EFFECTS OF PRECOMMERCIAL THINNING ON ANNUAL RADIAL GROWTH AND WOOD DENSITY IN BALSAM FIR (*Abies balsamea*)

Shinya Koga[1]

Visiting Scientist

S. Y. Zhang†

Senior Scientist and Group Leader
Resource Assessment and Utilization Group
Forintek Canada Corp.
319, rue Franquet
Sainte-Foy, Québec
Canada G1P 4R4

and

Jean Bégin

Professor
Department of Wood and Forest Sciences
Laval University
Sainte-Foy, Québec
Canada G1K 7P4

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ABSTRACT

This study examined effects of precommercial thinning (PCT) on annual radial growth (ring width) and wood density in balsam fir [*Abies balsamea* (L.) Mill.]. In addition, the responses to PCT were measured and compared at several stem heights (0.2 m, 0.7 m, 1.3 m, 3 m, 5 m, 7 m, 9 m). Fifty-four trees were collected from plots subjected to moderate thinning (nominal stand density of 2,150 stems/ha), and light thinning (nominal stand density of 4,200 stems/ha), and from control plots. Ring width and wood density of individual rings were measured by X-ray densitometry. Our results show that in balsam fir the annual radial growth rate showed a positive response to PCT, especially in the low part of the stem (up to 5 m high), and this response lasted for 7 years. To achieve a significant increase in annual diameter growth in this species, however, a moderate thinning intensity is needed. This study also revealed that the response of annual radial growth to PCT was limited primarily to the earlywood width, whereas the latewood width showed little response. As a result, the latewood percentage was affected by the moderate thinning. The light thinning and the control plots, however, had a comparable earlywood width and latewood percentage. Both earlywood density and latewood density showed little response to PCT. However, the wood density of growth rings tended to decrease following the moderate thinning, due to a decreased latewood percentage. In addition, the moderate thinning might somehow reduce the intra-ring variation in wood density and thus produce more uniform wood. This study also revealed that the responses to thinning in this species tended to weaken appreciably with increasing stem height. The remarkable responses were observed in the low part of the stem (up to 5 m high), whereas little response was found at the upper part of the stem. As a result, an increased stem taper may result from PCT in balsam fir.

Keywords: Balsam fir, precommercial thinning, ring width, wood density, earlywood, latewood, stem height.

[1] Present Address: Department of Forest and Forest Products Sciences, Faculty of Agriculture, Kyushu University, Tsubakuro 394, Sasaguri, Kasuya, Fukuoka, Japan 811-2415.
† Member of SWST.

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TABLE 1. *Average ring width, earlywood width, latewood width, and latewood percentage for the moderately and lightly thinned plots and the control plots before and after the treatment.*

	Ring width (mm)				Earlywood width (mm)			
	Moderate thinning	Light thinning	Control	*P*-value[d]	Moderate thinning	Light thinning	Control	*P*-value
Before the treatment[a]	2.59 (0.54)[c]	2.25 (0.55)	2.44 (0.64)	0.2263	2.35 (0.52)	2.02 (0.53)	2.20 (0.63)	0.2304
After the treatment[b]	1.93 (0.37)	1.59 (0.35)	1.52 (0.32)	0.0020	1.68 (0.33)	1.34 (0.32)	1.28 (0.28)	0.0007

[a] Average for the five rings (1965–1969) before the treatment (also in Tables 2–4).
[b] Average for the twenty-three ring (1970–1992) after the treatment (also in Tables 2–4).
[c] Standard deviation (also in Tables 2–4).
[d] *P*-value indicates the significant level of the differences in the mean of each parameter among the moderately and lightly thinned plots and the control (also in Tables 2–4).

INTRODUCTION

In eastern Canada and northeastern United States, young balsam fir [*Abies balsamea* (L.) Mill] stands are often overstocked (Ker 1981; Lavigne and Donnelly 1989). Karsh et al. (1994) reported a stand density of 35,000 to 62,000 stems/hectare for 18–24-year-old balsam fir stands in Newfoundland. McArthur (1965) recorded that 10-year-old balsam fir stands could reach 62,000 to 72,000 stems/hectare in the Gaspé region, Québec. The overstocking in balsam fir usually results in a high mortality, slow growth, and small-size sawlog trees which are associated with high harvesting and manufacturing costs and low lumber volume recovery. As sizable sawlogs

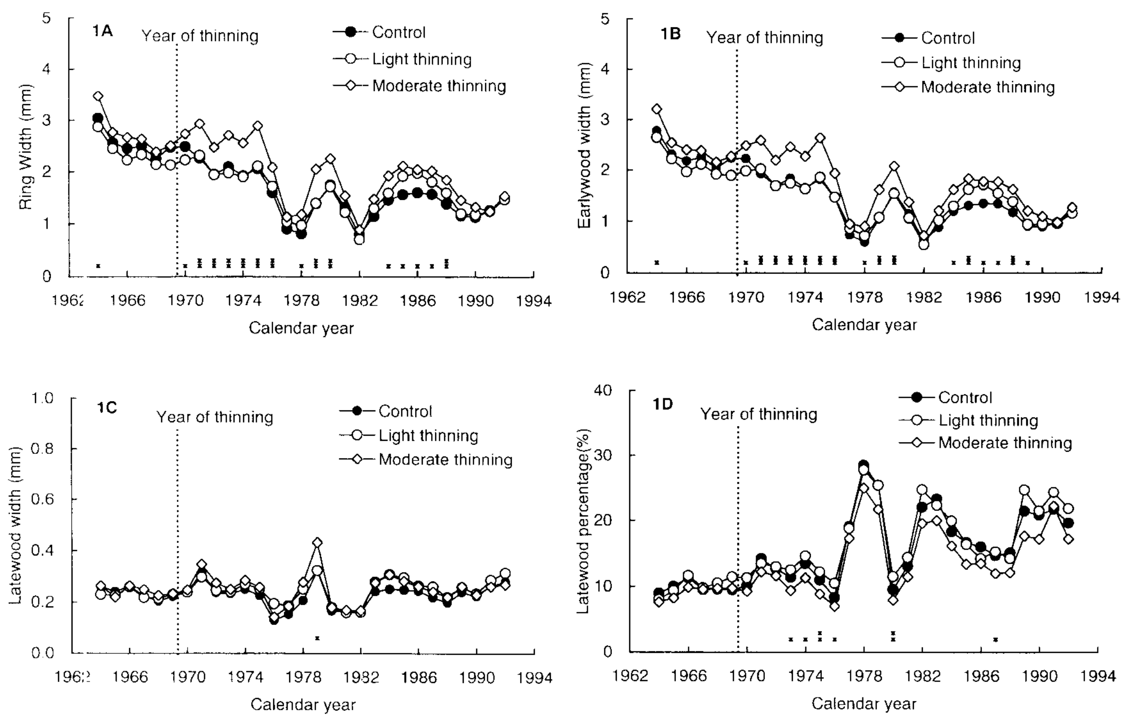

FIG. 1. Variation of ring width and its components with calendar year for the moderately and lightly thinned plots and the control. 1A: Ring width, 1B: Earlywood width, 1C: Latewood width, 1D: Latewood percentage. A star and two stars indicate significant (at the 0.05 level) and highly significant (at the 0.01 level) differences in the mean of each parameter for each year among the moderately and lightly thinned plots and the control (from Fig. 1–10).

TABLE 1. *Extended.*

Latewood width (mm)				Latewood percentage (%)			
Moderate thinning	Light thinning	Control	*P*-value	Moderate thinning	Light thinning	Control	*P*-value
0.24	0.23	0.23	0.9230	9.42	10.54	9.99	0.5598
(0.07)	(0.07)	(0.05)		(3.10)	(3.30)	(2.92)	
0.25	0.25	0.23	0.3984	14.50	17.60	16.80	0.0224
(0.07)	(0.07)	(0.05)		(2.31)	(4.42)	(3.01)	

are becoming scarce in eastern Canada and the forest industry in this region is moving toward intensive silviculture, precommercial thinning (PCT) of the young and dense balsam fir stands has become increasingly popular in recent years. For example, over 50,000 hectares of balsam fir stands were precommercially thinned in Québec in 1997, compared to less than 5,000 hectares in 1985 (Canadian Council of Forest Ministers 1996).

A number of studies (Ker 1981; Piene 1981; Mérette and Martel 1985; Ker 1987; Lavigne and Donnelly 1989; Karsh et al. 1994; Zarnovican and Laberge 1996; Schneider 2001) have reported that precommercial thinning applied to the young and dense balsam fir stands can reduce the mortality, accelerate the diameter growth of residual trees, and shorten the rotation age for sawlog production. On the other hand, it is well known that increased spacings generally lead to increased crown size, branch diameter, and ju-

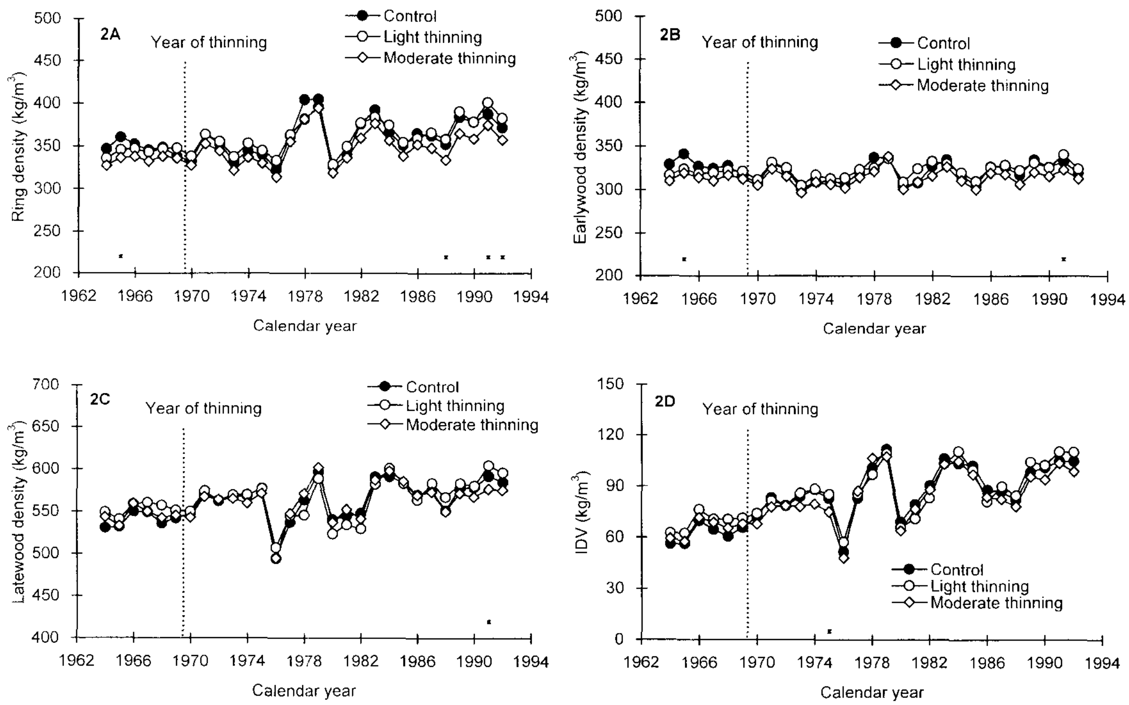

FIG. 2. Variation of wood density and its components with calendar year for the moderately and lightly thinned plots and the control. 2A: Ring density, 2B: Earlywood density, 2C: Latewood density, 2D: Intra-ring wood density variation (IDV).

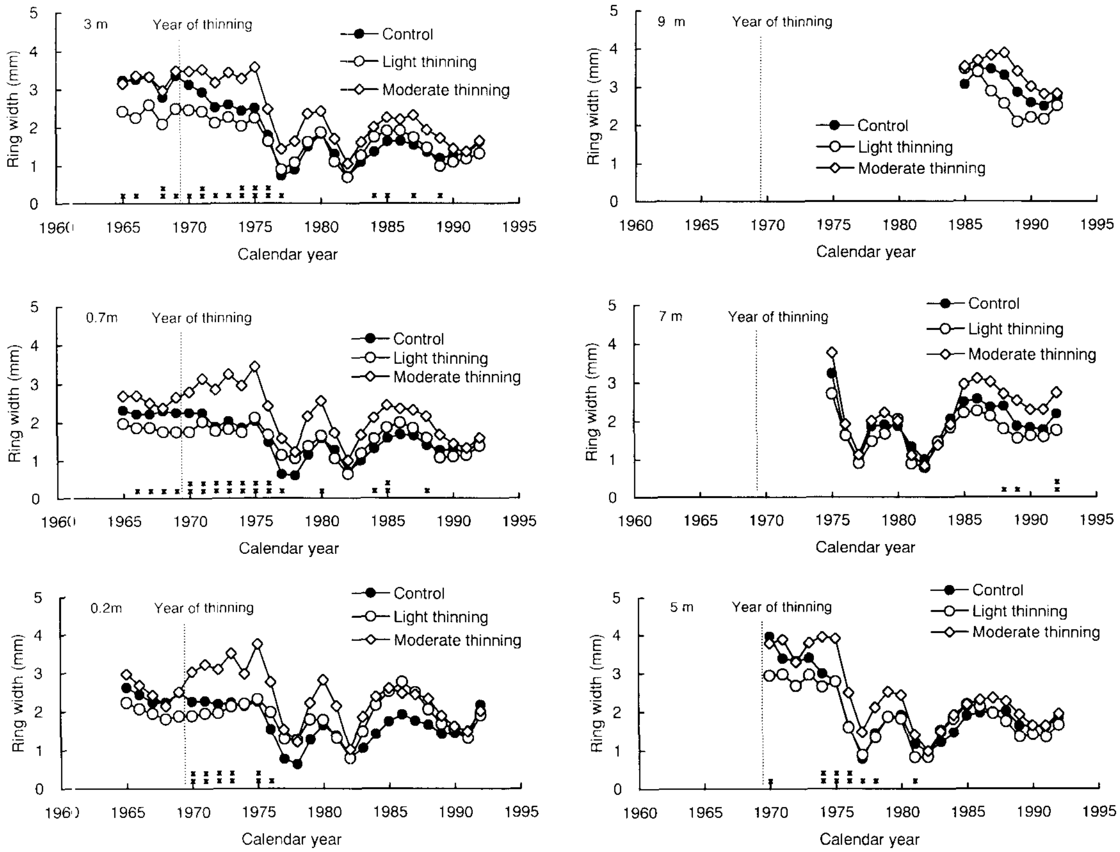

FIG. 3. Variation of ring width with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

venile wood, and to decreased stem straightness (Nicks 1991; Barbour et al. 1994). Therefore, the industry has shown increasing concern over the negative effects of this treatment on wood quality and end uses. A multidisciplinary project was initiated by Forintek to evaluate the impact of precommercial thinning on tree and wood characteristics, product quality, and value recovery in balsam fir (Zhang et al. 1998).

As part of this project, this study was intended to better understand the response of annual radial growth and wood density to precommercial thinning in balsam fir. More specifically, this study was intended to answer the following questions:

TABLE 2. *Weighted averages of ring density, earlywood density, latewood density, and intra-ring wood density variation (IDV) for the moderately and lightly thinned plots and the control plots before and after the treatment.*

	Wood density (kg/m³)				Earlywood density (kg/m³)			
	Moderate thinning	Light thinning	Control	*P*-value[d]	Moderate thinning	Light thinning	Control	*P*-value
Before the treatment[a]	336	346	349	0.1088	314	321	327	0.1179
	(22)[c]	(25)	(23)		(18)	(19)	(18)	
After the treatment[b]	346	361	357	0.1177	311	319	317	0.2652
	(15)	(30)	(18)		(11)	(21)	(12)	

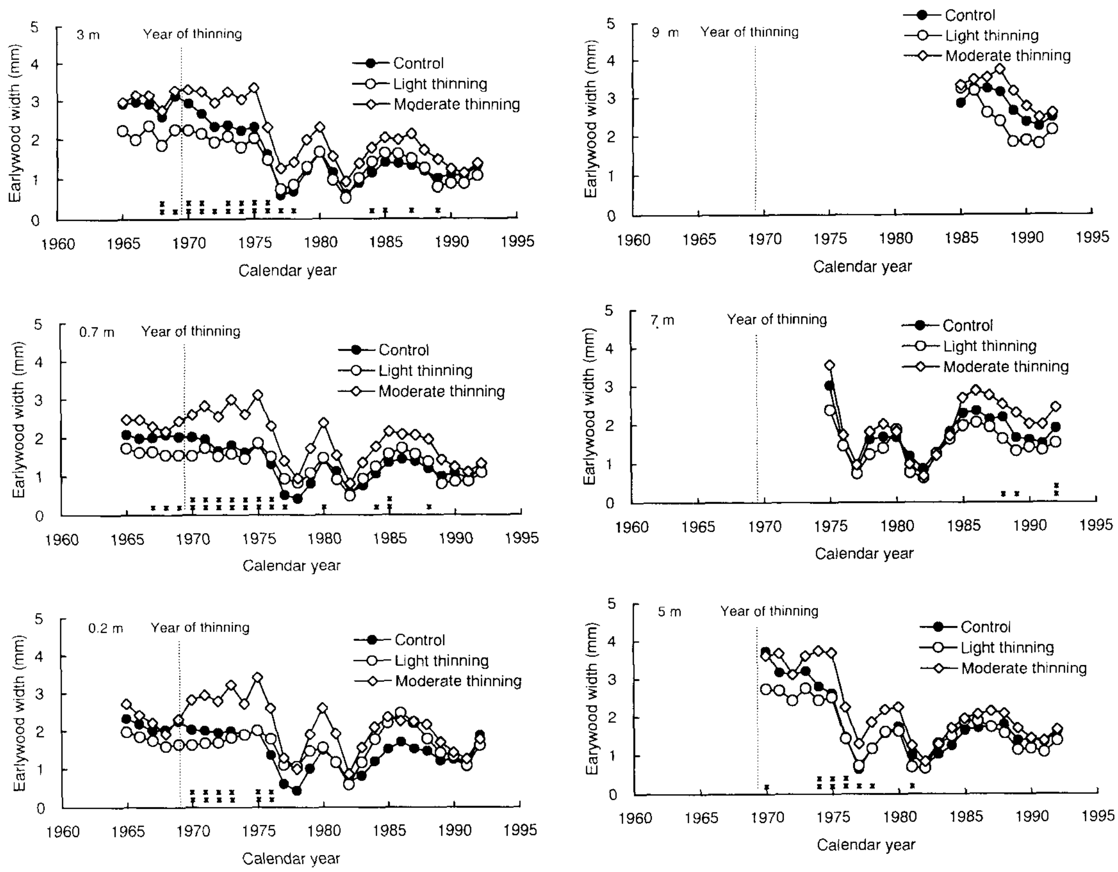

FIG. 4. Variation I of earlywood width with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

1) How do annual radial growth (ring width) and wood density respond to PCT?
2) Which part of the ring width (earlywood, latewood or both) responds to PCT?
3) How long does the response last?
4) Does the response vary along the height of the stem?
5) How does the thinning intensity affect the response?

MATERIALS AND METHODS

Materials used for this study came from a precommercial thinning trial located in the

TABLE 2. *Extended.*

Latewood density (kg/m³)				IDV (kg/m³)			
Moderate thinning	Light thinning	Control	*P*-value	Moderate thinning	Light thinning	Control	*P*-value
546	544	542	0.2332	60.3	64.3	60.6	0.3793
(25)	(23)	(28)		(8.9)	(10.3)	(10.2)	
571	576	573	0.8222	84.8	90.1	89.1	0.2819
(24)	(26)	(22)		(10.3)	(10.2)	(11.2)	

TABLE 3. *Average ring width, earlywood width, latewood width, and latewood percentage for the moderately and lightly thinned plots and the control at the six different stem heights before and after the treatment.*

	Ring width (mm)				Earlywood width (mm)			
Stem height	Moderate thinning	Light thinning	Control	*P*-value[d]	Moderate thinning	Light thinning	Control	*P*-value
Before the treatment[a]								
0.2 m	2.91	2.34	2.70	0.0711	2.64	2.09	2.41	0.0975
	(0.38)[c]	(0.30)	(0.50)		(0.42)	(0.28)	(0.49)	
0.7 m	3.10	2.57	2.73	0.0562	2.87	2.32	2.41	0.0230
	(0.28)	(0.31)	(0.46)		(0.28)	(0.30)	(0.40)	
3.0 m	3.47	2.85	3.16	0.0873	3.25	2.59	2.83	0.0744
	(0.46)	(0.19)	(0.60)		(0.44)	(0.20)	(0.64)	
5.0 m	3.68	3.15	3.00	0.6804	3.51	2.83	2.66	0.5560
	(0.45)	(0.31)	(1.24)		(0.45)	(0.25)	(1.25)	
After the treatment[b]								
0.2 m	2.37	1.85	1.63	0.0302	2.13	1.59	1.40	0.0214
	(0.52)	(0.54)	(0.14)		(0.47)	(0.52)	(0.14)	
0.7 m	2.18	1.50	1.47	0.0011	1.92	1.26	1.24	0.0007
	(0.30)	(0.39)	(0.15)		(0.28)	(0.35)	(0.12)	
3.0 m	2.26	1.62	1.69	0.0051	2.05	1.38	1.48	0.0023
	(0.25)	(0.45)	(0.16)		(0.24)	(0.42)	(0.13)	
5.0 m	2.37	1.86	2.02	0.0356	2.15	1.63	1.79	0.0145
	(0.22)	(0.41)	(0.27)		(0.22)	(0.36)	(0.21)	
7.0 m	2.54	1.91	2.08	0.0517	2.30	1.69	1.85	0.0343
	(0.59)	(0.22)	(0.16)		(0.53)	(0.23)	(0.11)	
9.0 m	3.22	2.70	2.88	0.6388	3.01	2.44	2.66	0.5767
	(0.80)	(0.94)	(0.61)		(0.79)	(0.91)	(0.56)	

Bas Saint-Laurent Region of Québec. This trial was naturally regenerated from a clearcutting in 1955. At the end of the growing season in 1969, three types of plots were established: lightly thinned, moderately thinned, and control plots. In the moderate thinning plots, all trees within a distance of 2.13 m (or 7 ft) around each residual tree were removed, which gives a nominal stand density of approximately 2,150 stems/ha; in the light thinning plots, all trees within a distance of 1.52 m (or 5 ft) around each residual tree were removed, which gives a nominal stand density of approximately 4,200 stems/ha. The control plots had a stand density of approximately 20,000 stems/ha in 1969. At the beginning of the growing season in 1993, 18 sample trees (6 trees/plot) were collected from each thinning intensity as well as control plots. In total, 54 sample trees ranging from 10 to 18 cm of diameter at breast height were collected for this study. From each sample tree, a 4-cm-thick disk was removed at breast height to study the effects of precommercial thinning on annual radial growth and wood density in this species. In addition, disks were removed at six other stem heights (0.2 m, 0.7 m, 3 m, 5 m, 7 m, and 9 m) to study the responses at different heights along the stem. For further information on this trial and sample trees collected, refer to Schneider (2001).

A radial segment was removed from each disk from pith to bark (1 cm longitudinally × 1 cm tangentially × radius) at northern direction. The segments were trimmed down to strips about 1.57 mm thick (longitudinally), with a specially designed pneumatic-carriage twin-bladed saw. The sawn strips were extracted with a cyclohexane/ethanol (2:1) solution for 24 h and then with hot water for another 24 h to remove extraneous compounds. After the extraction, the strips were air-dried under restraint to prevent warping. Using a direct reading X-ray densitometer, the

TABLE 3. *Extended.*

Latewood width (mm)				Latewood percentage (%)			
Moderate thinning	Light thinning	Control	*P*-value	Moderate thinning	Light thinning	Control	*P*-value
0.27	0.25	0.30	0.3977	9.50	10.52	11.21	0.5437
(0.06)	(0.06)	(0.07)		(2.72)	(2.62)	(2.56)	
0.25	0.25	0.33	0.3565	7.93	9.82	11.62	0.1411
(0.05)	(0.03)	(0.17)		(1.75)	(1.55)	(4.69)	
0.22	0.25	0.33	0.4528	6.37	8.92	10.52	0.3309
(0.08)	(0.07)	(0.23)		(2.02)	(2.39)	(7.52)	
0.17	0.31	0.34	0.2400	4.52	9.89	13.52	0.3767
(0.01)	(0.07)	(0.15)		(0.78)	(1.34)	(9.99)	
0.24	0.27	0.22	0.3193	10.11	15.04	13.73	0.0118
(0.05)	(0.05)	(0.04)		(0.95)	(3.54)	(2.43)	
0.26	0.25	0.23	0.4114	12.05	16.92	15.55	0.0043
(0.05)	(0.05)	(0.03)		(1.78)	(3.17)	(1.00)	
0.22	0.24	0.21	0.5705	9.56	15.21	12.43	0.0010
(0.04)	(0.05)	(0.04)		(1.41)	(2.92)	(1.44)	
0.22	0.23	0.23	0.8635	9.20	12.44	11.32	0.0247
(0.01)	(0.06)	(0.07)		(1.00)	(2.10)	(2.19)	
0.24	0.22	0.23	0.8799	9.22	11.46	10.90	0.1422
(0.07)	(0.02)	(0.07)		(0.50)	(2.05)	(2.53)	
0.22	0.26	0.22	0.3837	6.95	10.44	7.53	0.1014
(0.03)	(0.06)	(0.06)		(1.57)	(3.38)	(0.90)	

air-dried strips were scanned to determine the basic wood density (oven-dry weight/green volume) for each ring from pith to bark. The first few rings near the pith were excluded because they were too narrow for the densitometry analysis to be performed.

Based on the densitometric profiles, the earlywood and latewood boundary was determined for each ring by a predetermined fixed basic wood density (540 kg/m^3) as explained by Jozsa et al. (1987). Various ring width parameters (ring width, earlywood width, latewood width, latewood percentage) and ring density parameters (e.g., earlywood density, latewood density, and average wood density of individual growth rings) were obtained for each ring scanned. Furthermore, intra-ring wood density variation was estimated using the equation given by Vargas-Hernandez and Adams (1991). Averages of ring width, earlywood width, latewood width, and latewood percentage were computed for the last five rings before the thinning treatment (1965–1969) and for the twenty-three rings following the treatment (1970–1992). Based on the ring width and wood density data of individual growth rings, weighted averages of wood density, earlywood density, and latewood density were computed for the last five rings before the treatment and the twenty-three rings after the treatment, as described by Barbour et al. (1992). All the statistical analyses were performed using the Statistical Analysis System procedures (SAS Institute 1988).

RESULTS AND DISCUSSION

Effects on ring width and its components

Figure 1A shows the variations of ring width with calendar years in the trees from the lightly and moderately thinned plots and the control plots. Statistically, no significant differences in ring width were found between the thinned and control plots for the last five years

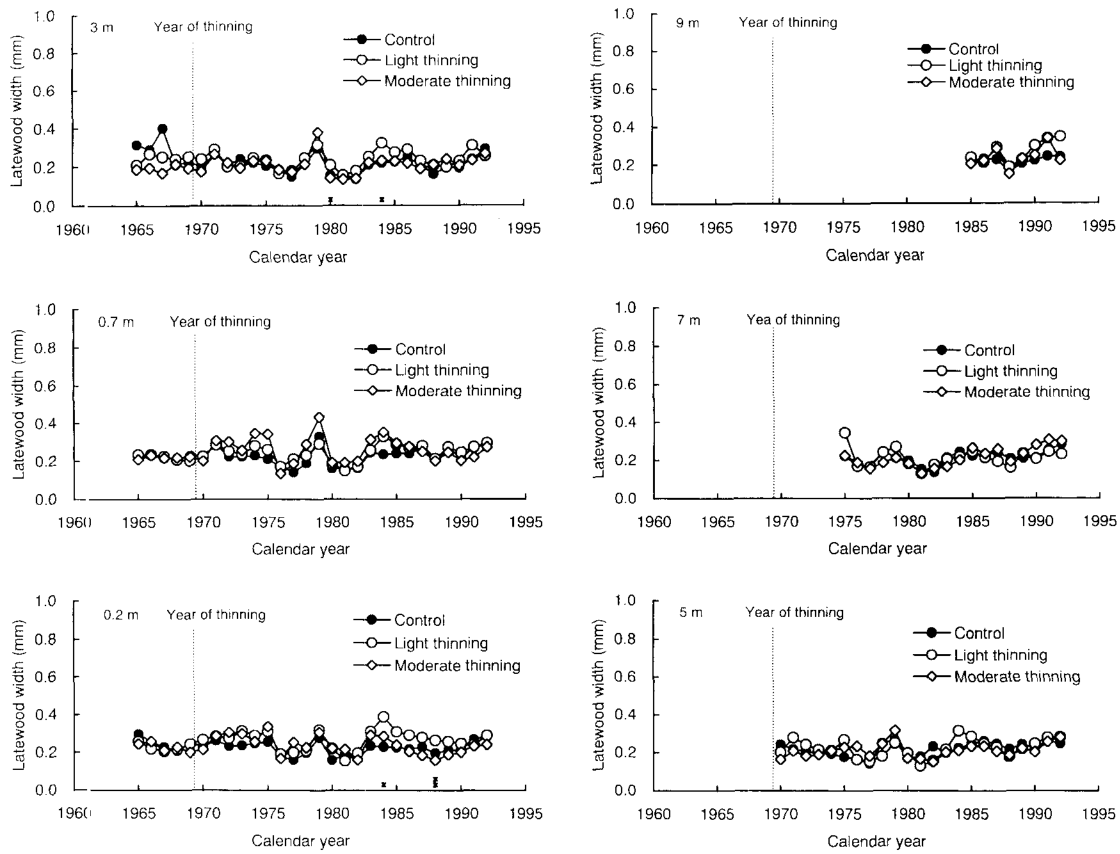

FIG. 5. Variation of latewood width with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

before the treatment (except for 1965). With increasing calendar year (age), annual radial growth rate in balsam fir tended to slow down despite some variation among the thinned and control plots. This pattern of variation in annual growth rate is different from that reported by Chui et al. (1997) for the same species. Figure 1A also shows that annual radial growth was unusually slow for the years 1977, 1978, and 1982. The extremely slow growth rate in these years corresponds to the spruce budworm attacks reported by Lachance et al. (1990).

Following the PCT treatment in 1969, annual growth rate in the moderately thinned plots increased remarkably, up to 3 mm (Fig. 1A), and the significantly higher annual growth rate lasted for 7 years after the treatment. In fact, significant differences in annual growth rate were found between the control and the moderately thinned plots for most years after the treatment. The differences in annual growth rate between the control and the moderately thinned plots, however, were not significant in the rings formed during the years the stand was attacked by the spruce budworm (1977, 1981, 1982 and 1983) and in the four most recently formed rings near the bark. The average width of the rings after the treatment in the moderately thinned plots was significantly higher (1.93 mm) than in the control (1.52 mm), as shown in Table 1. However, the response of annual growth rate was not appreciable in the lightly thinned plots despite a slight increase for the first 2 years following the PCT treatment (Fig. 1A). As shown in Ta-

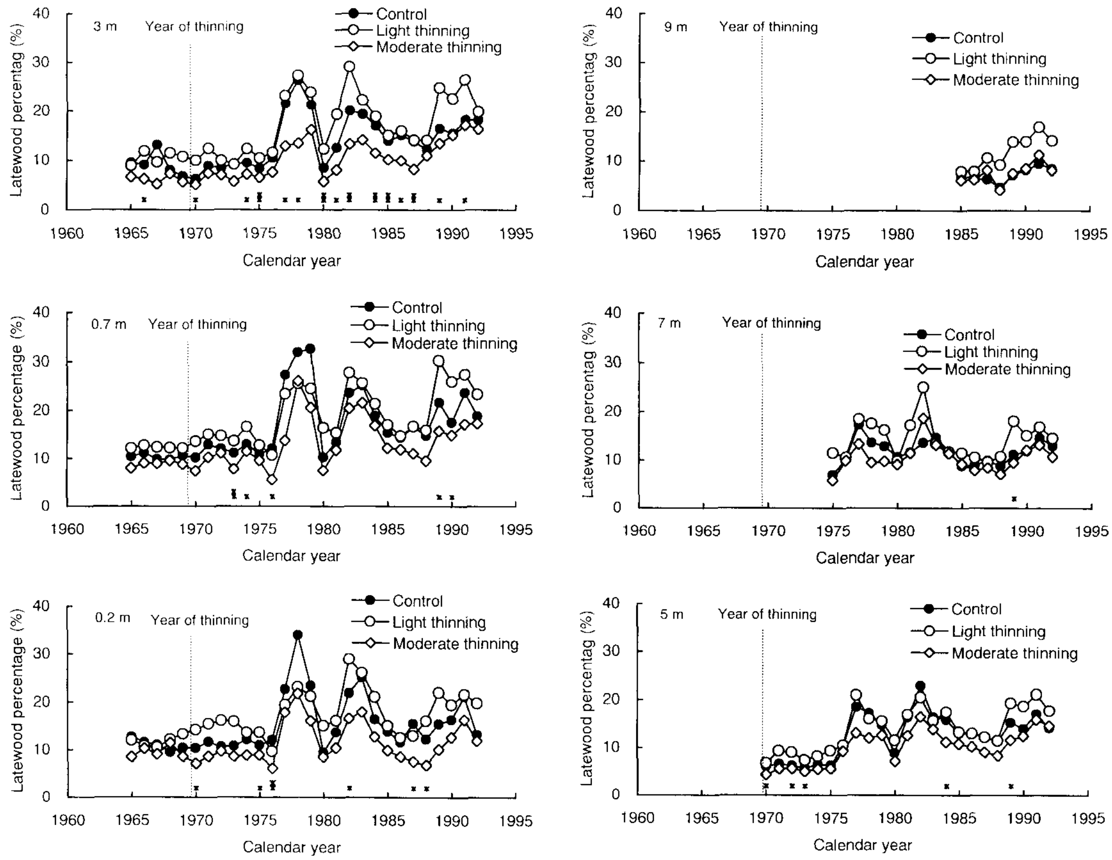

FIG. 6. Variation of latewood percentage with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

ble 1, the lightly thinned and the control plots had a very comparable average ring width after the treatment (1.59 and 1.52 mm, respectively). This indicates that although annual growth rate at breast height shows a positive response to the PCT in balsam fir, a moderate thinning intensity is needed to achieve a significant response in annual diameter growth. A similar result was reported by Zhang et al. (1998). In loblolly pine, Tasissa and Burkhart (1997) found that thinning effects on ring width persisted over 12 years after thinning. Yet, the ring width response to thinning showed a significant regional variation.

As shown in Fig. 1B and Table 1, the response of earlywood width to the PCT was very similar to that reported for ring width. The moderately thinned plots had the highest average earlywood width after the treatment (1.68 mm), and that of the lightly thinned plots was slightly higher (1.34 mm) than that of the control plots (1.28 mm). On the other hand, there were no significant differences in average latewood width after the treatment between the moderately thinned plots and the control (Table 1), although the control tended to have a slightly lower latewood width than both types of thinned plots (Fig. 1C). Moreover, despite some year-to-year variation, latewood width in this species tended to be relatively stable throughout the growth years, averaging 0.25 mm (Fig. 1C and Table 1). As a result of an increased earlywood width and a relatively stable latewood width after the treatment, the moderately thinned plots tended to have a lower

TABLE 4. *Weighted averages of wood density, earlywood density, latewood density, and intra-ring wood density variation (IDV) for the moderately and lightly thinned plots and the control at the six different stem heights before and after the treatment.*

	Wood density (kg/m³)				Earlywood density (kg/m³)			
Stem height	Moderate thinning	Light thinning	Control	*P*-value[d]	Moderate thinning	Light thinning	Control	*P*-value
Before the treatment[a]								
0.2 m	345	354	362	0.5941	325	332	340	0.6076
	(25)[c]	(31)	(29)		(22)	(26)	(25)	
0.7 m	330	348	346	0.2017	313	324	322	0.4257
	(21)	(17)	(14)		(18)	(15)	(12)	
3.0 m	323	349	345	0.3827	308	329	328	0.4567
	(25)	(22)	(47)		(26)	(22)	(41)	
5.0 m	313	355	383	0.3708	303	336	345	0.1655
	(7)	(12)	(77)		(6)	(15)	(29)	
After the treatment[b]								
0.2 m	335	363	358	0.0530	311	337	330	0.0372
	(19)	(24)	(15)		(19)	(16)	(12)	
0.7 m	338	367	357	0.0425	305	323	315	0.1665
	(15)	(25)	(12)		(13)	(20)	(13)	
3.0 m	323	356	340	0.0179	295	317	306	0.0632
	(13)	(24)	(12)		(12)	(21)	(8)	
5.0 m	325	352	338	0.0743	299	319	307	0.1175
	(16)	(22)	(18)		(15)	(18)	(14)	
7.0 m	333	346	338	0.6348	308	316	312	0.7616
	(20)	(20)	(26)		(19)	(17)	(21)	
9.0 m	324	345	322	0.0540	305	320	303	0.0621
	(12)	(15)	(17)		(10)	(11)	(14)	

latewood percentage than the control (Fig. 1D), but the differences between the lightly thinned plots and the control were not appreciable (Fig. 1D). Table 1 shows that the moderately thinned plots on average had a significantly lower latewood percentage after the treatment (14.5%) than the control (16.8%). These results indicate that the response in balsam fir was limited to earlywood width, latewood width showing little response to the PCT. This may reflect the fact that earlywood width in balsam fir is much more strongly correlated to ring width than to latewood width and that over 95% of the variation in ring width can be explained by earlywood width (Koga and Zhang 2001). However, Barbour et al. (1994) reported that, in jack pine, both earlywood and latewood width responded to thinning although the earlywood response was greater. In radiata pine (Cown 1973) and Japanese larch (Koga et al. 1996), the latewood width was also reported to show a remarkable response to thinning. In loblolly pine (Tasissa and Burkhart 1997), thinning did not alter the proportion of earlywood and latewood despite a significant effect on ring width. This suggests that in loblolly pine earlywood and latewood width may respond to thinning in the same proportion.

Effects on wood density and its components

Figure 2A shows the variations of average ring density in the trees from the moderately and lightly thinned plots and the control. As a whole, wood density tended to increase slightly toward the bark. This trend follows the general pattern reported for the *Abies* genus (Panshin and de Zeeuw 1980). An opposite pattern, however, was reported for this species by Chui et al. (1997). Figure 2A also shows that wood

TABLE 4. *Extended.*

	Latewood density (kg/m³)				IDV (kg/m³)			
Stem height	Moderate thinning	Light thinning	Control	*P*-value	Moderate thinning	Light thinning	Control	*P*-value
0.2 m	534	545	532	0.7520	58	64	59	0.6995
	(27)	(24)	(39)		(11)	(10)	(13)	
0.7 m	539	562	552	0.0991	59	70	66	0.0828
	(16)	(15)	(20)		(6)	(6)	(11)	
3.0 m	518	547	522	0.1898	48	61	51	0.0764
	(25)	(26)	(32)		(8)	(12)	(8)	
5.0 m	517	536	494	0.4304	44	56	54	0.7998
	(8)	(37)	(43)		(4)	(14)	(29)	
0.2 m	538	542	539	0.9426	66	69	70	0.6898
	(26)	(18)	(25)		(6)	(6)	(10)	
0.7 m	566	578	574	0.4709	82	92	91	0.1063
	(16)	(19)	(18)		(7)	(9)	(9)	
3.0 m	566	564	564	0.9882	79	86	84	0.4318
	(15)	(20)	(26)		(7)	(9)	(11)	
5.0 m	552	564	561	0.6022	75	81	80	0.3670
	(16)	(14)	(30)		(4)	(5)	(11)	
7.0 m	560	560	544	0.2908	73	77	72	0.4718
	(15)	(15)	(24)		(5)	(8)	(9)	
9.0 m	545	560	551	0.6070	62	71	64	0.4046
	(15)	(26)	(24)		(9)	(12)	(8)	

density fluctuated considerably in several growth rings (from 1977 to 1979, and from 1982 to 1984), which correspond to the spruce budworm attacks.

As shown in Fig. 2A, there were no significant differences in wood density between the thinned and control plots for the last five rings before the treatment (except for 1965). The same held true for the rings formed after the treatment (except for 1988, 1991, and 1992). As shown in Table 2, no significant differences in the average wood density after the treatment were found between the thinned and control plots, although the moderately thinned plots had a slightly lower average wood density (346 kg/m³) than the control (357 kg/m³). This indicates that in balsam fir precommercial thinning had a considerably smaller effect on wood density than on the annual radial growth rate. Tasissa and Burkhart (1997) also reported that in loblolly pine thinning did not affect ring density despite a significant effect on ring width.

Figure 2B shows the variations of earlywood density with the calendar year in the trees from the moderately and lightly thinned plots and the control. Earlywood density overall tended to be relatively stable throughout the growth years. There were no significant differences in earlywood density between the thinned and control plots for any year either before or after the treatment (except for 1965 and 1991), although the moderately thinned plots appeared to have a slightly lower wood density than the control. As shown in Table 2, no significant differences in average earlywood density after the treatment were found between the thinned and control plots. Their values were very comparable, ranging from 311 to 319 kg/m³ (Table 2). This indicates that in balsam fir earlywood density was not influenced significantly by precommercial thinning despite a significant effect on earlywood width. A similar result was found in loblolly pine (Moschler et al. 1989). However, in Douglas-fir, thinning was reported to result in an increase in earlywood density (Megraw and Nearn 1972).

Figure 2C shows the variations of latewood density with calendar year in the trees from the moderately and lightly thinned plots and the control. Latewood density tended to increase slightly toward the bark despite some variation in the rings formed during the years the stand was attacked by the spruce budworm (1976, 1980, 1981, and 1982). There were no statistically significant differences in latewood density between the thinned and control plots for any year either before or after the treatment (except for 1991). Furthermore, no significant differences in the average latewood density after the treatment were found between the thinned and control plot (Table 2). In fact, their values ranged from 571 to 576 kg/m³ (Table 2). This indicates that in balsam fir not only earlywood but also latewood density at breast height are not affected by precommercial thinning. Moschler et al. (1989), however, found that in loblolly pine thinning resulted in an increase in latewood density. As shown in Table 2, earlywood density and latewood density in balsam fir are highly different. Thus, a lower latewood percentage in the moderately thinned plots leads to a lower average ring density in balsam fir.

Figure 2D shows the intra-ring wood density variation (IDV) in relation to calendar year in the trees from the moderately and lightly thinned plots and the control. Overall, IDV tended to increase steadily toward the bark despite large fluctuations in a few rings (1976, 1980, 1981, and 1982) affected by the spruce budworm attacks. As shown in Fig. 2D, there were no statistically significant differences in IDV between the thinned and control plots for any ring either before or after the treatment (except for 1975), although the moderately thinned plots appeared to have a slightly lower IDV. Table 2 shows that the moderately thinned plots had on average a lower IDV (84.8 kg/m³) after the treatment than the control (89.1 kg/m³) and the lightly thinned plots (90.1 kg/m³), but the differences were not significant statistically. This indicates that in balsam fir moderate thinning may somehow reduce the intra-ring wood density variation and thus produce more uniform wood. In Douglas-fir, an increase in earlywood density and a decrease in latewood density following thinning reported by Megraw and Nearn (1972) also implies a reduced intra-ring variation in wood density, but results reported by Moschler et al. (1989) suggest that in loblolly pine thinning might increase the intra-ring wood density variation.

Effects at different stem heights

Figure 3 shows the variations of ring width with calendar year at the six different stem heights. At each of these stem heights (except 9 m), as with breast height, annual radial growth rate was also unusually slow in the years 1977, 1978, and 1982. It thus appears that the spruce budworm attacks affected the radial annual growth rate at all the stem heights.

As at breast height, at the lower stem heights (0.2 m and 0.7 m) the annual growth rate showed a remarkable increase after the moderate thinning, and this response lasted for 7 years (Fig. 3). This also applies, but to a lesser extent, to the 3-m height. At 5 m high, the moderately thinned plots had a significantly higher growth rate only for 3 years (1974 to 1976) after the treatment. At 7 m and 9 m high, there were no significant differences in annual growth rate between the moderately thinned plots and the control (Fig. 3). This indicates that in balsam fir the response of annual growth rate to the PCT weakens appreciably with increasing stem height. As shown in Table 3, the average width of the growth rings after the treatment in the moderately thinned plots was significantly higher than in the control at stem heights of up to 5 m. At 7 m and 9 m high, the average width of the growth rings after the treatment was not significantly different between the moderately

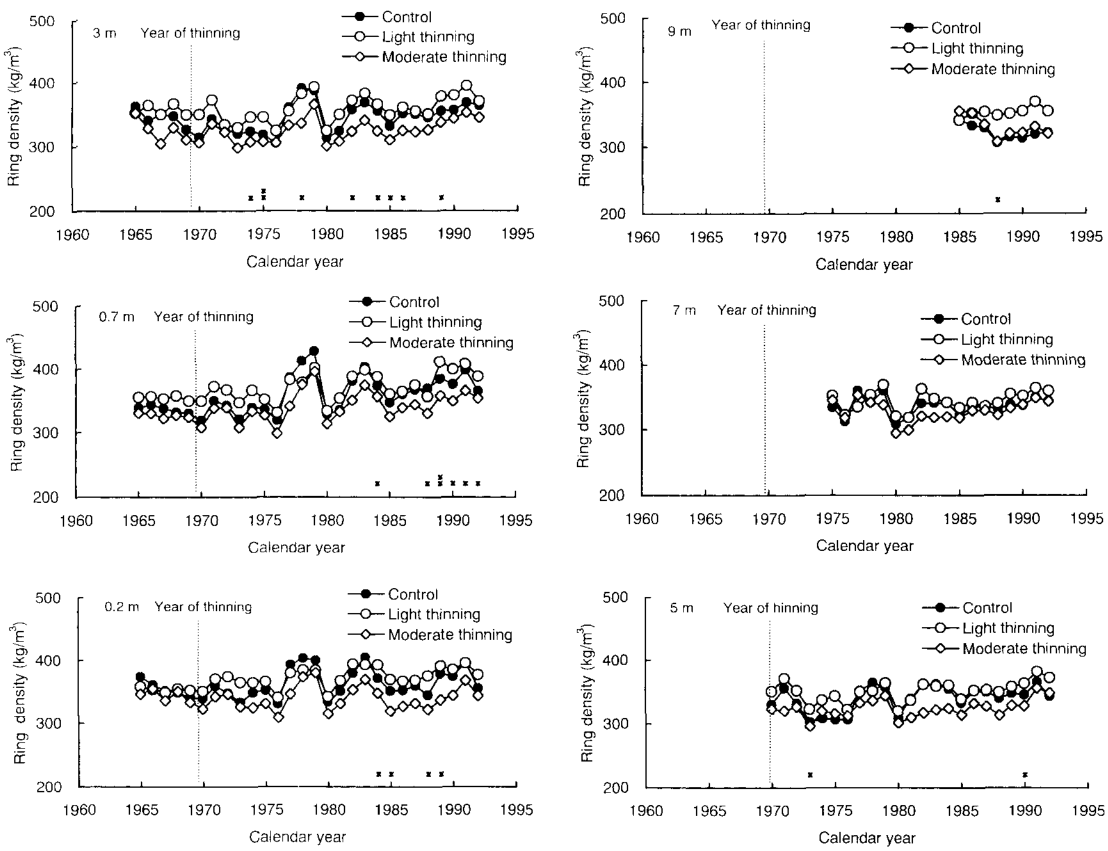

FIG. 7. Variation of wood density with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

thinned and the control plots. The weakening response of annual growth rate with increasing stem height suggests that an increased stem taper may result from the PCT in balsam fir, as reported by Zhang et al. (1998). Similar cases were reported for other species (Larson 1969; Barbour et al. 1992; Jozsa et al. 1987). On the other hand, the responses of the annual growth rate to the light thinning were not appreciable at any stem height, although in the first few years following the PCT the annual growth rate showed a slight increase at the lowest stem heights (0.2 m and 0.7 m high). Table 3 shows that differences in average ring width after the treatment between the lightly thinned and the control plots were not significant at any stem height, although the lightly thinned plots had a slightly higher ring width at the lowest stem heights (0.2 m and 0.7 m high). This again confirms that a moderate thinning intensity is needed to achieve a significant response in annual diameter growth in balsam fir.

The response of earlywood width to the PCT at the six stem heights was similar to that of the ring width at these heights (Fig. 4, Table 3). In other words, the response of earlywood width to the moderate thinning tended to weaken with increasing stem height. This suggests that in balsam fir a close relationship may exist between ring width and earlywood width at any stem height level. On the other hand, there were no significant differences in latewood width after the treatment between the control and the thinned plots at any stem height, as shown in Fig. 5 and Table 3. In

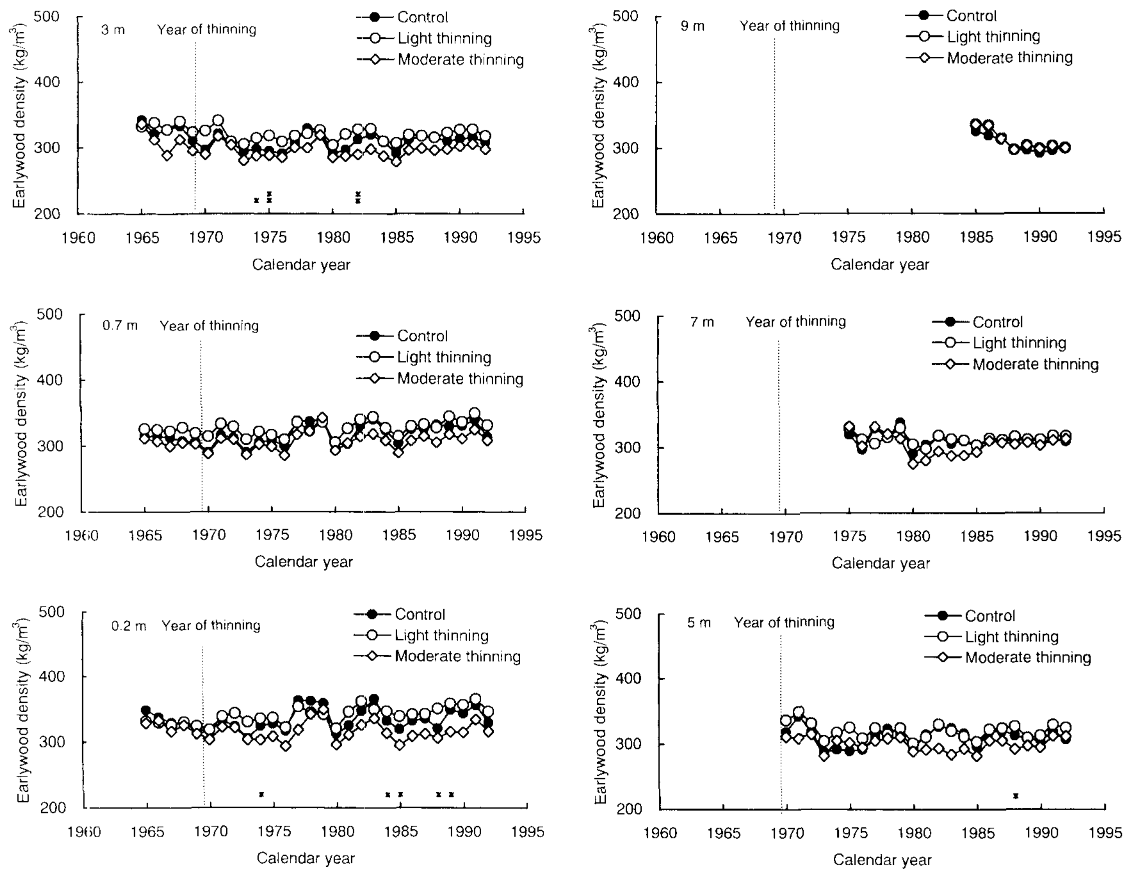

FIG. 8. Variation of earlywood density with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

addition, at any stem height, latewood width tended to be relatively stable throughout the growth years, and there was no appreciable difference among the six stem heights. This confirms that in balsam fir earlywood width showed a significant response, limited to the lower part of the stem (up to 5 m high), whereas latewood width showed little response regardless of the stem height level.

In the low part of the stem (up to 5 m high), the moderately thinned plots tended to have a lower latewood percentage than the control (Fig. 6), which results from an increased earlywood width and a relatively stable latewood width after the treatment. In fact, significant differences in the average latewood percentage after the treatment were found between the moderately thinned plots and the control in the low part of the stem (Table 3). However, in the upper part of the stem (7 m and 9 m high), the average latewood percentage in the moderately thinned plots and the control was comparable.

Figure 7 shows the variations of ring density at the six different stem heights. Overall, wood density tended to increase toward the bark at most stem heights. It also fluctuated considerably in the rings formed during the years the stand was attacked by the spruce budworm (from 1977 to 1979, and from 1982 to 1984) at all the stem heights studied (except at 9 m high). At each of the six stem heights, there were no significant differences in wood density between the thinned and control plots

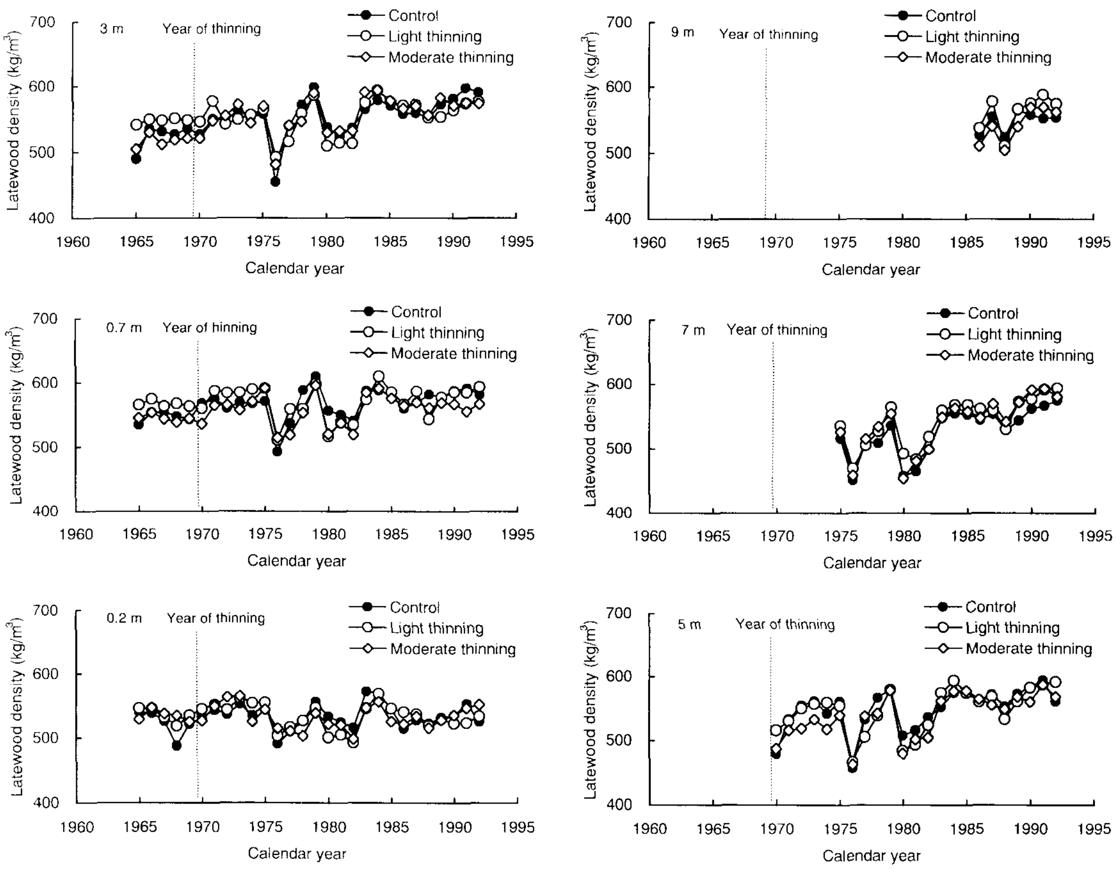

FIG. 9. Variation of latewood density with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

for most rings either before or after the treatment, although the moderately thinned plots appeared to have a slightly lower wood density. As shown in Table 4, at the stem heights of up to 5 m, average wood density after the treatment in the moderately thinned plots was slightly lower than the control, and the differences were statistically significant at the 10% level. However, significant differences between the moderately thinned plots and the control were not found at 7 m and 9 m. This confirms that in balsam fir, at any stem height, precommercial thinning had a considerably smaller effect on wood density than on the annual radial growth rate. Moreover, following the moderate thinning, wood density tended to decrease only in the low part of the stem (up to 5 m high). It should be pointed out, however, that thinning also affects other important wood quality attributes (e.g., crown structure, knottiness, clear log length, stem taper) which affect product quality and value recovery, as reported by Zhang et al. (1998). For example, Zhang et al. (1998) found that the wood density of heavily thinned balsam fir plots decreased by only 5.5% compared to the control, whereas the strength and stiffness of the lumber from the heavily thinned plots decreased by 11.3% and 13.3%, respectively. Much of the decrease in lumber strength and stiffness was due to increased knottiness in the heavily thinned plots. Therefore, in addition to wood density, other important wood quality attributes need to be considered in evaluating thinning impact on product quality and end uses.

Figure 8 shows the variations of earlywood

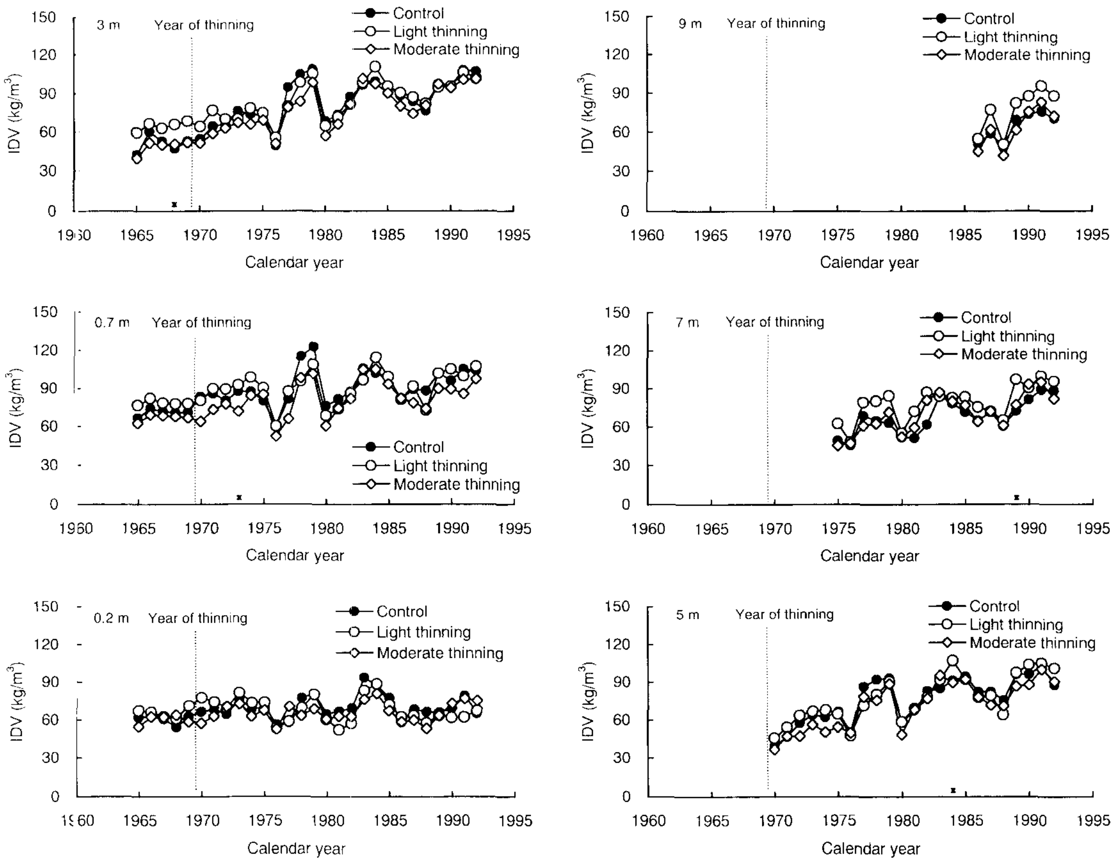

FIG. 0. Variation of intra-ring wood density variation (IDV) with calendar year for the moderately and lightly thinned plots and the control at the six different stem heights.

density with calendar years at the six different stem heights. At each stem height, earlywood density tended to be relatively stable throughout the growth years, and the differences among the six stem heights were not appreciable As shown in Fig. 8 and Table 4, the differences in earlywood density among the control and the moderately and lightly thinned plots at the six stem heights were similar to those found at breast height. In fact, earlywood density after the treatment for the thinned and control plots was very comparable, although the moderately thinned ones appeared to have a slightly lower wood density than the control. There were no significant differences in average earlywood density after the treatment at any stem height (except at 0.2 m high) between the thinned and control plots. This confirms that in balsam fir earlywood density was not affected significantly by precommercial thinning at any stem height.

Figure 9 shows the variations of latewood density with calendar year at the six different stem heights. At each height, latewood density tended to increase slightly toward the bark despite some variation in the rings formed during the years the stand was attacked by the spruce budworm (1976, 1980, 1981, and 1982). With increasing stem height, however, the tendency to increase with calendar year appeared to be increasingly pronounced. For example, latewood density at the 0.2-m stem height tended to increase little with calendar year, whereas at 5 m it showed a steady increase. As shown in Fig. 9, at any of the six heights there were no statistically significant differences in latewood density between the moderately and lightly thinned plots and the control for any year either before or after the treatment, as found at breast height. In addition, no significant differences in average latewood density after the treatment were found between the thinned and control plots (Table 4). This indicates that in balsam fir latewood density was not affected significantly by precommercial thinning at any stem height.

Figure 10 shows the intra-ring wood density variation (IDV) in relation to calendar year at the six different stem heights. At all heights, IDV overall tended to increase steadily toward the bark. With increasing stem height, however, the tendency to increase with calendar year appeared to be increasingly pronounced. At any of the six heights, like at breast height, there were no statistically significant differences in IDV between the thinned and control plots for most rings either before or after the treatment, although the moderately thinned plots tended to have a slightly lower IDV (Fig. 10). In fact, Table 4 shows that at the stem heights of up to 5 m, the moderately thinned plots on average had a slightly lower IDV after the treatment than the control and the lightly thinned plots, but the differences between the moderately thinned plots and the control plots were not statistically significant. These results suggest that in balsam fir moderate thinning may somehow reduce the intra-ring wood density variation, especially in the low part of the stem, and thus produce more uniform wood.

CONCLUSIONS

Based on the present study on balsam fir, the following conclusions can be drawn:

1. The annual radial growth rate of balsam fir showed a positive response to precommercial thinning (PCT), especially in the low part of the stem (up to 5 m high), and the response lasted for 7 years. A moderate thinning intensity, however, is needed to achieve a significant increase in annual diameter growth.
2. The thinning effect on annual radial growth was limited primarily to the earlywood width, whereas the latewood width showed little response to PCT. As a result, the latewood percentage was affected by PCT. The light thinning and control plots, however, had a comparable earlywood width and latewood percentage.
3. Both earlywood density and latewood density showed little response to PCT in balsam fir. However, average wood density of growth rings tended to be lower in the moderately thinned plots due to a decreased latewood percentage.
4. The moderate thinning intensity may somehow reduce the intra-ring wood density variation and thus produce more uniform wood in balsam fir.
5. In balsam fir the thinning responses tended to weaken appreciably with increasing stem height. The remarkable responses were observed in the low part of the stem (up to 5 m), whereas little responses were found in the upper part of the stem. As a result, an increased stem taper may result from PCT in balsam fir.

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