

Managing plantation density through initial spacing and commercial thinning: yield results from a 60-year-old red pine spacing trial experiment¹

Nelson Thiffault, Michael K. Hoepting, Jeff Fera, Jean-Martin Lussier, and Guy R. Larocque

Abstract: We report on a 60-year-old red pine (*Pinus resinosa* Aiton) spacing trial experiment located in Ontario, Canada, that included the combinations between six initial spacings (from 1.2 to 3.0 m) and the presence or absence of a commercial thinning (CT) regime, as well as their impacts on quadratic mean diameter (QMD) and stand volume yield. The CT regime, initiated at age 30, targeted a residual basal area (BA) of 38 m²·ha⁻¹ after each of four entries. Without thinning, as initial spacing increased, QMD increased; gross and net volume production peaked in the 2.1–2.4 m spacings. With thinning, similar trends with spacing were evident for QMD, although piece sizes were larger and differences between spacings were lower. The immediate increase of mean tree size caused by tree selection explained most of the differences in QMD between thinned and unthinned plots. Thinning to a common target BA resulted in similar standing volume across spacings. Cumulative gross yield was similar between spacings of <2.1 m for both thinned and unthinned stands and decreased for thinned plots for wider spacings. Greater net volume production in thinned stands with the narrower spacings confirmed that mortality was captured. Lower gross and net production for wider spacings suggested that thinning resulted in underutilized growing space.

Key words: silviculture, stand density management, plantation, thinning, *Pinus resinosa*, long-term silviculture experiment.

Résumé : Cette étude porte sur un dispositif expérimental d'espacement initial de pin rouge (*Pinus resinosa* Aiton) planté en Ontario, au Canada, il y a 60 ans. Le dispositif était composé des combinaisons de six espacements initiaux (de 1,2 à 3,0 m) et de la présence ou de l'absence d'un régime d'éclaircie commerciale (EC) et visait à évaluer l'impact des traitements sur le diamètre moyen quadratique (DMQ) et la production en volume du peuplement. Le régime d'EC, qui a débuté à 30 ans, visait à obtenir une surface terrière (G) résiduelle de 38 m²·ha⁻¹ après chacune des quatre interventions. En l'absence d'éclaircie, le DMQ augmentait avec l'espacement initial alors que les productions en volume brut et net ont atteint des valeurs maximales pour des espacements entre 2,1 et 2,4 m. Quand le régime d'éclaircie était appliqué, nous avons observé des tendances similaires d'augmentation du DMQ avec l'espacement, même si la taille des arbres était plus grande et que les différences entre les espacements étaient plus faibles. Une grande partie des différences du DMQ entre les placettes éclaircies et non éclaircies était expliquée par l'augmentation immédiate de la taille moyenne des arbres causée par la récolte des arbres sélectionnés. La G résiduelle commune à toutes les éclaircies a mené à des volumes sur pied similaires, peu importe l'espacement initial. La production brute cumulée était similaire entre les espacements plus petits que 2,1 m dans le cas des peuplements éclaircis et non éclaircis, et était plus faible pour les espacements plus grands dans le cas des placettes éclaircies. Une plus grande production en volume net dans les peuplements éclaircis dont les espacements étaient les plus petits indique que la mortalité a été récoltée. Des productions en volume brut et net plus faibles dans le cas des espacements plus grands indiquent que l'éclaircie a provoqué une sous-utilisation de l'espace de croissance. [Traduit par la Rédaction]

Mots-clés : silviculture, gestion de la densité des peuplements, plantation, éclaircie, *Pinus resinosa*, expérience sylvicole de longue durée.

Introduction

Planted forests are estimated to provide about one-third of the world's industrial stemwood production (Jürgensen et al. 2014). This proportion has globally increased over the past two and half

decades (Payn et al. 2015). In terms of fibre production, plantation forestry offers an opportunity for increased productivity compared with natural forests, a combined result of planted material that comes from breeding program strategies, optimized stocking

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of desired species that maximize space use, and applications of cultural treatments at many stages of stand development (Savill et al. 1997; West 2014). The high yields of planted forests are also viewed as an opportunity for achieving wood fibre production and allowing the provision of other ecosystem services (e.g., wildlife habitats, carbon sequestration, and conservation) at the landscape level (Malouin et al. 2016; Messier et al. 2003; Paquette and Messier 2010; Park and Wilson 2007). However, the success of this zoning strategy relies on the capacity of the planted areas to provide the expected timber production, both in terms of quantity and quality, so that harvesting pressure can be reduced on the remaining landscape (Tittler et al. 2012). Moreover, achieving plantation forestry objectives is dependent on substantial investments (e.g., tree breeding, nursery production, and seedling delivery, handling, and planting), most of which appear early in silviculture scenarios, thus increasing their pressure on financial returns. Hence, it is critical that plantation silviculture scenarios be optimized so that planted forests meet the expected production objectives.

Density control is a key element by which foresters manipulate stand growth and yield (Davis et al. 2001). In plantation forestry, stand density can be managed at the plantation initiation stage by varying the distance between the planted trees. Whereas higher planting densities result in greater volume production at the stand level because site occupancy is optimized, individual tree size is maximized at lower density because of reduced intraspecific competition. This pattern of an antagonistic effect of planting density on stand wood yields and mean tree size has been observed for many species and many parts of the world (see West 2014). Stand density can also be managed later in the development of a stand through thinning operations. Stand thinning, either before or after trees have reached a commercial size, is used to concentrate the finite site environmental resources on a few, selected individual crop trees (Savill et al. 1997). By reducing stand density, thinning generally reduces intraspecific competition and increases light and nutrient availability to residual trees, hence improving their growth and reducing the rotation age to achieve a target tree size (Smith et al. 1997). Thinnings also have a harvesting function, providing intermediate income from small-sized products, prior to the final harvest. These are potential solutions to mitigate mid-term timber supply shortages at the scale of forest management units caused by major forest disturbances.

For many decades, red pine (*Pinus resinosa* Aiton) has been extensively planted in the northern United States and southeastern Canada (Rudolf 1990). It grows fairly rapidly compared with most North American tree species and has the potential for high-value products, particularly utility poles (Gilmore and Palik 2006). Moreover, the species presents potential for the rehabilitation of sites that have been degraded after decades of farming activities (McPherson and Timmer 2002). Many studies have investigated the short- to long-term impact of establishment plantation density on red pine plantation productivity (Homagain et al. 2011; Larocque and Marshall 1993; Lundgren 1981; Stiell 1964; Stiell and Berry 1973), whereas others have documented how thinning regimes influence individual stem growth and stand yield (Bradford and Palik 2009; Liechty et al. 1986; Powers et al. 2010). However, to our knowledge, few have looked at the long-term interactions between these silviculture decisions, compared with other species and context such as loblolly pine (*Pinus taeda* L.) in the southern United States (Baldwin et al. 2000). Optimum planting densities and thinning intensities can be derived from density management diagrams (Smith and Woods 1997), but they are generally based on assumptions derived from the observations of unmanaged stands, rather than empirical data from real stand density management treatments. Long-term studies investigating the main and interacting effects of initial density and thinning are highly valuable

(Pretzsch et al. 2019); they provide empirical data to support decision-making and are used in growth and yield modelling (e.g., Larocque 2002).

We investigated the main and interacting long-term effects of initial planting density and a commercial thinning (CT) regime on tree- and stand-level growth development of red pine plantations established in the Great Lakes – St. Lawrence forest region of Ontario, Canada. The data we used are derived from a 60-year-old red pine plantation experiment comprising all the combinations between six initial spacings and the presence or absence of a CT regime comprising a series of thinning, combining row and crown thinning of crop trees, in addition to the harvest of small and low-vigour trees, to reach a constant residual basal area (BA) target. This experiment was at the core of studies on the effects of competition on growth efficiency and crown development (Larocque and Marshall 1993, 1994a, 1994b), wood density (Larocque and Marshall 1995; Larocque 1997), and development of a distance-dependent competition model (Larocque 2002).

We tested the general hypothesis that there is a multiplicative effect between density management at planting and at the CT stage to influence tree size and volume production at the stand level at the age of 60 years. We posited that mean tree size, expressed in terms of quadratic mean diameter (QMD), would be greater in thinned plots than in unthinned plots, but that these differences would decrease as initial spacing increased, because

- (i) the immediate increase of the mean tree size due to tree selection (also known as the “chainsaw effect”) is more important in denser plots with such a thinning prescription and
- (ii) the mean release of the competition around the residual trees will be more pronounced in denser plots (i.e., greater reduction of intraspecific competition) because the initial competition pressure and the number of released trees per hectare are greater than those of plots with lower initial density.

As a corollary, we also expected that individual tree size would increase with increasing initial spacing, but that this effect after 60 years would be less important in thinned plots than in unthinned plots. At the stand level, based on Langsaeter’s hypothesis (Smith et al. 1997), we expected all treatments to produce a similar cumulative gross yield, and that the thinning regime would increase net production by decreasing tree mortality.

Materials and methods

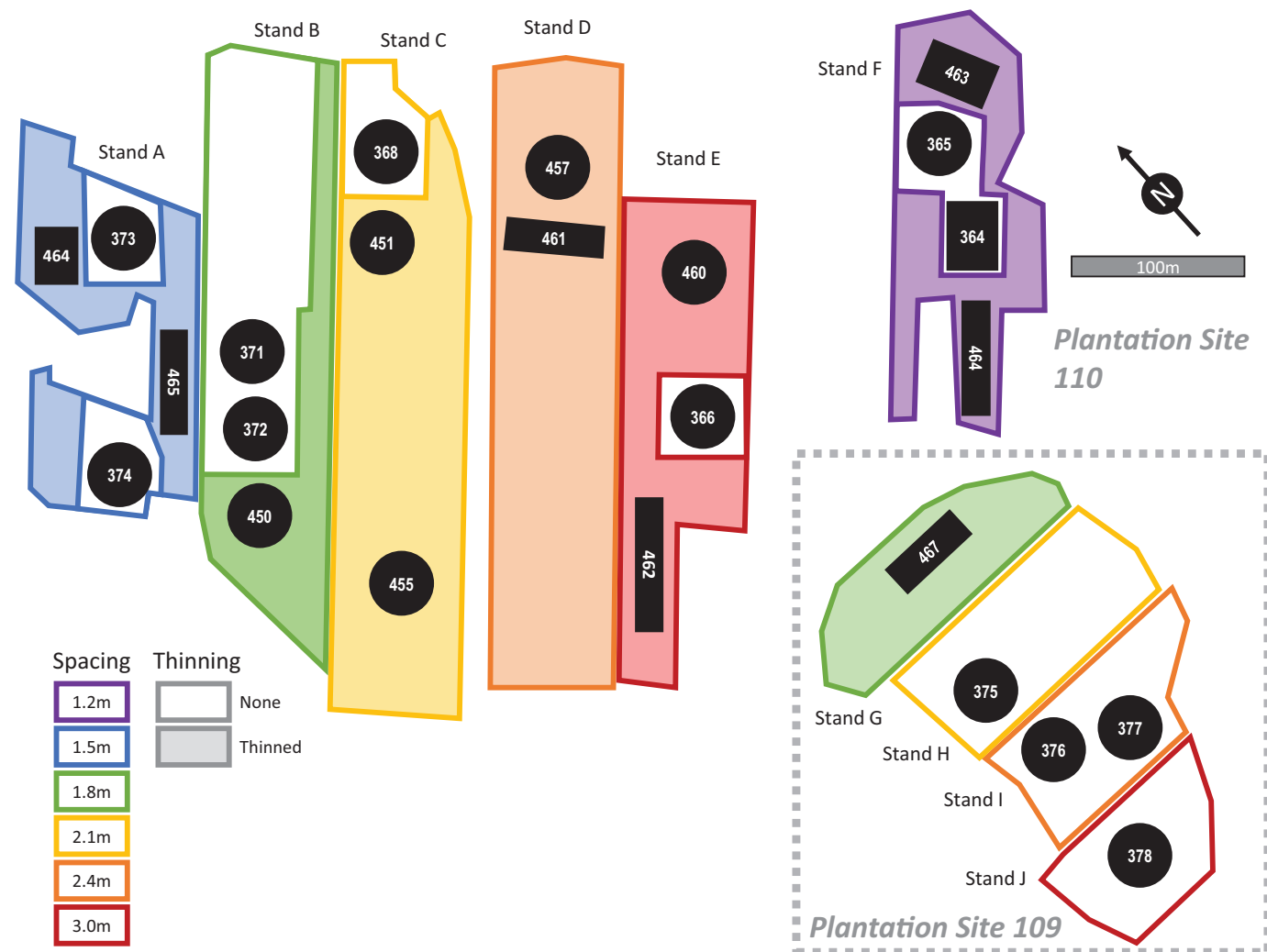
Study region and site

We conducted the study in two red pine plantation sites, established on an abandoned farmland in 1953 and located a few hundred metres apart, at the Canadian Nuclear Laboratories (formerly Atomic Energy of Canada Ltd.), near the Petawawa Research Forest (formerly the Petawawa National Forestry Institute) in Chalk River, Ontario (46°00′N, 77°26′W). The daily mean temperature is 5.6 °C, with mean total rainfall of 682 mm and total snowfall of 182 cm (Environment Canada 2010). The soil of both plantation sites is a deep aeolian sand deposit providing uniform growth conditions for red pine (Penner et al. 2001). Site index is estimated at 24 m at 50 years, which is one of the highest values for this species (Buckman et al. 2006; Plonski 1974).

Study design and treatments

The experiment was originally established as a factorial design with two plantation sites to test the effects of initial spacing on planted red pine growth and yield. Ten stands of 1.6 ha (on average) were planted in 1953, using 2 + 2 bareroot stock, creating a gradient of six planting densities with initial square spacings of 1.2, 1.5, 1.8, 2.1, 2.4, and 3.0 m (Fig. 1) and allocated randomly to

Fig. 1. Schematic map of the two plantation sites and 10 stands, along with the distribution of spacing and thinning treatments and sampling plots (in black) at the red pine (*Pinus resinosa*) spacing trial experiment of the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories (Chalk River, Ontario, Canada). [Colour online.]



experimental stands. In 1954 (1 year after planting), dead seedlings were replaced through fill-planting to maintain the target initial planting densities. In 1962, two 0.101 ha sampling plots were established for each spacing and measured periodically (see Measurements). For spacings of 1.2 and 1.5 m, both sampling plots were located within the same planted area, as the treatment was not established in the second one.

In 1982, thinning was included in the experiment (Figs. 1 and 2). Although three thinning regimes (plus a control) were implemented overall, this paper focusses on the single thinning regime that was applied to all six spacing treatments. In the first and largest plantation site, subplots were created within the initial stands, with a randomized application of the thinning treatment (with or without thinning) (Fig. 1). The area of the subplots varied among the stands. In the second and smaller plantation site, only the 1.8 m spacing treatment was thinned, whereas the others were not. Additional 0.10 ha (0.08 ha in one instance) sampling plots were established in 1981, to have two sampling plots per combination of spacing \times thinning treatments, for a total of 24 sampling plots (Fig. 1). As thinning treatments and sampling plots were not evenly distributed among the stands, the experiment setup does not qualify as a split-plot design.

The thinning regime consisted of four successive interventions maintaining a target residual BA of $37.9 \text{ m}^2 \cdot \text{ha}^{-1}$ ($165 \text{ ft}^2 \cdot \text{acre}^{-1}$) (based on the recommendation of Smithers 1954). This corresponds to about 70% of the highest BA found among the initial 12 experimental units ($54.2 \text{ m}^2 \cdot \text{ha}^{-1}$). Variations in the thinning modalities were applied within the experimental units in regard to tree selection (row, crown, or low thinning), but these were not considered in the analysis. The thinning treatment was repeated systematically in 1992, 2002, and 2013, bringing BA down to the same original residual BA target value of $37.9 \text{ m}^2 \cdot \text{ha}^{-1}$. In the first three thinnings, all felling was done motor-manually, along with cable skidding. For the fourth thinning, a single-grip harvester was used for felling and bucking, and a forwarder was used to extract the logs.

Measurements

Tree dimensions (diameter at breast height (DBH; measured at 1.3 m) and height) were assessed before each of the thinning entries, using the permanent sampling plots (0.08–0.101 ha) established in each spacing \times thinning treatment combination. Whereas DBH was measured for every tree in each sample plot, we measured total height on a subsample of trees (19%–76% of live stems)

Fig. 2. Examples of (A) unthinned and (B) thinned experimental units at the red pine spacing trial experiment of the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories. Photographs were taken in 2018 (age 65). [Colour online.]



through the range of diameters. Postthinning metrics are based on subtracting thinned trees from prethinning assessments. This paper focusses on 60-year-old measurements (data collected in 2013, before and after the last thinning entry).

Calculations and statistical analyses

We performed all data handling and analyses using R statistical software version 3.6.1 (R Core Team 2013). We predicted the heights for the remaining stems with a height–diameter function of the following form: $\text{height} = 1.3 + e^{a + b/(\text{DBH} + 1)}$ (Wykoff et al. 1982; described by Huang et al. 1992), using a mixed-effect model. We calculated the random parameter estimates (a and b) specific to each sampling plot and measurement year (see parameters for each spacing \times thinning \times year combination in Supplementary data²) using the nlme function of the nlme package in R (Pinheiro et al. 2019) and applied it to predict tree height for the individuals without explicit height measurements. By doing so, the possible spacing and thinning treatment effects on the height–diameter relationship were considered in the plot-level random effect.

Top height (mean of the tallest 100 stems per hectare, in metres), BA, QMD, merchantable volume, and total volume were calculated for each sampling plot. BA (in square metres per hectare) was calculated for each live tree using DBH and plot area, and then at the stand level by summing all the trees within the sampling plots. QMD (in centimetres), which represents the tree of mean BA, was calculated using BA and live stem density (in number of stems per hectare). The chainsaw effect was the difference in QMD before and immediately after each thinning, with the cumulative chainsaw effect being the sum of the effect resulting from all four thinning entries. The total volume lost to mortality was tracked starting in 1982, corresponding with the establishment of the sampling plots in the thinned stands. For each experimental unit, we calculated total standing, thinned, and dead volumes and

cumulative gross and net volumes (from 1982 onwards, in cubic metres per hectare) after each thinning entry using Zakrzewski and Penner's (2013) volume equations. Cumulative gross yield was calculated as the total standing volume plus total volume lost to mortality plus the total volume removed during all four of the thinning entries. Cumulative net yield was calculated as the cumulative gross yield minus the cumulative mortality volume. Based on regional market requirements, merchantable volume calculations were made based on a minimum stem length of 2.4 m (8 ft log + 0.2 m trim), a stump height of 0.2 m, and a minimum inside-bark top diameter of 12.7 cm (5 inches).

We used analyses of variance (ANOVAs) to evaluate the effects of initial spacing and thinning and their interaction on QMD and standing volume, merchantable volume, cumulative volume lost to mortality, and cumulative gross and net yields of the stands after the last thinning using linear models (lm function). Using Bartlett's tests and standard graphical procedures (normal histograms and quantile–quantile (Q–Q) plots), we examined model residuals to ensure that assumptions of homogeneity and normality were satisfied; no transformations were deemed necessary. We calculated estimated marginal means and Tukey's honestly significant difference (HSD) pairwise comparisons with the emmeans package (Lenth 2019) and used $\alpha = 0.05$ as a threshold for significance. Finally, we used correlation analyses to explore relationships between differences in QMD in thinned and unthinned plots and the gradient of initial spacing.

Results

At age 60, after the latest CT in fall 2013, the mean top height was 27 m (range: 26.3–28.5 m). BA averaged $65.3 \text{ m}^2 \cdot \text{ha}^{-1}$ in the unthinned plots (range: $58.7\text{--}70.4 \text{ m}^2 \cdot \text{ha}^{-1}$) and $37.9 \text{ m}^2 \cdot \text{ha}^{-1}$ in the thinned plots (range: $37.2\text{--}38.3 \text{ m}^2 \cdot \text{ha}^{-1}$).

²Supplementary data are available with the article at <https://doi.org/10.1139/cjfr-2020-0246>.

Fig. 3. Cumulative differences between the initial and residual quadratic mean diameter (QMD) of planted red pine for the four consecutive thinnings as a function of initial spacing at the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories. This is equal to the cumulative chainsaw effect, which is the change in mean tree diameter caused directly by the tree selection during the thinnings. Data are presented as mean \pm standard error from the sample plots. Both sample plots in the 1.5 m initial spacing resulted in similar values, hence the absence of error bars. [Colour online.]

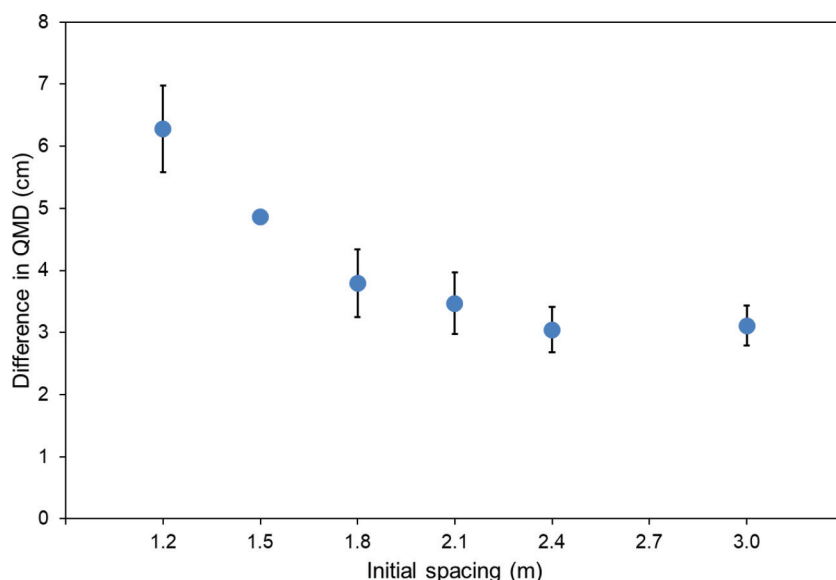


Table 1. Summary of analysis of variance (ANOVA) results for the main and interacting effects of initial planting density and a commercial thinning (CT) regime on quadratic mean diameter (QMD); total volume of standing, dead, and harvested trees; and cumulative gross yield 60 years after plantation of red pine (*Pinus resinosa*) at the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories.

Fixed effect	Num df	Den df	Volume ($\text{m}^3 \cdot \text{ha}^{-1}$)											
			QMD (cm)		Standing		Cumulative mortality		Cumulative harvest		Cumulative gross yield		Merchantable	
			F	p value	F	p value	F	p value	F	p value	F	p value	F	p value
Spacing	5	11	114.9	<0.001	20.5	<0.001	75.4	<0.001	8.3	0.011	10.7	<0.001	23.6	<0.001
Thinning	1	11	704.8	<0.001	2082.1	<0.001	443.7	<0.001			10.1	0.008	997.8	<0.001
Spacing \times thinning	5	11	6.3	0.004	31.5	<0.001	60.0	<0.001			8.7	0.001	31.1	<0.001

Note: Num df, numerator degrees of freedom; Den df, denominator degrees of freedom. A one-way ANOVA was used for Cumulative harvest, with Num df = 5 and Den df = 5.

At the onset of the thinning regime in 1982, BA ranged from 42 to 58 $\text{m}^2 \cdot \text{ha}^{-1}$ and stand density ranged from 960 to 4366 trees $\cdot \text{ha}^{-1}$, after the gradient created by the different initial spacings (see number of stems per hectare in Supplementary data²). At the first thinning, the reduction in BA to a uniform residual value led to a greater reduction in stem density in the plots with smaller spacing, but still left a greater number of residual trees than in the wider spacings. Differences in thinning intensity and residual density among spacing treatments decreased progressively after the subsequent thinnings (see Supplementary data²).

The tree selection rules applied at each thinning caused an instantaneous increase in QMD, which, once cumulated for the four treatments, ranged from 3.1 to 6.3 cm, in favour of the narrowest spacing (Fig. 3).

Tree-level response

Initial planting density and CT interacted to influence QMD (Table 1). In unthinned plots, mean QMD did not differ significantly among initial spacings of 1.2, 1.5, and 1.8 m (Fig. 4). Without a CT regime to reduce density, a spacing of at least 2.1 m was necessary to detect a significant increase in tree diameter compared with the narrower spacings. A 9 cm gain in QMD was obtained between the 2.1 and 3 m spacings over 60 years. Without

thinning, a 2.4 m initial spacing was required to reach the minimal diameter observed in thinned plots, which occurred in the 1.5 m spacing (Fig. 4).

Thinning slightly increased the number of large trees for the narrower spacings, but not as much for the larger spacings. In these cases, the thinning regime eliminated the smaller size classes (see histograms of diameter distribution in Supplementary data²). Thinning caused a significant increase in QMD for all initial spacings; however, differences among the levels of initial spacing were statistically different only when reaching the 2.4 m initial spacing. The difference between thinned and unthinned plots ranged from 4.9 to 9.1 cm, with a correlation of -0.78 with initial spacing. However, most of this difference was caused by the chainsaw effect, which was highly correlated with initial spacing ($r = -0.87$). By subtracting the chainsaw effect from the observed difference between thinned and unthinned plots, we approximated the effect of thinning on tree growth. This ranged from 1.9 to 3.9 cm, with no significant correlation with the initial spacing ($r = -0.006$).

Stand-level response

After 60 years, standing volume in the unthinned plots peaked in the 2.1 and 2.4 m treatments (910–930 $\text{m}^3 \cdot \text{ha}^{-1}$) and was unaffected by

Fig. 4. Interacting effect of initial planting density and a commercial thinning (CT) regime on QMD of planted red pine 60 years after plantation establishment at the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories. Data are presented as mean \pm standard error (parameter estimates from the fixed effects of the analysis of variance (ANOVA)). Data points with the same lowercase letters for both thinned and unthinned sample plots are not significantly different at $\alpha = 0.05$ based on Tukey's honestly significant difference (HSD) pairwise comparisons. [Colour online.]

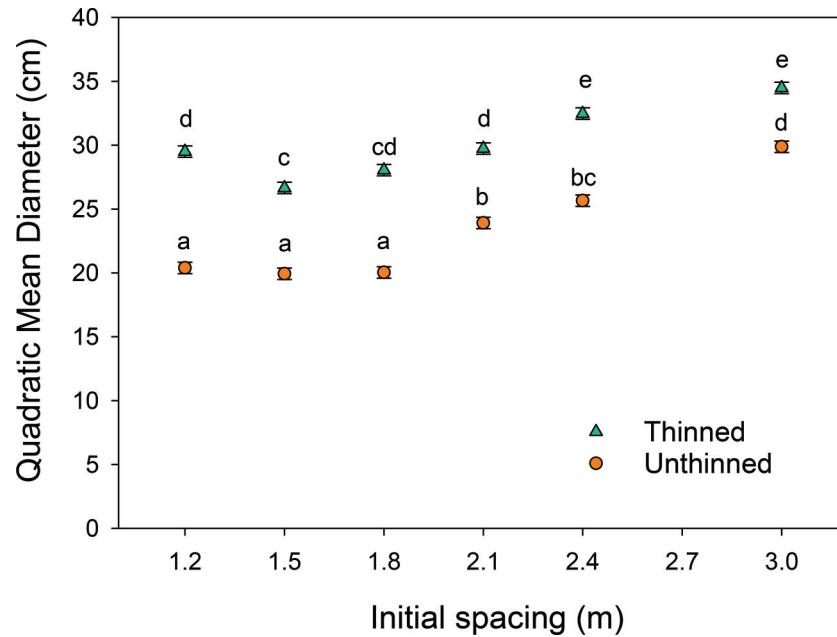


Table 2. Least squares means for thinning and initial spacing treatments 60 years after plantation of red pine at the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories.

Fixed effect		Total volume ($\text{m}^3 \cdot \text{ha}^{-1}$)											
		Standing			Merchantable			Cumulative mortality			Cumulative thinning harvest		
Thinning	Spacing (m)	Mean	SE	Diff.	Mean	SE	Diff.	Mean	SE	Diff.	Mean	SE	Diff.
No	1.2	707.0	13.5	b	611.8	16.4	b	246.9	7.9	d			
	1.5	722.8	13.5	b	616.1	16.4	b	182.3	7.9	c			
	1.8	751.2	13.5	b	644.1	16.4	b	86.2	7.9	b			
	2.1	911.3	13.5	cd	843.1	16.4	c	83.3	7.9	b			
	2.4	925.2	13.5	d	868.4	16.4	c	27.7	7.9	a			
	3.0	847.8	13.5	c	809.6	16.4	c	12.4	7.9	a			
Yes	1.2	469.9	13.5	a	448.4	16.4	a	20.4	7.9	a	526.1	28.3	b
	1.5	459.3	13.5	a	433.5	16.4	a	14.0	7.9	a	420.4	28.3	ab
	1.8	468.2	13.5	a	444.8	16.4	a	11.3	7.9	a	445.8	28.3	ab
	2.1	445.1	13.5	a	424.7	16.4	a	6.9	7.9	a	359.6	28.3	a
	2.4	450.3	13.5	a	432.8	16.4	a	11.9	7.9	a	378.2	28.3	ab
	3.0	434.3	13.5	a	418.4	16.4	a	1.4	7.9	a	286.5	28.3	a

Note: For a given variable, values with the same lowercase letters are not significantly different at $\alpha = 0.05$ based on Tukey's honestly significant difference (HSD) pairwise comparisons. SE, standard error; Diff., difference.

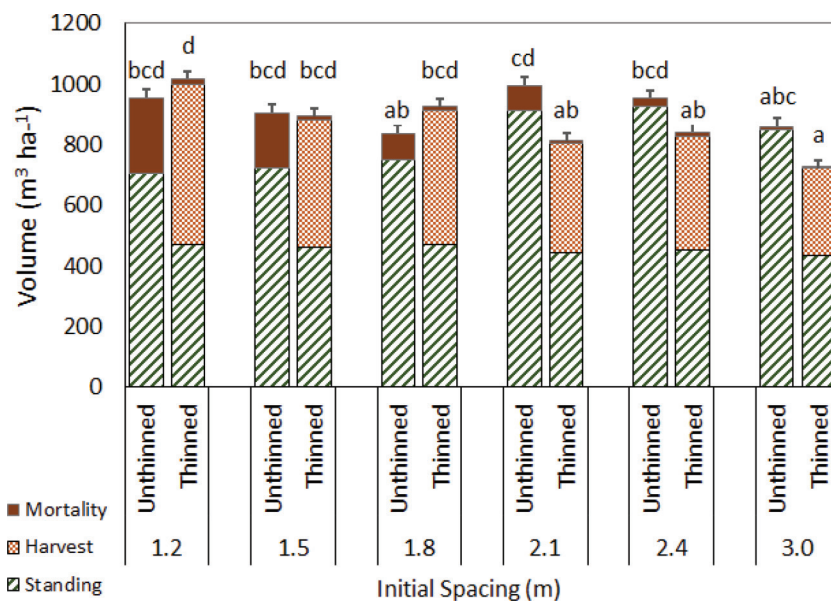
initial spacing in the 1.2–1.8 m treatments ($710\text{--}750 \text{ m}^3 \cdot \text{ha}^{-1}$) (Table 2; Fig. 5). After four thinning occurrences, total standing volume was lower than in the unthinned plots but did not differ significantly among all spacing treatments ($430\text{--}470 \text{ m}^3 \cdot \text{ha}^{-1}$). Similarly, merchantable volume was higher in unthinned plots than in thinned stands, with the highest volumes found in the 2.1–3.0 m spacing treatments ($p < 0.001$; Table 2). Merchantable volume in thinned stands was consistent across spacing treatments (Table 2).

Thinning effectively reduced mortality: on average, $15.0 \text{ m}^3 \cdot \text{ha}^{-1}$ across the initial spacings were lost to mortality between 1982 and 2013 (Table 2). Conversely, mortality volume in the controls

was as high as $247 \text{ m}^3 \cdot \text{ha}^{-1}$ in the 1.2 m spacing, declined as spacing increased, and became relatively close to levels in thinned plots for the 2.4 and 3.0 m spacings (Table 2).

The cumulative harvest volume from the four thinnings only differed significantly between the 1.2 and 3.0 m spacings, with 45% more volume harvested in narrower spacings (Table 2). Cumulative gross yield was similar between thinned and unthinned plots across the range of initial spacings, with the exception of the 2.1 m treatment for which the yield in unthinned plots was over $180 \text{ m}^3 \cdot \text{ha}^{-1}$ greater than that of thinned plots, thus triggering a significant interaction effect. The cumulative net yield was

Fig. 5. Interacting effect of initial planting density and a CT regime on cumulative gross yield of planted red pine 60 years after planting at the Petawawa Research Forest, on the lands of the Canadian Nuclear Laboratories. Cumulative gross yield was calculated as the total standing volume + cumulative total volume lost to mortality + cumulative total volume removed during all four of the thinning entries. Data are presented as stacked bars \pm standard error of the total yield. Bars with the same lowercase letters do not have statistically different cumulative gross yield at $\alpha = 0.05$ based on Tukey's HSD pairwise comparisons. See Table 2 for standard error and pairwise comparisons of total standing, mortality, and harvested volumes. [Colour online.]



22%–40% greater for thinned plots for spacing of <2.1 m, and 10%–15% lower beyond this threshold (Fig. 5).

Discussion

We first observed that, for all initial planting densities, mean tree size expressed in terms of QMD was greater in thinned plots than in unthinned plots. This thinning effect on individual tree size is in agreement with our predictions and confirms results reported in many density management studies (e.g., Albaugh et al. 2017; Das Gupta et al. 2020; Gauthier and Tremblay 2019). By reducing density in stands that have reached the stem exclusion stage, thinning redistributes resources to fewer individuals, hence resulting in increased growth compared with unthinned conditions (Oliver and Larson 1996). A mix of crown thinning and thinning from below was employed in all thinnings, except in 1982 when row thinning was required for the first entry in spacings narrower than 2.4 m to allow for machine circulation. This thinning method, in addition to increasing resource availability for the remaining trees, also increased the mean tree size by removing the smaller and poorer quality stems (Ferguson et al. 2011). This chainsaw (selection) effect has an immediate impact on diameter distribution (Hynynen 1995; Nogueira et al. 2015).

We expected that the positive influence of thinning on tree size would be dependent upon initial spacing. This prediction also proved true, with a significant interaction between initial planting density and the thinning treatment in driving QMD. We observed smaller differences in tree QMD between the thinned and unthinned plots in the larger initial spacings than in the narrower initial spacings (e.g., a 44% increase in QMD in the 1.2 m spacing, compared with a 17% increase in QMD in the 3.0 m spacing). The chainsaw effect was responsible for 60%–70% of the differences in QMD between thinned and unthinned plots at 60 years, with a strong correlation with initial spacing.

We further expected that individual tree size would increase with increasing initial spacing, but that this effect would be less

important in thinned plots than in unthinned plots. This was also the case: QMD increased by 44% from the 1.2 m to the 3.0 m spacing in the unthinned plots and by 17% in the thinned plots. Consequently, thinning tended to buffer the differences among spacings observed without thinning, an effect that was also reflected in merchantable volume.

Diameter growth is strongly affected by initial tree density and the density left after thinning (Larocque and Marshall 1993; Lundgren 1981), as cambial meristems are weak sinks for photosynthates (Kozłowski 1992) and thus sensitive to small variation in resource levels (Lanner 1985). Hence, both the increase in initial spacing and the CT regime brought the trees closer to optimal conditions for diameter growth, thereby reducing the relative gain associated with the other treatment. Trees growing in narrower spacings were initially subjected to greater levels of intraspecific competition than trees growing in wider spacings (Newton 2015a). In principle, the CT regime increased the base level of environmental resources, reducing the relative gain associated with a reduction in initial density. Our results suggest that the thinning regime cancelled the differences in resource availability among initial spacing plots: once the chainsaw effect was removed from the observed difference in QMD (thus estimating the difference in QMD caused by growth and survival after thinning), QMD was still greater for thinned plots than for unthinned plots; however, there was little significant difference between initial spacings.

At the stand level, we expected all treatments to produce a similar cumulative gross yield (Smith et al. 1997) and that the thinning regime would have captured tree mortality. However, we observed that cumulative gross yield varied as a function of interactions between the initial planting density and the CT regime and that some treatment combinations led to significantly greater cumulative gross yield than others. The trend towards greater cumulative gross yield in the unthinned plots with spacings of 2.1 m and wider compared with their thinned counterparts suggests that, at wider spacings, thinning to the standard 37.9 m²·ha⁻¹ BA target resulted in underutilized growing space.

Although thinning improves growth efficiency of residual trees, the treatment can also increase wind damage and tree mortality (Kuehne et al. 2016), with impacts on cumulative net yield (harvested + residual) (Moulinier et al. 2015). By examining the components of yield in unthinned stands, we observed that the 2.1–3.0 m initial spacings had greater standing volume and lower self-thinning mortality than the 1.2–1.8 m initial spacings. This, coupled with the generally larger trees, as indicated by QMD and merchantable volume, suggests that the larger spacings have produced more commercially favourable stands at age 60 years. Thinning allowed for some volume to be harvested earlier and, with the exception of plots with wider initial spacing (≥ 2.1 m), did not reduce cumulative net yield. The four thinning entries did remove more total volume in the stands with initial narrower spacings. However, given the lower value of smaller diameter trees, greater thinning harvest volume per hectare does not necessarily translate into higher value. In practice, selling small-sized red pine trees from thinnings in Eastern Canada is often challenging because there is little demand for either pulp or sawlog for this species. For overall value, an additional consideration is that when larger spacings are used to increase tree size, an increase in branch and knot size can be expected, which can have negative effects on product potential (Laidly and Barse 1979). Based on measurements 15 years earlier on the same study site, Penner et al. (2001) expressed the same caution and suggested that an initial spacing of 2.4 m or less should be used to reduce the number of stems disqualified from being utility poles. Overall, it appears that the 2.1 m spacing is optimal in terms of tree size and volume production and that the main benefit of thinning is to grow larger trees faster, although there may be a sacrifice in cumulative volume production. However, further analysis is needed to conclude about the economic optimality of the spacing and thinning regimes, considering current silviculture costs and product prices. Moreover, further analytical efforts could focus on interpreting these data using stand density management diagrams and (or) relative density estimations. Combined with information about end products and their value, such analyses could point to “best” density management regimes that would be useful to managers.

Our results are based on a unique long-term study that exemplifies both the challenges and the value of long-term silviculture experiments (Pretzsch et al. 2019). Long-term silviculture studies can present analytical limitations due to a limited number of replicates (either by design or because they have been destroyed), incomplete designs, or small experimental units, among other factors. With this in mind, generalization and statistical inference from our results should be made cautiously because the study included only two sampling plots representing each of the 12 treatment combinations. For example, in thinned plots, we observed that the 1.5 m initial spacing led to a significant decrease in QMD. This effect is difficult to interpret and might be an artefact associated with the limited number of plots. Because of this, the reader is invited to consider only the differences of large amplitude and the general trends; interpretation of the statistical tests must be done with a critical mind (Oksanen 2001). On the other hand, long-term silviculture experiments offer unique occasions to accumulate empirical data to support silviculture decisions. For example, this legacy trial offers valuable information for red pine, a high-value species. Data from this experiment can further be used to support (i) economic analyses accounting for the net present value of the treatments considering piece sizes, products (including carbon sequestration), and markets (e.g., Amateis and Burkhart 2013); (ii) model development (e.g., Larocque 2002; Newton 2015b); and (iii) validation of density management diagrams (Smith and Woods 1997). Further, we provide Supplementary data² to allow meta-analyses in the future, combining the observations from this study with others from the scientific literature. Moreover, this legacy experiment established within a recognized and protected research forest provides a unique opportunity to study

the long-term effects of density management on issues not foreseen when the trial was developed, for example, forest soil and nutrition (Prescott 2014).

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