders to 25–30 cm. However, the effects on leader growth and bud density could improve overall tree density, which is desirable in Christmas trees.

5. Conclusions

From this and our earlier study we conclude that GA-inhibitors, especially paclobutrazol, can partially off-set the effect of endogenous GAs and reduce coning and shoot growth in Fraser fir. Paclobutrazol has good residual activity, and a single application can affect coning for up to four years after initial application. Based on our trials, it appears application of paclobutrazol can reduce, but not eliminate coning in Fraser fir. To date, we have observed that a 40% reduction in coning is possible across a range. We hypothesize that the compound is effectively delaying tree maturation and that applying at younger ages (i.e., before trees begin to cone) may be an effective strategy to reduce coning. Additional research on combining soil and foliar applications would be useful to determine if combined application might result in synergistic effects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14010025/s1, Table S1: Initial tree attributes and soil characteristics for trial sites for 2016 and 2017 Paclobutrazol trials; Table S2: Initial tree attributes and soil characteristics for trial sites 2018 Foliar PGR trials; Table S3: Products used for Michigan State University Plant Growth Regulator (PGR) trials; Table S4: Mean bud counts on terminal leader and mean terminal bud density of Fraser fir trees treated with three rates soil applied paclobutrazol, treated with foliar applied paclobutrazol, or left untreated (Control). Top: trees treated with soil application in 2016 or foliar-treated annually 2016–2018. Bottom: trees treated with soil application in 2017 or foliar-treated annually 2017–2019.; Table S5: Mean bud counts on terminal leader and mean bud density of Fraser fir trees treated with four plant growth regulators or left untreated (Control). Each PGR was applied once (1×) or applied a second time approximately 1 week later (2×). Foliar treatments were applied annually in 2018 and 2019.

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